Experimental Demonstration of Optical Network Partitioning and Parallel Configuration for Autonomous Power Re-Equalization

Chenyu Sun(1,2,3,*), Louis Aknin(3,4), Reda Ayassi(3),
Photios A. Stavrou(2), Yvan Pointurier(3), Gabriel Charlet(3)

(1) Sorbonne Université, Paris, France
(2) EURECOM, Sophia-Antipolis, France, * chenyu.sun@eurecom.fr
(3) Huawei Technologies France, Boulogne-Billancourt, France
(4) École Centrale de Lyon, Lyon, France

Abstract *We propose and experimentally demonstrate a digital twin–based optical network partitioning strategy on a 7-OMS mesh optical network testbed. By leveraging parallel closed-loop control across subnets, the proposed approach reduces power re-equalization time by over 80%.*

Introduction

With the continuous expansion of optical network scale and the increasing demand for high data rates and flexible service provisioning, optical network automation faces growing challenges [1]. Among various operational parameters, per-channel launch power configuration plays a critical role in determining transmission performance, directly affecting the signal-to-noise ratio (SNR) hence bit error rate (BER) and ultimately overall network capacity. In practical deployments, optical networks often operate for long periods in a “set-and-forget” mode or experience topology and physical-layer changes after events such as fibre repair or service reconfiguration. Under these conditions, services’ power settings gradually deviate from their optimal values, making periodic power re-equalization necessary [2].

However, in large-scale networks composed of multiple optical multiplexing sections (OMSs), power reconfiguration is inherently non-local. Adjusting the launch power in a single OMS propagates to downstream sections through optical amplifiers and fibre spans, introducing inter-OMS power coupling and nonlinear interactions [3][4]. As a result, conventional sequential and open-loop power adjustment schemes may cause transient SNR degradation and even service disruption, which severely limits their applicability in operational networks. Digital twins (DT) address these challenges by constructing a high-fidelity virtual replica of the physical network within the control plane [5]-[8]: a DT enables real-time state mirroring and performance prediction prior to executing configuration changes. This capability allows power optimization decisions to be evaluated in advance, significantly improving operational safety [9]. Nevertheless, DT–assisted power reconfiguration faces scalability challenges, including high computational complexity, long commissioning time, and limited parallelization ability [10].

To improve the scalability of power reconfiguration in large-scale optical networks, this paper proposes a network partitioning–based parallel configuration strategy. By dividing the original network into multiple weakly coupled subnets and deploying independent DTs for each subnet, power re-equalization can be carried out in parallel, substantially reducing optimization complexity and execution time.

Principles

Power Re-Equalization with DTs

In wavelength-division multiplex (WDM) optical networks, services, or optical channels (OCHs), typically traverse multiple OMSs, power variations introduced in a single OMS propagate downstream, making power equalization a global, network-wide optimization problem with strong interdependencies.

A DT is a high-fidelity virtual representation of the physical optical network that continuously incorporates network topology information, fibre and amplifier parameters, and monitored channel power spectra. Based on this information, physical models, such as the Gaussian Noise (GN) model [11][12], or data-driven estimators [13] are used to predict the SNR of all active services under different power configurations.

By leveraging DTs, optical network power equalization is transformed from a conventional open-loop and experience-driven operation into a closed-loop “observe–predict–operation” control process, shown in Fig. 1. During the power re-

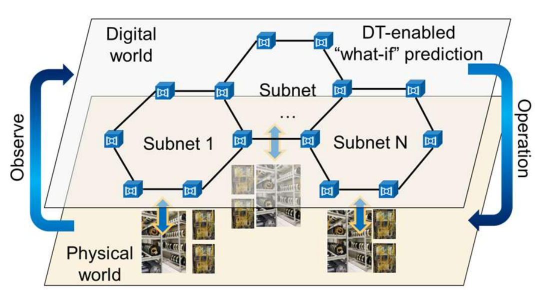

Fig. 1: Digital twin-enabled close-loop control.

equalization process, the DT first computes the differences between current and target power profiles for individual OMSs. Candidate power adjustment actions are then emulated within the DT, explicitly accounting for power propagation across multiple OMSs and the accumulation of nonlinear impairments. Only when the predicted results indicate that the SNR of all active services remains within acceptable limits are the corresponding configurations applied to the physical network.

This prediction-driven mechanism not only enhances the safety and reliability of power reconfiguration but also establishes a unified foundation for advanced strategies such as multi-step lookahead [10], parallel configuration, and network partitioning, which are essential for scalable optimization in large-scale optical networks.

Network Partitioning

As shown in Fig. 2 and Fig. 3, given some integer K_p, the proposed partitioning algorithm adopts a convex edge-based approach to divide a network into K_p subnets. The optical network is modelled as a weighted multigraph where each node is a ROADM and each edge is an OMS, which weight is the number of services using this edge. The objective is to generate topologically compact and well-balanced partitions while minimizing the impact of inter-partition services.

