GSNR Oriented EDFA Control and Channel Power Equalization of ROADM in Open Optical Networks

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***Abstract*—The proposed end-to-end power optimization scheme based on CMA-ES maximizes GSNR average and flatness by adjusting EDFA settings and channel power equalization of WSS-based ROADM nodes. Simulations with GNPy as QoT estimator demonstrate the effectiveness.**

Keywords—CMA-ES, GSNR, EDFA, ROADM, GNPy, QoT

I. INTRODUCTION

To improve the efficiency of optical networks, network operators are implementing the deployment of open disaggregated optical networks supporting white boxes, which is facilitated by the development of coherent optical technologies and software defined network (SDN) technology [1]. In open disaggregated optical networks, signals of different wavelengths in the same transmission system usually come from different device vendors, which can be managed by the same control software. In the multi-channel and multi-link optical transmission system, the significant deviation of power evolution and the non-uniform quality of transmission (QoT) are caused by the non-ideal performance of erbium doped fiber amplifier (EDFA) and fiber nonlinear effect [2]. In optical networks, the generalized signal-to-noise ratio (GSNR) has been established as a crucial benchmark for estimating QoT. Consequently, optimizing the GSNR values of channels in wavelength division multiplexing (WDM) optical transmission systems can improve QoT. Transparent optical networks achieve end-to-end (E2E) signal transmission through transceivers, optical line systems (OLS), and reconfigurable optical add-drop multiplexer (ROADM) nodes. The adjustable components in OLSs and ROADM nodes are EDFAs and wavelength selective switches (WSS), respectively. In this scenario, transmission impairments can be classified into two main types: the GSNR impairment in each OLS and the filtering impairment at ROADM nodes.

Recently, heuristic algorithms have been applied to the power optimization in transparent optical networks. Specifically, the GSNR of each channel can be optimized by configuring EDFA settings [3-5] or allocating the power of each channel [6-7] at ROADM nodes. However, the aforementioned schemes only account for a subset of the overall optimization parameters such as EDFA settings in each OLS or each channel attenuation of the WSSs at ROADM nodes. The optimization scenario only applies to a portion of the transmission link in the optical network. As a result, it is unable to achieve global power optimization, which poses challenges for the construction and operation of the multi-link WDM transmission system.

In this paper, a power optimization scheme based on the covariance matrix adaptation evolutionary strategy (CMA-ES) is proposed to maximize GSNR average and flatness by adjusting EDFA settings (i.e., gain and tilt values) in OLSs and each channel attenuation of WSSs at ROADM nodes. GNPy is used as QoT estimator (QoT-E) to simulate the signal transmission of optical networks. Meanwhile, the power evolution of WDM signals, the nonlinear interference (NLI), the non-flat gain profile of EDFAs, the noise figure profile of EDFAs, and the filtering effect of WSSs are taken into account at the same time. We complete the simulation and optimization scheme test in a transmission link with 2 optical multiplexing sections (OMS), which demonstrates excellent performance of our scheme. Specifically, by defining the optimal configuration including EDFA settings and channel power equalization of ROADM nodes, the scheme ensures a maximum GSNR average of 19.99dB at the receiver with a minimum standard deviation of 0.11.

II. TRANSMISSION SYSTEM MODEL

In E2E transmission of the open optical network, the key transmission modules consist of OLSs (i.e., fiber spans and EDFAs) and ROADM nodes based on WSS, as indicated by Fig. 1. We consider the corresponding models of the key transmission modules, which are introduced in detail as follows.

A. Optical Line System

OLSs play a critical role in the power evolution of the signal and noise, which is definitely related to the GSNR. OLSs are commonly considered as fiber spans that undergo periodic amplifications by in-line amplifiers. The detailed model structure for OLSs in the simulation is shown in Fig. 1(b). OLS controllers, as a part of optical network controllers (ONC), can set the operating point of each EDFA to adjust the input power of each fiber span, which optimizes the power evolution and reduces the noise of the transmission link. To enhance the accuracy of simulating OLSs, non-flat gain and noise figure profiles are extracted from the corresponding commercial EDFA. Based on gaussian noise (GN) model , the effect of fiber spans on the power evolution of each channel includes two aspects:

- Power loss is associated with the fiber loss coefficient, and power transfer produced by the Stimulated Raman Scattering (SRS) is generally formalized as the SRS set of ordinary differential equations (ODE).
- Due to nonlinear crosstalk among channels caused by Kerr effect, the signal transmission on fiber spans introduces NLI, which is an additive gaussian random process. NLI consists of two types: self-channel NLI (SC-NLI) and cross-channel NLI (XC-NLI). Both NLI and the amplified spontaneous emission (ASE) noise

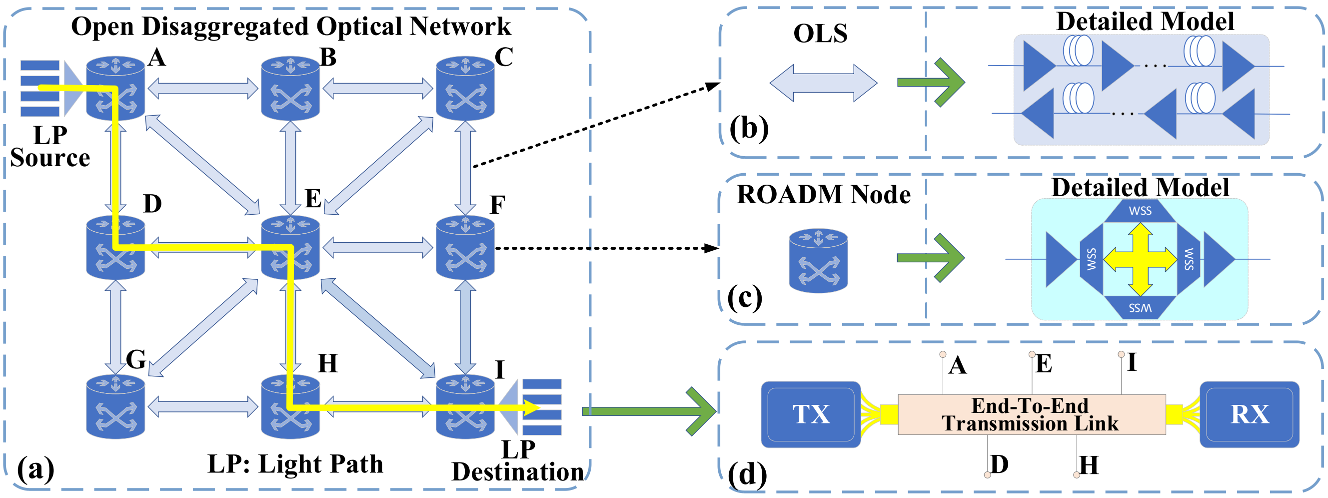

Fig. 1. (a) Open disaggregated optical network; (b) OLS; (c) ROADM node; (d) Example of the E2E transmission link.

generated by in-line amplifiers can significantly deteriorate the overall GSNR.

B. WSS-based ROADM Node

As a network element responsible for the transmission and routing of WDM signals in open optical networks, ROADM nodes can realize the addition and deletion of service wavelengths through remote reconfiguration where the power of service wavelengths can also be managed. At ROADM nodes, it is necessary to realize the channel power equalization of different wavelength channels.

The switching or reconfiguration function of ROADM nodes achieves through various switching technologies, such as MEMS, liquid crystal, WSS, and tunable optical filter technology. ROADMs based on WSS have gradually become the preferred technology for ROADMs above 4 degrees. The composition modules of ROADMs vary with the application. The main functional modules of most ROADM nodes include: channel power equalization through each channel attenuation of WSSs and built-in amplifiers including preamplifiers and boosters. The detailed model structure for four-dimensional ROADM nodes in the simulation is shown in Fig. 1(c).

III. Power Optimization Scheme

In the multi-channel and multi-link optical transmission system, the signal is affected by the loss and interference of OLSs and the filtering penalty of ROADM nodes. In this context, the power optimization scheme for E2E transmission is responsible for the configurable components in the transmission link including the EDFA settings in OLSs and each channel attenuation of WSSs at ROADM nodes.

