Intra super-channel fiber nonlinearity compensation in flex-grid optical networks

Danish Rafique,1,* Talha Rahman,1,2 Antonio Napoli,1 and Bernhard Spinnler,1

1Coriant R&D GmbH, St.-Martin-Str. 76, 81541, Munich, Germany
2Eindhoven University of Technology, Eindhoven, The Netherlands
*danish.rafique@coriant.com

Abstract: We report on the nonlinear transmission limits of various super-channel configurations in a flex-grid network upgrade scenario. In particular, we consider flexible data-rates ranging from 180Gb/s to 1.2Tb/s, employing either single-carrier, dual-carrier, or penta-carrier polarization multiplexed m-state quadrature amplitude modulation (PM-8QAM/PM-16QAM) –termed as super-channels, and establish transmission performance margins for each configuration, both with and without super-channel fiber nonlinearity compensation. Our results show that the benefit of intra super-channel nonlinearity mitigation (nonlinear compensation addressing full super-channel bandwidth) reduces with increasing sub-carrier count within the super-channel, and that single-carrier super-channel achieves the maximum improvement from nonlinearity mitigation (up to ~4.5dB, in Q-factor), better than dual-carrier (up to ~3.5dB) and penta-carrier (up to ~2dB) configurations. Moreover, the maximum reach improvement, compared to linear compensation only, is found to be ~170% (180Gb/s, PM-8QAM), ~150% (240Gb/s, PM-16QAM), ~100% (360Gb/s, PM-8QAM), ~100% (480Gb/s, PM-16QAM), and ~65% (1.2Tb/s, PM-16QAM).

References and links
1. Introduction

With the recent advent and uninterrupted growth in bandwidth-intense user applications, cloud services, high-speed computing networks, the global data traffic is continuing to increase at an exuberating rate of ~30-40% per year [1]. In order to address the looming capacity crunch, various solutions are considered by research and industrial community, including space division multiplexing [2,3], fiber nonlinearity compensation [4], flex-grid networks [5], etc. Although spatial multiplexing, in one form or the other, will enable uninterrupted capacity growth, it is still an immature technology, and a more practical solution is favored for near- and medium-term network deployments.

Flex-grid networks, or software defined networks have recently gained significant interest, in order to cater the ever-increasing dynamic bandwidth demands [5–9]. The core concept of flex-grid networks is borrowed from radio communications, where an agile control plane is able to switch the link to employ the most optimum modulation type, data-rate, spectral-grid, etc., based on a given demand. This, in principle, would allow full agility across the network, not only increasing the net capacity, by filling up the spectrum more efficiently, but also be able to address the dynamics of demands. However, one of the problems intrinsic to flex-grid networks is the limitation of transmission performance due to fiber nonlinearities, owing to the mix of densely packed channels, operating at variable higher-order modulation formats and data-rates. Consequently, although flex-grid networks enable higher system capacity, this is achieved at the cost of reduced transmission reach and system margins [7,8].

On the other hand, fiber nonlinearity compensation has recently been employed in both optical and digital domain [10–12], and enables interesting prospects for network growth scenarios. The key problem associated with digital nonlinearity compensation, typically known as digital back-propagation, is the complexity involved, even for intra-channel or single-channel nonlinearity compensation [13]. Although wide-band digital nonlinear compensation has been shown to enable significant performance margins [14], it only comes at the cost of prohibitive complexity, and parallel phase-locked receivers. Much of the
aforementioned problems may be solved by employing optical or optoelectronic spectral inversion [15,16], where significant performance benefits may be ascertained.

In this paper we report on intra super-channel nonlinearity mitigation, in a flex-grid network upgrade scenario, employing variable data-rates (180Gb/s, 240Gb/s, 360Gb/s, 480Gb/s, 1.2Tb/s) and single/dual/penta-carrier polarization multiplexed m-state quadrature amplitude modulation (PM-8QAM/16QAM) – termed as super-channels from now on. We show that, although intra super-channel nonlinearity compensation enables significant performance improvements, compared to linear compensation only, the performance margins reduce for super-channels employing greater than one sub-carrier based transmitter configuration. Moreover, we demonstrate the reach improvements across a range of flex-grid super-channels configurations, and show that for linear compensation only, the maximum reach, for super-channels operating up to 1.2Tb/s, is limited to ~1600km, whereas with intra super-channel nonlinearity mitigation, the reach may be extended up to ~4000km.

2. Transmission configurations

Figure 1(a) shows the transmission setup, and consisted of PM-mQAM ($m = 8, 16$) central channel, at a fixed baud-rate of 30Gbaud, where different super-channel structures were modeled using 1-carrier PM-8QAM (180Gb/s), 1-carrier PM-16QAM (240Gb/s), 2-carriers PM-8QAM (360Gb/s), 2-carriers PM-16QAM (480Gb/s), and 5-carriers PM-16QAM (1.2Tb/s). In order to minimize the impact of linear sub-carrier crosstalk, and dense spectral grid, spectral shaping was applied in digital domain, where the roll-off coefficient was fixed at 0.2 [17]. Moreover, the spacing within the subcarriers was also optimized, and fixed at ~1.15xBaud-rate. The super-channel structures for 1, 2 and 5 sub-carriers were set to have the spectral widths of 37.5GHz, 75GHz, and 187.5GHz respectively.

