

Toward a Power-Efficient Backbone Network: The State of Research

M. Nishan Dharmaweera, Rajendran Parthiban, and Y. Ahmet Şekercioğlu

Abstract—The year-by-year increase in electricity consumption significantly affects all nations today from environmental, social, and economic perspectives. Various studies show that, among the contributors of this increase, power consumption of the equipment forming the Internet infrastructure is significant. Consequently, considerable attention is given to finding solutions to reduce power consumption of the systems that run the Internet. Current literature suggests that the optical backbone network is responsible for the majority of the consumed power, particularly at high traffic loads. This highlights the importance of formulating solutions to reduce power consumption in backbone networks. In this paper, we provide a comprehensive survey of the most relevant research efforts on minimizing power consumption of backbone networks. We categorize our review into four broad approaches: network redesign, traffic engineering, power-aware networking, and load-adaptive operation. We highlight the findings of relevant studies and provide an analysis of their limitations. We also evaluate the technological differences of similar work and identify a number of future directions. Finally, we demonstrate that the adoption of these technologies is gathering pace among prominent research bodies, device manufacturers, and network operators.

Index Terms—Optical fiber networks, energy consumption, next generation networking, internet, optical communication equipment.

I. INTRODUCTION

INCREASING power consumption has become a pressing concern [1] as rapidly depleting fossil fuel reserves elevates the cost of power generation [2] and translates into higher consumer spending [3]–[5]. With an estimated annual growth rate in power consumption of 10% [4], in 2012, the telecommunications industry alone consumed well over 250 Terawatt-hour (TWh) of electricity and accounted for 2% of global carbon dioxide emissions [6]. Power consumption of the Internet and its three constituent domains, which are the access, metro, and core networks [7], is estimated at 1% of total electricity consumption in broadband-enabled countries [8].

It comes as no surprise then that the past few decades have seen the formation of a number of policies, protocols, special projects and regulations due to the need to reduce power consumption of global telecommunication networks for

both economic and environmental reasons [9]–[11]. Not surprisingly, the importance given to the efforts for reducing power consumption has resulted in the emergence of a number of power-efficient technologies and power-aware algorithms and frameworks. These have been covered in earlier surveys published between 2010 and 2012 in various levels of rigor [12]–[16]. Three of these studies [12]–[14] are extensive and cover power-efficient solutions targeted for core, access, and metropolitan networks. On the other hand, [15] and [16] focus only on access network issues. The power-efficient solutions reviewed by these research surveys can be classified into four main categories:

- 1) **Network redesign:** Designing power-efficient networks using optical and electronic technologies;
- 2) **Traffic engineering:** Developing energy-aware traffic grooming schemes;
- 3) **Power-aware networking:** Switching devices between different operating states;
- 4) **Load-adaptive operation:** Adopting rate-adaptive and multi-line/link rate techniques.

Here, in contrast to the studies mentioned above, our survey differs in three significant aspects:

First, this survey devotes greater attention to existing research efforts on reducing power consumption of the integrated core and metro networks (i.e., backbone network) [17]. The decision for this choice was based partly on predictions that the volume of global Internet traffic would exceed the zettabyte threshold [18], and on the knowledge that, at such high traffic volumes, power consumption of the backbone network is expected to surpass that of the access network [19]. Current evidence points to the dominance of wired and wireless access networks in the Internet's power consumption. However, while power consumption of access networks is proportional to the number of subscribers, power consumption of the backbone network is dependent on traffic volume [19] which, as previously mentioned, is expected to soon exceed the zettabyte threshold. At such high traffic volumes, power consumption of the backbone network is very likely to overtake power consumption of the access networks [7], [8]. Baliga *et al.* [8] report that, as the access rate per household exceeds 100 Mbps, the backbone network would consume 34.5% of total network power, provided that power efficiency of network devices increases annually by 10%. In a more recent study, Kilper *et al.* [20] estimate that power consumption of the backbone network (10.5 W/Mbps) will surpass that of the fixed-access (8 W/Mbps) network beyond the year 2020. Considering the technologies of 2008, Tucker *et al.* [7] have shown that the

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TABLE I
COMPARISON BETWEEN THIS STUDY AND AVAILABLE SURVEYS

Approach	Key concepts	This study	Bolla <i>et al.</i> [13]	Bianzio <i>et al.</i> [14]	Zhang <i>et al.</i> [12]
Network Redesign	Electronics vs. optical technologies	✓	✓		✓
	Point-to-point WDM networks (PTP-WDM)	✓			
	Optical packet switched networks (OPS)	✓			
	Optical burst switched networks (OBS)	✓		✓	
	Optical circuit switched networks (OCS)	✓			
	Hybrid core nodes	✓			
	Topology optimization	✓			
Traffic Engineering	Wavelength grooming	✓		✓	✓
	Waveband grooming	✓			
	Multicast grooming	✓			
Power Aware Networking	Switch-off/Sleep mode operation	✓	✓	✓	✓
	Re-configuration cost	✓			
Load-adaptive Operation	Handling drawbacks	✓	✓	✓	✓
	Single and Mixed Line Rates (SLR/MLR)	✓			✓
Operation	ALR, Rate adaptivity, Elastic & SEON networks	✓	✓	✓	✓
	Compare SLR, MLR, and ALR	✓			

backbone network consumes more power than access networks as the average access rate per user exceeds 4 Mbps. Furthermore, to make things more challenging, the backbone network is only expected to gain an increment of 64% in power efficiency in the year 2020 relative to 2010, while wired and wireless access networks are expected to gain an increase of 449% and 1043% in power efficiency, respectively.

Second, being the first survey to review recent research efforts on reducing power consumption of the backbone network alone, we are able to analyze concepts, findings, and limitations of existing studies more comprehensively and report power savings in terms of absolute values and percentages. Our survey also reviews novel and important concepts such as optical circuit/burst/packet-switched networks, hybrid networks, topology optimization techniques, waveband grooming, multicast grooming, spectrum elastic networks, and multi-line rates in the context of reducing power consumption. Table I shows the key concepts reviewed under each approach in this study vis-à-vis those addressed in the existing surveys by Zhang *et al.* [12], Bolla *et al.* [13], and Bianzino *et al.* [14]. Furthermore, while these three surveys only cover studies published until 2011, our survey extends this body of literature to include more recent studies published after 2011.

Third, despite being power-efficient, certain solutions reviewed in the three surveys cannot be effectively implemented due to limitations such as space and cost constraints. In this survey, we explore how alternative mechanisms that were developed to achieve other objectives, such as reducing cost and increasing bandwidth utilization, can be integrated with the proposed power-efficient solutions to overcome their limitations.

The remainder of this paper is organized as follows. An overview of the Internet's backbone network, its devices, and their respective power consumption values are presented in Section II. The subsequent sections are devoted to an examination of the four approaches. The first approach is discussed in Section III where, first, we examine the redesign of the core node using electronic or all-optical technologies and, second,

assess the possibility of optimizing the link topology to reduce power consumption. The second approach is examined in Section IV, where we investigate how traffic grooming could be used efficiently to reduce power consumption by employing wavelength, waveband, and multicast grooming techniques. Section V explores the possibility of conserving power at the device level by dynamically switching on and switching off network devices. Section VI reviews studies that have formulated power-efficient solutions by incorporating Adaptive-Line Rates (ALRs) and Mixed-Line/Link Rates (MLRs) techniques. We compare these load adaptive techniques in terms of power consumption and identify their weaknesses. Section VII evaluates the practical relevance of the four approaches and, finally, Section VIII presents important conclusions that are drawn from this survey.

II. ARCHITECTURE OF THE OPTICAL BACKBONE NETWORK

The fundamental architecture of a backbone network consisting of core nodes and links is depicted in Fig. 1. The backbone network consists of core nodes interconnected via bundled optical fibers that are installed within conduits. A conduit connecting two core nodes could also be referred to as a physical link. Today, in most advanced backbone networks, core nodes consist of core routers and Optical Cross Connects (OXC). The Internet Protocol (IP) traffic originating at the access networks reaches the backbone network via access routers. The term *local traffic* is used to represent traffic *added to or dropped from* a core node from/to the respective access network of the local site. The term *pass-through traffic* is used to represent non-local traffic that traverses an intermediate core node.

The devices that constitute an optical backbone network are illustrated in Fig. 2. As illustrated in Fig. 2, the backbone network can be split into two layers: "IP" and "WDM" layers. IP traffic originating at the access network is processed, switched, and aggregated by core routers using high-speed electronics.

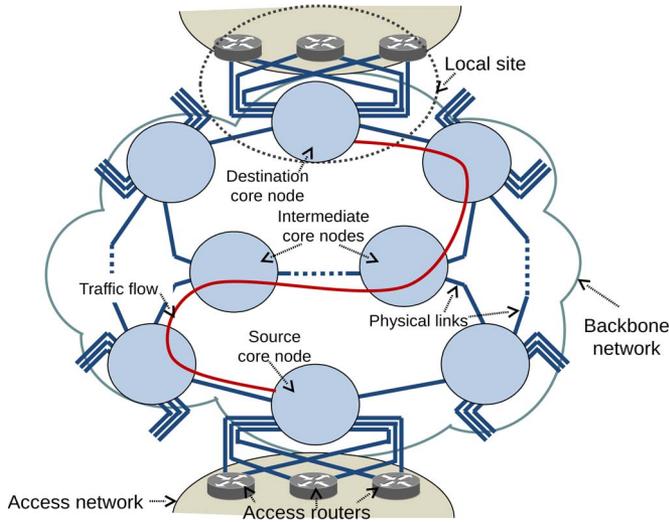


Fig. 1. The fundamental architecture of a backbone network [17].

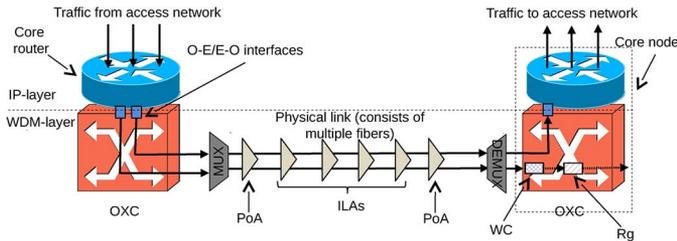


Fig. 2. Constituting devices of the backbone network.

Traffic is exchanged between core routers through lightpaths that are established in the form of wavelength channels. Thus, the electronic signals emanating from the core routers are converted into optical wavelengths by the O-E/E-O converters that reside within transceivers or transponders. Using Wavelength Division Multiplexing (WDM) technique, the wavelengths are multiplexed into a single optical fiber. An OXC consists of an optical switch fabric, a set of multiplexers/de-multiplexers (MUX/DE-MUXs), and input/output (I/O) ports.

