Minimizing Power Consumption in IPoWDM Networks with ZR/ZR+ using Network Reconfiguration

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***Abstract*—We evaluate power consumption savings in IPoWDM networks with ZR/ZR+ using network reconfiguration with daily varying traffic profile. Although network reconfiguration with ZR+ is less effective than with long-haul muxponder, ZR+ is still more power-efficient.**

***Index Terms*—Network reconfiguration, pluggable optics, energy efficiency, IPoWDM networks**

I. Introduction

The rapid growth of optical networks, driven by the surge in cloud computing, video streaming, and social media, has significantly boosted global communication capabilities [1], [2]. Optical networks form the essential backbone of modern data exchange, carrying vast information that underpins the digital world [3]. However, as communication networks account for 2-3% of global energy consumption [4], leading to a considerable environmental cost, devising new solutions to reduce energy consumption in optical networks is crucial for sustainable development [5], [6].

Recently, ZR and ZR+ pluggable transceivers have emerged as preferred solutions for high-bandwidth, short-reach data transmission in "IP over Wavelength Division Multiplexing" (IPoWDM) networks, offering substantial power efficiency and cost savings compared to conventional long-haul muxponders [7]. Many works have demonstrated that ZR/ZR+ pluggable modules have superior energy efficiency compared to long-haul muxponders under static traffic conditions [8]. However, the daily traffic exhibits a pattern with predictable fluctuations [9], and *the network-wide energy consumption of ZR/ZR+ pluggable modules under such dynamic conditions remains unexplored*. Improving the energy efficiency of optical networks with long-haul muxponders is a well-studied problem [10]–[13], which is typically addressed through network reconfigurations(e.g., re-routing or changing modulation format). While significant progress has been made in reconfiguring *IPoWDM networks with long-haul muxponders* under daily varying traffic profile, network reconfiguration approaches for *IPoWDM networks with ZR/ZR+* have never been investigated.

Unlike long-haul muxponders, the IPoWDM network with ZR/ZR+ is much less flexible to reconfigure due to its limited transmission distance and lower capacity. Moreover, 400G ZR/ZR+ is connected to 400G ports, consuming 400 Gb/s of traffic in the router even after reducing the modulation format, and the carried traffic is lower than 400 Gb/s. Hence, network reconfiguration may reduce power consumption less in networks with ZR/ZR+ compared to those with long-haul muxponders, and it remains unclear if ZR/ZR+ can still be more energy-efficient than long-haul muxponders when considering network reconfiguration.

Given that daily traffic patterns are inherently variable, our research investigates how these two classes of transceivers (ZR/ZR+ vs muxponders) handle power consumption during fluctuating traffic loads and network reconfigurations. By simulating various network configurations and leveraging real-world traffic data from the Amsterdam Internet Exchange [9], we aim to assess whether ZR/ZR+ modules, despite being less flexible in reconfiguration, continue to offer higher energy efficiency over long-haul muxponders in such conditions. Our main contributions are:

- We investigate the impact of various network reconfiguration approaches, including different combinations of IP layer re-routing, optical layer re-routing, and change of modulation format.
- We develop scalable heuristic algorithms to optimize reconfiguration decisions across both IP and optical layers for all the considered approaches in IPoWDM networks under varying daily traffic profile.
- We provide a comprehensive power consumption comparison between ZR/ZR+ pluggables and long-haul muxponders across various network architectures (i.e., opaque vs. transparent architectures) and diverse topologies.

The remaining part of the paper is organized as follows. In Section II, we discuss various network reconfiguration strategies aimed at reducing power consumption in IPoWDM networks, as well as power consumption models for different architectures. Section III presents a set of heuristic algorithms developed to minimize power consumption for all the considered reconfiguration strategies. In Section IV, we provide numerical results that demonstrate the impact of our proposed approaches across different network topologies. Finally, Section V concludes the paper, summarizing the key findings and outlining potential directions for future research.

