Digital Twin-Enabled Optical Network Channel Power Management by WSS and Booster Auto-Adjustment

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Abstract: With a digital twin implementing a multi-step lookahead mechanism, we experimentally demonstrate how to increase WSS adjustment margin budget for enhanced power management in optical networks.

1. Introduction

Digital twin (DT) has been used in optical network for automation and management [1][2]. For instance, optical networks need periodic power re-equalization while ensuring that services are not interrupted during operation. By leveraging a digital twin, in [3] we were able to predict the signal-to-noise ratio (SNR) variation before carrying out any power adjustment operation e.g., when modifying the attenuation profile of a wavelength selective switch (WSS). Using a specific search technique called multi-step lookahead, we were able to find a sequence of optimization steps (WSS attenuation changes) that ensured monotonous SNR improvement for all services and avoid transient states that degrade SNR during the network-wide power optimization process.

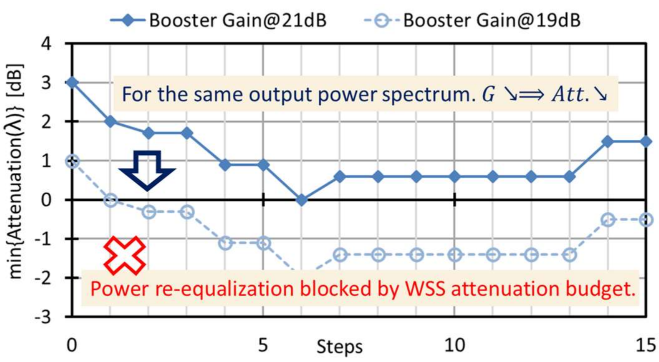
However, adjusting only the WSS attenuation may limit the power setting operations [4]. For instance, when the WSS is a minimum attenuation, yet higher power is desired for *some* channels after a booster amplifier (the first amplifier in a transmission line). A solution is to increase the booster gain and compensate for the undesired power increase on the *other* channels by increasing the WSS attenuation. Such a spectrum-wide gain change impacts the SNR of many channels simultaneously.

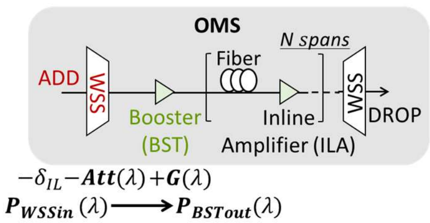
In this work, we used a digital twin and the multi-step lookahead technique to remove this bottleneck and ensure that even when WSS reach an attenuation bottleneck and booster amplifier gain needs to be adjusted during network power optimization, the SNR of any service does not degrade. The technique is experimentally demonstrated on a C-band meshed network testbed.

2. Principle

Optical transport networks consist of optical multiplexing sections (OMSs), as shown in Figure 1: a pair of WSSs (ADD/DROP) for adding/dropping optical channels (services), N fiber spans and N+1 optical amplifiers (OAs). The launch power profile of the booster in the OMS can be tuned by adjusting the WSS attenuation profile, so that power equalization can be implemented to optimize the performance of services. Based on physical model, e.g., Gaussian noise (GN) model [5], the SNR can be optimized by balancing the amplified spontaneous emission (ASE) and the non-linear (NL) noises to 3dB. The booster output power spectrum $\boldsymbol{P_{BSTout}}(\lambda)$ is written as:

$$\boldsymbol{P_{BSTout}}(\lambda) = \boldsymbol{P_{WSSin}}(\lambda) - \delta_{IL} - \boldsymbol{Att}(\lambda) + \boldsymbol{G}(\lambda)$$





Att.	Gain	OSNR
High	High	Low
Low	Low	High

Figure 1. WSS attenuation budget blocks power re-equalization. Left: solid dark blue curve is the experimental results [3] with proper gain setting, dash light blue curve represents the fact that there'll be no attenuation budget with a non-proper gain setting.