For all the sub-carriers both the polarization states were modulated independently using de-correlated bit sequences. Each digital sequence was de-multiplexed separately into two multi-level output symbol streams which were used to modulate an in-phase and a quadrature phase carrier. The optical transmitters consisted of continuous wave laser sources, followed...
by two nested Mach-Zehnder Modulator structures for x- and y-polarization states, and the two polarization states were combined using an ideal polarization beam combiner. For wavelength division multiplexing (WDM) transmission, we employed heterogeneous transmission scenario, where the neighboring channels were considered to be 120Gb/s quadrature phase shifted keying (QPSK). The number of neighbors was always fixed to 10 channels, and the spectral grid was fixed at typical 50GHz. Figure 1(b) shows optical spectrum at the transmitter for various super-channel configurations in WDM scenario.

The signals were multiplexed, and propagated over standard single mode fiber (SSMF), with parameters: fiber loss: 0.21 dB/km, fiber dispersion: 16.8 ps/nm/km, fiber dispersion slope: 0.058 ps/nm²/km, fiber polarization mode dispersion: 0.06 ps/√(km), fiber nonlinearity coefficient: 1.14 W/km. As shown in Fig. 1(a), the transmission link consisted of 80 km spans, no inline dispersion compensation and single-stage erbium doped fibre amplifiers (EDFAs). Each amplifier stage was modelled with a 5 dB noise figure and the total amplification gain was set to be equal to the total loss in each span. In case of intra super-channel nonlinearity compensation (INLC), at the centre of the link, a reconfigurable optical add-drop multiplexer (ROADM) site was considered, where the transmitted channels were de-multiplexed, and ideal spectral inversion (SI) was employed for the super-channel structure, before re-multiplexing the signals. Also, a ~60km dispersion compensation module was placed before the SI stage to enable nonlinear link symmetry [15]. Note that, in case of 2, and 5 sub-carrier super-channel SI, symmetric wavelength shift SI may be obtained (see Fig. 1(c)), as shown in [18], also SI with <1dB penalty have been recently shown [15]. It is worth mentioning that the results based on SI are applicable to digital nonlinear compensation approaches as well [19]. At the coherent polarization diversity receiver, coherent channel selection was employed to de-multiplex the test sub-carrier (in case of 2 and 5 sub-carrier based transmission, first and third sub-carriers were evaluated, respectively). The signal was then detected using four balanced detectors to give the baseband electrical signal, sampled at ~2 samples per symbol. Transmission impairments were digitally compensated using conventional digital signal processing blocks, clock recovery, frequency domain dispersion compensation (only for linear compensation scenario), polarization de-multiplexing, and carrier recovery [20]. Finally, the symbol decisions were made, and the performance assessed by direct error counting (~400000 bits, converted into Q-factor).

3. Results and discussions

3.1. Performance margins

Figure 2(a) shows Q-factor as a function of launch power per subcarrier for PM-8QAM super-channel configuration, after 2400km, for both linear compensation (LC) only, and linear compensation plus intra super-channel nonlinearity compensation (INLC). The launch power of the neighboring traffic was fixed at nominal value of 0dBm [8], representing a flex-grid network growth scenario.

It can be seen that for both upgrade scenarios, the performance is initially optical signal-to-noise ratio (OSNR) limited, before reaching the optimal launch power, or nonlinear threshold (NLT), and eventually it is degraded by fiber nonlinearities. In particular, it is clear that when LC is employed, both super-channels (180Gb/s and 360Gb/s) achieve similar performance, limited by intra- and inter-channel nonlinear fiber impairments. Furthermore, Fig. 2(a) also depicts that, compared to LC, when INLC is employed, 1-carrier 180Gb/s enables the maximum performance improvement (~4.5dB), followed by an improvement of ~3.5dB by 2-carrier 360Gb/s super-channel configuration, and that maximum performance after INLC is eventually limited. These two observations can be explained together by considering that since the launch power of the neighboring traffic is fixed, when the super-channel power is increased, the signal is eventually dominated by intra-channel nonlinear effects, and their compensation via INLC enables performance improvements. On the other hand, signal and noise interactions eventually limit the maximum transmission performance, which are intrinsically non-deterministic and thereby not mitigated by spectral inversion.
Although such limitations have been reported before [21], this result is somehow counterintuitive since wide-band nonlinearity compensation is expected to provide greater performance benefits, compared to narrow band nonlinearity mitigation [14]. This behavior can be attributed to the fact that in case of 2-carrier super-channel the total power for the super-channel structure is higher, compared to that of 1-carrier super-channel, and consequently, the impact of signal-noise interaction is greater for 2-carrier super-channel. Figure 2(b) and Fig. 2(c) qualitatively show the constellation plots for 1-carrier transmission for LC and INLC, respectively. It is clear from the constellation diagrams that the nonlinearity mitigation significantly enhances the transmission performance.