II. Network Reconfiguration for Reducing Power Consumption

In this section, we first describe network reconfiguration approaches, and then discuss how network reconfiguration reduces the power consumption of optical networks.

A. Network Reconfiguration Approaches

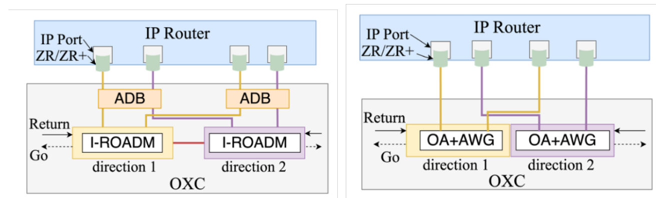
In the context of IPoWDM networks, reconfiguration can involve techniques such as traffic re-routing, traffic re-grooming, modulation format adjustments, and sleep mode activation [14]–[16]. Each approach focuses on different aspects of network management, such as modulation format adjustments and routing decisions, and Table I below summarizes the abbreviations for these key approaches considered in our study. MF involves switching to a lower modulation format that consumes less power. RE involves two aspects: grooming requests at the IP layer to optimize traffic flow, when requests are on the same path or edge and sufficient capacity is available, or switching data streams between different wavelengths in the optical layer to improve network efficiency. The separate or combined application of these techniques results in five distinct approaches, applicable to both the IP layer alone and in conjunction with the optical layer.

TABLE I: Approach Abbreviations in IPoWDM Networks

Approach	Abbreviation
Modulation Format Reconfiguration	MF
Re-Routing in IP Layer	RE (ip)
Re-Routing in IP & Optical Layer	RE (ip+op)
Modulation Format Reconfiguration and Re-Routing in IP Layer	MFRE (ip)
Modulation Format Reconfiguration and Re-Routing in IP & Optical Layer	MFRE (ip+op)

B. Power Consumption Models

We consider both opaque and transparent IPoWDM network architectures. Opaque IPoWDM architectures employ electronic regeneration at each node in the network. The incoming optical signal is converted back to the electrical domain, electronically processed, and then re-converted to an optical signal for transmission on the outgoing link [17]. In a transparent optical network architecture, optical signals can pass through intermediate nodes without being converted back to electrical signals [17]. This eliminates the need for electronic regeneration at intermediate nodes, resulting in lower power consumption. The opaque and transparent network architectures differ in terms of the node structure, as illustrated in Fig. 1, particularly in how they manage wavelengths. Both architectures utilize IP ports, pluggables or muxponders, and an optical shelf (i.e., a container to hold optical devices). However, the opaque architecture relies only on Optical Amplifiers (OA) and Arrayed Waveguide Gratings (AWG) for wavelength management. In contrast, the transparent architecture employs an Add-Drop Block (ADB) and Integrated Reconfigurable Optical Add-Drop Multiplexers (I-ROADM).



(a) Transparent Network (b) Opaque Network

Fig. 1: Node Architectures

The power consumption of different network elements is listed in Table II, and presented in normalized units rather than in watts. The power consumption of the router is based on a 36 Tb/s Router, comprising a fixed part and a modular part related to the traffic [18], [19]. Specifically, 100 Gb/s of traffic in the router corresponds to 1 unit of power consumption. Since ZR/ZR+ modules connect via 400G ports, they consume 400 Gb/s (4 units) regardless of the actual data rate. In contrast, long-haul muxponders connect through 100G I/O cards, each consuming 100 Gb/s and 1 unit of power.