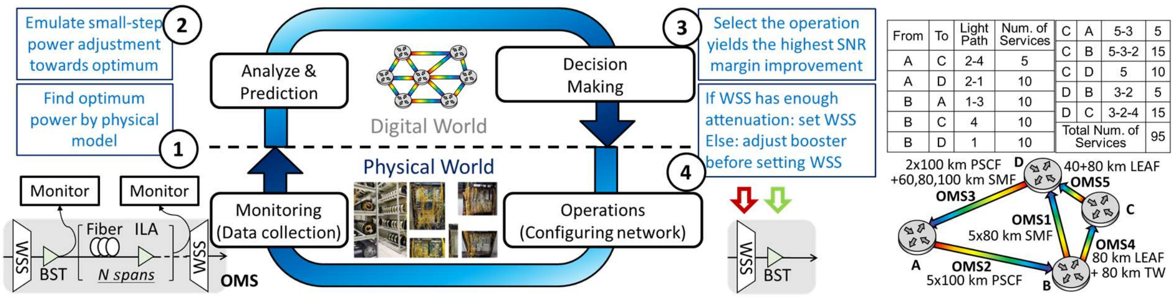


Figure 2. Digital twin enabled power auto-adjustment method and 5-OMS meshed network experimental setup.

where $\boldsymbol{P_{WSSin}}(\lambda)$ is the WSS (ADD) input power spectrum, δ_{IL} represents insertion losses, $\boldsymbol{Att}(\lambda)$ is WSS (ADD) attenuation profile, and $\boldsymbol{G}(\lambda)$ is the booster gain profile. The different combinations of WSS attenuation profile and booster gain can yield the same booster output power spectrum. But a lower booster gain yields lower ASE, thereby increasing the Optical SNR. Hence, some operators set the gain to a lower value at the network's beginning of life. However, lower gain requires lower WSS attenuation, which decreases the WSS attenuation budget and could block power re-equalization later on if negative WSS attenuation is needed to achieve the optimal power setting, as shown in Fig. 1 (left). To avoid such optimization blockages and the aforementioned SNR degradations incurred by spectrum-wide booster gain change, we propose the following power optimization strategy, based on a digital twin (Fig. 2):

Step 1: By leveraging the information (amplifier gain, tilt, power spectrum) from physical layer, the digital twin finds the optimum launch power $P_{n,optim}(\lambda)$ of each OMS_n in the network.

Step 2: The digital twin emulates the small-step power adjustment with multi-step lookahead to adjust launch power $P_n(\lambda)$ of channel λ of OMS_n by:

$$\Delta P_n(\lambda) = \begin{cases} P_{n,optim}(\lambda) - P_n(\lambda), & \text{if } \left|P_{n,optim}(\lambda) - P_n(\lambda)\right| < \delta \\ \delta \cdot \text{sign}\left(P_{n,optim}(\lambda) - P_n(\lambda)\right), & \text{otherwise} \end{cases}$$

where δ is a fixed power step size. The digital twin then predicts the SNR variation for all impacted services.

Step 3: Select the operation that maximizes the improvement in *network SNR margin* (min SNR of all services).

Step 4: **If** the WSS has sufficient attenuation tuning range, **then** implement the power adjustment selected in Step 3; **else**, adjust booster gain and WSS attenuation step-by-step.

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Pseudocode: Step 3 and Step 4
if Att_n(λ) − ΔP_n(λ) ≥ 0, then:
    Set OMS_n WSS attenuation to Att_n(λ) − ΔP_n(λ).
else:
    for k = 1, …, N:   # N is the adjustment step number determined by digital twin, so that ΔG is smaller
        Adjust booster gain by ΔG = δ/N.   # enough to make sure there is no SNR margin degradation
        Adjust WSS attenuation profile by ΔP_n(λ) + ΔG.
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3. Experimental Setup

Our commercial products-based testbed is a 5-OMS C-band meshed network, as shown in Fig. 2 (right). We emulate 95 services using ASE loading in the network; we emulate set-and-forget loading such that channels are not well equalized. A real-time 400 Gb/s (PDM-PCS16QAM, 100 GHz grid) transponder enables SNR measurements.

