ROADM Bypassing for Energy-Efficient EONs Capacity Upgrade

Mirko Zitkovich
Chair of Communication Networks
University of the Bundeswehr München
Munich, Germany

Anjali Sharma
Chair of Communication Networks
University of the Bundeswehr München
Munich, Germany

Carmen Mas-Machuca
Chair of Communication Networks
University of the Bundeswehr München
Munich, Germany

***Abstract*—As optical networks continue to scale to meet exponential traffic growth, energy efficiency has become as critical as capital cost. This paper quantifies the power consumption of ROADM bypassing, a capacity-scaling strategy that establishes dedicated point-to-point paths via dark-fiber splicing, bypassing intermediate ROADMs. We benchmark power consumption against multi-fiber C-band (C-MF) and multi-band C+L-band (MB-MF) architectures across four topologies, considering the required transponders (TPs), erbium-doped fiber amplifiers (EDFAs), and wavelength-selective switches (WSSs). Results show that the proposed strategy enables power savings of approximately 11–21% with current TP technology. However, as TP power consumption decreases with ultra-long-haul pluggables, EDFA power consumption outweighs TP power savings. Since such pluggables are not yet suitable for long-reach applications, ROADM bypassing remains a compelling energy- and cost-efficient solution for capacity expansion in fiber-rich brownfield networks.**

***Index Terms*—ROADM, power consumption, elastic optical networks, multi-fiber, multi-band**

I. Introduction

Optical core networks face sustained traffic growth exceeding 20% annually [1], requiring continuous capacity expansion through the deployment of additional active optical components. This expansion, however, comes at the cost of increased energy consumption: information and communication technology (ICT) electricity consumption is projected to reach 1,100–1,245 TWh by 2030 [2], driven primarily by networks and data centers. As a result, energy efficiency has become a key requirement for operators facing sustainability targets and aiming to reduce their operational and capital expenditures.

Operators address capacity increases through multi-band (MB) transmission, which extends operation into the L-band to effectively double the usable spectrum [1], and space-division multiplexing (SDM) via multi-core, multi-mode, or multi-fiber (MF) systems [3]. Among these alternatives, MF deployment is generally the most cost-efficient, as fibers are typically already installed in high-count cables, enabling capacity expansion through the use of dark fiber.

However, these capacity expansion techniques preserve per-link spectrum sharing among multiple lightpaths. As a result, transponders (TPs) must often operate below their maximum line rates to avoid spectrum contention and blocking. In this case, more TPs are required overall to meet growing traffic demands, which in turn directly increases both capital expenditure and operational energy consumption. Addressing these spectral and energy inefficiencies is a core motivation for the alternative strategy proposed in this work.

In [4], we proposed *ROADM bypassing* as an alternative architecture in brownfield scenarios for elastic optical networks (EONs) with available dark fiber. This approach establishes dedicated point-to-point (P2P) paths by splicing dark fiber to bypass intermediate ROADMs. These P2P paths (i) reduce the need for wavelength-selective switches (WSSs) and (ii) remove spectrum sharing, which enables TPs to operate at their maximum line rates, thereby reducing the required TP count. A techno-economic analysis showed cost savings of 5.6%–17% compared to multi-fiber C-band (C-MF) and multi-band (MB-MF) solutions.

That analysis, however, disregarded operational power consumption. ROADM bypassing introduces a component trade-off by reducing the number of TPs and WSSs, while increasing the deployment of erbium-doped fiber amplifiers (EDFAs) required to support the activated fibers. Since network power consumption is determined by both device counts and per-unit power draw, the overall impact depends on the relative power consumption of these components, as well as on network topology and traffic distribution. This paper quantifies this trade-off by benchmarking ROADM bypassing against C-MF and MB-MF across four topologies, including a sensitivity analysis with respect to TP power consumption.