Modulation format reconfiguration and re-routing can play an important role in reducing power consumption. Modulation format reconfiguration can reduce power consumption, as the power consumption of different transceivers reduces when reconfigured at a lower modulation format [20]. As shown in Table II, the power consumption of ZR/ZR+ decreases when operating at lower modulation formats. For more detailed information on power consumption of ZR, please refer to Ref. [21]. Given that we only have the power consumption data for long-haul muxponders at 800 Gb/s, we assume the same reduction in power consumption as observed in ZR+ when the data rate decreases by every 100 Gb/s. Re-routing plays a significant role in reducing the power consumption of both opaque and transparent architectures. In opaque architectures, when the requested data rate reduces, traffic on different wavelengths can be groomed to a single wavelength, reducing the number of active transponders. Moreover, as detailed in Ref. [19], re-routing can decrease router power consumption by optimizing the network path and reducing the number of active ports. For transparent architectures, power consumption can be further reduced through re-routing. As the requested data rate decreases, transponders can switch to a lower modulation format, which allows for longer transmission distances. This enables more nodes to be bypassed, thereby reducing router power consumption.

C. Problem Statement

This study focuses on leveraging daily traffic profiles to dynamically re-configure the network, aiming to minimize power consumption by eliminating under-utilization of network elements. We consider both ZR/ZR+ and long-haul muxponders. The reach tables of ZR/ZR+ and long-haul muxponders are shown in Table III and Table IV [19]. As shown in these tables,

TABLE II: Normalized Power Consumption of Network Elements [19], [21]–[24]

Device	Type	Power
Transponder	ZR 400G	1.0
	ZR+ 400G	1.3
	ZR+ 300G	1.17
	ZR+ 200G	1.04
	Long-Haul 800G	8.0
	Long-Haul 700G	7.87
	Long-Haul 600G	7.74
	Long-Haul 500G	7.61
	Long-Haul 400G	7.48
	Long-Haul 300G	7.35
	Long-Haul 200G	7.22
IP Router	Fixed Part	50
	Modular Part	4
Optical Side	Add-Drop Block (ADB)	4
	I-ROADM (bidirectional)	4.1
	OA (undirectional)	1.7
	AWG	0.3
	Shelf	20
Monitoring	Opaque (bidirectional)	0.3
	Transparent (bidirectional)	1.5

long-haul muxponders support data rates from 200 to 800 Gb/s and can achieve a maximum reach of up to 5700 km, offering greater flexibility compared to the shorter reach capabilities of ZR/ZR+ pluggables. The optimization problem for minimizing power consumption in optical networks, incorporating re-routing and modulation format reconfiguration, can be framed as follows:

TABLE III: Reach table for ZR/ZR+ Pluggables

Module	Data Rate (Gb/s)	Modulation Format	Spacing (GHz)	Reach (km)
ZR	400	16-QAM	100	120
ZR+	400	16-QAM	75	600
ZR+	300	8-QAM	75	1800
ZR+	200	QPSK	75	3000

TABLE IV: Reach Table for Long-Haul Muxponders

Module	Data Rate (Gb/s)	Modulation Format	Spacing (GHz)	Reach (km)
Long-Haul	800	PCS 64-QAM	100	150
Long-Haul	700	PCS 64-QAM	100	400
Long-Haul	600	16-QAM	100	700
Long-Haul	500	PCS 16-QAM	100	1300
Long-Haul	400	PCS 16-QAM	100	2500
Long-Haul	300	PCS 16-QAM	100	4700
Long-Haul	200	PCS 16-QAM	100	5700

Given: Selected network architecture, chosen network reconfiguration approach in Table I, network topology and available spectrum resources in each link, a set of traffic demands at different times of the day, the power consumption of different network elements (i.e., routers, transponders, and optical components), and the reach table of ZR/ZR+ and long-haul muxponders.

Decide: The optimal routing paths for each traffic demand, the appropriate modulation format for each channel, and whether to adjust the routing at the IP layer alone or in conjunction with optical layer reconfiguration to optimize overall network performance and efficiency.

Constrained by: Ensuring all traffic demands are met within the network's capacity limits and adhering to the physical and operational constraints of the network, including the maximum reach of modulation formats and the capacity of network elements.

Objective: Minimize the total power consumption of the network over a 24-hour period as the primary objective.

