Experimental Assessment of Joint Impact of Equalization and Link Failure in Meshed Networks

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Abstract *We experimentally evaluate the impact of link failure on existing services with different design strategies in a commercial equipment-based meshed network. SNR-based power equalization yields 0.7 dB SNR margin improvement; a max 1 dB SNR penalty-reduction compared with blind scenario is achieved by parameters refinement. ©2023 The Author(s)*

Introduction

Signal-to-Noise Ratio (SNR) which is derived from Bit Error Rate (BER) measured by coherent receivers is the most significant evaluation criterion for the Quality of Transmission (QoT) of optical services. To improve the SNR margin in optical networks, service-level launch power optimization methods that balance Amplified Spontaneous Emission (ASE) and Nonlinear (NL) noise have been proposed [1]. Moreover, power perturbation, e.g. due to amplifier gain/spectrum variation along nework life, incurs an SNR penalty on existing services, especially when power increases compared with the design power, thereby pushing services in the nonlinear regime [2]. For instance, in an optical network composed of multiple links or Optical Multiplex Sections (OMS), link failure causes channel drop hence power drop on the remaining links, and the dynamic gain of amplifier will yield perturbation of the optical power of the remaining services, which will also affect existing services' working point after equalization.

In addition, not all parameters can be monitored in real optical networks [4], and these unknown parameters will affect the estimation of linear and nonlinear noise hence the accuracy of power equalization.

This paper demonstrates that, by monitoring the physical layer of a commercial equipment-based optical network, a digital twin can be used to perform QoT estimation and automatically optimize the network. When combined with a parameters refinement process to combat the lack of monitoring of key physical layer parameters (connector losses), power equalization improves the SNR margin of established services .

Concept

Consider a meshed optical network. We set amplifiers such that the optimal total transmission power according to the Local-Optimum Global-Optimum (LOGO) which yields flat launch power allocation. Then, using a QoT modelling tool based on the Gaussian Noise model, we set the launch power for each service, at each OMS such that the ASE-to-NL noise ratio is equal to 3 dB ("ASENL") [1]. Then we have 2 design and equalization strategies to be compared:

1. LOGO + Flat Launch Power (LOGO+Flat)
2. LOGO + ASENL (hereafter ASENL)

To obtain the optimal gain and tilt for amplifiers by LOGO design strategy, and compute the ASENL equalization power profile, we need monitored information from the physical layer. Hence, three experiment scenarios can be defined based on the monitored data:

- Ground Truth (GT): Gain profile of each amplifier and lumped losses of each span are monitored. This is not realistic but given as a reference.
- Inputs Refinement (IR) [6]: Power profile of booster and preamplifier are monitored. Connector losses are unknown. Using parameters refinement called IR to refine the gain profile of inline amplifiers (ILAs) and connector losses at the start and end of each span. This is the proposed, realistic scenario.
- Blind: Power profile of booster and preamplifier are monitored and used to approximate the ILA gain profiles through linear interpolation. Connector losses are unknown. This is a realistic but less advanced scenario.

Experimental Setup

Experiments are performed on an autonomous optical network testbed based on our software-defined networking (SDN) framework named AI-Light [5], shown as Fig. 1.

In the physical layer, the network is composed of 6 reconfigurable add-drop multiplexers (ROADMs) nodes interconnected by 8 OMSes. Commercial Erbium-Doped Fiber Amplifiers (EDFAs), Wavelength Selective Switches