II. Proposed Strategy

The proposed strategy adopts the *70–70 congestion management policy* introduced in [4]. The policy is named after its trigger and target thresholds. Bypass capacity is activated when link utilization exceeds 70% or when underprovisioning occurs, i.e., when the required capacity of at least one node pair cannot be satisfied. Once triggered, the added bypass capacity is dimensioned to bring utilization back below 70%. The corresponding bypass paths are determined by the ILP model in [4], which minimizes newly activated bypass paths and maximizes lightpath migration, subject to satisfying all underprovisioned demands and reducing link utilization below the target threshold. Prior work showed that this configuration

This work has been funded by the Federal Ministry of Research, Technology and Space in Germany (BMFTR) under the projects HyperCORE (Grant ID 16KIS2100) and SUSTAINET-ADVANCE (grant ID 16KIS2283).

achieves cost performance comparable to more aggressive policies while activating fewer fibers.

The evaluation of this strategy considers a brownfield EON with N nodes and $|L|$ links, where each link $l \in L$ consists of an M-count fiber cable with a single active fiber pair; the remaining $M-1$ fibers are available as dark fibers. In C-MF and MB-MF baselines, additional fibers are activated and integrated into the shared EON, preserving spectrum sharing. In contrast, ROADM bypassing uses dark fibers exclusively for dedicated P2P paths via splicing.

A multi-period traffic planning following the methodology in [5] is considered, where traffic demands evolve over discrete periods with a fixed annual growth rate of 29%. In each period, per-link spectrum utilization is assessed after provisioning. If triggered, the ILP model determines the minimum bypass paths and associated lightpath migrations required to restore target utilization and satisfy all demands.

The evaluation covers four reference core-network topologies—*DT-17*, *DT-50*, *Spain*, and *Nobel-EU*—over 15 planning periods. The ILP is solved using Gurobi; for larger topologies, a time limit of 3 600 s is imposed per planning period, with the best feasible solution accepted if optimality is not proven within this window.

Network power consumption is modeled as:

$$P_{\text{total}} = N_{\text{TP}} P_{\text{TP}} + N_{\text{EDFA}} P_{\text{EDFA}} + N_{\text{WSS}} P_{\text{WSS}}, \quad (1)$$

where N_{TP}, N_{EDFA}, and N_{WSS} denote TP, EDFA, and WSS counts, respectively, and P_{TP}, P_{EDFA}, and P_{WSS} denote the power consumption of a single TP, EDFA, and WSS, respectively. For the MB-MF architecture, these counts account for band-specific devices required for dual-band operation.

Table I summarizes the assumed power values. Since TPs dominate overall power consumption due to their high per-unit draw and large deployment count, a sensitivity analysis is performed considering three TP power values: P_{TPlow} (low-power current-generation), P_{TPhigh} (higher-power current-generation), and P_{TPulh} (future ultra-long-haul coherent pluggables). TP power is modeled as a fixed per-device quantity and is therefore not explicitly linked to individual modulation-format and bit-rate configurations. These cases capture how transceiver-efficiency affects the power trade-off between ROADM bypassing and the baseline architectures. EDFA and WSS power values are kept fixed across all scenarios.

TABLE I: Power consumption values [6]. Considered TP configuration spans 100–600 Gb/s in steps of 50 Gb/s.

Component	Power [W]
Transponder (low)	$P_{\text{TPlow}} = 180$
Transponder (high)	$P_{\text{TPhigh}} = 630$
Transponder (ULH)	$P_{\text{TPulh}} = 24$
EDFA	$P_{\text{EDFA}} = 30$
WSS	$P_{\text{WSS}} = 28$

III. Results and Discussion

Fig. 1 shows the distribution of active fibers per link at period 15 in *Nobel-EU*. MB-MF (avg. ≈ 10, max 19) and C-MF (avg. ≈ 17, max 35) require fewer fibers due to spectrum-based sharing across demands; for MB-MF, this advantage is further reinforced by dual-band operation. By contrast, ROADM bypassing requires substantially more fibers (avg. ≈ 32, max 92), since dedicated point-to-point paths consume additional fiber resources. The annotated EDFA counts follow the same trend: 5 358 for MB-MF, 9 668 for C-MF, and 18 054 for ROADM bypassing—since each active fiber requires one EDFA per span.