An optical fiber is equipped with a Pre-Amplifier (Pre-Amp) and a Post-Amplifier (Post-Amp) at either end. A set of evenly spaced In-Line Amplifiers (ILAs) are placed along the fiber. If the need arises, an incoming wavelength could be converted to a wavelength of a different color using a Wavelength Converter (WC). Relevant wavelengths can be regenerated to extend the reach of a lightpath by using a Regenerator (Rg). In Fig. 2, the wavelength carrying pass-through traffic is converted to another wavelength (solid line to dotted line) by the WC and is then regenerated by the Rg.

Power consumption values of the backbone network devices are shown in Table II. In comparison to other devices, a core router consumes a significant amount of electricity. Discrepancies are observed in the power consumption values of the same device from different manufacturers. Traditionally, high-capacity devices consume more power than those with low capacity, but with a declining power-to-capacity ratio (i.e., volume discount [21], [22]). A detailed list of power consumption values of the backbone network devices can be found in [23] and [24].

TABLE II
POWER CONSUMPTION VALUES OF BACKBONE NETWORK COMPONENTS

Device	Product	Capacity	Pwr. Consumption
Core router	Cisco CRS-1	1.2 Tbps	9.63 kW [25]
	Cisco CRS-3	4.4 Tbps	12.3 kW [26]
	Juniper T1600	1.6 Tbps	8.35 kW [27]
	Juniper T4000	4 Tbps	9.83 kW [27]
Transponder	Fujitsu Flashwave 7200	2.5 Gbps	37.2 W [28]
	Fujitsu Flashwave 7200	10 Gbps	68.5 W [28]
	Transmode 10G tunable	10 Gbps	25 W [28]
OXC	Cisco 40-channel OXC	2-degree	400 W [28]
	Cisco 80-channel OXC	2-degree	550 W [28]
Amplifiers	Cisco ONS 1454 pre/post amplifier	1 fiber	78 W [28]
	Alcatel LM1600 line amplifier	1 fiber	52 W [28]
	Cisco ONS 1454 in-line amplifier	1 fiber	46 W [28]
	Infra in-line amplifier (EDFA)	1 fiber	106 W [28]
Regenerator	Cisco optical regenerator	2.5 Gb/s	100 W [23]
	iLynx Regenerator	2.5 Gb/s	8 W [23]
	40G electronic regenerator	40 Gb/s	126 W [29]
	All-optical regenerator (AOR)	per lightpath	6-80 W [30-32]
Converter	Tunable Wavelength Converter (TWC)	per lightpath	500-800 mW [33, 34]
	Fixed Wavelength Converter (FWC)	per lightpath	600 mW [34]
	All-optical wavelength converter (AOWC)	per lightpath	2 W [35, 36]

III. NETWORK REDESIGN APPROACHES

Power consumption of a backbone network can be reduced by re-designing its two main constituting devices, namely, the core nodes and the physical links, to be more power-efficient.

Core nodes have primarily relied on electronic technology while physical links mainly run on optical technology [7]. However, electronic devices of the core nodes are now gradually being replaced by high-speed optical switching devices in order to increase network capacity and speed [7], [37]. While most researchers agree that optical devices are faster than electronics, they are skeptical about their power-saving abilities [38]–[40]. These scholars argue with evidence that electronic devices consume less power than optical devices [7], [34], [39]–[44]. Nevertheless, as will be discussed in Section III-A below, certain limitations of electronic technology, inevitable in the future, imply that core nodes would eventually rely on optical technology. Solutions then need to be developed to increase power efficiency of optical technologies that replace electronics in core nodes. These solutions are summarized in Section III-A2–A5.

Another critical factor in reducing power consumption of the backbone network is physical topology redesign by optimizing assignment of physical links [45]. This means that network operators must take power consumption into consideration when designing the physical topology, in addition to infrastructure cost [46], [47], Quality of Service (QoS) constraints (e.g., delay, signal loss, resilience) [48], [49], and geographical constraints [50]. The existing literature on power-efficient physical topology redesign is reviewed in Section III-B.

A. Core Node Redesign

This section first explains how core nodes are evolving from PtP-WDM networks to advanced optical backbone networks. We then comparatively analyze available and prospective electronic and all-optical technologies in core nodes that can reduce power consumption of backbone networks.

1) *Evolution of Optical Core Nodes:* Today, in most backbone networks, IP packets transit across multiple core routers (also known as Electronic Packet Switches (EPS)) connected via point-to-point WDM links [7], [42]. Such networks are commonly referred to as Point-to-Point WDM (PtP-WDM) networks [7]. In PtP-WDM networks, an electronic router is predominantly composed of Complementary-symmetry Metal-Oxide-Semiconductor (CMOS) based electronic devices. CMOS-based electronic devices come in many forms and perform different tasks, such as converting signals between electrical and optical domains (E-O-E conversion), buffering, processing, and switching.

The commercially-available single-shelf Cisco CRS-3 electronic core router consumes 12.2 kW of electricity and has a maximum switching capacity of 4.4 Tbps [26]. Although switching capacity of an electronic core router can be increased by combining multiple shelves [51], the result is an increase in power consumption due to provisioning of additional interfacing devices and the need for a much larger cooling system [42]. For example, in comparison to 9.6 kW of power consumed by a single-shelf Cisco CRS-1, a 72-shelf Cisco CRS-1 consumes 800 kW of power. If current technologies prevail, Aleksic [52], [53] predicts that future electronic core routers with a maximum switching capacity of 1 Pbps will consume 10 MW or more power.

Advancements in electronic technology [54]–[56] convince one to believe that each new generation of electronic core routers will be more power-efficient [39], [40], [44], [57]. This is made possible by the development of small-sized, high-capacity semiconductors. For example, the most recent 14 nm Intel Broadwell CPU is 30% more power-efficient than the existing 22 nm Haswell CPU [58]. However, some researchers believe that CMOS scaling may halt in the near future [59], [60], making it a challenge to further increase the power efficiency of semiconductors without incurring large production costs [61].

To provide an overview of a PtP-WDM network, a simple example is shown in Fig. 3(a). Here, three sub-wavelength connections are transported from node i to nodes j and k . The solid lines indicate optical lightpaths, while dotted lines indicate electronically-processed signals. The blue checkered squares represent electronic IP packets. Notations E-O and O-E denote electrical-to-optical and optical-to-electrical conversions, respectively. The pass-through traffic is electronically processed at the intermediate node j .

Due to the forecasted halting of CMOS scaling and resultant inability to further exploit power efficiencies of electronic devices, optical devices are gradually being introduced into core nodes. By replacing core routers with Optical Cross Connects (OXC), a PtP-WDM network can be transformed into an All-Optical Circuit-Switched (A-OCS) network as depicted in Fig. 3(b). Replacing a core router with an OXC is advantageous in eliminating the capacity bottleneck caused by electronic processing. Yet, the OXC fails to efficiently utilize available bandwidth when traffic arrives from the access networks at sub-wavelength granularity [17]. For example, in Fig. 3(b), the A-OCS network accommodates incoming traffic using 5 wavelengths instead of 2 wavelengths used in the PtP-WDM network (Fig. 3(a)). To increase bandwidth utilization, core

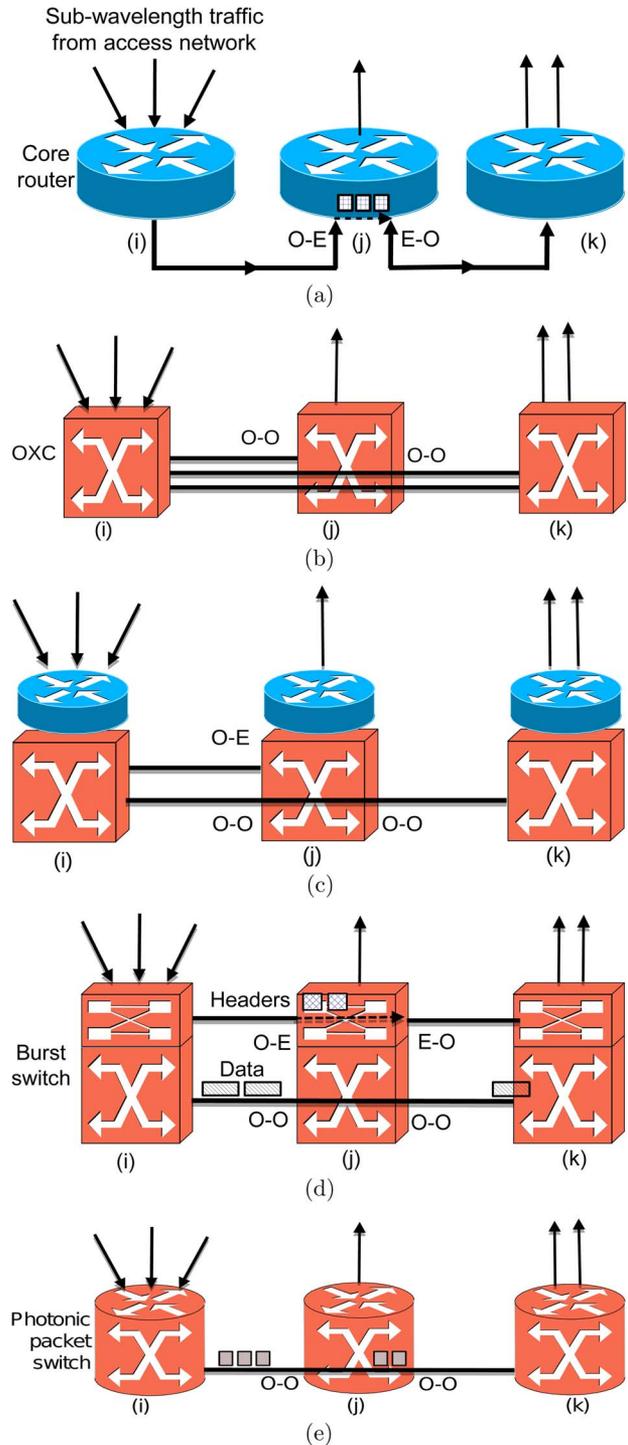


Fig. 3. Different core node architectures. (a) PtP-WDM network. (b) All-optical circuit switched (A-OCS) network. (c) Optical circuit switched (OCS) network. (d) Optical burst switched (OBS) network. (e) Optical packet switched (OPS) network.

nodes of OCS networks today are often provisioned with both core routers and OXCs [17] as illustrated in Fig. 3(c). Such OCS networks could be referred to as IP over Optical Transport Networks (IP-OTNs) [17].