The partitioning process starts by randomly selecting K_p edges as partition seeds. A multi-source breadth-first search (BFS) is then performed on the implicit line graph, where nodes are OMSs, and edges are added whenever 2 OMSs share a ROADM. Through this expansion, neighbouring edges are progressively assigned to the same partition, ensuring topological continuity and convexity. If an edge can be reached by multiple partition seeds at the same distance, it is temporarily associated with multiple partitions, capturing partition boundary ambiguities.

To further improve partition quality, a multi-objective refinement is applied. Two metrics are jointly considered: (i) partition size balance J_{size}, quantified by the standard deviation of the number of edges per partition; (ii) topology proximity J_{prox}, or compactness, measured as the average distance between edges within the same partition in the implicit line graph $L(G)$:

$$J_{size} = \sqrt{\frac{1}{K_p}\sum_i^{K_p}(|E_i| - \mu)^2}, \quad (1)$$

$$J_{prox} = \frac{1}{K_p}\sum_i^{K_p}\frac{1}{\binom{|E_i|}{2}}\sum_{\{e,f\}\subseteq E_i} d_{L(G)}(e,f), \quad (2)$$

where E_i is the edge set assigned to partition subnet i, μ is the mean partition size, $\binom{|E_i|}{2}$ is the number of unordered pairs of distinct edges within partition i, $d_{L(G)}(e,f)$ is the shortest-path (in hops) between edges e and f in $L(G)$.

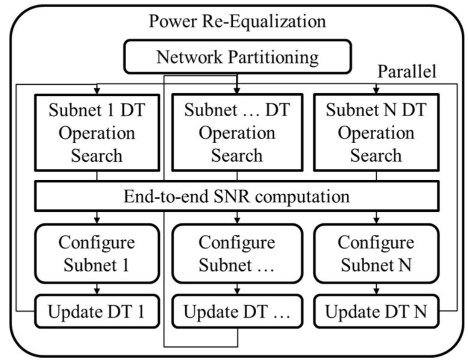

Fig. 2: Parallel DT-enabled power re-equalization workflow.

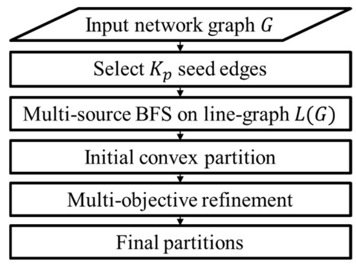

Fig. 3: Network partitioning workflow.

A greedy refinement iteratively reassigns edges to partitions to minimize a weighted combination $score = w \cdot J_{size} + (1 - w) \cdot J_{prox}$ of these metrics preserving partition connectivity.

This partitioning strategy provides a scalable and topology-aware foundation for parallel network control and DT-based emulation, enabling independent and concurrent optimization tasks—such as power re-equalization—within each subnet. By partitioning the network into K_p subnets, the time complexity of DT-enabled multi-step lookahead algorithm [10] is reduced from $\mathcal{O}(N_{OMS}^{K_m})$ to $\mathcal{O}\left(\left(N_{OMS}/K_p\right)^{K_m}\right)$, where N_{OMS} is the number of OMSs in the network and K_m is the lookahead depth, typically limited to 1 or 2 for scalability.

Experimental Setup

The proposed technique was experimentally validated on a C-band mesh optical network testbed using commercial products, shown in Fig. 4. The network consists of six nodes interconnected in a mesh topology with 7 OMSs. Each OMS is composed of add/drop WSS, multiple fibre spans with various of types, and erbium-doped fibre amplifiers (EDFAs) operating in gain-lock mode. All optical power spectra are measured using optical power monitors (OPMs) installed at the outputs of booster amplifiers and pre-amplifiers.

A total of 40 end-to-end OCHs are deployed in the network using ASE loading with a 150 GHz channel spacing and measured by 800 Gb/s 140GBaud PCS-16QAM real time transponder. Traffic is distributed among all node pairs, with two services established for each source–

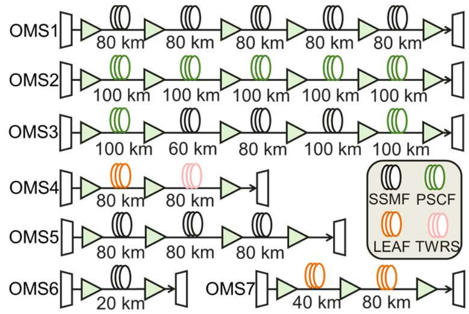

Fig. 4: Experimental setup.

