Experimental Study of Intra- vs. Inter-Superchannel Spectral Equalization in Flexible Grid Systems

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Abstract: Benefits of intra-superchannel spectral-equalization are demonstrated in a production 8Tbps system. ~1.2dB OSNR improvement and ~4.5dB reduction in power-spread is measured relative to inter-superchannel equalization. Tradeoff between OSNR and nonlinearity dictates the net reach improvement.

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1. Introduction
As network traffic demand continues to grow, carriers are faced with the challenge of improving spectral efficiency and scaling transponder line card capacity. New generation optical backbones can support 8-10 Tbps of capacity by utilizing 100Gbps per channel transport via PM-QPSK modulation. Further increase in transport capacity can be achieved by transitioning to a flexible grid instead of a fixed ITU grid [1-2] to improve spectrum utilization and by introducing higher order modulation formats [3] such as 16-QAM. With these formats, spectral efficiencies of 4b/s/Hz or above can be achieved, significantly increasing the capacity of today’s networks.

One of the main enablers of spectrally-efficient, high-capacity networks is the optical superchannel (SC) [2]. An SC is defined as a group of optical carriers that are treated as a single transport entity. Since future networks may employ SCs of varying total capacity (and spectral width), comprised of different numbers of carriers, adaptive filtering technologies are needed [4]. These technologies, called “Flexible Grid” drive hardware and control requirements for the new generation of Wavelength Selective Switches (WSS) designed to support SC transport. Two WSS parameters that critically influence the design of flexible grid systems are (i) Switching granularity: granularity at which bandwidth can be switched for the purpose of adding, dropping or expressing SCs, and (ii) Attenuation granularity: granularity at which the spectrum occupied by a single SC can be attenuated/shaped.

The ability to shape the spectrum and counteract the spectral variation introduced by optical amplifiers, over and above that enabled by traditional gain-flattening filters, is critical to maximizing the OSNR achieved at the end of a link. Hence, it is of great importance to understand the consequences of different attenuation granularity options available in next generation WSSs. As shown in Fig. 1, if the WSS only allows SC level attenuation control (termed inter-SC equalization), only the average power of each SC can be equalized across the C band, but power variation between carriers ‘within’ an SC cannot be equalized. On the other hand carrier level (or finer) attenuation granularity (termed intra-SC equalization) in a WSS enables equalization of the carriers within an SC as well. This

Fig. 1. Spectrum at the output of last equalizer in 16 span link. Each group of 20 carriers is a superchannel. Intra-SC equalization flattens spectrum across C-band while Inter-SC only equalizes average superchannel power across C-band.

Fig. 2. Experimental setup. 16 span LEAF link, hybrid Raman-EDFA amplifiers and 3 WaveShapers. 80 Dual-Carrier 100G QPSK signals.
paper attempts to quantitatively compare these two equalization schemes in an optical network implementing flexible grid technology based on next generation WSSs and SCs. We report that >1 dB OSNR benefit can be obtained for a representative 16 span link via intra-SC equalization but only ~half of it contributes to reach improvement due to a simultaneous increase in nonlinear penalties.

2. Framework to compare inter- vs. intra-SC equalization

In order to mimic SCs, we have created a frequency comb of 25GHz spaced carriers carrying 8Tbps of data in the C-band using Infinera’s commercial 500G PIC-based coherent transponders [5]. For the purpose of this study we treat each group of 20 carriers as a 500GHz-wide SC. As shown in Fig. 2, the line system consists of hybrid Raman-EDFA amplifiers. The specific amplifiers used were hand-picked to create large spectral power ripple (Fig. 1 left) across 16 spans in order to provide a suitable platform for equalization studies. All 16 spans were composed of LEAF fiber ranging from 75 to 100km in length, totaling ~1400km with no inline dispersion compensation. The amplifiers after the 4th, 8th and 12th spans included a WaveShaper to mimic the attenuation provided by a WSS. Initial measurements were performed with PM-QPSK carriers launched at -4.5 dBm/cARRIER into each span.

The algorithms used to mimic equalization in a WSS using the WaveShaper are as follows:

(a) For intra-SC equalization, each carrier’s peak power at the amplifier output is read using an OSA, the lowest carrier power is determined and the WaveShaper is set to a profile that will attenuate each carrier down to the level of the lowest carrier. The average per-carrier launch power into the span is maintained at -4.5 dBm.

(b) For inter-SC equalization, each carrier’s peak power at the amplifier output is read using an OSA, SC power is determined from the individual powers of each of its 20 carriers and the lowest power SC across the band is identified. The WaveShaper is set to a profile that provides a flat attenuation across an SC such that the power of that SC drops to that of the lowest power SC. The average per-carrier launch power into the span is maintained at -4.5 dBm.