In Fig. 3, we extend our analysis to PM-16QAM based super-channels, and show LC and INLC compensation for PM-16QAM configurations, representing flex-grid upgrade option employing 240Gb/s, 480Gb/s, and 1.2Tb/s. The conditions are similar to Fig. 2, except the maximum transmission distance, fixed at 1280km. It can be seen that, similar to Fig. 2, 1-carrier super-channel enables performance improvement of ~3.5dB, followed by 2-carrier and 5-carrier super-channel Q-improvements of ~2.5dB and ~2dB, respectively. Note that, compared to PM-8QAM, slightly reduced performance benefits are observed in PM-16QAM super-channels due to its reduced Euclidean distances, leading to increased crosstalk. Figure 3(b) and Fig. 3(c) qualitatively show the constellations at optimum power for both LC and INLC, for 1-carrier 240Gb/s transmission scenario. Note that recently, a 1Tb/s super-channel wide-band digital nonlinear compensation was reported in [22,23], showing reduced improvement, compared to conventional single-carrier transmission systems [13], consistent with our results.

It is also worth mentioning that although we presented maximum performance gains in Fig. 2 and Fig. 3, even in case the super-channel is required to operate at power lower than its NLT, due to power allocation strategies [17,24,25], still ≥2dB performance margins are visible for any given configuration.
3.2. Reach analysis

Having established the performance improvements available from intra super-channel nonlinearity compensation, in this section we establish the maximum attainable distance by different super-channels, employing both linear compensation and intra super channel nonlinearity compensation. Figure 4(a) shows the Q-factor as a function of transmission reach, where each data-point is taken at NLT, from plots similar to Fig. 2 and Fig. 3. Different super-channel configurations, discussed above, are employed and it can be seen that the maximum distance that could be traversed by PM-8QAM and PM-16QAM super-channels is limited to ~1400km and ~800km, respectively (at bit error rate of 1e-3, or Q-factor of ~9.8dB). It is clear that the achievable distances for various configurations are not sufficient to bridge majority of the links in a medium to long-haul network infrastructure. Also, it is worth mentioning that typically super-channels would be operating at higher forward error correction (FEC) thresholds (soft-decision FEC); however we evaluate the maximum reach at BER of 1e-3, and assume that the additional FEC margin will be utilized for system margin allocation [26].

In order to improve the maximum attainable distance, we employed INLC, as shown in Fig. 4(b). It can be seen that the achievable reach is different for various super-channel configurations, as discussed in section 3.1. In particular, the maximum reach for 1-carrier and 2-carrier PM-8QAM can be increased to ~4000km and ~3000km, respectively -corresponding to reach increase, compared to LC, of ~170% and ~100%. Likewise, for 1-carrier, 2-carrier, and 5-carrier PM-16QAM super-channels, the reach attainable is ~2000km, ~1500km, and ~680km respectively, -corresponding to reach increase, compared to LC, of ~150%, ~100%, and ~65%. It is clear that the maximum reach is not only dependent on the modulation format itself (high or low required OSNR), but also on the extent of fiber nonlinearity compensation, based on the super-channel configuration, effectively limited by non-deterministic nonlinear fiber impairments. These results provide an interesting and practical insight into various flexgrid network upgrade options, establishing performance regimes for different super-channel configurations, employing either linear or intra super-channel nonlinearity compensation. A detailed study, quantifying the impact of INLC, in a fully dynamic meshed network employing various nodes is underway.
4. Conclusion

We have reported, for the first time to our knowledge, on the dynamics of intra super-channel fiber nonlinearity mitigation, for various super-channel configurations, employing flexible data-rates (180Gb/s, 240Gb/s, 360Gb/s, 480Gb/s, 1.2Tb/s) and PM-8QAM/PM-16QAM based flex-grid network upgrade options. In particular, we showed that performance improvements from intra super-channel nonlinearity mitigation reduce with increasing number of sub-carriers within a super-channel, i.e. single-carrier super-channels benefit more from super-channel nonlinear mitigation, compared to dual-carrier and penta-carrier super-channels, with reported improvements of up to ~4.5dB, ~3.5dB, and ~2dB, respectively. Moreover, we quantified the maximum transmittable reach, if linear compensation only is replaced with intra super-channel nonlinear mitigation, and showed that the maximum attainable distance for various super-channel may be increased up to 170%, with specific improvements of: 180Gb/s PM-8QAM (~1500km to 4000km), 240Gb/s PM-16QAM
(~800km to ~2000km), 360Gb/s PM-8QAM (~1500km to ~3000km), 480Gb/s PM-16QAM (~700km to ~1500km), and 1.2Tb/s PM-16QAM (~680km to ~1120km).

Our results suggest that, in practical flex-grid network upgrade, intra super-channel nonlinear mitigation (addressing full super-channel bandwidth) may enable significant reach improvements, however it’s potential to bridge medium to long-haul distances, would depend on super-channel granularity.

Acknowledgment

This work was supported by European FP-7 project, IDEALIST, under grant number 317999.