High Capacity Innovations Enabling Scalable Optical Transmission Networks

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Abstract: We review the key optical innovations that enable scalable, efficient high capacity optical transmission networks and present results from recent industry leading technology trials in field deployed network and successful demonstration of emerging 400ZR/ZR+ technologies

1. Introduction

Bandwidth demands continue to grow driven by broadband, 5G, video, cloud and data center applications. Such growth places massive demands on optical transmission networks, driving the need for innovative solutions to ensure that the networks can deliver high capacities efficiently. 100G first became available ~10 years ago owing to practical innovation in coherent technology [1]. To meet the bandwidth demands, 100G is widely deployed in existing networks which are pre-dominantly on 50GHz WDM grid. In recent years, extensive research and development have been carried out on technologies beyond 100G [2-4], leveraging advanced modulation formats and higher baud rates. 200/400G are now being deployed in the networks, higher speeds beyond 400G are rapidly emerging, which will further improve spectral efficiency and network capacity. Another key technology is flexible grid which removes the fixed 50GHz grid restriction providing configurable spectral allocation to support higher speed optical channels and better spectral utilization. On the client side, traffic has also increased significantly over the years. Ethernet speeds at 10G and 100G are common in today's networks, e.g., from router interfaces, and is already increasing beyond 100GE following the IEEE 802.3bs standard on 200/400GE. With recent development in silicon technologies enabling from over 19Tbps in a single 1RU platform to digital coherent optics, coherent technologies are being implemented in pluggable optics, e.g., 400ZR/ZR+, allowing 400G Ethernet transmission from short reach through to longer reach DWDM distances within the same client optics ports. In this paper, we review key optical innovations which allow network operators to scale their optical infrastructures efficiently, such as advanced modulation format, flexible grid, superchannel as well as 400GE client, and show results from recent industry leading trials focusing on long reach probabilistic constellation shaping (PCS) DP-16QAM superchannel transporting 400GE in a live network [5]. We also look at emerging 400G ZR/ZR+ technologies and present results from successful experimental demonstration of 400G IP over DWDM. These leading edge technology trials and demonstration enable network operators to understand the performance, maturity and practical viability of emerging technologies, thereby giving confidence that they are fit for purpose and ready to deploy when required.

2. Key technologies enabling scalable optical transmission

Fig. 1 illustrates key enablers for scaling optical transmission speeds and capacities with three fundamental degrees of freedom: baud rate (or symbol rate), bits per symbol and number of wavelength channels. Advanced modulation formats (e.g., QPSK, 8QAM and 16QAM) allows more bits per symbol while advanced modulation formats and higher baud rates increase the speed of individual wavelength channels. Commercial optical transponders are now implemented with flexible modulation formats and baud rates as high as ~95GBaud, even higher baud rates in research laboratories [6]. The best choice of modulation formats depends on the rate and reach requirement as well as required operational margin. A recent development in modulation format is the probabilistic constellation shaping whereby shaping of the modulation constellation profile offers improved tolerance to noise and fiber nonlinearity leading to improved performance [7-8]. PCS also offers more granular line speeds to further optimize the capacity based on optical link quality. The third degree of freedom is the number of wavelength channels. Traditional DWDM networks use 50GHz fixed grid filters, typically with ~80-96 wavelengths in C band depending on specific vendor implementations. The 50GHz grid can be extremely limiting in supporting higher speed optical signals, also restricting how closely optical channels can be spaced, thereby limiting optimal utilization and capacity of a single fibre. Flexible grid based infrastructures do not restrict spectral allocation, thereby supporting higher speed channels such as 400Gb/s as well as improved spectral utilization by allowing channels closer when it is feasible. In the flexible grid regime, the concept of an optical channel is no longer a single wavelength, instead it can be a single capacity entity comprising multiple sub-channels which form an aggregate optical capacity often referred to as a 'superchannel'. Depending on the reach requirement, a given superchannel, e.g., 400G capacity, can be realized in different ways using: (a) 4×100Gb/s superchannel for ultra-long haul, (b) 2×200Gb/s superchannel for long haul and (c) a 400Gb/s single carrier for metro/regional distances. These technologies have been demonstrated and reported in several publications including 64GBaud signals over one of the first live deployed flexible grid networks [4]. It is also important to consider the evolution of client side technologies. Ethernet based traffic continues to play a dominant role in driving demands on optical transmission networks. Most of today's networks have Ethernet speeds at 10G/100G, which will evolve to 400GE and beyond following the IEEE 802.3bs standardization, where 400GE client interfaces are typically defined for 100m to 40km. Most recently coherent technology has been developed for shorter reach data center and metro applications with cost, footprint and interoperability being key priorities. 400ZR/ZR+ are the latest developments in this area where coherent transceivers with integrated DSP have been implemented in compact pluggable modules of same form factors as 400GE client optics. Table 1 summarizes key features of OIF 400ZR [9] and 400ZR+ based on OpenZR+ [10], where advanced modulation formats and high baud rates are used, allowing transport of 400GE beyond client optics for metro and regional distances. A key application is IP over DWDM with 400ZR/ZR+ optics in routers, compared with the first 100G IP over DWDM demonstration [11], 400ZR/ZR+ enables efficient IP over DWDM solution with same high port density as client optics.