In the evolution of optical switching technologies [7], Optical Burst Switching (OBS) follows OCS (both A-OCS and IP-OTN) [7]. Burst switching was first used in the early 1980s

[62] to statistically multiplex data in traditional PtP-WDM networks. As illustrated in Fig. 3(d), core nodes in an OBS network consist of Burst Switches (BuS). A data burst is generated by aggregating multiple IP packets. The header is sent ahead to the burst on a separate wavelength. Fig. 3(d) provides a simple example of an OBS network. At intermediate nodes, the header (illustrated by a crossed square) is processed by the electronic devices, and the burst (illustrated by a striped rectangle) is switched by the optical devices. OBS allows multiple bursts to share the capacity of a single wavelength, thereby increasing bandwidth utilization.

Optical Packet Switched (OPS) networks appear to be the last frontier of the optical switching technology evolution [7]. Research on OPS networks first began in the 1990s and test-bed experiments were performed toward the end of the same decade [62]. OPS networks mimic the operation of PtP-WDM networks. The similarities between OPS and PtP-WDM networks can be observed by referring to Fig. 3(a) and (e). In an OPS network, core nodes consist of Photonic Packet Switches (PPS). Replicating the core routers' function of electronic processing, PPS optically buffer, process, and switch IP packets (illustrated by the solid gray squares) at intermediate nodes.

In order to replace electronic core routers with optical core nodes in OCS, OBS, and OPS networks, power-efficient optical devices are expected to perform tasks such as buffering, processing, and switching. In the following subsection, we review technologies, architectures, and alternative mechanisms that could be utilized to develop power-efficient optical core nodes.

2) *Electronic Versus Optical Buffers*: In an electronic core router, buffers are used to temporarily store IP packets as the control information is processed [59], [63], [64]. Being able to store IP packets is critical in avoiding wavelength contentions and performing packet synchronization especially in PtP-WDM networks [59], [63], [64]. In the electric core router, buffers are realized using electronic random access memory (RAM) technology [42]. In an optical core node, buffering could be realized using Fiber Delay Lines (FDLs) [42], [57], [65] or Slow-Light Optical Buffers (SLOBs) [65], [66].

In comparison to proposed all-optical buffering technologies (such as FDL and SLOB), RAM not only provides more capacity (e.g., RAM used in line cards of the Cisco CRS-1 has a capacity of 4 Gb), but also happens to consume less power [42]. However, the capacity bottleneck of electronics constrains the maximum achievable store-and-retrieve speed of RAMs [67]. In [42], Tucker *et al.* report that FDL-based optical buffers consume 40 mW of power in comparison to 8 mW of power consumed by CMOS-based RAMs when the buffer capacity is 40 Mb. Among the optical buffering technologies, FDLs consume less power (approximately 44 pW) than SLOBs (approximately 80 mW) when the buffer capacity is 400 kb [42]. However, FDLs are considered infeasible due to their large physical size [42], [65]. In an interesting study, Yoo *et al.* [59] analyzed the power consumption of FDL-based cascaded serial and parallel optical buffers. Their results show that cascaded optical buffers consume only 1 kW of power in comparison to 35 kW of power consumed by electronic RAMs. However, due to complexity associated with the control circuitry, an OPS network utilizing cascaded optical buffers consumes 347 kW

of power in comparison to 317 kW consumed by a PtP-WDM network.

Since optical buffers appear to consume more power, optical core nodes can exploit wavelength and space domain contention resolution schemes [68], [69] to perform the necessary functions with limited buffers [68]–[71]. In [72] and [73], wavelength conversion was used to minimize buffering and reduce power consumption of an OPS network. Wavelength conversion can be performed using both electronic and optical technologies [74]. However, studies show that all-optical wavelength converters consume less power than electronic converters [74]–[78]. According to [35] and [36], an all-optical wavelength converter consumes approximately 2 W of power.

OCS and OBS networks can be implemented with limited buffering, thus proving to be power-efficient network solutions. Unlike in a PtP-WDM network, intermediate core nodes of an OCS network do not possess buffers or fast switches [7], [52], [53]. As a result, these intermediate nodes consume less power than electronic core routers in a PtP-WDM network [79]. According to Peng *et al.* [80], intermediate core nodes of an OBS network also consume less power than the core routers in a PtP-WDM network. However, the burst assembly routers (which aggregate multiple IP packets into bursts) of an OBS network require large buffers and consume significantly more power than electronic core routers at the network edge.

3) *Electronic Versus Optical Processing*: In a PtP-WDM network, an IP packet is formed by combining the payload (i.e., packet content) and the header (i.e., packet information) in a series. At an intermediate node, the header is processed while the packet is momentarily stored in the RAM. Unlike in an electronic core router of a PtP-WDM network, optical core nodes in general do not possess a mature buffering technology like RAM. Therefore, in place of the electronic packet-header processing mechanism, Optical Label Switching (OLS) can be adopted in optical core nodes to reduce power consumption of OCS, OPS, and OBS networks [59], [63], [64].

Optical labels that perform the task of a header can be sent parallel to the payload on a separate wavelength. Since a label carries only a small amount of data, it could be converted and processed by low-power CMOS-based electronics working at moderate speeds. As the payload is transported separately, it can be switched by an optical switch using minimum optical buffering [59], [63], [64]. Resultantly, an OLS-based OPS network consumes less power (e.g., 16.8 kW) compared to a buffered OPS network (e.g., 347 kW) in a similar traffic environment [59], [63], [64]. However, OLS still uses electronic devices and involves O-E/E-O conversions. Hence, it may be beneficial to replace OLS with All-Optical Label Switching (A-OLS) [59], [81], which does not involve electronics, in order to further reduce power consumption.

Traffic in PtP-WDM and OCS (i.e., IP-OTN) networks is groomed by electronic devices. An OBS network allows a wavelength to be shared among multiple bursts and, thus, traffic grooming is an integrated functionality of OBS networks. However, optical core nodes of an OPS network lack a viable all-optical traffic grooming mechanism. Given this limitation, Musumeci *et al.* proposed a novel Time-Driven Switching (TDS) technique for grooming in optical core nodes [82], [83].

TDS exploits the time coordination of network elements to optically switch and groom sub-wavelength traffic tributaries. Results indicate that TDS-based all-optical traffic grooming consumes 55% less power than electronic grooming [82], [83].

4) *Electronic Versus Optical Switching*: In large electronic core routers, switching is performed by CMOS-based fast switches [84], [85]. In an optical core node, a fast switch can be constructed using Semiconductor-Optical-Amplifier Gate Arrays (SOA-GAs), a Micro-Ring Resonator (MRR), Arrayed-Waveguide-Gratings with Tunable Wavelength Converters (AWG-TWCs), and Electro-Optic-Phased Arrays (EOP-As) [34], [39], [42], [57].

It has been suggested quite often that SOA-GA and EOP-A fast switches consume more power in comparison to CMOS-based electronic switches [34]. The MRR fast switch consumes less power than an electronic switch; yet, large scale implementation of the MRR is challenging due to difficulties in controlling resonance wavelengths [34]. The results presented in [34] indicate that in the year 2020, electronic, SOA-GA, AWG-TWC, MRR, and EOP-A switches will consume, 10 kW, 100 kW, 7 kW, 8 kW, and 10 MW of electricity, respectively, while providing a throughput of 1 Pbps. Among the available optical fast switches, AWG-TWC consumes the least amount of power [34], [39], [42], [57], [86], [87]. In [88] and [89], Aleksic *et al.* reported that the AWG-TWC switch consumes 25% less power than a SOA-GA switch. However, practical application of AWG-TWC switches is still pending due to unavailability of rapid Tunable-Wavelength-Converters (TWCs) [34], [42]. According to [34], Tucker concluded that, because optical fast switches are driven by electronic circuits, it is important to afford attention to reducing power consumption of the electronic drive circuits in order to increase the power efficiency of optical fast switches and, thus, optical core nodes.

While fast optical switches are essential in OPS networks, slow optical switches (such as Micro-Electro-Mechanical-Systems (MEMS) switches) can still be used in OCS and OBS networks given that the bursts are long [90]. Different measurements of power consumed by MEMS switches have been provided in past studies. For example, in [39], MEMS switches consume less than 10 pJ/b of power. In [91], an 80×80 port MEMS switch consumes 8.5 W of power. According to Murakami *et al.* [92], a 3D-MEMS optical switch consumes 8 kW (1/7th of an electronic slow switch) of power per 1000 ports, and provides a total switching capacity of 1 Tbps.

5) *Networks With Hybrid Core Nodes (NHCNs)*: A Hybrid Core Node (HCN) consists of a hybrid core router that is assigned an electronic RAM, electronic packet processor, and an optical switch [93]. While packet processing, grooming, buffering, and controlling are performed by electronic circuitry, switching is performed by optical switches. According to [93] and [94], a hybrid core router consumes only 5.6×10^{-10} W per bit of transmitted traffic in comparison to 1×10^{-9} W of power consumed by a Cisco CRS-1 core router. Nonetheless, regular use of E-O and O-E converters in the hybrid core router restricts its maximum achievable power efficiency.

An HCN with a different architecture was used in [95] and [96] to reduce power consumption of Hybrid Optical Switched (HOS) networks. A core node of an HOS network consists

of an electronic or SOA-GA fast switch and a MEMS slow optical switch [97]–[101]. When traffic arrives at a core node, the control plane decides if traffic should be switched fast or slowly. By re-directing circuit-oriented traffic and long data bursts to the slow optical switch, the load on the power-hungry fast switch is reduced, thus reducing overall power consumption. As pointed out in [99] and [97], if an HOS network is employed with SOA-GA fast switches, power consumption can be reduced by 1000% over ordinary PtP-WDM networks and by 600% over HOS networks with electronic fast switches. In two separate studies, an HOS network with SOA-GA fast switches and an HOS network with electronic fast switches were found to consume 9 and 2 times less power [100] and produce 10 and 3 times less CO₂ than a PtP-WDM network, respectively [98].

An optical core node of an OCS network (i.e., IP-OTN), which consists of an OXC and a core router, could also be regarded as an HCN, since it involves both electronic traffic processing and optical switching. In such networks, an HCN can be constructed with opaque, transparent, and translucent architectures [102]–[104]. According to [102]–[104], core nodes of the translucent architecture are the most power-efficient. This is partly due to the fact that wavelength regeneration and switching in translucent core nodes are performed within the OXC. In order to further reduce power consumption in a translucent core node, wavelength regeneration can be performed by an all-optical regenerator, which only consumes 50–80 W of power [30]–[32] in comparison to 100 W of power consumed by an electronic regenerator (i.e., a back-to-back transponder) [24], [28]. The work in [102] indicates that an OCS network provisioned with translucent core nodes consumes 60% less power in comparison to PtP-WDM networks with electronic core routers.

B. Physical Topology Redesign

As high cost makes it impractical to modify the physical topology of an existing backbone network, new backbone networks need to be designed using the Greenfield approach (i.e., a design in which no prior restrictions are imposed on it due to the absence of pre-existing infrastructure) in order to reduce power consumption [45]. Deployment cost of an optical backbone network is dominated by the link laying cost. Therefore, to reduce cost, core nodes have to be interconnected via a minimum number of links.