In this work, we take the E2E transmission link as the optimization scenario, and propose the power optimization scheme considering both OLSs and ROADM nodes from the perspective of ONC. As the simulation platform of this scheme, GNPy has been fully verified in terms of QoT prediction accuracy for the physical layer of optical networks [8]. By combining CMA-ES as the optimization algorithm with GNPy as QoT-E, we are able to maximize the object function F of GSNR. This approach achieves the optimal configuration of EDFAs and ROADM nodes, as depicted in Fig. 2. The objective function F is shown as follows:

$$F(G_i, T_i, A_j) = \overline{GSNR}(G_i, T_i, A_j) - \sigma_{GSNR}(G_i, T_i, A_j) \tag{1}$$

where i ($1 \le i \le 12$) and j ($1 \le j \le 2$) are the index number of EDFA and ROADM, respectively. $\overline{GSNR}$ and σ_{GSNR} are the GSNR average and standard deviation for the given configuration respectively. The expected optimal configuration of the optimization scheme is expressed as follows:

$$\left\{G_i, T_i, A_j\right\} = arg\ max\ F(G_i, T_i, A_j)\ ,\ i \in [1,12], j \in [1,2] \tag{2}$$

The fundamental principle underlying CMA-ES involves the integration of the covariance matrix from a multidimensional normal distribution, which assimilates pertinent information from past generations into the covariance matrix update and global compensation process. By updating the covariance matrix, the direction of population evolution can be effectively controlled. Because of exceptional global optimization capabilities, CMA-ES is well-suited for multi-objective optimization scenarios.

The ROADM nodes achieve power equalization by adjusting each channel attenuation of the built-in WSSs. To achieve optimal power equalization, it is generally necessary to specify the power attenuation value for each channel. However, the large number of wavelength channels in WDM signals seriously degrades the convergence rate of CMA-ES. To improve the convergence rate of CMA-ES during the optimization of ROADM nodes, the equalization method of ROADM nodes in the GNPy platform is enhanced as follows:

$$P_n^{out} = \begin{cases} P_n^{in}, & P_n^{in} \le P_{limit}^{out} \\ P_{limit}^{out}, & otherwise \end{cases} \tag{3}$$

where P_n^{in} is the input signal power in the n th channel, and $P_{limit}^{out} = P_{min}^{in} - A \xrightarrow{Improved} P_{limit}^{out} = \overline{P_{in}} - A$. The power profile of the input signal shown in Fig. 3(a) is composed of the signal power value of each channel including the n th channel. By referring to (3), after obtaining the power average $\overline{P_{in}}$ and the power minimum P_{min}^{in} of the input signal, we can determine the maximum power limit value P_{limit}^{out} of the output signal for each channel by subtracting the equalization attenuation A

