Distributed Span Degradation Self-Aware Detection and Compensation for C+L-band Transmission Systems

Shengnan Li[1,*], Chen Zhu[1], Shuo Wang[1], Feng Gao[1], Yongxin Cui[1], Gang Cheng[1], Xu Zhou[1]
[1]*Baidu, Network Infrastructure Department, Kuike Technology Building, No.9 Shangdi Information Road, Haidian District, Beijing, China*
*Email: *lishengnan04@baidu.com*

Abstract: We propose a distributed approach that enables OLAs to instantaneously self-aware its preceding span's degradation and apply the gain/tilt adjustments, this ultra-fast method is experimentally demonstrated in both C96+L96 and C120+L100 systems with near-optimal performance. © 2023 The Author(s)

1. Introduction

The upgrade from C-band to C+L-band WDM system [1] attracts increasing attentions to support higher long-haul optical transmission capacity. A myriad of optical amplifier (OA) gain/tilt configuration algorithms [2-4] that take into account strong stimulated Raman scattering (SRS) effect between C and L bands have been proposed to optimize the generalized signal-to-noise ratio (GSNR) of C+L wavelengths. The optimality of the conventional algorithms depends on the accuracy of the input link parameters. As in the production network each fiber span may suffer additional degradation at any time due to fiber bending, squeezing, etc. [5], the OAs have to be adjusted dynamically in order to maintain the quality of transmission, in particular for the long L-band wavelengths due to more severe loss of SRS gain from C-band. The traditional approaches require a centralized controller to update the OA configurations based on polling the link parameters, detect the span degradation, recalculate gain/tilts and push to the devices, the entire process would take at least seconds to complete mainly due to the 1-second interval of streaming telemetry [6].

In this paper, we propose a distributed span degradation self-aware approach that allows all optical line amplifiers (OLAs) to detect if there is extra loss occur on the span right precede to it. Each OLA operates independently by sensing only the total input optical powers of C-band and L-band (P_C and P_L), which enables milli-second detection and compensation. We show that after establishing a power evolution model from the original steady-state of the system, each OLA sees different combinations of P_C and P_L for any span degradation (locations and loss degrees), hence the OLAs can conduct parallel detection without conflict, therefore ultra-fast detection could be realized by avoiding communication between OLAs and centralized controller. We further prove that the amount of SRS change corresponds to a fixed tilt change, hence gain/tilt compensation can be determined right upon detection. The proposed strategy is verified on commercial 10-span C96+L96 and C120+L100 systems, 5dB span degradation can be compensated instantaneously with less than 0.5dB mean Q-factor penalty compare to the steady-state performance.

2. Span degradation self-aware detection and compensation

As shown in Figure 1, the proposed scheme consists of two steps: based on the initial steady-state link parameters, the span degradation detection and compensation strategy are first calculated for and pushed to each OLA, which will then be executed by each amplifier node independently for real-time distributed span degradation compensation.

Step1: After the steady state C+L system configurations are optimized, the per-wavelength launch power profiles and fiber parameters (fiber type, length, lumped loss) of each span are collected for power evolution modelling when loss degradation occurs on this span. The power evolution model predicts the total C-band and L-band input power (P_C and P_L) of the OLA right next to the span against different degradation locations and degrees, by solving the following derivative equation [7]:

$$\frac{\partial P_n(z)}{\partial z} = -\alpha P_n(z) + \sum_{m=1}^{N} \frac{g_R(\omega_m - \omega_n)}{A_{eff}} P_n(z) P_m(z) \tag{1}$$

where the second half of Eq.1 contains the linear fiber loss and nonlinear SRS interplay between different wavelengths, we use GNPy [8] as the numeric solution in our approach. For a given kth OLA, we denote the difference between instantaneous and steady-state total received optical power of C/L-bands as $\Delta P_{C/L}$ w.r.t. $\Delta P_{C/L} = P_{C/L} - P_{steady,C/L}$. Span degradation not only impose similar linear fiber loss on both bands, but also reduces the SRS transfer between C band L bands, which is the only cause for the change of ΔP_C-ΔP_L, hence ΔP_C-ΔP_L is used as a core component to indicate the SRS change. However, SRS change is not sufficient for parallel detection as different combinations of loss degrees and locations can lead to same ΔP_C-ΔP_L observation. For the same ΔP_C-ΔP_L observed by an OLA, the loss degree strictly decreases with further degradation location due to the accumulation nature of SRS change over distance, therefore we introduce an extra dimension P_C to evaluate the absolute loss degree for exact span degradation detection.