In Fig. 4(a) and (b), we depict two different physical topologies designed to minimize cost and power consumption, respectively. Nodes n and k are located in high-population cities and, thus, they source (i.e., add) and sink (i.e., drop) more traffic (busy nodes). The ring topology in Fig. 4(a) costs less as it has fewer links. Yet, the topology in Fig. 4(b) consumes less power than the topology in Fig. 4(a) as the busy nodes are directly connected to other nodes, and traffic therefore travels via a reduced number of links and fibers and through a minimum number of intermediate core nodes.

While the majority of the existing literature attempts to reduce cost and packet loss as well as ensure resilience of the physical topology, only a few studies seek to optimize power consumption of the backbone network. Dong *et al.* [105] developed a Mixed-Integer-Linear-Programming (MILP)

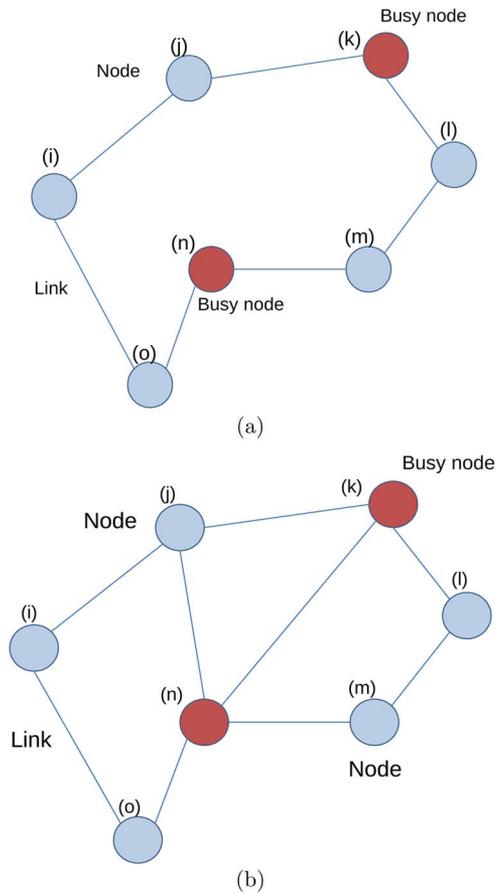


Fig. 4. Two different physical topologies connecting 7 core nodes. (a) A ring network. (b) Optimized partial mesh topology.

based formulation to optimize the physical topology, to reduce power consumption. Their experiments show that the proposed scheme reduces power consumption by 10% without increasing the number of physical links of the National Science Foundation (NSF) network. It is also highlighted that if the network is allowed to use a full mesh topology or a star topology, power consumption could be reduced by a staggering 95% and 92%, respectively. The authors also investigated the possibility of optimizing the physical topology by accounting for the presence of renewable energy sources in the network. The resultant network offers 10% more power savings over their initially proposed network. Further analyzing the results of [105], it becomes apparent that a network optimized to consume less power will also be cost-effective. Nevertheless, one drawback of the proposed optimization scheme is the increase in propagation delay.

Carmello *et al.* [106] proposed a multi-objective evolutionary algorithm to optimize the physical topology. The algorithm attempts to simultaneously minimize cost, blocking probability, and power consumption by configuring the physical topology and the node capacities. The authors pronounced their work as the first to jointly analyze these three aspects under a single objective function. To measure power consumption, Carmello *et al.* considered the normalized power consumption values of transmitters, amplifiers, and OXCs. After running the algorithm multiple times, they obtained a variety of net-

work solutions, some of which succeeded in reducing cost and power consumption, but at the expense of high blocking probability [106]. Thus, a trade-off between reducing cost, power consumption, and blocking probability was observed.

Reducing cost and power consumption of the backbone network by optimizing the physical topology was also studied separately in [107]. Here, the authors investigated the problem of designing a cost-efficient physical topology when explicitly targeting the minimization of power consumption. The topology design problem is solved using ILP formulations with the objectives of minimizing cost and power consumption while considering the realistic Single Path Routing (SPR) constraint [107]. SPR constrains traffic between a node pair to travel along a fixed route. Alternatively, if the SPR constraint is relaxed, traffic between a node pair can take multiple routes. The simulation results in [107] indicate that the proposed model is cost-efficient and only consumes 26.5% extra power in comparison to topologies optimized by relaxing the SPR constraint.

C. Network Redesign Approach: Summary of Findings

The increasing production cost of semiconductors [61] and the possible end of Moore's law [59], [60] motivate network operators to shift from electronic core routers to optical ones. Our review of the current state-of-the-art in research has uncovered some of the key limitations of existing optical core nodes and provides possible, alternative solutions, as summarized below:

- The unavailability of a feasible buffer technology is the main drawback of optical core nodes (especially in PPS). High-capacity FDLs and slow-light buffers consume more power than RAMs and are space-consuming. It is then important to minimize the use of buffers in optical core nodes. This can be achieved by using wavelength converters and space domain contention (deflection-routing) resolution schemes. All-Optical Label Switching (A-OLS) and Time-Driven Switching (TDS) can also be adopted in optical core nodes to minimize the need of optical buffers and to increase power efficiency. Alternatively, the use of buffers and electronic processing can be minimized by using OCS or OBS, instead of OPS networks.
- High power consumption of fast optical switches poses a challenge to the realization of optical core nodes, particularly in OPS networks. Both OCS and OBS networks can use MEMS-based slow optical switches, which consume less power than both fast optical switches and electronic switches.
- Combining the best of both worlds, HCNs consume less power than electronic core routers and are least susceptible to the limitations of optical buffers, processors, and fast switches.

In Table III, we provide a brief summary of power consumption of electronic, all-optical, and hybrid core nodes. Specifically, for each network, we highlight the buffering, processing, and switching technologies that are used in their respective core

TABLE III
IMPLICATIONS FOR POWER CONSUMPTION OF ELECTRONIC, OPTICAL, AND HYBRID CORE NODES

Network type	PtP-WDM	OCS		OBS	OPS
Node type	EPS	OXC	Hybrid	BuS	PPS
<i>-Advantages</i>	Mature electronic technology, supports connectionless IP traffic, high bandwidth utilization	Mature optical technology, fully transparent data transmission	Combines the best of electronic and optical technologies	Connectionless transparent data transmission, supports statistical traffic grooming	Mimics PtP-WDM using all-optical technology, supports statistical traffic grooming, connectionless data transmission
<i>-Limitations</i>	Increased complexity, power consumption, cost, heat dissipation, and footprint of high-capacity core routers	Low bandwidth utilization, latency caused by two-way reservation process	Complexity associated with optical electronic integration, increased cost	Complex burst assembly algorithms, use of a separate control wavelength channel, latency due to offset time	Lacks feasible optical buffering and processing technologies
Buffers	Electronic RAMs	No data buffering	Electronic RAMs	No buffering*	FDLs, SLOBs
<i>-Pwr. consumption</i>	Lower than FDLs and SLOB at high capacities	NA	Same as RAMs	NA	Lower than RAMs at lower capacities
<i>-Limitations</i>	Store/retrieve speed is restricted by the speed of electronics	NA	Same as RAMs	NA	Infeasible physical size, high intrinsic loss
Processors					
<i>-Data processing</i>	Use electronics	NA	Use electronics	NA	All-optical packet processing which is yet to be developed
<i>-Control info.</i>	Use electronics	Use electronics or OLS, A-OLS			
<i>-Resolve contentions in</i>	Time domain	Space and wavelength domain	Time, space, and wavelength domain		
<i>-Pwr. consumption</i>	O-E/E-O converters consume high power	OLS and all-optical wavelength converters consume less power than electronic header processing and contention resolution methods			A-OLS, FDLs, and all optical wavelength converters consume less power than electronic counter parts
<i>-Limitations</i>	Limited speed of electronics	Limited packet/header penetration only allows simple operations, space domain contention resolution may cause traffic synchronization problems in OPS networks			
Switches	Electronic fast switches	MEMS-based slow switches		Electronic/optical fast switches** or MEMS-based slow switches	SOA-GA, AWG-TWC, MRR, and EOP-A fast switches
<i>-Pwr. consumption</i>	Consume less power than SOA-GA and EOP-A fast switches	Consumes less power than optical and electrical fast switches			MRR and AWG-TWC consume power than electronic and other optical fast switches
<i>-Limitations</i>	Switching speed is restrained by the limited speed of electronics	High switch configuration time, slow switching speeds are only suitable for connection-oriented traffic or large bursts			SOA-GA and EOP-A consume high power, MRR is impractical due to difficulties in controlling resonance wavelengths, AWG-TWC is dependent on the development of rapid TWCS

Note: * OBS edge routers contain electronic or all-optical buffers, ** Fast switches were used in [80,108], *** MEMS is used in [90].

nodes and explain how they compare against each other in terms of power consumption. We also report the key limitations of these technologies.

Summarizing the above findings, we argue that core nodes must rely on both optical and electronic technologies in order to minimize power consumption and increase capacity utilization. While buffering, processing, and grooming could be realized using electronic technology, switching and contention resolution could be performed using optical technology. Among

the examined core node architectures, we are then inclined to believe that hybrid core nodes is the way forward.

Finally, our review shows that optimizing the physical topology is also critical in reducing power consumption, as past research has provided evidence that an optimized network topology accommodates traffic using fewer devices. Then, to maximize power savings and reduce operational cost in the future, network operators may opt to replace legacy network topologies with newer topologies.

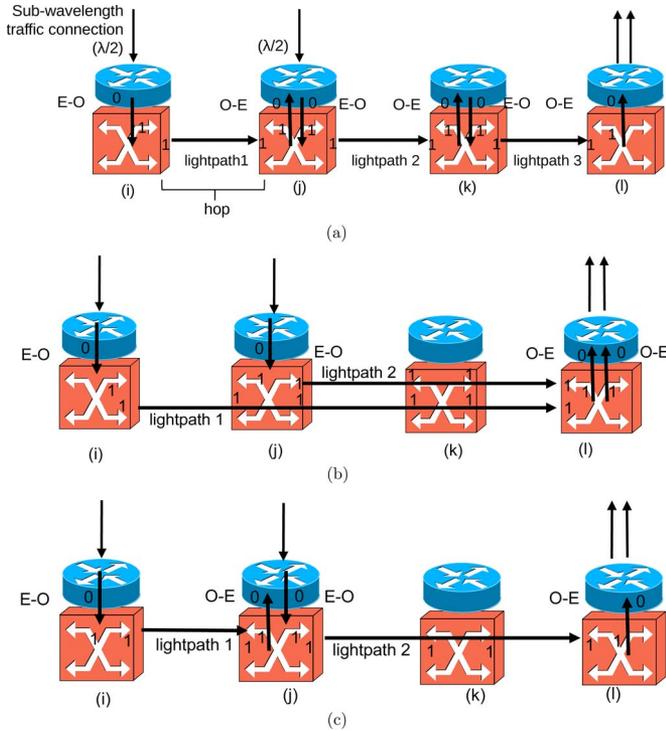


Fig. 5. Comparison of the three wavelength grooming schemes. (a) No-bypass (NB) grooming. (b) Direct-bypass (DB) grooming. (c) Multi-hop with bypass (MHB) grooming.