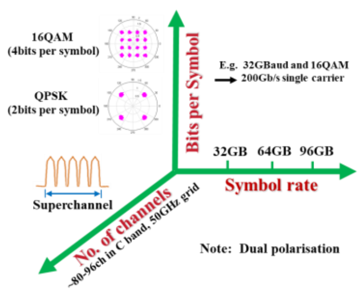

Fig. 1 Key enablers for scaling optical transmission capacity

	400ZR	400ZR+ (OpenZR+)
Reach	80 – 120km (in a single span)	>120km (Regional/long haul) ~400km for 400Gb/s
Client	400GE	Multi-rate Ethernet: 100/200/400GE
Line speed	400Gb/s	Multi-rate: 100/200/300/400Gb/s
Line technology	DP-16QAM, 59.8Gbaud	DP-QPSK/DP-8QAM/DP-16QAM, 60.1Gbaud
Soft Decision FEC	Concatenated FEC (C-FEC)	OpenFEC (OFEC)
Form factor	QSFP-DD/OSFP	QSFP-DD/OSFP
Standard/MSA	OIF	OpenZR+ MSA

Table 1 Key features of 400ZR and ZR+

3. Field trial and laboratory experimental demonstration results

First, we show results from a recent industry leading technology trial of 400GE transport over a 727km live flexible grid link between London and Dublin [4]. The live link has 10 spans of standard G.652 SMF including an unrepeatered 133km undersea span. EDFA amplifiers are used except for the undersea span with 37dB span loss, where hybrid Raman/EDFA amplifiers are used to improve noise performance.

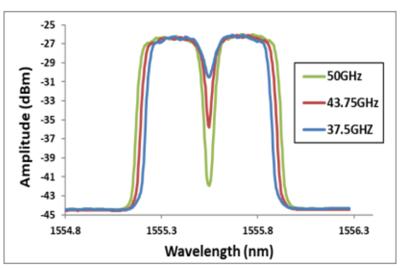

Fig. 2 spectra of 2×200G PCS superchannel at different sub-channel spacings

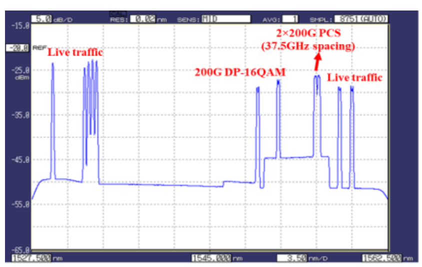

Fig.3 Spectrum of live traffic, 2×200G PCS superchannel and 200G DP-16QAM channel

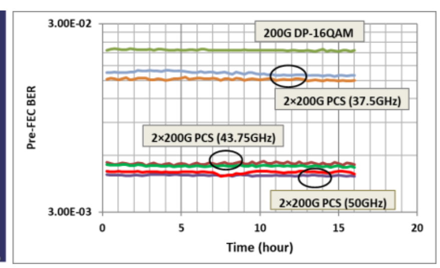

Fig. 4 Performance of PCS superchannels and 200G DP-16QAM over the 727km live link

To transport 400GE client, a 400G superchannel is formed by 2×200G PCS DP-16QAM sub-channels and the 400GE client signal is mapped into 2×OTUC2 (200G) data streams in the 2×200G PCS superchannel [5]. Fig. 2 shows the PCS superchannel at different sub-channel spacings (50GHz, 43.75GHz and 37.5GHz), where more overlapping is seen between the sub-channels as the spacing narrows. Fig. 3 shows the spectrum of all the wavelength channels over the link including live traffic at 40/100G, a conventional 200G DP-16QAM channel and the PCS DP-16QAM superchannel at 37.5GHz spacing. Long term error free operation was achieved for all the superchannels as shown in Fig. 4 with pre-FEC BER well below the threshold of $\sim 3.4\times 10^{-2}$. Compared with 50GHz spacing, as expected, pre-FEC BER has degraded for 43.75GHz and 37.5GHz spacings due to linear and nonlinear crosstalk. End to end error free performance was verified for all the PCS superchannels using a 400GE tester. With 37.5GHz spacing, a spectral efficiency improvement of 33.3% was achieved compared to 50GHz spacing. The conventional 200G DP-16QAM channel was also measured error free, in comparison the PCS DP-16QAM optical channel shows much improved performance and optical margin, demonstrating the advantage of PCS technique.