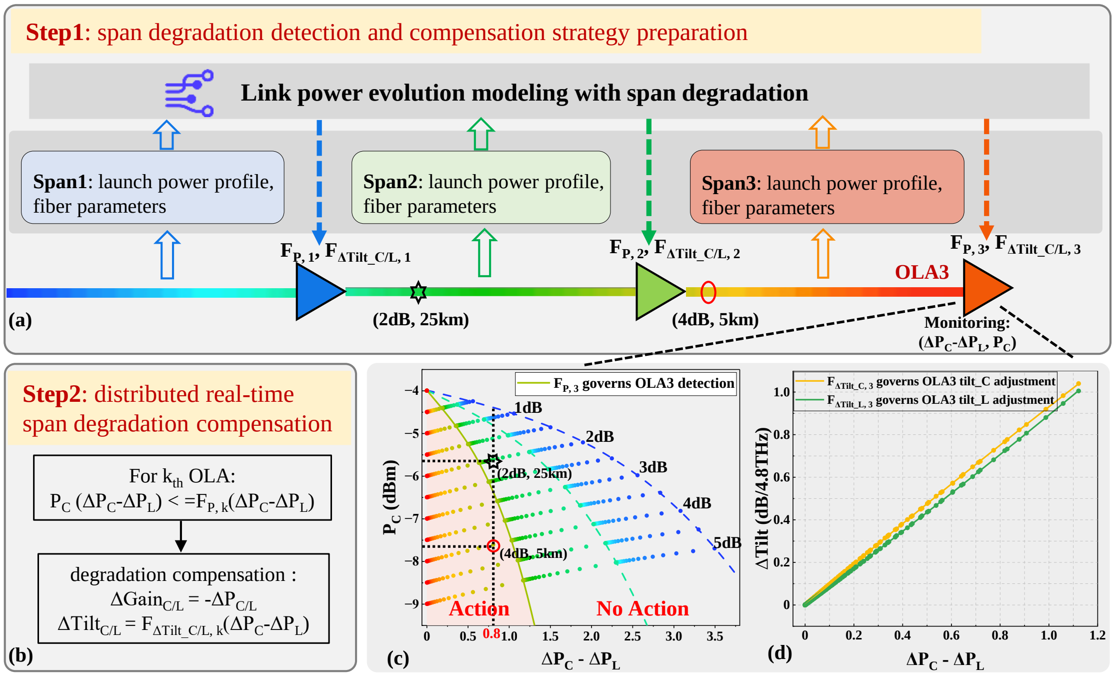

Fig.1. (a) Span degradation detection and compensation strategy preparation, (b) degradation compensation, and (c)-(d) the correspondence between ΔP_C-ΔP_L and P_C/ΔTilt received by OLA3 at different degradation locations and loss degrees.

Fig.1(a) shows a 3-span (100, 90, 100km) C96+L96 simulation system established to illustrate the proposed concept. Fiber degradation up to 5dB (in 0.5dB step) was set every 5 km for each span, with a total of 580 simulated cases. ΔP_C-ΔP_L and P_C detected by OLA3 are shown in Fig.1(c), where the three colors represent three spans, and the dots between the lines stand for the degradation locations within each span. It's clear that each degradation case maps to a unique 2D coordinate value of [ΔP_C-ΔP_L, P_C]. For a given ΔP_C-ΔP_L value, the closer the degradation location is to OLA3, the smaller P_C there is (i.e., larger loss degree). As an example, 4dB span degradation on the 5th km of 3rd span and 2dB extra loss on the 25th km of 2nd span generated the same SRS change of 0.8dB seen by OLA3. Therefore, when the fiber degradation occurs at the beginning of the span, the SRS change and P_C relationship could be used to govern the degradation detection of the corresponding OLA. More importantly, this relationship can be fitted as a cubic polynomial instead of look-up table to speed up the detection process. As shown in Fig.1(c), OLA3 determines if there is a degradation occur on span3 if [ΔP_C-ΔP_L, P_C] falls into the pink area under the decision curve $F_{P,3}$.