IV. TRAFFIC ENGINEERING APPROACHES

An alternative approach to the reduction of power consumption of the backbone network is to minimize the use of network devices (e.g., fibers, ports, traffic processors, etc.) by employing traffic grooming approaches [7], [8], [109]. By aggregating multiple, low-granularity traffic flows into few, high-granularity traffic flows, traffic grooming cuts down the number of wavelengths traversing the backbone network, thereby lowering the demand on network resources [110]–[113]. Traffic grooming is performed at wavelength, waveband, and fiber granularities [114], [115]. The process of aggregating sub-wavelength traffic (i.e., IP packets) into a single wavelength is referred to as wavelength grooming, and aggregating multiple wavelengths into a single waveband is referred to as waveband grooming. Recall that core nodes communicate with each other through lightpaths realized using wavelength channels.

In a backbone network, where core nodes consist of core routers and OXCs, wavelength grooming can be performed using three different schemes, namely, Non-Bypass (NB), Direct-Bypass (DB), and Multi-Hop with Bypass (MHB) [116]. These three wavelength grooming schemes are explained using Fig. 5. With NB, sub-wavelength traffic is aggregated into point-to-point lightpaths. At each intermediate core node as shown in Fig. 5(a), the wavelengths of point-to-point lightpaths are O-E converted, disassembled into sub-wavelength traffic (i.e., IP packets), and electronically processed by the intermediate core routers. With DB, sub-wavelength traffic between every node pair is groomed into dedicated end-to-end lightpaths. As shown in Fig. 5(b), wavelengths of an end-to-end lightpath are

switched by the OXC of each intermediate core node, avoiding electronic processing (also referred to as optical bypassing). With MHB as shown in Fig. 5(c), sub-wavelength traffic that shares a set of physical links in the same route, with a minimum hop distance of two, is aggregated into a multi-hop lightpath.

In the example depicted in Fig. 5, NB, DB, and MHB wavelength grooming schemes produce 3, 2, and 2 lightpaths and consume 12, 14, and 10 OXC input/output ports (denoted as “1”), respectively. The three schemes also consume 6, 4, and 4 core router ports (denoted as “0”) and process a total of 3.5λ , 2λ , and 2.5λ wavelength traffic, respectively. While it appears that the MHB scheme produces fewer wavelengths and consumes fewer ports, the DB scheme involves less traffic processing. Given the benefits and trade-offs with each wavelength grooming scheme, it is important to know how the three grooming schemes affect power consumption of the backbone network and how they can be improved to consume less power.

A. Wavelength Grooming for Static Traffic

Power consumed by different wavelength grooming schemes has been analyzed by past studies in both static and dynamic traffic environments. A static traffic model is used when information about connection requests is available and when network traffic shows minimum variation over long periods of time [117]. The primary objective of most studies using a static traffic model has been to identify the most power-efficient wavelength grooming scheme in a static traffic environment [118]–[121]. However, notable differences among these studies are the considered core node architecture, power consumption values of network devices, the optimization technique, and their inter-relationships.

In [119], the authors used MILP optimization techniques and heuristic-based algorithms to demonstrate that MHB consumes 45% less power compared to NB. A similar conclusion was drawn from Integer-Linear-Programming-based (ILP-based) work in [118] whose results indicated that MHB consumes 28% and 53% less power compared to NB when tested on the European Optical Network (EON) and the NSF network, respectively. We observe that the MHB scheme tends to send traffic connections via longer paths, which elevates power consumed by the transport system. However, this increase is compensated for by minimizing both electronic processing and the number of active transponders, through the establishment of fewer lightpaths, which helps to save power.

Depending on the wavelength grooming scheme used, the core node will consist of different devices. While NB grooming is performed by electronic devices, DB and MHB grooming require both electronic and optical devices. In [120], it is clear that MHB consumes less power when electronic and optical devices have comparable power consumption values. If electronic devices are more power-hungry, then of the three grooming schemes, DB consumes the least amount of power. Referring to our example in Fig. 5, DB consumes 4 electronic core router ports and 2 wavelength traffic connections compared to 6 and 3.5 by NB and 4 and 2.5 by MHB. On the contrary, if

optical devices are more power-hungry, then NB looks to be the most power-efficient wavelength grooming scheme. Based on this analysis, we contend that selection of the appropriate wavelength grooming scheme should be based on actual power consumption values of both electronic and optical devices.

Yetginer *et al.* [121] evaluated the power consumption of three different wavelength grooming strategies (MinL, MinP, and MinT) with respect to increasing network traffic. The first strategy, denoted as Minimize Lightpaths (MinL), was developed to optimize the number of lightpaths in the network, similar to the MHB grooming scheme. The second strategy, Minimize Transponders (MinT), optimizes the network to use a minimum number of transponders and electronic processing, resembling the DB grooming scheme. The third strategy, known as Minimize Power (MinP), combines MinL and MinT to achieve a balance between reducing the number of lightpaths and the number of transponders. The authors discovered that the highest reduction in power consumption is achieved by optimizing the network using MinP. When network traffic is low, MinT and MinL consume 95% and 10% more power compared to MinP, respectively. Conversely, when network traffic is high, MinT and MinL consume 2.5% and 5% more power compared to MinP, respectively. Between MinT and MinL, the former is more power-efficient when network traffic is high and the latter when network traffic is low. The reason is that at high traffic loads, MinL cannot further increase lightpath utilization because only a limited bandwidth (i.e., available capacity) remains under-utilized in end-to-end lightpaths. On the other hand, when network traffic is low, several sub-wavelength traffic connections can be groomed into a single lightpath, thereby reducing the use of transponders and maximizing optical bypass.

Similar to the MinP strategy proposed in [121], Coiro *et al.* [122] developed a heuristic algorithm that effectively combines DB with MHB. The objective of the proposed algorithm was to reduce the amount of power consumed by the line cards connected to the fibers. In the first stage of the algorithm, traffic is routed along paths on a virtual topology derived using the DB grooming scheme. The algorithm then eliminates unnecessary links (effectively switching off line cards) by re-routing traffic and re-grooming wavelengths using the MHB grooming scheme. Re-routing paths are selected based on a cost function that takes into account the number of new line cards that need to be switched on and the load distribution in the fibers. By minimizing the cost function, the proposed scheme is able to groom and route traffic using a minimum number of fibers. The results in [122] indicate that the proposed algorithm attains an 80%–95% increase in power efficiency over a network using only DB grooming. This work highlights the potential of MHB in reducing power consumption of line cards by grooming traffic into a fewer number of wavelengths and accommodating them through a limited number of optical fibers.

B. Wavelength Grooming for Dynamic Traffic

The dynamic nature of the Internet demands frequent alteration of network connections. Thus, connection requests arrive

randomly and last for varying time periods. Under such conditions, all connection requests cannot be served concurrently as in static traffic models, but would have to be dealt with individually. Past research efforts on traffic grooming with dynamic traffic models proposed several approaches to reduce power consumption, which we label as First, Second, and Third approaches.

The First Approach (FA) attempts to groom new connections into existing lightpaths [5], [116], [123], [124], thereby reducing the activation of new network devices and lightpaths. The Second Approach (SA) follows the first approach but allows existing lightpaths to be re-configured when necessary [125]. The Third Approach (TA) is similar to the first approach, yet does not allow the resource holding time to be extended [126]–[128]. It is important to keep in mind that the first two approaches, FA and SA, do not account for time and are thus oblivious to resource holding times.

Using the FA approach, Xia *et al.* developed a power-aware grooming algorithm [5], [116]. As the authors demonstrated, grooming new connection requests into existing lightpaths comes at the expense of additional electronic processing. Contrarily, if a new lightpath is established for each new request, extra devices need to be activated (e.g., transponders, receivers). Using an auxiliary graph and arc weight assignment technique, the proposed power-aware traffic grooming algorithm accommodates traffic demands by activating a minimum number of network devices without excessively increasing electronic processing. In comparison to DB and NB grooming schemes, the proposed algorithm reduces power consumption by 28% and 12%, respectively. The proposed algorithm is also able to reduce the Bandwidth Blocking Ratio (BBR) by using network devices more efficiently.

Similarly, in [123], the authors developed a dynamic, energy-aware traffic grooming scheme. By optimizing an energy-cost function, the proposed scheme saves as much as 30% of power compared to MHB and NB. In designing the cost function, the authors accounted for the power consumption of core node devices. By minimizing the energy-cost function, connection requests are accommodated via the path that consumes the least amount of power. When network traffic is low, the proposed grooming scheme aggregates new connection requests into existing lightpaths, minimizing the need to activate new devices. When network traffic is high, new lightpaths are initiated as existing lightpaths will have run out of bandwidth.

One of the major drawbacks of wavelength grooming is that it involves electronic processing at aggregation and de-aggregation nodes. With the aim of reducing electronic processing at de-aggregation nodes, Farahmand *et al.* [129] introduced a new type of OXC which supports a Drop-And-Continue (DAC) functionality. The proposed DAC-enabled OXC (D-OXC) allows a lightpath to be shared among many connection requests whose destination is located along the route of the lightpath. At intermediate nodes, groomed traffic is dropped from the lightpath using passive devices of the D-OXC. Electronic processing is then limited to source nodes. The D-OXCs were tested with several grooming schemes based on the FA [129]. Their results showed that by grooming new connection requests onto existing lightpaths with the objective

of minimizing electronic processing or the number of logical hops, power consumption can be reduced by 80%. However, grooming traffic with different objectives, such as to minimize initialization of new lightpaths or to minimize the travelling distance of connection requests, failed to offer similar power savings.

Guo *et al.* in [125] discerned that the SA is more effective in reducing power consumption over the FA in a dynamic traffic environment. In their proposed Power-Efficient Grooming Algorithm (PEGA), new connection requests are groomed onto existing lightpaths unless existing lightpaths lack capacity at which point new lightpaths are established. Unlike the FA, as in [5], [116], [123], however, the PEGA reconfigures (i.e., splits and re-grooms) existing lightpaths whenever necessary in order to increase power savings.