III. Heuristic Algorithm

We developed a set of heuristic algorithms for all the considered approaches in Table I following the general procedure as in Fig. 2, focusing on dynamic re-routing at both the IP and optical layers, as well as adjustments to the modulation formats.

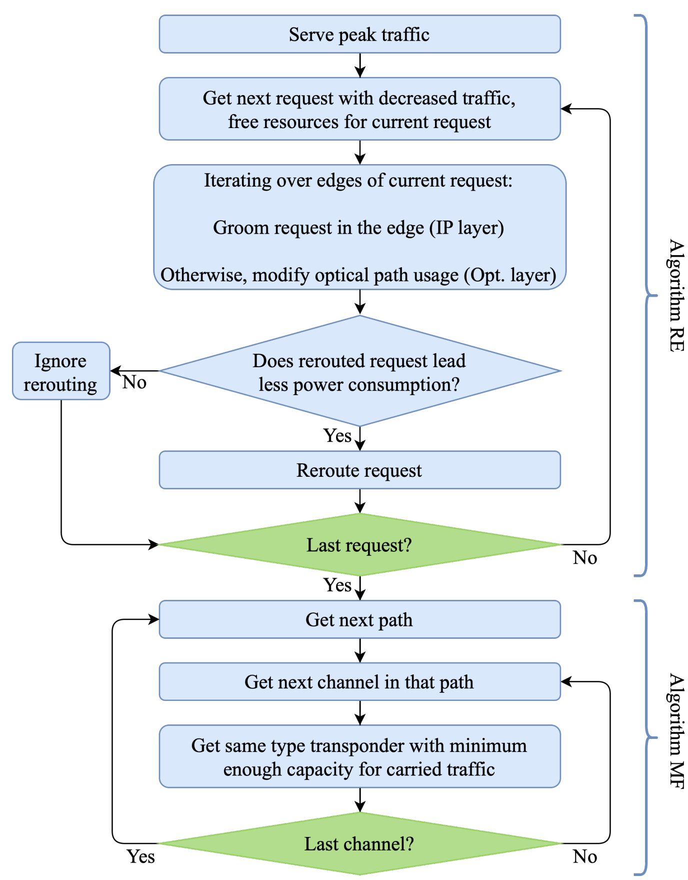
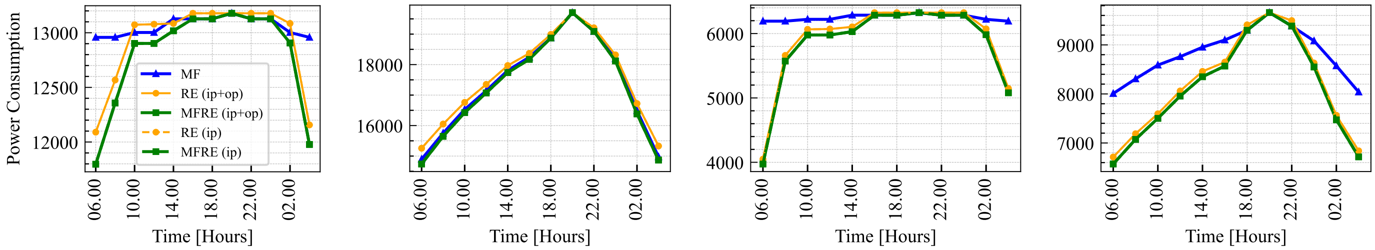


Fig. 2: Algorithm Flow Chart

As illustrated in Fig. 2, re-routing process begins by serving peak traffic and then handling subsequent requests with decreased traffic. Our proposed algorithm, when solving the scenario RE (ip), first attempts to groom the traffic within the existing IP layer edges. If this approach does not yield sufficient power savings, it considers modifying the optical path



(a) ZR/ZR+ Opaque Architecture (b) Long-Haul Opaque Architecture (c) ZR/ZR+ Transparent Architecture (d) Long-Haul Transparent

Fig. 3: Daily Power Consumption for Japan Topology

usage by evaluating the potential power savings of alternative routes, which are enabled by RE (ip+op) for the optical layer. By iterating over the edges of the current traffic request, the algorithm determines whether grooming within the IP layer or modifying the optical path usage would lead to lower power consumption. If re-routing is determined to be beneficial, the request is re-routed to optimize power efficiency.