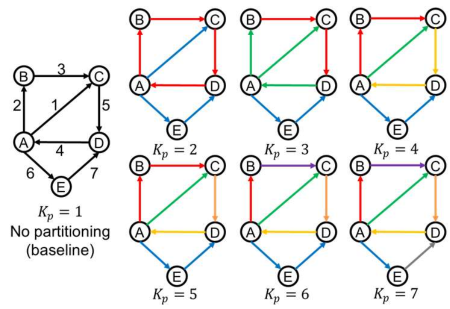

Fig. 5: Network topology and network partitioning.

destination pair. All services are provisioned following the set-and-forget strategy with flat power target and are established in a random order, resulting in a non-optimized initial power profile and realistic power imbalance across OMSs.

Based on the DT, the network is partitioned into K_p=1,…,7 subnets using a partitioning score weight w=0.5. This enables parallel emulation and optimization of power re-equalization using a one-step lookahead with a 1dB adjustment step size. Telemetry data are collected by distributed sub-DT controllers to update the corresponding sub-DTs. For performance evaluation, the convergence threshold is set to ε=0.3/0.5dB in terms of the maximum absolute error with respect to the target power profile.

Results

Resulting partitions are shown in Fig. 5. The evolution of the max and average power error are shown in Fig. 6. The baseline K_p=1 corresponds to no partitioning. For intermediate values (K_p=2–6), the power error decreases rapidly and converges within a small number of operations, demonstrating that parallel configuration mitigates power coupling and accelerates convergence. Whereas, for K_p=7, the system fails to reach the 0.3dB threshold and shows non-convergent behavior because power adjustments performed independently in each subnet induce inter-OMS power propagation that continuously perturbs previously optimized OMSs, preventing monotonic error reduction.

Fig. 7 provides a comprehensive view of the trade-offs introduced by partitioning. As K_p

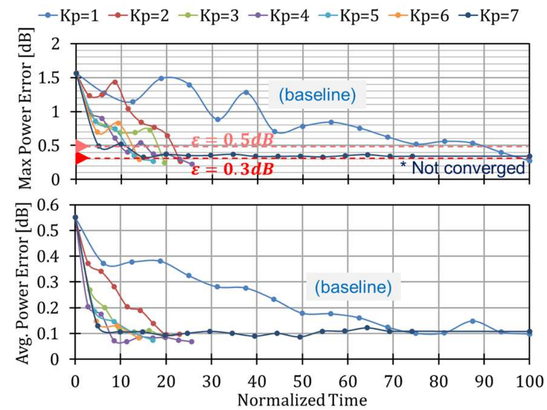

Fig. 6: Power error evolution vs. normalized time.

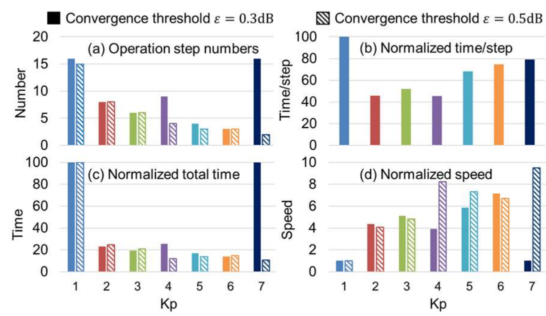

Fig. 7: Quantitative performance metrics with different convergence threshold $\boldsymbol{\varepsilon}$=0.3/0.5dB. (a) operation numbers vs. $\boldsymbol{K_p}$. (b) normalized time/step vs. $\boldsymbol{K_p}$. (c) normalized total time vs. $\boldsymbol{K_p}$. (d) normalized speed (inverse of time) vs. $\boldsymbol{K_p}$.

increases, the number of operation steps drops sharply, leading to a strong reduction in total commissioning time despite a gradual increase in time per step due to coordination overhead. This results in a clear speed-up gain, with the normalized speed peaking around K_p=4. Beyond this region, further partitioning brings diminishing returns as shown in Fig. 7(d) dash bars.

The impact of the convergence threshold is also evident. The relaxed threshold (0.5dB) consistently requires fewer steps than the stricter one (0.3dB), highlighting a trade-off between convergence speed and accuracy. In particular, for K_p=7, the system fails to converge under the stricter threshold, confirming that excessive partitioning degrades stability.

Overall, K_p=4 emerges as the optimal operating point, achieving up to 80% reduction in total time compared to the baseline, while maintaining reliable convergence.

Conclusions

The proposed approach achieves over 80% reduction in power re-equalization time by reducing the number of operations through parallel partitioning. These results demonstrate that network partitioning is a key enabler for scalable optical network automation, with an optimal partitioning level balancing convergence speed and stability.