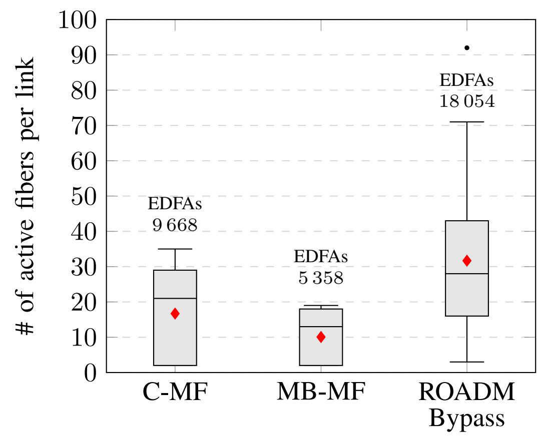


Fig. 1: Distribution of active fibers per link at period 15 for the *Nobel-EU* topology. Red diamonds indicate averages; labels above boxplots show total EDFA counts.

Fig. 2 shows TP count evolution over the simulated planning horizon. As traffic increases, the number of TPs also increases. At period 15, C-MF and MB-MF deploy 27,864 and 29,656 TPs, respectively, while ROADM bypassing reduces the number of required TPs to 23,352—16–21% fewer than the other two solutions. This reduction results from TPs operating at higher line rates.

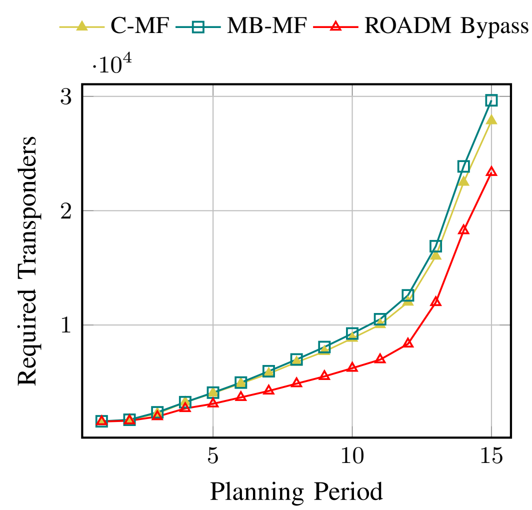
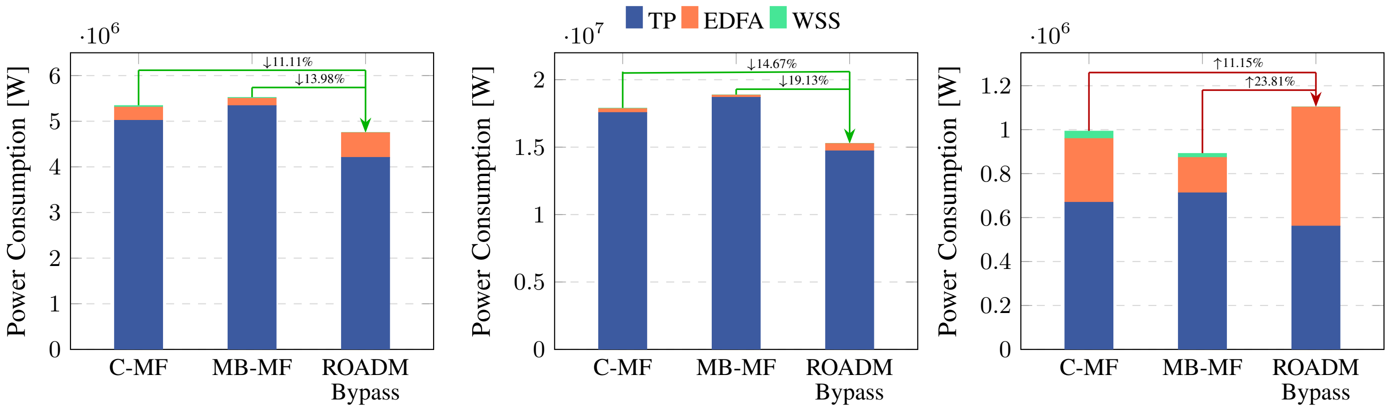


Fig. 2: Required transponders per planning period (*Nobel-EU*).