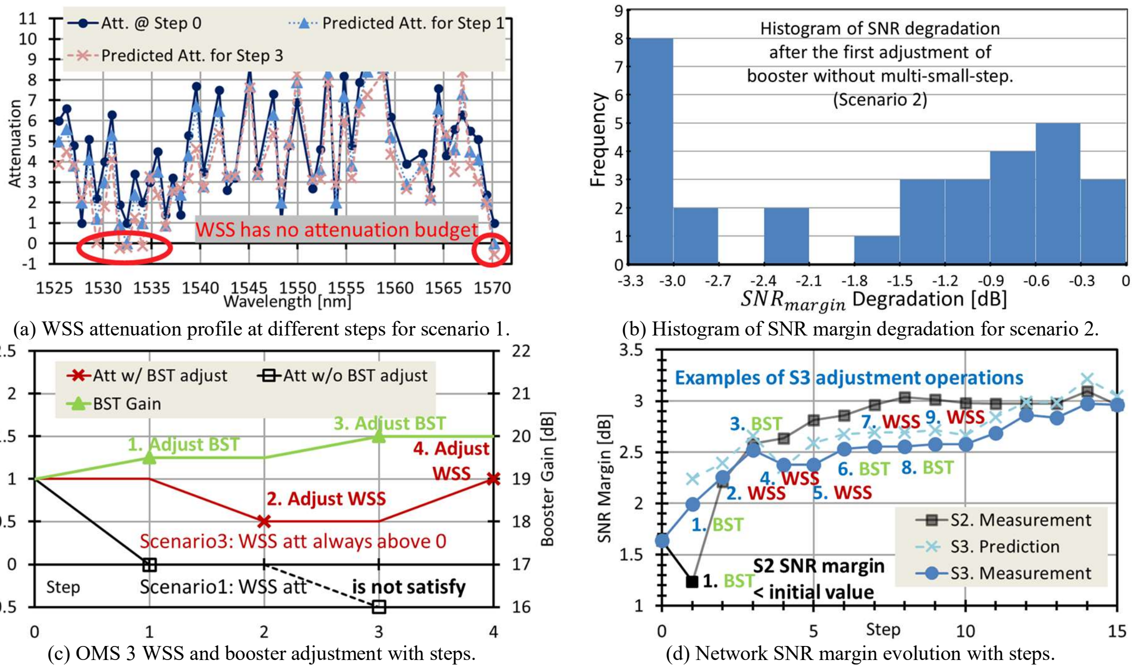
The testbed is automated with our software-defined networking framework. It automatically collects and refines [6] the physical parameters to build the digital twin and prediction the SNR performance to implement the proposed algorithm. For multi-step power adjustment, we apply WSS adjustment step size $\delta = 1dB$ and 2-step look-ahead for parallel configuration as in [3].

4. Results

For experimental validation, there are 3 scenarios of booster adjustment with WSS attenuation budget constraint:

Table 1. **Booster adjustment** methods for power re-equalization and their results.

Scenarios	S1: Don't adjust booster	S2: Single step at first	S3: DT-enabled multi-step (***proposed***)
Results	WSS attenuation blocks	SNR degradation	SNR margin never below initial value
Figures	Fig. 3(a), (c) black	Fig. 3(b), (d) black	Fig. 3(c), (d)



(a) WSS attenuation profile at different steps for scenario 1.
(b) Histogram of SNR margin degradation for scenario 2.
(c) OMS 3 WSS and booster adjustment with steps.
(d) Network SNR margin evolution with steps.

Figure 3. Experimental results with different scenarios (S1-S3).

For demonstration's sake and to motivate small steps optimizations, we first set the OMS3 booster gain 2dB lower than the optimum. Then, after loading channels with the "set-and-forget" method, the WSS attenuation profile is shown in Figure 3(a) Step 0. To balance ASE/NL noise, the power is re-equalized step-by-step through adjusting the WSS attenuation profile. As shown in Fig. 3(c), the OMS 3 booster gain is 19dB and minimum attenuation of WSS is only 1dB. At some point, power re-equalization requires increasing the power of the channel which has the min attenuation, and power cannot be re-equalized, as shown in the black dash curve in Fig. 3(c).

Scenario 1: With fixed booster gain value, negative attenuation is sometimes needed during power optimization, which is impossible, as shown in Fig. 3(a), Steps 1&3(simulation results), and in Fig. 3(c), black curve.

Scenario 2: We recover the attenuation range margin by increasing the booster gain (and output power) in a single step without predicting the global impact on SNR within digital twin. In the 5-OMS network, there are 2^5-1=31 boosters gain preset (2dB lower than the optimum) combinations. We show the impact of such changes on SNR by simulation in Fig. 3(b) – without proposed digital twin enabled technique, the first step of booster gain adjustment can degrade SNR margin by several dB, if there are multiple boosters need to be adjusted. We experimentally demonstrate such a SNR margin degradation with only 1 booster gain adjustment by 2dB at the first step of black curve in Fig. 3(d).

Scenario 3: Last but not least, we experimentally validate the digital twin enabled multi-step-lookahead WSS and booster adjustment which avoids the SNR margin degradation. With our technique, the digital twin enabled algorithm arranges the order and step-size of both WSS and booster adjustment (Fig. 3(c)) with prediction of SNR margin, thereby growing the SNR margin safely during the power re-equalization. The SNR margin prediction/measurement before/after each operation are shown in Fig. 3(d). The digital twin prediction accuracy is within 0.3dB.

5. Conclusion

We experimentally demonstrated the digital twin enabled power adjustment with multi-step lookahead prediction of WSS and booster operations can conquer WSS attenuation budget constrain in C-band optical network.

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