The gain compensation targets to maintain the original total output power on both bands. For tilt compensation, Fig.1(d) proves that the tilt variation also has unique linear relationship with the SRS change, which is reasonable as it's well documented that stronger SRS effect produces sharper linear optical power spectrum tilt [9].

Step2: After link power evolution modelling that detailed in step1, each OLA will be loaded with its own detection and tilt compensation polynomial. Upon completion of detection, C and L-band OAs will be pumping for the same extra gains as ΔP_C and ΔP_L, with corresponding tilt adjustments that offsets the SRS change induced tilt variation. The proposed scheme not only guarantees that only one OLA will be in action mode with a single span degradation, but also enables ultra-fast link loss compensation due to its distributed nature.

3. Experimental Setup and Results

Fig.2(a) depicts the experimental setup to verify the proposed distributed span degradation self-aware and gain/tilt compensation strategy for C+L-band system. 69-GBd DP-QPSK optical transponder units were multiplexed at 100GHz channel spacing, the WDM signal propagated through 10 span G.652.D fibers with different lengths ranging from 75km to 100km, and dynamic gain equalization (DGE) site was set after 5 spans to eliminate the accumulated power profile ripple. We have configured each node such that the total power of C-band and L-band launching into each span is around 21dBm and 20dBm, respectively. And each span's launch power profile was properly tilted to minimize the variance of received wavelengths' GSNR performance. Fig.2(b) depicts an example of 4dB degradation at the beginning of span1, compare to steady-state, the degraded optical spectrum shows severe L-band wavelength power drops, especially on the longer wavelengths that are shown in the zoom-in figure. Subsequently L-band Q-factors are reduced, where the longest wavelength lost 5.8dB Q margin and started to produce post-FEC errors, as the longest L-band wavelength absorbs the most SRS gain from all other wavelengths (therefore lost the most SRS upon span degradation). This further illustrates the necessity of a timely compensator to minimize the service disruption.

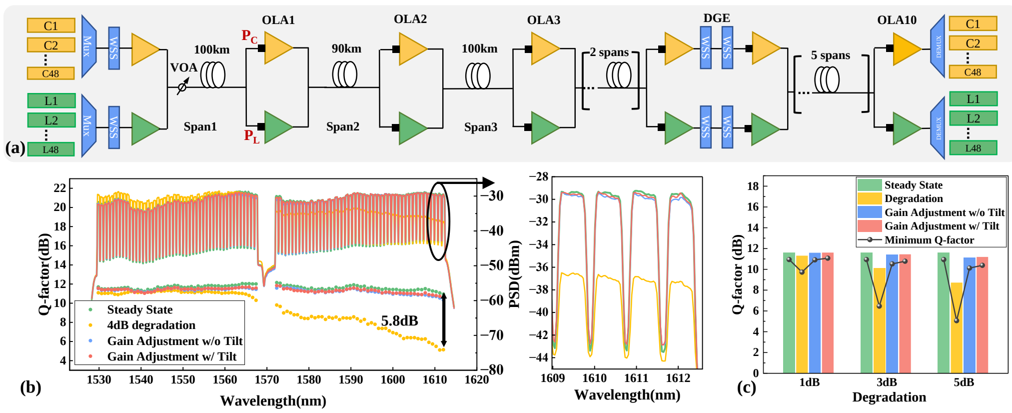

Fig.2. (a) Experimental setup, (b) optical spectra and Q-factors with 4dB 1st span degradation, (c) mean/min Q-factor with different degradations.