The decision-making process is repeated for each request until all traffic demands are satisfied, ensuring the network's adaptability to changing conditions. The flowchart also highlights the iterative nature of the algorithm, emphasizing the step-by-step optimization for both power consumption and network performance.

In cases where modulation formats need to be reconfigured, the algorithm MF checks the used capacity after processing the decreased traffic for each request and switches to transponders with the minimum necessary capacity.

When MFRE is deployed, the process begins by addressing decreased traffic conditions in the network with RE for the chosen layers. The algorithm sequentially processes each request, adapting to the current network state. After serving all requests, the algorithm proceeds to adjust the modulation formats based on updated traffic conditions, further optimizing network performance and efficiency.

IV. Numerical Results

A. Simulation Settings

The simulations are implemented in Python 3.8. We evaluate two different topologies: a 14-node Japan, where link lengths range from 40 to 320 km with an average link length of 154 km [25], and a 50-node German (G50), where link lengths from 32 to 219 km with an average link length of 130 km [26]. Each network topology handles a scaled traffic load of AMS-IX traffic statistics [9], with a target blocking rate of 1% for ZR/ZR+ modules in the case of peak traffic. Specifically, for Japan topology, when the network handles peak traffic with ZR/ZR+ pluggables, a blocking rate of 0.01 is reached at a traffic load of around 147 Tb/s and 141 Tb/s for opaque and transparent architectures, respectively. For G50, a blocking rate of 0.01 is reached at a total traffic load of 325.5 Tb/s for transparent architecture. The trend observed in G50 is similar to that in Japan topology, so only transparent architecture results are provided here for brevity.

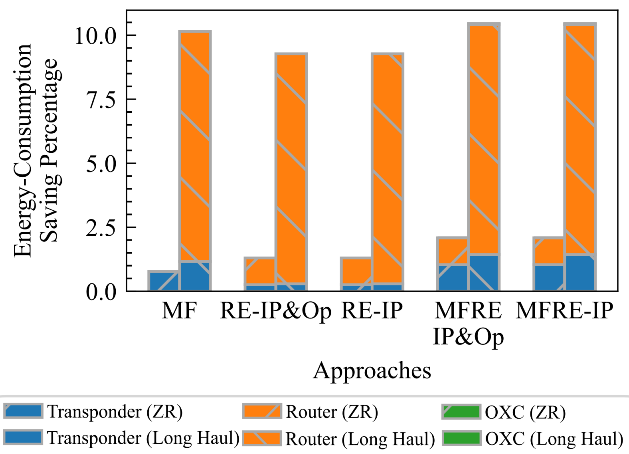
The simulation incorporates a reconfiguration interval of 2 hours and compares the use of ZR/ZR+ pluggables versus long-haul muxponders. This approach allows for flexible and detailed analysis of the network under varying conditions and configurations. For all the considered scenarios, we first evaluate the power consumption at different time periods during the day. Then, we calculate the total daily energy consumption by multiplying the power used in each period by the duration of that period, and then summing these values. To provide more insights on the energy consumption savings for ZR/ZR+ and long-haul muxponders, we also show the contribution of different components to the total power consumption. Specifically, energy savings of transponder, router, and OXC for ZR/ZR+ are named with *Transponder (ZR)*, *Router (ZR)*, and *OXC (ZR)*, respectively. The energy savings of transponder, router, and OXC for long-haul muxponders are named with *Transponder (Long Haul)*, *Router (Long Haul)*, and *OXC (Long Haul)*, respectively.