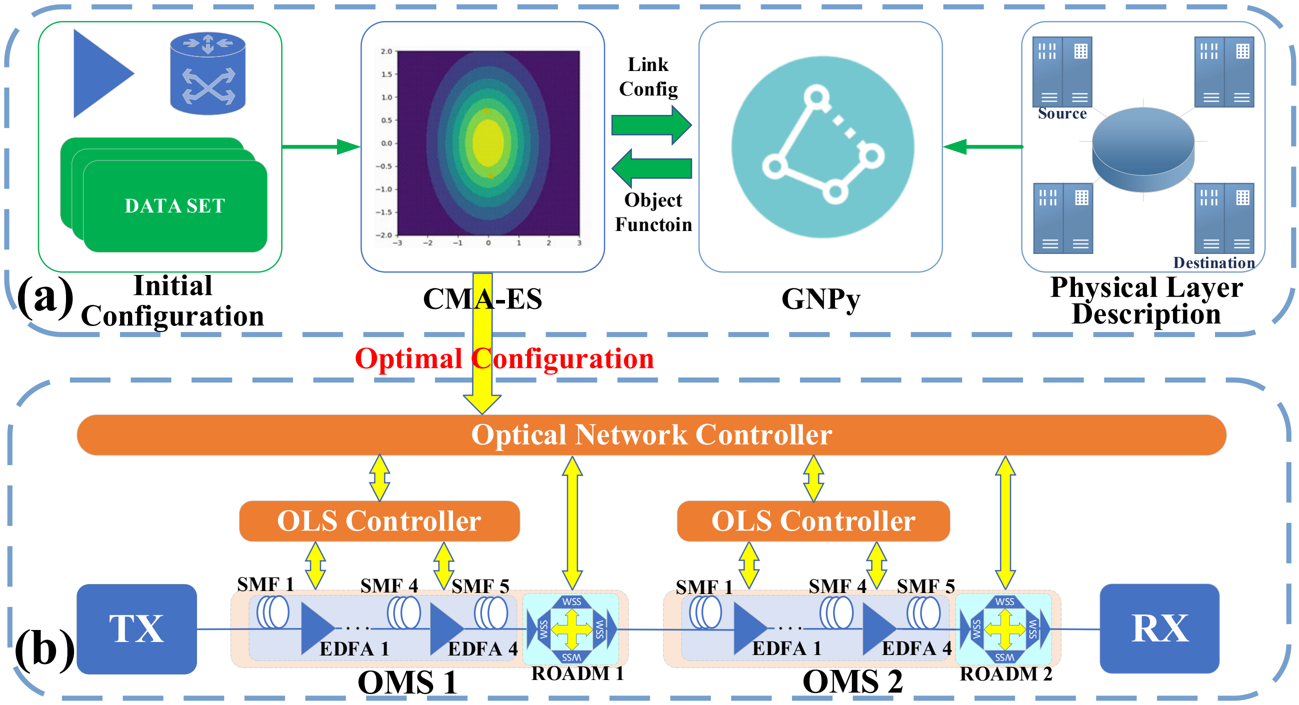

Fig. 2. (a) End-to-end power optimization scheme; (b) Optical network management architecture.

from the derived values. When the input signal power P_n^{in} of the n th channel is greater than the maximum power P_{limit}^{out}, the signal power will be attenuated to P_{limit}^{out}. Otherwise, the original power will be maintained without power attenuation. The examples for the original equalization mode and the improved equalization mode of ROADM nodes are shown respectively in Fig. 3(b) and Fig. 3(c).

IV. Simulation Setup and Results

The transmission link in the simulatin is shown in Fig. 2(b). It is comprised of 2 OMSs with 5 single-mode fiber (SMF) spans, 4 in-line EDFAs, and a WSS-based ROADM node.

In order to simulate the actual transmission link in the optical network, we randomly select the length of each fiber span in the range of 50km to 110km. Since the total loss of each fiber span is the sum of fixed insertion loss and the product of the length and fiber loss coefficient, the total loss of each fiber span in the transmission link is also randomized. The length and corresponding loss of each fiber span in 2 OMSs are shown in Table 1, where fiber loss coefficient is 0.2dB/km, and fixed insertion loss is 4dB.

TABLE I. The length and loss of each fiber span

OMS1	**SMF1**	**SMF2**	**SMF3**	**SMF4**	**SMF5**
Length(km)	50	80	60	90	70
Loss(dB)	14	20	16	22	18
OMS2	**SMF1**	**SMF2**	**SMF3**	**SMF4**	**SMF5**
Length(km)	90	110	70	100	80
Loss(dB)	22	26	18	24	20

The in-line EDFA has non-flat gain profile and noise figure profile. The amplification performance of in-line EDFAs is different from that of other EDFAs including preamplifiers and boosters in the transmission link. Aiming at realistically simulating the impact of the ROADM node on WDM signals passing through including the inherent filtering effect and equalization loss, we expand the ROADM node of GNPy for a flexible equalization capability depicted in Fig. 3, and add the preamplifier, the booster and the power loss component representing the insertion loss of WSSs on both sides of the ROADM node. The specific parameters of WSSs are shown in Table 2.