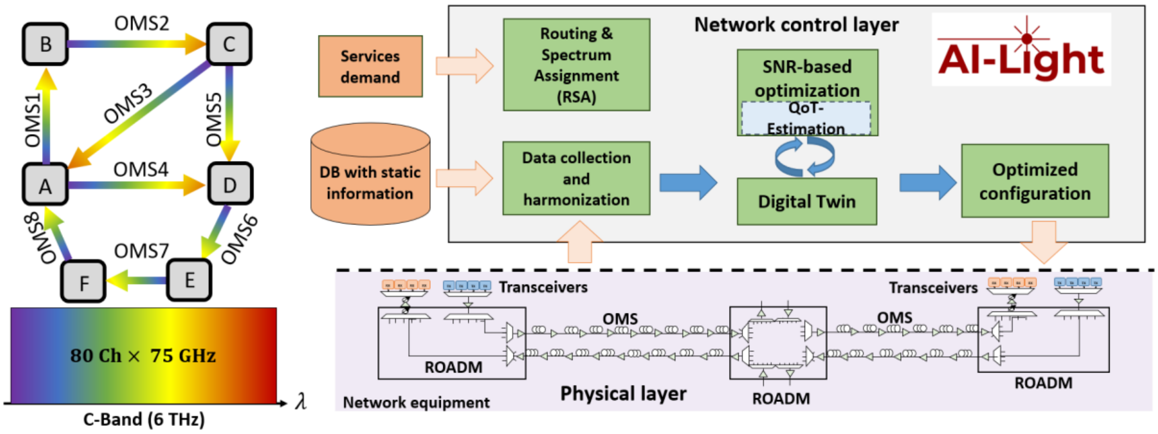

Fig. 1: Experimental setup. Left: Topology of the meshed network. Right: Network optimization framework.

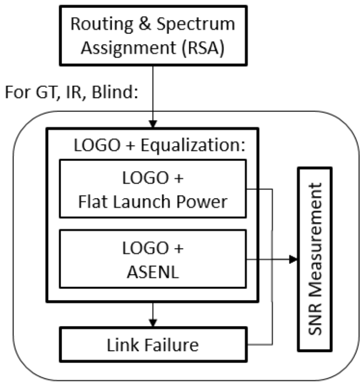

Fig. 2: Experiment steps for different scenarios.

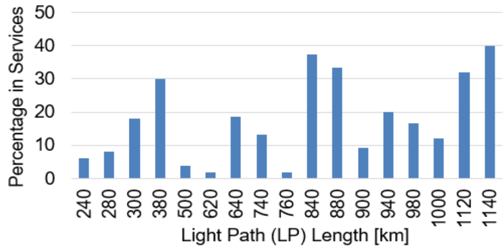

Fig. 3: Histogram of LP length of generated services.

(WSSes) and transponders are included. In addition, different fiber types are used as per Tab. 1. The experiment is carried on a 6 THz C-band optical network which has 80 channels with 75 GHz spacing. The real-time transponder is set to 200 Gb/s PDM-QPSK (68 GBaud).

In the control layer, leveraging data collected from the physical layer, a digital twin can be generated for QoT estimation, network optimization and power equalization, and IR. For monitoring, we use an Optical Spectrum Analyzer (OSA) to measure the input and output power spectrum of amplifiers to compute the gain profile (in a real network, a commercial optical power monitor able to return per-channel power, i.e. with similar function, would be used). The total connector losses per span can be calculated by extracting fiber loss from span loss yielded by reading the ILA total input and output power; IR computes the connector loss at beginning/end of span as per [6] while the "blind" scenario spreads those losses evenly between beginning/end of each span.

The experiment flow is shown as Fig. 2:

1. Routing and Spectrum Assignment (RSA): Randomly generate node pairs, then using short-path and first-fit (in frequency) to establish the Light Path.

Then, for each scenario (GT, IR, Blind):

2. Design the booster output power allocation, ILA gain and tilt by LOGO (LOGO+Flat); Measure SNR.
3. Equalize the booster output power using ASENL (LOGO+ASENL); Measure SNR.
4. Emulate a link failure; Measure SNR of remaining services.

Tab. 1: Span numbers, fiber type and fiber length of each OMS.

Name	OMS1	OMS2	OMS3	OMS4	OMS5	OMS6	OMS7	OMS8
N_{span}	5	5	5	2	3	1	2	2
Span details	5x80 km SSMF	5x100 km PSCF	2x100 km PSCF & 60+80+ 100 km SSMF	80 km LEAF & 80 km TW	3x80 km SSMF	20 km SSMF	40+80 km LEAF	20+80 km SSMF
Min/Avg/ Max span loss [dB]	19.6/ 19.6/ 19.6	23.9/ 24.0/ 24.1	19.9/ 21.9/ 24.7	23.5/ 23.5/ 23.5	19.3/ 21.8/ 23.0	16.0/ 16.0/ 16.0	16.3/ 18.3/ 20.9	16.3/ 18.7/ 21.0

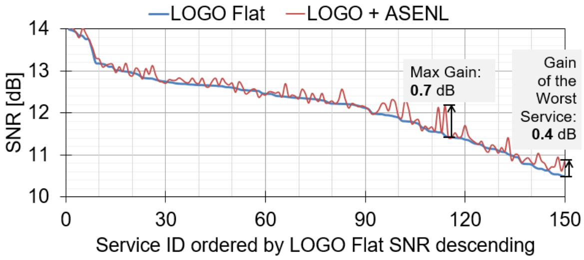

Fig. 4: SNR before (LOGO Flat) and after (ASENL) equalization using GT physical layer information.