A network device when activated consumes a fixed amount of power, and as long as the device remains active, it continues to draw power. In a network where traffic is represented using a dynamic model, a connection request only lasts for a brief interval. Certain devices could then be de-activated the moment a connection terminates unless they serve another connection request. The third traffic grooming approach (i.e., TA) not only reduces device activations but also decreases the time that devices remain active. Shuqiang *et al.* [127] suggested that if grooming new connections onto existing lightpaths forces the devices to remain active for much longer than necessary, power consumption would escalate. Alternatively, if new connections can be groomed onto lightpaths without lengthening the time that the devices remain active, power consumption can be reduced. Taking the above into account, Time-Aware Traffic Grooming (TATG) was proposed in [126], [127]. The proposed TATG heuristic consumed less power than the DB and MHB grooming schemes when network traffic was low, but consumed more when network traffic was high.

In [128], the authors developed a similar time-aware traffic grooming scheme by taking into account the connection holding time and power consumption of network devices. Wavelength converters were used to maximize lightpath reuse and to reduce BBR. Their experiments indicate that the proposed grooming scheme consumes less power than both DB and MHB. An important point to note is that the MHB grooming scheme which was shown to be the most power-efficient in a static traffic environment comes second to time-aware grooming schemes proposed under TA in [126]–[128] in a dynamic traffic environment. This is due to the fact that both DB and MHB do not use time domain information unlike in time-aware traffic grooming.

Applying the time-aware grooming concept to the Spectrum Elastic Optical Network (SEON) [130], [131], Zhang *et al.* [132] proposed a Time-Aware Provisioning with Bandwidth Reservation (TAP-BR) protocol. The TAP-BR incorporates both time and bandwidth information to facilitate power-efficient traffic grooming. To further reduce power and increase resource utilization, the TAP-BR grooms the majority of new traffic demands onto existing lightpaths that last longer. Simulation results in [132] indicate that the proposed TAP-BR in the SEON consumes 68%, 51%, and 27% less power than NB, DB and MHB grooming schemes, respectively.

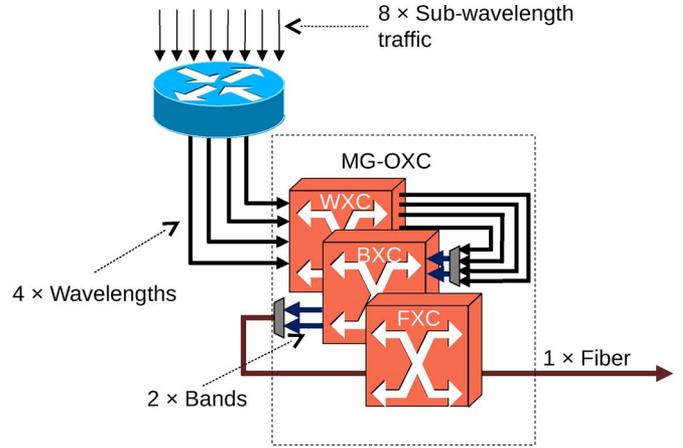


Fig. 6. Aggregating traffic at multiple granularities by an MG-OXC of a Band Switched Network (BSN).

C. Waveband Grooming

As network traffic continues to grow, even with wavelength grooming, a large number of lightpaths would continue to enter the backbone network. Consequently, high-capacity OXCs are essential to carry out switching [91]. However, as reported in [133], [134], high-capacity OXCs are expensive, complex, have poor scalability, and consume more power. In order to reduce the amount of switching by the OXCs, waveband grooming [114], [134], [135] is useful.

A waveband is generated by aggregating a set of wavelengths using either Same-Ends (SE) or Intermediate (INT) band grouping policies. At an intermediate node, a waveband is switched by a single input-output switching port. With the SE grouping policy, a waveband is generated at the source node, whereas with the INT grouping policy, a waveband can be generated at either the source or intermediate node. The term Band Switched Network (BSN) is used in reference to a backbone network that utilizes waveband grooming. In a BSN, OXCs are replaced with a Hybrid Optical Cross Connect (HOXC) or a Multi-Granular-Optical-Cross-Connect (MG-OXC) [136], [137]. A detailed survey on different node architectures, grouping policies, and band configurations of BSNs was presented by Wang and Cao in [136]. Fig. 6 shows how traffic grooming is performed in a BSN. At the core node, 8 sub-wavelength traffic connections are groomed into four wavelengths, which are then multiplexed into two wavebands. The two wavebands are multiplexed into a single fiber using the WDM technique. The core node consists of an MG-OXC comprising of Wavelength, Band, and Fiber cross-connects [136].

Waveband grooming is often used concurrently with wavelength grooming schemes to attain different objectives. In [138], Hou *et al.* developed a novel Robust Integrated Grooming (RIG) algorithm, which jointly reduces power consumption and port consumption in dynamic traffic environments. To reduce power consumption of the electronic devices (e.g., transponders and router ports) in the BSN, traffic is aggregated into fewer wavelengths using RIG. Then, by grooming these wavelengths into wavebands, RIG minimizes the use of optical switching ports. In comparison to existing state-of-the-art robust algorithms [139], the proposed RIG algorithm is 15%

more power-efficient and consumes 32% fewer switching ports. Extending this work, Hou *et al.* developed the Maximizing Hop First (MXHF) heuristic in [140] to reduce both power consumption and switching ports in a network serving dynamic, multi-granular connection requests (e.g., OC-1, OC-3, and OC-12). The proposed MXHF heuristic adopts the MHB grooming scheme to improve power efficiency and the intermediate waveband grouping policy to reduce the number of switching ports. Simulations show that the MXHF is more power-efficient than other robust algorithms proposed in [141].

Survivable BSNs (i.e., BSNs that are resilient against device failures) were previously studied in [133] and [142]. Extending this past work, the authors in [143] developed two heuristic wavelength routing algorithms, namely, “Single-hop Survivable Grooming considering Power Efficiency” (SSGPE) and “Multi-hop Survivable Grooming considering Power Efficiency” (MSGPE), to provide resilience against link failures and to reduce power consumption. While link resilience was guaranteed using a dedicated path protection scheme, power consumption was reduced through wavelength grooming. Waveband grooming was utilized to reduce optical switching ports. Results show that MSGPE is 200% and 130% more power-efficient than SSGPE when experimented on the USA and NSF networks respectively. However, the authors in [138], [140], [143] intentionally omitted the power consumption of optical switching ports from their calculations as they were assumed to consume a negligible amount of power [140]. Therefore, waveband grooming did not have any impact on power consumption. Nevertheless, it is our understanding that power savings, albeit limited, may be offered by reducing the number of optical switching ports.

While minimizing the amount of switching by OXCs remains the primary objective of waveband grooming [115], [144]–[146], it could also be used to reduce power consumption [147]–[149]. In their pioneering work [115], [144]–[146], Hou *et al.*, Guo *et al.*, and Wang *et al.* developed integrated grooming schemes by combining wavelength and waveband grooming to reduce the number of optical switching ports of HOXCs. Hou *et al.* [147] were the first to jointly analyze port cost and power savings in a BSN. The authors first developed an ILP formulation to reduce both switching ports and power consumption of a BSN [147]. As the developed ILP formulation was only solvable for small networks, the authors then proposed two heuristic schemes. Their results show that the SE grouping policy consumes less power but more switching ports than the INT grouping policy. INT consumes more power as it requires more electrical processing. The reason is that for lightpaths to be grouped into wavebands, they need to be assigned appropriate wavelengths at intermediate nodes. However, as HOXCs do not possess wavelength converters at the optical switch [147], lightpaths have to enter the electronic layer to be assigned wavelengths, increasing the amount of electrical processing. On the other hand, SE consumes less power as waveband grouping does not occur at intermediate nodes. It is also observed that increasing waveband granularity had a negative effect on reducing power consumption.

In a separate study, Wang *et al.* [148] obtained identical results after experimenting with both static and dynamic traffic

models. Considering their results and that of Hou *et al.* [147], we contend that SE grouping is more power-efficient than INT, and a small band size is favorable in reducing power consumption. However, it is unclear if the above statement holds true for BSNs employing MG-OXCs instead of HOXCs or when optical switches are provisioned with all-optical wavelength converters.

While [147] and [148] experimented with BSNs using HOXCs, [149]–[151] analyzed power consumption of BSNs with MG-OXCs. According to their survey [136], Wang *et al.* report that the three-layered MG-OXC provides the most switching port savings. Recent efforts in [149], [150] provide some interesting insights into the power consumption of a BSN employing three-layered MG-OXCs. To understand the relationship between design parameters (i.e., wavelength capacity (represented by notation “C”), waveband size (denoted as “W”), number of wavebands per fiber (denoted as “B”), number of fibers per unidirectional physical link (denoted as “F”)) and power consumption, Naas *et al.* [149] carried out several experiments on the EON and NSF network. Their experiments reveal that with the selection of an optimum combination of C-W-B (that is a function of the network topology, network traffic, and fiber capacity), the BSN consumes, on average, 50% less power than ordinary IP-over-WDM networks (with wavelength grooming only) under both fiber-scarce and fiber-plentiful situations.

In a similar study, Naas *et al.* [150], [151] analyzed how the optical reach of lightpaths would affect power consumption and cost of a BSN. Their results show that increasing the optical reach of a lightpath beyond a certain threshold, despite reducing power consumption by a small percentage, would considerably elevate cost. It is then important to pinpoint the threshold that provides the optimum balance between cost and power consumption. However, if the MG-OXC is provisioned with all-optical regenerators [74], [152], wavelengths can be regenerated within the optical switch without involving electronic processing. If so, the results obtained in [150] might not hold true.

D. Wavelength and Waveband Grooming in Multicast Networks

Multicast traffic grooming is an extension of wavelength traffic grooming that is applied to single-point to multi-point traffic distributions. Multicast applications such as digital media broadcasting, multi-party conferencing, video distribution, network news distribution, collaborative processing and web content distribution are becoming more and more popular [110]. The downside to these is their high bandwidth requirements [153]. Optical multicasting using “light tree” [154] provides an excellent solution, allowing multiple multicast sessions to share the capacity on a single wavelength channel. The concept of grooming in multicast networks can be explained using a simple example shown in Fig. 7. As can be observed, two nodes (i and o) transmit multicast demands to all other nodes. Instead of using two separate paths, the multicast demand of node i is aggregated with that of node o and then distributed, thereby reducing the load on links (i, j) , (j, k) , and (k, l) .