B. Numerical Results for Japan

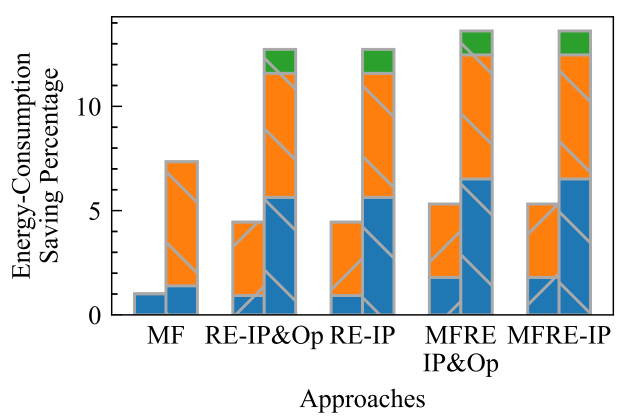
We first evaluate how different reconfiguration strategies impact power consumption for opaque architecture with ZR/ZR+ pluggables. As shown in Fig. 3 (a), the initial power consumption during peak traffic is around 13,178.2 units. Applying the RE algorithm reduces this consumption by 8.3% to 12,090.4 units when traffic is at its minimum rate. Further reduction is achieved with the MFRE algorithm, lowering energy consumption by 10.5% to 11,796.6 units. Additionally, it is observed that re-routing strategies that focus only on the IP layer (RE (ip)) and those considering both IP and optical layers (RE (ip+op)) yield nearly identical results. This is because a highly optimized IP layer already closely aligns with the optimal paths suggested by joint IP and optical layer considerations.

Compared to ZR/ZR+, a higher reduction in power consumption can be observed in IPoWDM networks with long-haul muxponders due to higher capacity and longer transmission distance. However, despite saving less power than long-haul muxponders, they still offer lower overall power consumption values. Specifically, as shown in Fig. 3 (b), starting with an initial consumption of 19,704.0 units, the RE algorithm reduces this by ∼22% to 15,256.6 units, with further reduction to 14,739.46 units (∼25%) when applying the MFRE algorithm. Hence, with the MFRE approach, ZR/ZR+ sees a 1.2% reduction between 14:00-22:00, as illustrated in Fig. 3 (a). This reduction grows to 2.1% between 10:00-24:00 before reaching 19% between 06.00-04.00.

Let us now consider the performance of network reconfiguration on transparent architectures. As shown in Fig. 3 (c) and (d), the power consumption of both ZR/ZR+ and long-haul muxponders follows a consistent trend as in opaque architectures. It is worth noting that the maximum reduction of power consumption for IPoWDM networks with ZR/ZR+ is only up to 5.5% with MFRE approach between 10:00-24:00 as shown in Fig. 3 (c), while the power consumption reduction already reaches up to 13.5% between 14:00-22:00 and further reaches 22.6% between 10:00-24:00 with MFRE approach as shown in Fig. 3 (d).



(a) Opaque Architecture



(b) Transparent Architecture

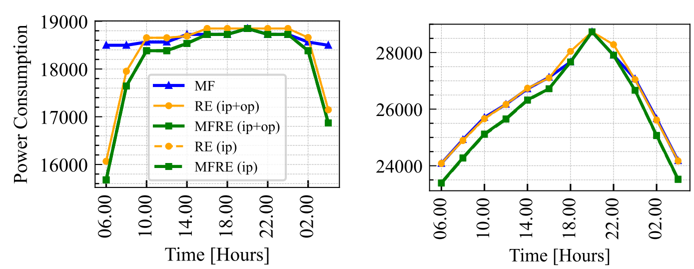
Fig. 4: Daily Energy-Consumption Reduction Percentages for Japan Topology

We then evaluate the total energy consumption during the day using different approaches. As shown in Fig. 4, ZR/ZR+ can lead 5% power saving, while long-haul can yield 13.5% in a day. Among all the network components, the router contributes to the most savings, reaching up to around 6-9% for long-haul muxponders and 1-3% for ZR/ZR+. This difference arises due to the direct contribution of the router power model. Specifically, for ZR/ZR+, 400G router traffic can only be removed when no traffic is being carried for ZR/ZR+. In contrast, for long-haul muxponders, 100G router traffic can be reduced as 100G carried traffic is reduced.