Based on $F_{P,1}$, OLA1 determined that degradation occurred at the beginning of span1 and applied the compensation, the optical spectra and Q-factors after gain-only and gain+tilt adjustment were displayed in Fig.2(b) that shows similar performance as the steady state. Crucially, the whole detection and compensation process can be completed within 3ms, including photon detector (PD) power detection time of about 100 microseconds, microcontroller unit (MCU) degradation judge program running time of a few microseconds, and OA pump adjustment time of about 2ms. In order to better show the tilt adjustment benefit, we recorded the mean and minimum values of all channels' Q-factors corresponding to the steady state and degradation scenarios: 1/3/5dB loss at the beginning of span1 with gain-only and gain+tilt adjustments. As shown in Fig.2(c), the mean Q-factor with gain-only compensation is restored with less than 0.5dB penalty compare to steady-state, and tilt adjustment can further improve the worst channel by about 0.3dB.

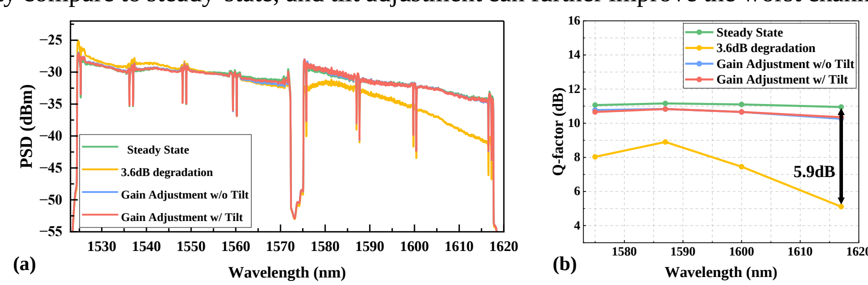

Fig.3. (a)-(b) Optical spectra and Q-factor of C120+L100 system at steady state, 3.6dB degradation, gain adjustment w/o and w/ tilt.

We perform a similar 10-span C120+L100 transmission system experiment to further prove the generality of the proposed approach. There are only 4 C-band and 4 L-band real-time transceivers in this setup, the received optical spectrum and Q-factor results are shown in Fig.3(a) and (b), respectively. As more C-band channels produce higher SRS transfer than the C96+L96 system, 3.6dB first span degradation could already cause a 5.9dB Q-factor reduction on the longest L-band wavelength as shown in Fig.3(b). The detection and compensation scheme are similar to the previous experiment except that the link power evolution modelling part due to different wavelength distributions, the system performance could also be successfully improved to be comparable as the steady state.

4. Conclusions

In this paper, we propose and experimentally demonstrate a distributed fiber degradation span self-aware detection and gain/tilt compensation technique for C+L-band transmission systems. The compensation of each OLA is triggered by sensing if the combination of SRS change and total C-band input power falls into the pre-fitted decision area, which enables an ultra-fast span degradation compensation that is critical for long-haul C+L-band system deployment.

5. Acknowledgements

The authors wish to thank the Accelink and Huawei for providing hardware.

6. References

[1] M. Cantono et al., "Opportunities and Challenges of C+L Transmission Systems," JLT. 38, 1050-1060 (2020).
[2] G. Borraccini et al., "Cognitive and autonomous QoT-driven optical line controller," JOCN, 13, E23-E31 (2021).
[3] B. Correia et al., "Optical Power Control Strategies for Optimized C+L+S-bands Network Performance," in OFC, W1F.8, 2021.
[4] Y. Song et al., "A Fast Amplifier Gain and Tilt Configuration Algorithm for Dynamic C+L-band Networks," in OFC, Th1H.2, 2022.
[5] K. Abdelli et al., "Reflective fiber fault detection and characterization using long short-term memory," JOCN, 13, E32-E41 (2021).
[6] F. Paolucci et al., "Network Telemetry Streaming Services in SDN-Based Disaggregated Optical Networks," JLT. 36, 3142-3149 (2018).
[7] I. Roberts et al., "Channel Power Optimization of WDM Systems Following Gaussian Noise Nonlinearity …," JLT, 35, 5237-5249 (2017).
[8] A. Ferrari et al., "GNPy: an open source application for physical layer aware open optical networks," JOCN, 12, C31-C40 (2020).
[9] S. Tariq et al., "A computer model of non-dispersion-limited stimulated Raman scattering …," JLT, 11, 1914-1924 (1993).