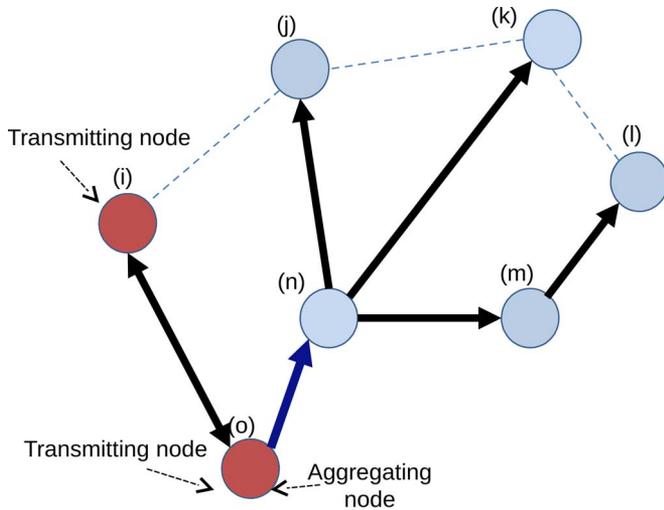


Fig. 7. Multicast network: grooming two multicast demands at node (o).

During the past decade, researchers have showed a great deal of interest in reducing the cost of multicast networks [155]–[157]. Integration of waveband grooming and multicast grooming in single-domain and multi-domain networks was extensively studied in [158] and [159], respectively. Despite providing excellent component cost reduction, these studies were unable to provide solutions to the increasing power consumption of the backbone network. Improving power efficiency of multicast grooming is a hot topic in wireless networks [160], [161]. With the intention of extending investigated power-efficient concepts to IP-over-WDM networks, the authors in [162], [163] developed a novel auxiliary graph algorithm. They first proposed four different multicast grooming policies which were used to form four different policy combinations, namely, Multicast-Green-Grooming (MGG), Multicast-Grooming 1 (MG.1), MG.2, and MG.3. These policy combinations were then evaluated for their Bandwidth Blocking Probability (BBP) and Average Energy Consumption (AEC). The results indicate that as network traffic grows, BBP increases while AEC reduces. The study also demonstrates that optical bypass reduces power consumption significantly. Although the authors state that MGG consumes less power in comparison to the other three policies, equal BBP and AEC performance is observed with both MGG and MG.1.

In a separate study [164], Zhu and Jue studied the power consumption minimization problem of multicast-groomed backbone networks. An ILP model and a heuristic algorithm were developed with the objective of minimizing total power consumption. The heuristic that was derived from their previous work in [165] determines the aggregation node and appropriate link rate (also referred to as line rate) for each light tree. Basically, each light tree is assigned a link rate based on the power consumption information of the transponders to conserve maximum electricity. If a higher link rate can provide a smaller ratio of power consumption to link rate, then the light tree is assigned the higher link rate. Else, it is assigned a lower link rate.

Kantarci and Mouftah [166] proposed an optimization model to reduce power consumption of a multicast cloud service. Based on the optimization model, an evolutionary algo-

rithm was developed. The proposed algorithm saves power by permitting wavelength routing modules of some core nodes to enter a “sleep” state while light trees are routed through the nodes that remain active. An extension of this work is presented in [167] where three MILP models were proposed to either reduce power consumption or minimize propagation delay in a multicast-based cloud service of an IP-over WDM network in which high-performance data centers are located at the core nodes. To reduce power consumption, the developed MILP models attempt to use a smaller number of devices of the IP and WDM layers and the data centers. Two heuristics were then proposed to mimic the developed MILP models. Experiments conducted using realistic power consumption data show that power savings can be achieved at the expense of increased propagation delay. A third heuristic was developed by accounting for propagation delay and power consumption of network devices which provided a balance between reducing power consumption and increasing propagation delay.

E. Traffic Engineering Approach: Summary of Findings

Important conclusions drawn from the reviewed research are summarized in Table IV. In Table IV, the studies examined are first categorized according to the grooming technique (i.e., wavelength, waveband, or multicast grooming) and the nature of traffic requests (i.e., static or dynamic traffic models). The core node architecture and relevant findings related to power consumption are then presented.

By aggregating traffic into fewer wavelengths, wavelength grooming reduces power consumption of the amplifiers and line cards. It also helps to minimize the O-E/E-O interfaces required to add and drop traffic between WDM and IP-layers of the backbone network. However, wavelength grooming involves traffic processing which comes at the expense of power hungry O-E/E-O conversions. Thus, if not handled appropriately, wavelength grooming could result in increased power consumption. Among the available wavelength grooming schemes, MHB consumes the least amount of power under static traffic environments in experiments performed in most studies. However, DB is more effective when electronic devices (e.g., O-E/E-O converters, core routers) consume a significant amount of power in relation to optical devices. Under dynamic traffic environments, time-aware wavelength grooming schemes (e.g., TATG, TAP-BR) show superior results. To minimize power consumption under dynamic traffic environments, it is required that traffic is served using a reduced number of network devices that remain active for a minimum duration.

Waveband grooming is the process of aggregating multiple wavelengths into a single waveband which is switched using a single I/O pair of an OXC. As I/O ports consume a small amount of power, waveband grooming was previously believed to have only a small impact on reducing power consumption. Therefore, most researchers did not quantify actual power savings of waveband grooming. However, as reported in [104] and [168], ports in the switching layers of a three-layer MG-OXC are equipped with pre/post amplifiers, add/drop multiplexers, and modules for termination of the Optical

TABLE IV
SUMMARY OF POWER-REDUCING GROOMING EFFORTS

Type	Traffic model	Policy	Core node	Outcome(s)	Studies
Wavelength Grooming	Static	NB, DB, MHB	Core router + OXC, Digital Cross Connect (DXC) + Optical Add/Drop Multiplexer (OADM)*	Out of three schemes, MHB is more power-efficient.	[118, 119], [120]*
			Core router + OXC, Digital Cross Connect (DXC) + OXC*	A combination of DB and MHB offers excellent power savings.	[122], [121]*
	Dynamic	FA, SA, TA	Core router + OXC, Core router only * Core router + OXC Core router + OXC	FA is more power-efficient than NB, DB, and MHB. SA is more power-efficient than FA. TA is more power-efficient than DB and MHB.	[5, 116], [123]* [125] [126, 127, 132] and [128]
Waveband Grooming	Static	Heuristics	Electronic Cross Connect (EXC) + a three-layered MG-OXC	If C , W , B , and F design parameters are selected correctly, a network employing waveband grooming consumes 50% less power than a network that only relies on wavelength grooming.	[149–151]
	Dynamic	MHB combined with INT	Core router + HOXC	Power consumption is reduced by limiting IP-layer electronic processing.	[138–141, 143]
	Static and dynamic	SE and INT		SE consumes less power than INT.	[147, 148]
Multicast Netw.	Static	ILP and heuristic optimization	Core router + OXC	By appropriately selecting the aggregating node and the line rate for each demand, power consumption can be reduced. By optimizing the route of the multicast demands, power consumption can be reduced.	[164] [166, 167]
	Dynamic	MGG, MG.1, MG.2, MG.3	Core router + OXC	MGG consumes less power than MG.1, MG.2, and MG.3.	[162, 163]

Supervisory Channel (OSC). Thus, Murakami *et al.* [92], [169] show that the I/O port consumes approximately 8 W of power, which is non-negligible. Furthermore, translucent OXCs in the future would not only perform switching but may also convert and regenerate wavelengths using both single-wavelength and multi-wavelength all-optical devices [74], [152], [170]–[172]. If multi-wavelength devices could be used to convert and regenerate wavebands without demultiplexing them into individual wavelengths, we believe that waveband grooming would be able to offer greater power savings, although this has yet to be investigated. We also believe that more research should be conducted to quantify actual power savings of BSNs employing different MG-OXCs and various design parameters (e.g., grooming scheme, band size, etc.).

In summary, traffic grooming is the process of aggregating multiple low-granularity traffic into few high-granularity traffic flows. Traffic grooming plays an important role in reducing power consumption by increasing resource (e.g., bandwidth, capacity) utilization and minimizing the use of network devices. To maximize power reduction, traffic can be groomed at wavelength and waveband granularities. Inclusion of all-optical devices helps to increase power savings of traffic grooming.

V. POWER-AWARE NETWORKING APPROACHES

When designing a backbone network, typically, capacities of the devices are dimensioned to support peak-hour traffic [127]. However, according to [173] and [174], network traffic experiences cyclic variations. During early morning hours or after midnight when network traffic is low [174], certain devices needlessly consume power without performing any task, wasting a significant amount of power.

According to many scholars [1], [175]–[177], unnecessary power waste can be curtailed by shutting down network devices or switching them into low-power-consuming sleep mode (i.e., idle state). A simple scenario of the sleep mode of operation is presented in Fig. 8. By switching nodes j and l (the dotted circles) into sleep mode, power consumption is reduced at nodes j and l and links between node pairs (i, j) , (j, k) , and (k, l) (dotted lines). In order for network devices to be shut off or switched off, the network architecture and routing protocols need to be modified [1], which calls for the development of power-aware networking schemes. Over the past years, a number of different power-aware networking schemes have been developed [176], [178]–[182]. These schemes can be

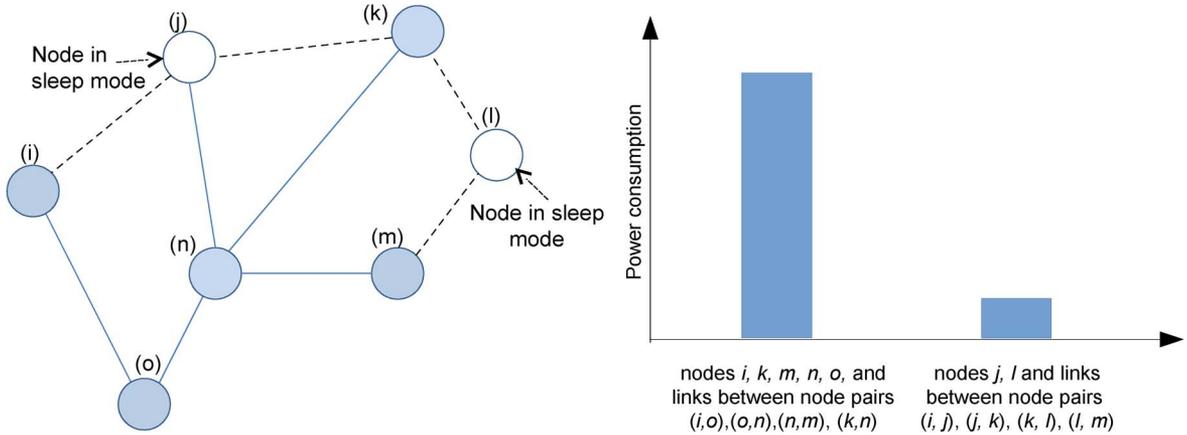


Fig. 8. Switching nodes into sleep mode to reduce power consumption.

categorized as power-aware network designs and power-aware routing protocols.