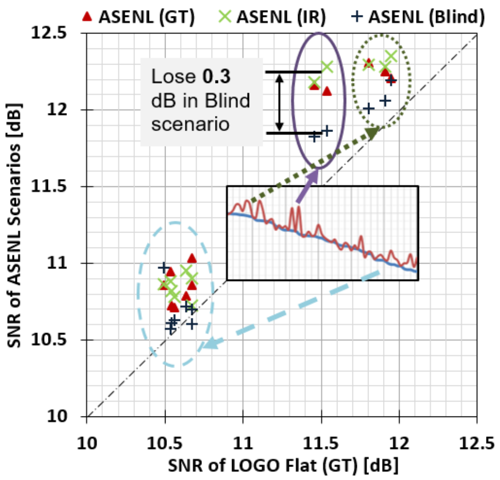

Fig. 5: SNR with different scenarios before link failure.

Results

We generate 150 services with length distribution shown in Fig. 3. Then we measure the SNR of different design strategies: LOGO+Flat and LOGO+ASENL. We assess the SNR of typical services in each of the 3 scenarios (GT, IR, Blind) to show the necessity of using IR for equalization to improve the SNR margin. Then we disable OMS 3 to emulate a link failure such as a fiber cut, and re-measure the SNR for all remaining services. It needs to be emphasized again that the optical network we built is based on OMS with commercial equipment, fiber spans are heterogeneous. Since commercial EDFAs are not ideal devices, some design values are not achievable (in particular, total output power) and therefore a few links work in sub-optimal state; yet we can still observe the impact of equalization and link failure.

SNR before and after ASENL Equalization

In the GT scenario, after power equalization, the SNR of the system has been improved, with an overall maximum gain of 0.7 dB and a gain of 0.4 dB SNR of the worst service, shown in Fig. 4. Even in case of amplifier power and gain constraint, ASENL equalization improves performance over flat power.

Moreover, as shown in Fig. 5, for several services with high benefits after equalization, if we apply the blind scenario, we lose up to 0.3 dB in SNR, while using IR can be almost consistent with GT.

Tab. 2: Number of services N_{svc} before and after link failure.

OMS	1	2	3	4	5	6	7	8
N_{svc} before	**78**	**78**	**43**	17	39	64	76	59
N_{svc} after	**50**	**63**	**0**	17	39	64	76	59

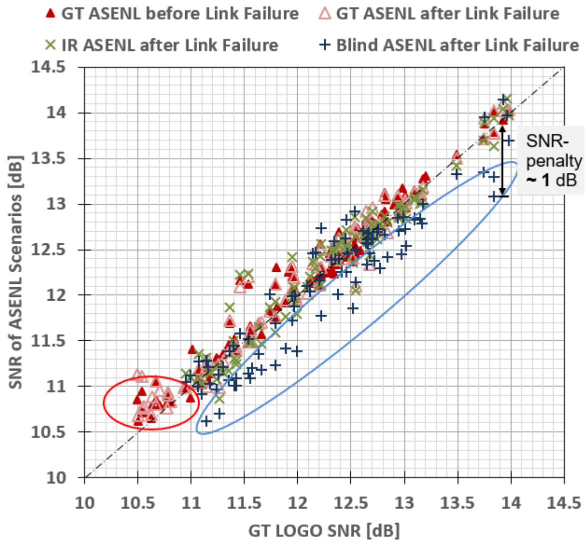

Fig. 6: SNR before and after link failure for different scenarios.

SNR before and after Link Failure

After link failure, services going through OMS 3 are lost, leading to channel drop in other OMSes, as shown in Tab. 2 for OMS 1 and 2.

Fig. 6 compares the performance before and after link failure for different equalization scenarios. The red circle shows that in the GT scenario after the link failure, the SNR margin of the system is basically unchanged, which proves that ASENL has good robustness to link failure.

Besides, in Fig. 6, focusing on the blue circle and observe the distance between '+' marker (Blind case) and triangle marker (GT case), 'x' marker (IR case) and triangle marker, it shows that the performance of IR is much closer to GT. A large SNR-penalty in the presence of link failure, up to 1 dB for some services, is due to lack of knowledge of connector losses ("blind"). On the contrary, IR can still provide good robustness in the context of link failure.

Conclusion

Through experiments, the robustness of ASENL power equalization under link failure is demonstrated, and the necessity of IR for power equalization is proved. Before link failure, compared with LOGO, IR+ASENL can improve the system margin by 0.5 dB; after link failure, parameters refinement improves SNR by 1 dB.

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