Next, we show results from laboratory demonstration of emerging 400G ZR/ZR+ technologies for IP over DWDM network applications. Fig. 5 shows the Cisco 400G ZRP pluggable modules used as line interfaces in Cisco 8202 routers (Fig. 5b), optical links of (a) single span 125km and (b) multi-span 251.8km provide connectivity between the two routers. The 400G ZRP module supports both ZR and ZR+ mode using C-FEC and OFEC respectively, chromatic dispersion compensation in ZR mode can operate beyond the OIF specification of 2400ps/nm, hence allowing longer distances than the specified 120km. Fig. 5c and 5d show the optical spectrum of 400G ZR and ZR+ signals respectively together with 40G/100G channels.

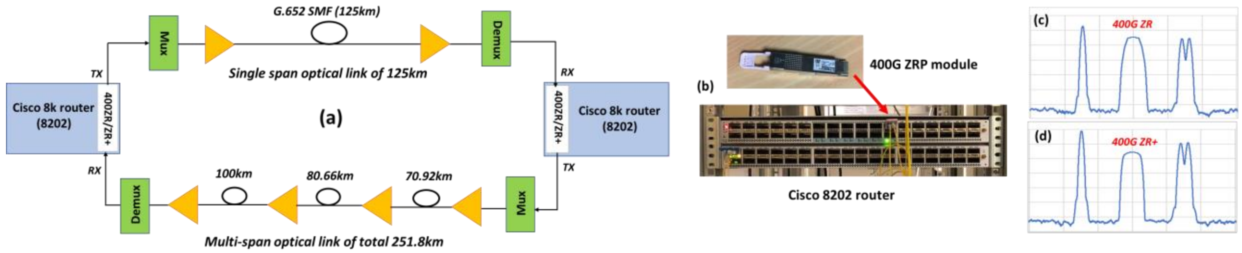

Fig. 5 400G IP over DWDM demonstration (a) system configuration; (b) 400G ZRP module in 8202 router; (c) 400G ZR and (d) ZR+ signal

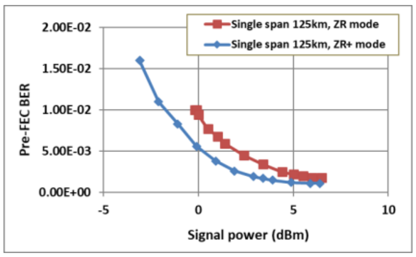

Fig. 6 Pre-FEC BER vs. signal power for single span 125km in ZR and ZR+ mode

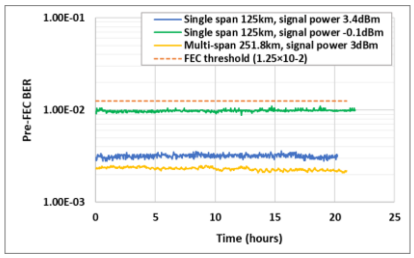

Fig. 7 Pre-FEC BER for single span 125km and multi-span 251.8km, ZR mode

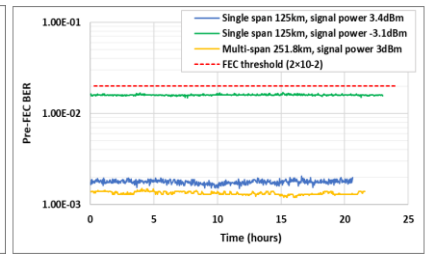

Fig. 8 Pre-FEC BER for single span 125km and multi-span 251.8km, ZR+ mode

We investigated the performance of 400G ZR and ZR+ over the single span 125km link (26.5dB span loss). Fig. 6 shows their performance as a function of signal launch power. The pre-FEC BER improves quickly at first when the launch power increases due to increased OSNR, as the signal power further increases the improvement becomes smaller due to more nonlinear effects, the optimum power is ~6dBm for both 400ZR and ZR+. For ZR mode, a minimum signal power of -0.3dBm is measured for error free performance corresponding to an OSNR of ~24.5dB. For ZR+, a minimum launch power of -3.6dBm was measured for error free performance with an OSNR of ~21.5dB, giving 3dB more optical margin compared with 400ZR. Fig. 7 and 8 show longer term performance for 400G ZR and ZR+ respectively. For the single span link, we show error free performance for different signal powers including a low launch power of -0.1dBm for ZR and -3.1dBm for ZR+ (close to FEC thresholds) and a higher signal power of 3.4dBm (larger optical margins). 400G ZR and ZR+ performance over the multi-span 251.8km link was also measured with a signal power of 3dBm, a chromatic dispersion compensation of ~4237ps/nm is required for the 251.8km link. Longer term error free performance was shown in Fig. 7 and 8 for 400ZR and ZR+ over 251.8km with significant margins. End to end IP connectivity via the 400ZR/ZR+ link was also verified.

4. Conclusions

We described key optical innovations enabling scalable, efficient optical transmission and network capacities. We have shown results from recent industry leading technology trials of transporting 400GE using PCS DP-16QAM superchannels over a long haul live network. We have also successfully demonstrated emerging 400G ZR/ZR+ technologies and efficient 400G IP over DWDM solution over metro/regional distances. These leading edge technology trials and demonstration give network operators important understandings on the emerging technologies.

5. References

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