For the purpose of this study we have identified two spectral zones of interest where spectral ripple is most pronounced. These are shown in Fig. 1 (left) and correspond to spectral areas covered by SC # 2-3, and 7-8. In order to quantify the performance differences between intra-SC and inter-SC equalization, we focus on the following metrics, (i) OSNR: lowest carrier OSNR across C band will determine reach, (ii) Q: to elucidate the tradeoff between improving OSNR and worsening nonlinearities via spectral equalization, (iii) Carrier power spread: drives receiver dynamic range and interferer rejection requirements.

3. Results and discussion

Fig. 3 compares the end-of-link OSNRs for no equalization (dash), inter-SC equalization (dot) and intra-SC equalization (solid) with the unequalized reference spectrum in the background. Inter-SC equalization improves the worst channel’s OSNR by ~0.7dB while intra-SC equalization improves it by ~1.8 dB. Intra-SC equalization also minimizes the OSNR spread. It is worth noting that the inter-SC curve has sudden changes in OSNR at the boundaries of the SCs since the WaveShaper profiles can have discontinuities if the pre-equalization average powers for neighboring SCs are significantly different, as would be the case in regions of large ripple.

![Fig. 3. Comparison of end-of-link OSNR for no equalization, inter-SC equalization and intra-SC equalization](image)

A direct comparison of the OSNR difference between intra-SC and inter-SC equalization is shown in Fig. 4 (solid curve). Note that some carriers have a negative ordinate value because equalization reduces the preferential...
power evolution of these carriers. These channels, however, do not govern the reach since they have high OSNR initially. As shown in Fig. 4, the benefit in OSNR does not translate equivalently to the Q values measured for the carriers. Carriers whose OSNRs are improved by 1.2 dB, exhibit a relative Q improvement of only ~0.6 dB. We conducted two more experiments to confirm that the Q improvement is limited by the tradeoff between improving OSNR and increasing nonlinear penalty. If a lower per-carrier launch power of -7.5 dBm is used (Fig. 5), the Q benefit strongly tracks the OSNR benefit. In such a linear system, even though we increase the carrier launch power of the worst OSNR channels through equalization, the increase in power does not lead to a significant increase in nonlinear penalties. However, as shown in Fig. 6, in a more nonlinear system (per-carrier launch power of -1.5 dBm), we observe anticorrelated behavior between changes in Q and OSNR. Here, the OSNR benefit obtained by increasing the launch power is completely negated by the even larger increase in nonlinear penalties. The recently developed Gaussian Noise model [6,7] shows that nonlinear interference (NLI) can be modeled as additive Gaussian noise and that ASE noise and NLI noise can simply be added, leading to a total effective OSNR, OSNR(Tot)=P(Ch)/(P(ASE) + P(NLI)) that exhibits a good correlation to Q. This methodology allows one to calculate the net system performance and optimal power targets across multiple network design realizations. This model appears to align well with the presented experimental results.

The last metric studied is the carrier power spread within an SC at the end of the link. As shown in Fig. 7, for no equalization the carrier power spread is ~6.3 dB while it can be reduced to ~1.5 dB via intra-SC equalization. The receiver for the lowest power carrier needs to be able to reject all the other high power carriers within that SC through coherent detection. If the spectrum received by the detector was perfectly flat for the case of a 20-carrier SC, the receiver would only need to reject the power equivalent to 19 interfering aggressors. However, due to the large carrier power spread for inter-SC equalization, the rejection requirement increases to 35 aggressors (calculated for SC #2 in Fig. 7). In future flexible grid systems, coherent transponders will be format-agile, being able to operate with not just QPSK, but other higher-order formats as well. The required OSNR for these formats could lead to a different view of the reach benefit garnered through improved OSNR via intra-SC spectral equalization. Also, as carriers are squeezed closer together by taking advantage of DAC-based spectral shaping, they will no longer be aligned to standard WSS spectral grids. In such systems, the finer granularity of intra-SC WSS attenuation, down to sub-carrier-width, will play an even more important role.

4. Conclusion
We demonstrated ~1.2 dB OSNR improvement (for the worst channel) for intra-superchannel equalization compared to inter-superchannel equalization. The resulting Q benefit will depend upon the fiber type and launch powers chosen for the link design. Additional benefits of intra-superchannel equalization will be realized via reducing the dynamic range and rejection capability requirements of coherent receivers.

5. References