References

[1] N. Andriolli, A. Giorgetti, P. Castoldi, G. Cecchetti, I. Cerutti, N. Sambo, A. Sgambelluri, L. Valcarenghi, F. Cugini, B. Martini, and F. Paolucci, "Optical networks management and control: A review and recent challenges," Optical Switching and Networking, vol. 44, 2022, DOI: 10.1016/j.osn.2021.100652

[2] X. Yang, A. Ferrari, D. Le Gac, G. Charlet, M. Tornatore, and Y. Pointurier, "Experimental impact of power re-optimization in a mesh network," *Journal of Optical Communications and Networking*, vol. 15, no. 7, p.p. C20-C28, 2023, DOI: 10.1364/JOCN.482298

[3] J.-P. Elbers and C. Fürst, "Chapter 7 - Spectral Power Fluctuations in DWDM Networks Caused by Spectral-Hole Burning and Stimulated Raman Scattering," *Optically Amplified WDM Networks* (J. Zyskind and A. Srivastava, eds.), pp. 201–219, Oxford: Academic Press, 2011, DOI: 10.1016/B978-0-12-374965-9.10007-X

[4] J. Junio, D. C. Kilper and V. W. S. Chan, "Channel power excursions from single-step channel provisioning," *Journal of Optical Communications and Networking*, vol. 4, no. 9, pp. A1-A7, 2012, DOI: 10.1364/JOCN.4.0000A1

[5] D. Wang, Y. Song, Y. Zhang, X. Jiang, J. Dong, F. N. Khan, T. Sasai, S. Huang, A. P. T. Lau, M. Tornatore, and M. Zhang, "Digital Twin of Optical Networks: A Review of Recent Advances and Future Trends," *Journal of Lightwave Technology*, vol. 42, no. 12, p.p. 4233–4259, 2024, DOI: 10.1109/JLT.2024.3401419

[6] Q. Zhuge, X. Liu, Y. Zhang, M. Cai, Y. Liu, Q. Qiu, X. Zhong, J. Wu, R. Gao, L. Yi, and W. Hu, "Building a digital twin for intelligent optical networks [Invited Tutorial]," *Journal of Optical Communications and Networking*, vol. 15, C242–C262, 2023, DOI: 10.1364/JOCN.483600

[7] R. Vilalta, L. Gifre, R. Casellas, R. Muñoz, R. Martínez, A. Mozo, A. Pastor, D. López, and J. P. Fernández-Palacios, "Applying Digital Twins to Optical Networks with Cloud-Native SDN Controllers," *IEEE Communications Magazine*, vol. 61, p.p. 128–134, 2023, DOI: 10.1109/MCOM.003.2300105

[8] M. S. Faruk and S. J. Savory, "Measurement Informed Models and Digital Twins for Optical Fiber Communication Systems," *Journal of Lightwave Technology*, vol. 42, no. 3, p.p. 1016–1030, 2024, DOI: 10.1109/JLT.2023.3328765

[9] K. Christodoulopoulos, C. Delezoide, N. Sambo, A. Kretsis, I. Sartzetakis, A. Sgambelluri, N. Argyris, G. Kanakis, P. Giardina, G. Bernini, D. Roccato, A. Percelsi, R. Morro, H. Avramopoulos, P. Castoldi, P. Layec, and S. Bigo, "Toward efficient, reliable, and autonomous optical networks: the ORCHESTRA solution [Invited]," *Journal of Optical Communications and Networking*, vol. 11, no. 9, pp. C10-C24, 2019, DOI: 10.1364/JOCN.11.000C10

[10] C. Sun, X. Yang, G. Charlet, P. A. Stavrou, and Y. Pointurier, "Digital twin-enabled multi-step strategies for autonomous power equalization in optical networks," *Journal of Optical Communications and Networking*, vol. 17, no. 7, p.p. C41-C50, 2025, DOI: 10.1364/JOCN.549934

[11] P. Poggiolini, G. Bosco, A. Carena, V. Curri, Y. Jiang, and F. Forghieri, "The GN-Model of Fiber Non-Linear Propagation and its Applications," *Journal of Lightwave Technology*, vol. 32, no. 4, p.p. 694-721, Feb. 2014, DOI: JLT.2013.2295208

[12] D. Semrau, R. I. Killey and P. Bayvel, "A Closed-Form Approximation of the Gaussian Noise Model in the Presence of Inter-Channel Stimulated Raman Scattering," *Journal of Lightwave Technology*, vol. 37, no. 9, pp. 1924-1936, 2019, DOI: 10.1109/JLT.2019.2895237

[13] Y. He, Z. Zhai, L. Dou, L. Wang, Y. Yan, C. Xie, C. Lu, and A. P. T. Lau, "Improved QoT estimations through refined signal power measurements and data-driven parameter optimizations in a disaggregated and partially loaded live production network," *Journal of Optical Communications and Networking*, vol. 15, no. 9, p.p. 638–648, 2023, DOI: 10.1364/JOCN.496720