TABLE II. Specific parameters of WSSs

Parameter	**value**
Operating wavelength range (nm)	1527.61 - 1568.77
Channel spacing (GHz)	100, 50
Maximum total input power (dBm)	24
Inherent loss (dB)	8
VOA attenuation range (dB)	15
VOA attenuation resolution (dB)	0.1

In terms of transmission simulation setup, at the transmitter, the 80-channel WDM signal with 194THz as the center frequency, the WDM grid spacing of 50GHz, the baud rate of 32GBaud, and the modulation format of QPSK is generated and transmitted in the link. Upon traversing 2 OMSs, the WDM signal undergoes reception and analysis at the receiver end. Our analysis involves detecting the power distribution of both signal and noise in each channel, with the GSNR serving as the primary metric along the link.

Fig. 4(a) and Fig. 4(c) illustrate the process of initializing parameters for the configurable components within the

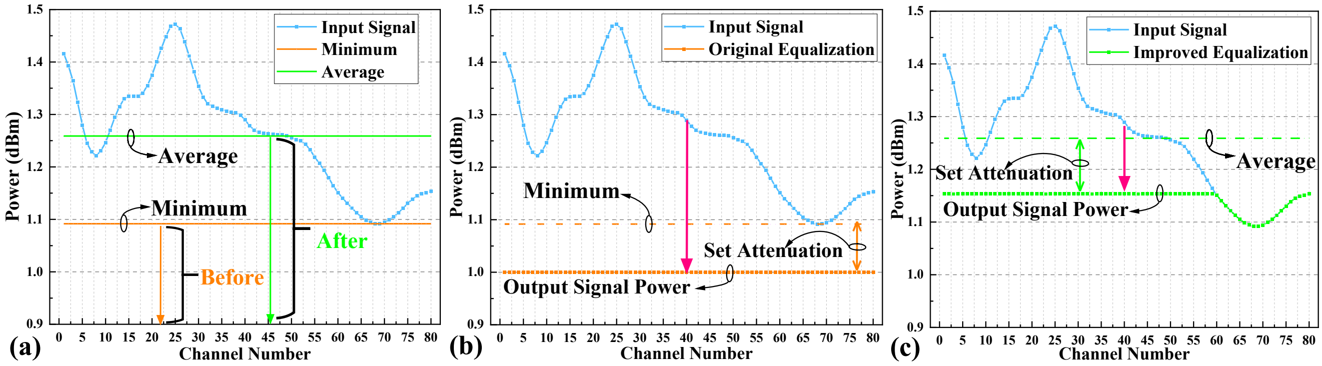

Fig. 3. Example of ROADM node equalization: (a) Input signal; (b) Original equalization mode; (c) Improved equalization mode

transmission link. Specifically, we set the initial gain value G of the preamplifier to 16dB, equivalent to the inherent loss of the ROADM node, and determine the initial value G of the gain for both the in-line amplifier and booster based on the power loss value of the preceding fiber span with the tilt T set to 0dB. The equalization attenuation values A of ROADM nodes are set to 0dB.

As to optimization algorithm setting, the power optimization scheme is designed for defining the gain values G and tilt values T of 12 EDFAs and the equalization attenuation values A of 2 ROADM nodes, which means 26 variables to be optimized. We shorten the convergence time of the optimization algorithm by constraining the adjustable parameters within reasonable ranges. The gain G of the EDFAs is limited to [-1dB, +2.5dB] based on the initial gain value, the tilt T is restricted to [-1.5dB/nm, 1.5dB/nm], and the equalization attenuation A of ROADM nodes is kept within [0dB, 3dB]. The step size of the optimization algorithm is set to 0.1.

Through the combination of the optimization algorithm and QoT-E, the optimal configuration is finally converged. The comparison between the initialization configuration and the optimal configuration is shown in Fig. 4. Specifically, Fig. 4(a) displays the G and tilt values of 12 EDFAs under the initial configuration and the optimal configuration. Fig. 4(b) shows the G values of the 12 EDFAs under 4 different contrast configurations, while Fig. 4(c) displays the equalization attenuation A values of 2 ROADM nodes under the initial configuration, the optimal configuration, and 2 contrast configurations.