C. Numerical Results for G50

We now evaluate the performance of different approaches on G50. As shown in Fig. 5, all the approaches have a performance in line as the one seen in Japan topology. Specifically, the initial energy consumption is 18,848.36 with ZR/ZR+, and applying the RE algorithm for only IP or both IP and optical layer re-routing further reduces the energy consumption by ∼15% to 16,066.78. The lowest energy consumption is achieved with the MFRE algorithm, which brings the energy consumption down by ∼17% to 15,677.56. For the transparent case with long-haul muxponders, the initial energy consumption is 28,732.9. Also can be seen in Fig. 5 (b), the RE algorithm alone reduces the energy consumption by ∼16% to 24,075.38. The MFRE algorithm further lowers it by ∼19% to 23,384.3. In the transparent architecture of G50, ZR/ZR+ reaches a reduction of 17%, which is slightly lower than long-haul, which yields 19%.

However, despite having lower values than long-haul muxponders, power consumption with ZR/ZR+ stays constant until the final stages of reconfiguration, where it then drops significantly. In contrast, long-haul muxponders reduce power early, as observed in the Japan topology. Notably, the reduction with ZR/ZR+ using the MFRE approach reaches 1.7% between 14:00-22:00, as shown in Fig. 5 (a) and further increases to 2.5% between 10:00-24:00.



(a) ZR/ZR+ Transparent Architecture (b) Long-Haul Transparent

Fig. 5: Daily Power Consumption for G50 Topology

As illustrated in Fig. 6, ZR/ZR+ can lead 2.5% power saving where long-haul can yield 8.5% in a day. Of all the network components, the router provides the largest savings, with reductions of up to 5.5% for long-haul muxponders and 1.5% for ZR/ZR+. This behavior mirrors the trend observed in the Japan topology and confirms our earlier observations, which are attributed to the router model used in both topologies.

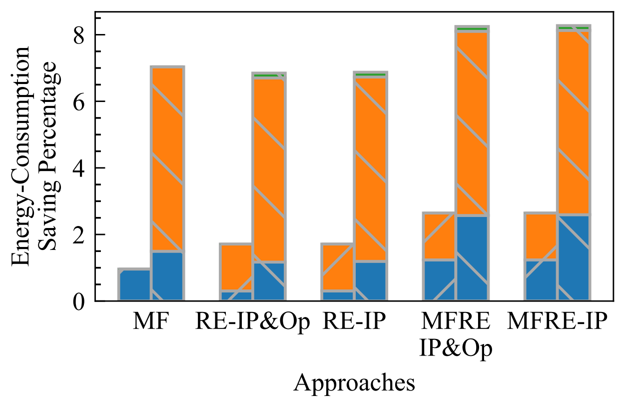


Fig. 6: Daily Energy-Consumption Reduction Percentage for G50 Topology (Transparent)

V. Conclusion

This study evaluated the performance of network reconfiguration for minimizing power consumption in IPoWDM networks with ZR/ZR+ pluggables and long-haul muxponders across different network topologies. Results show that long-haul muxponders can achieve up to 13.5% daily energy-consumption savings, while ZR/ZR+ can only achieve 5% savings, as it is less flexible to perform network reconfiguration with ZR/ZR+. Nonetheless, ZR/ZR+ pluggables demonstrated 22% to 34% lower power consumption in a day by eliminating the need for traditional transponders. We plan to develop Integer Linear Programming (ILP) models for optical network reconfiguration in the future.

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