These component counts translate directly into power consumption, as illustrated in Fig. 3, which shows the total power consumption at period 15 for each strategy in the *Nobel-EU*



(a) Low TP power ($P_{\text{TPlow}} = 180\,W$) (b) High TP power ($P_{\text{TPhigh}} = 630\,W$) (c) ULH pluggables ($P_{\text{TPulh}} = 24\,W$)

Fig. 3: Total power consumption at period 15 (*Nobel-EU*). Bars: TPs (blue), EDFAs (orange), WSSs (green). Annotations indicate ROADM-bypass power savings or penalties relative to the baselines.

topology under the three TP power scenarios. The stacked bars decompose the total into TP, EDFA, and WSS contributions. In all scenarios, TPs dominate overall power consumption, while EDFAs and WSSs contribute smaller shares.

For the P_{TPlow} scenario (Fig. 3a), ROADM bypassing reduces power consumption by 11.11% compared to C-MF and by 13.98% compared to MB-MF. These savings increase substantially in the P_{TPhigh} scenario (Fig. 3b), reaching 14.67% and 19.13%, respectively, as the higher per-TP power amplifies the benefit of deploying fewer transponders.

However, this trend reverses for the P_{TPulh} scenario (Fig. 3c). Since ROADM bypassing trades TP reductions for additional EDFAs, lowering the per-TP power to 24 W diminishes the transponder savings while the EDFA contribution becomes significant. Consequently, ROADM bypassing consumes 11.15% and 23.81% more power than C-MF and MB-MF, respectively, demonstrating that this strategy is most favorable under current TP power assumptions.

Table II summarizes the power savings (or penalties) of the proposed strategy relative to C-MF and MB-MF across all topologies and TP power values. Under P_{TPlow} and P_{TPhigh}, ROADM bypassing reduces power consumption across all topologies, with larger networks (*DT-50* and *Nobel-EU*) achieving greater savings. In contrast, under the P_{TPulh} scenario, results diverge: larger topologies incur power penalties as EDFA power consumption outweighs TP power savings, while smaller topologies (*Spain* and *DT-17*) remain competitive with C-MF but lose advantage over MB-MF.

TABLE II: Energy savings of ROADM bypassing vs. baselines (%). Green: savings; red: increased consumption.

	TP_{low}		TP_{high}		TP_{ulh}	
Topology	C-MF	MB-MF	C-MF	MB-MF	C-MF	MB-MF
DT-50	17.3	17.7	20.2	21.4	–4.4	–12.3
Nobel-EU	11.1	14.0	14.7	19.1	–11.2	–23.8
DT-17	12.5	13.0	13.6	15.1	3.7	–3.0
Spain	11.9	11.1	11.6	12.8	14.3	–3.0

IV. CONCLUSION

This paper has quantified operational energy consumption of ROADM bypassing for capacity scaling in brownfield EONs. Under current TP technology, ROADM bypassing achieves 11–21% power savings over C-MF and MB-MF architectures, with larger topologies such as *DT-50* reaching up to 21% savings, while smaller topologies such as *Spain* and *DT-17* achieve 11–15%. Combined with the cost advantages demonstrated in [4], these results confirm ROADM bypassing as an energy- and cost-efficient capacity-expansion strategy for brownfield networks with available dark fiber under current transponder technology constraints. However, as transceiver efficiency improves toward ULH pluggables, the additional EDFA overhead may negate these savings. If ULH pluggable TPs become sufficiently mature for long-reach deployment, the viability of this approach will depend on complementary advances such as lower-power inline amplification or fiber technologies requiring fewer amplification stages, such as hollow-core fiber.

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