Fig. 5 displays the power profile changes of signals under both initial and optimal configurations at the first ROADM node, denoted as ROADM1, in the link. Under the initial configuration, the input signal with non-flat power profile is attenuated at RAODM1, where the channel powers ($P_n^{in} > \overline{P_{in}}$) are attenuated to $\overline{P_{in}}$ with the remaining channel powers unchanged. Under the optimal configuration, it is difficult to observe the specific equalization attenuation of ROADM1 due to the non-zero tilt T configuration of EDFAs in the link. We find out that the flatness of power profile has gotten greatly improved, although the average of channel powers is reduced by a certain extent.

Fig. 6(a) and Fig. 6(b) display the GSNR profiles at the receiver under the initial and optimal configurations, along with 6 contrast configurations. These contrasts involve adjusting the G configuration of the first EDFA, denoted as EDFA1, in the link by ±1dB and ±2dB, and varying the equalization attenuation A configuration of ROADM1 by +1dB and +2dB relative to the optimal configuration. For the sake of clarity, we label the aforementioned 8 different configurations as shown in the table in Fig. 6(b).

Under the initial configuration, the GSNR profile shows considerable fluctuations with a rapid decrease of GSNR starting from the first channel and reaching a minimum at the 26th channel. Then it gradually increases and reaches its maximum at the 80th channel. The $\overline{GSNR}$ under this circumstance is 19.79876dB, with a standard deviation σ_{GSNR} of 0.19556. Through the comparison of the GSNR profiles under both the initial and optimal configurations, it is apparent that the optimal configuration improves the $\overline{GSNR}$ of 80 channels by nearly 0.2 dB. Specifically, the first 75 channels

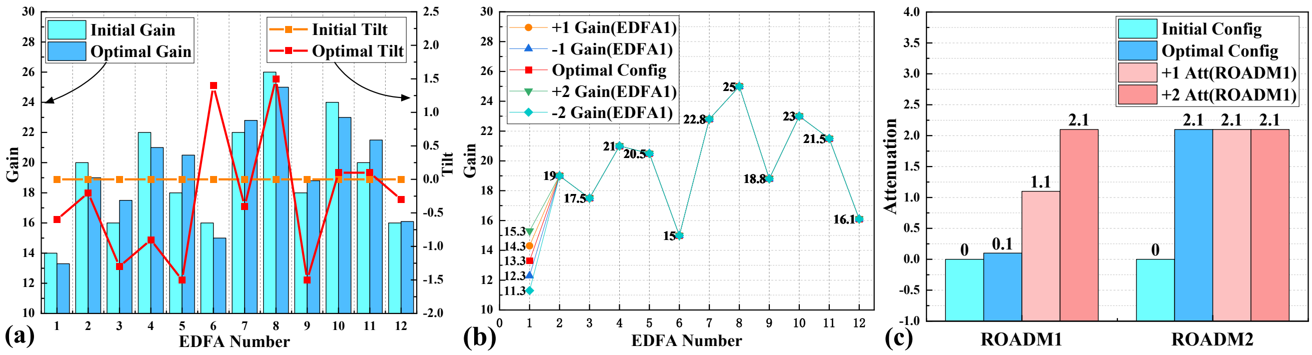

Fig. 4. Configuration comparison for 2 OMSs (a) Initial and optimal configuration for 12 EDFAs; (b) Contrast configuration for 12 EDFAs; (c) Initial, optimal and contrast configuration for 2 ROADMs

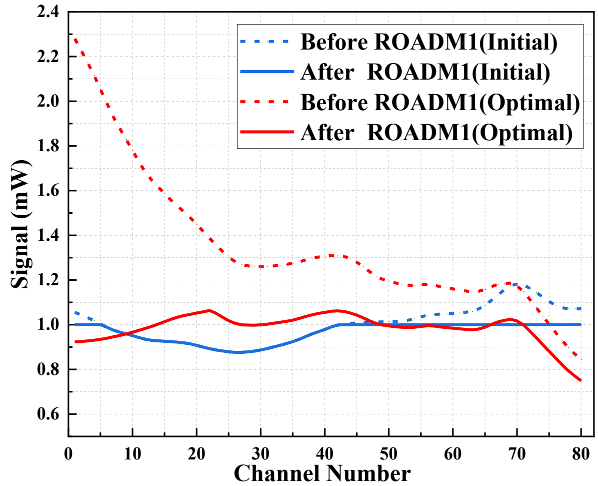

Fig. 5. Power profile change of signals around ROADM1 under initial and optimal configuration

exhibit varying degrees of GSNR improvement under the optimal configuration, while the last 5 channels experience a slight reduction. Consequently, the σ_{GSNR} of the GSNR profile under the optimal configuration is relatively low, with a reduction of nearly 0.09 in comparison to the initial configuration.

The analysis of the GSNR profiles of the 4 contrast configurations in Fig. 6(a) reveals that adjusting the G of EDFA1 in the optimal configuration decreases GSNR for most channels. However, we note that increasing the G by n dB, as opposed to reducing it, results in a higher degree of flatness of GSNR, as indicated by the decreased σ_{GSNR}. Fig. 6(b) illustrates that increasing the equalization attenuation A of ROADM1 by 1dB and 2dB in the optimal configuration results in a significant improvement in the GSNR of the first 15 channels, whereas the GSNR of the last 60 channels experiences a slight decrease. This implies that increasing the equalization attenuation A of ROADM1 leads to a larger σ_{GSNR} compared to the optimal configuration.

According to Fig. 6(c), $\overline{GSNR}$ under the optimal configuration, denoted as Con.1, reaches the maximum value of 19.98847 which is slightly improved over that under the +1Att ROADM1 configuration, and the σ_{GSNR} reaches the minimum value of 0.10683. The GSNR profile obtained from the optimal configuration results in the objective function F being maximized at a value of 19.88165. Hence, it can be inferred that the power optimization scheme proposed in this study generates an optimal configuration that achieves the highest GSNR average with maximum flatness.

V. Conclusion

We propose a GSNR oriented power optimization scheme for the transmission system in open optical networks to achieve the optimal configuration of configurable components including EDFAs and ROADM nodes in the E2E link. By utilizing GNPy as QoT-E in the simulation, we substantiate the effectiveness of the proposed power optimization scheme. The results of the simulation reveal that the proposed optimization method can determine the optimal configuration for the E2E link consisting of 2 OMSs. This configuration allows for the maintenance of the GSNR average of 80 channels at the receiver at 19.99dB, and reduces the standard deviation to 0.11.

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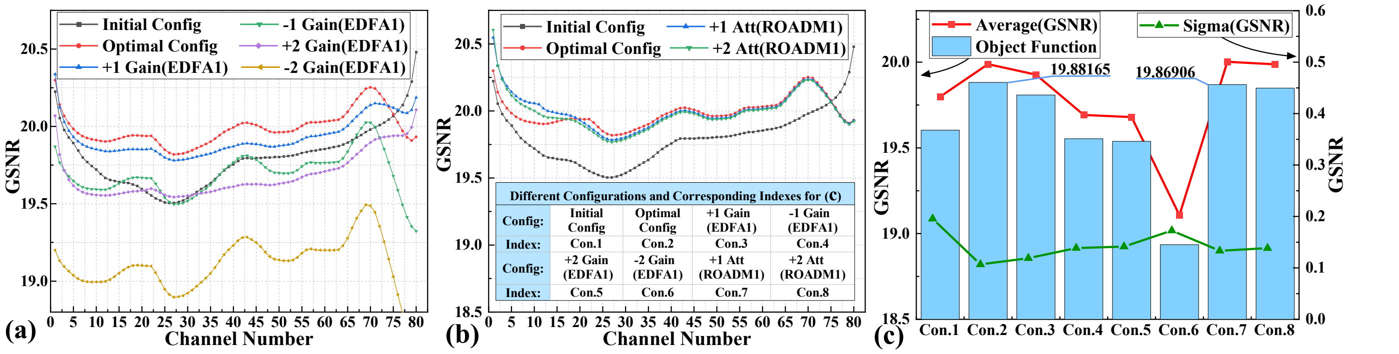

Fig. 6. Simulation results under the initial configuration, the optimal configuration, and 6 contrast configurations

(a) GSNR profile at the receiver; (b) aggregated metrics: average ($\overline{GSNR}$), sigma (σ_{GSNR}), object function F