By minimizing the use of network devices, traffic grooming schemes explained in Section IV and power-aware networking schemes discussed in this section share a common outcome of reduced power consumption. However, their fundamental objectives differ. The primary objective of traffic grooming is to reduce the number of lightpaths, while that of power-aware networking is to shut down as many devices as possible. To achieve the latter objective, power-aware networking, performed either by optimizing a cost function using integer programming techniques or by running a heuristic algorithm, serves traffic using fewer network devices.

A. Power-Aware Network Design

Power-aware networking schemes, specifically the sleep mode of operation, were first adopted in Ethernet and Local Area Networks [175], [183], [184], and most schemes were developed by considering daily traffic variations. In 2008, power-aware networking was introduced to backbone networks by Chabarek *et al.* [180]. Chabarek *et al.* measured power consumption of two widely-used Cisco routers and, then, determined the optimum router-configuration at each core node in the tested network for different network traffic levels. The result was a power-aware network design. Subsequently, specific line cards and router chassis were switched off by routing traffic using a power-aware routing scheme. The end result produced a 2% and 65% increase in power savings in a 12-node network with 24 and 134 links, respectively. The authors highlighted that a larger number of links provides an opportunity to save more power and ensure robustness against link failures [180].

Power consumption of the network devices can be represented using different energy models [185], [186]. In [185], device power consumption was modeled using linear, logarithmic, cubic, and on-off energy profiles [185]. By taking into consideration these energy profiles, the authors developed an Energy Profile Aware Routing (EPAR) scheme which was optimized using integer programming [185]. The objective of this algorithm was to force traffic to route via the most power-efficient network devices. Results show that the EPAR offers a 10%, 10%, 0%, and 35% increase in power efficiency

over the Shortest Path Routing (SPR) scheme when network devices use on-off, logarithmic, linear, and cubic energy profiles, respectively.

The authors of [186] developed a green power-aware routing scheme by assuming three different energy profiles (energy-agnostic, idleEnergy, and fully proportional). A device with an energy-agnostic profile always remains powered-on, while a device with an idleEnergy profile may operate in off, idle, and fully-on states. Essentially, the authors in [186] developed an ILP formulation to reduce power consumption while satisfying the Quality of Service (QoS) constraints on maximum link utilization. The results show that devices with idleEnergy profiles consume, on average, 0.2% less power than devices having an energy-agnostic profile. Although devices with a fully proportional energy profile consume the least amount of power, such devices are not available today. The study further indicates that utilizing devices with an idleEnergy profile to reduce power consumption has a limited impact on QoS constraints but may raise some reliability issues. It is noted that switching-off nodes (although impractical, as nodes always generate and receive traffic) has a higher potential in reducing power consumption than switching off links.

B. Power-Aware Routing

Research on power-aware routing protocols has garnered considerable interest in recent times. In [179], the authors developed three different power-aware routing schemes and investigated the power efficiency of each. The main objective of the study was to accommodate a given set of traffic demands (when network traffic load is low) using a minimum number of line cards. This was the first study to investigate the impact of re-routing traffic in IP and WDM layers, individually, on power consumption.

The first routing scheme proposed in [179] uses virtual (at IP layer) and physical routing paths that are fixed. The second scheme allows flexibility in the virtual routing paths, but the physical paths remain fixed. The third scheme allows changes to be made to both virtual and physical routing paths. Using MILP optimization techniques, the three schemes are compared in terms of power consumption with respect to network traffic variations. The results demonstrate that the first, second, and

third schemes offer a 40%, 63%, and 66% increase in power efficiency, respectively, when the network traffic load is 5 Tbps, which evinces that power savings arise from jointly reconfiguring routes in the IP and physical layers that allows more devices to be switched off. This work is comprehensively discussed again in [187].

In another study published in 2010 [188], the authors developed a three-phase Energy Aware Routing (EAR) heuristic algorithm to reduce power consumption by switching off links in the network. The developed algorithm allows a subset of routers to connect to other nodes using Shortest Path Trees (SPT) and forces the remaining nodes to utilize these SPTs to route traffic instead of creating their own SPTs, thereby increasing link reuse. The proposed algorithm is able to switch off up to 60% of existing links. It is noted that the EAR algorithm is able to evenly distribute traffic on links that remain switched on.

Chiaraviglio *et al.* [178], [189], [190] reduced power consumption by selectively switching off network devices according to traffic variations during the day. In [178], [190], Chiaraviglio *et al.* first defined an analytical model and a cost function by taking into account the power consumption of the nodes and links. They then proposed a heuristic algorithm after showing that optimizing the analytical model runs into the multi-commodity flow problem making it difficult to be solved within a feasible time period. The heuristic algorithm, which is tested on synthetic and realistic networks, identifies and switches off nodes and links when network traffic is low. In the first stage of the algorithm, nodes are sorted and switched off in succession by using four different policies, namely, random, least-link, least-flow, and Opt-Edge (OE). While least-link takes into account the number of links that are attached to each core node, least-flow accounts for the amount of traffic that flows through each core node. On the other hand, OE considers the redundancy of edge nodes. In the second stage, links are sorted and switched off using the random and least-flow sorting criteria. Power consumption values were tabulated by experimenting with different combinations of node and link sorting criteria. The obtained results indicate that 50% of core nodes and 30% of links can be switched off by using a sorting criteria combination of OE for nodes and least-flow for links.

In a recent study, Coiro *et al.* [181] developed an algorithm that reduced power consumption by switching off individual fiber links depending on network traffic variation. This was the first study to jointly analyze power consumption and network resilience. To conserve power, links are sorted and removed using three criteria. First, authors switch off fibers according to the Most Amplifier (MA) criterion. Then, the difference between the number of amplifiers in the removed fiber and the number of amplifiers in fibers constituting the working path is used as the second sorting criterion. To offer resilience against link failures, working paths are protected by backup paths. Lastly, following the third criterion, the fibers are sorted according to the difference between the number of amplifiers in the removed fiber and the number of amplifiers in the fibers that constitute the backup path. Results indicate that the third criterion reduces the most amount of power (35% reduction) in comparison to the first two criteria. Contrarily, the MA criterion reduces the least amount of power. The novel heuristic algo-

gorithm proposed by the same authors in [122] achieves power efficiency between 80% and 100% depending on the traffic load. The developed algorithm, named “Start Single-Hop and Reroute (Start-SH&ReR),” first grooms traffic demands using the single-hop (i.e., DB scheme) wavelength grooming scheme, and then switches off unnecessary links by reconfiguring traffic demands using the MHB grooming scheme.

Power-Aware Routing with Wavelength Assignment (PARWA) was first investigated in [191]. Two heuristics were developed to perform routing and wavelength assignment in separate stages and reduce power consumption in a network with a static traffic matrix. Routing was performed using Most Used Path (MUP) algorithm where lightpaths are forced to share links. Wavelengths were assigned using the Two-Phased First-Fit (TP-FF) algorithm that gathers lightpaths into fewer fibers. Extending this work, in [192], Coiro *et al.* developed a Load Based Cost (LBC) routing algorithm and two wavelength assignment schemes, namely, Least Cost Wavelength (LCW) and Least Additional Power First Fit (LAP-FF). By taking into account link load and power consumption information, the LBC routing algorithm routes traffic via a reduced number of links. LCW and LAP-FF consider the wavelength load within each fiber and try to provision new lightpaths along used fibers without activating new fibers and allowing low-utilized fibers to be switched off.

To validate performance in power consumption, LBC was compared against Shortest Path (ShP), Least Congested Path (LCP), and MUP algorithms, while LCW and LAP-FF were compared against the TP-FF algorithm. Results indicate that, among the routing algorithms, LBC and ShP consume less power at a high network load, while LBC and MUP consume less power at low to moderate network loads. Power efficiency of LBC is found to be between 85% and 95% at varying traffic loads. However, LCP offers the best results in terms of traffic blocking. Among the wavelength assignment schemes, TP-FF consumes more power than LAP-FF and LCW schemes, while LCW consumes 10% less power than LAP-FF.

Contrary to the idea of switching off links (i.e., destructive mechanism), the authors in a recent study [182] developed a novel scheme where additional links in the network were activated or switched-on (i.e., constructive mechanisms) based on the network traffic load [182]. The results obtained in this study show that the proposed switch-on scheme is more power-efficient in comparison to available switch-off schemes. On average, the switch-on scheme provides 15% savings in power consumption, while switch-off schemes only offer 11% savings during the course of a day. On the negative side, the proposed switch-on algorithm employs a higher number of low-speed transponders, which increases the critical factor of cost.

C. Reconfiguration

The reconfiguration cost of power-aware routing was first studied by Zhang *et al.* [193]. They proposed three power-aware routing schemes, namely, Unconstrained Reconfiguration (UR), Virtual-Topology-Constrained Reconfiguration (VTCR), and Full-Constrained Reconfiguration (FCR) to save power by shutting down idle line cards and chassis of routers based on

network traffic variation. At each traffic interval, the network was optimized individually with UR, VTCR, and FCR schemes using MILP. The UR scheme allows lightpaths to be re-routed and devices to be re-configured (i.e., switched on or off) at each traffic interval. With VTCR, the network is first optimized to carry maximum traffic. As traffic decreases, lightpaths are re-routed and excess devices are switched off appropriately. However, new devices would not be powered-on. Lastly, FCR does not allow lightpaths to be re-routed and only excess devices can be switched off. Comparing the three schemes, it is clear that the UR scheme consumes the least power but involves more lightpath re-routing and device reconfiguration. On the other hand, VTCR consumes almost the same amount of power as UR, but involves less re-routing and re-configuration. FCR eliminates re-routing and involves even fewer re-configuration, and yet it consumes 22.36% more power than UR and FCR. Hence, the most favored scheme in both curtailing power consumption and reducing re-routing and reconfiguration appears to be VTCR.

In [194], the authors investigated the possibility of switching off links during periods of low traffic while limiting the number of configurations allowed within a day. Unlike their previous work [178], [181], [190], where network resources were free to switch between different operating states at the end of each hour, in this particular study [194], the number of resource reconfigurations per day was restricted to a maximum of three. Based on random graph theory, traffic variations, and QoS constraints, the developed model produces power savings even with the limited configurations allowed.

In a related study [195], Bonetto *et al.* developed three different algorithms, namely, Least Flow Algorithm (LFA), Genetic Algorithm (GA), and Energy Watermark Algorithm (EWA) by extending past efforts in [190], [196], [197] to jointly reduce power consumption and re-configuration cost. This was also modeled as an MILP formulation in [198]. LFA, which was introduced in [190], sorts links according to utilization and then switches them off in succession. GA, first introduced in [196], optimizes the network at lightpath level by using a meta-heuristic that is based on the principal of natural evolution, a set of parameters, and a fitness value that is defined as a function of power consumption and re-configuration cost. EWA, derived from the work of [199], uses lightpath utilization information to identify and switch off line cards [197]. The three algorithms were tested on three different networks using actual traffic information. The results show that a substantial amount of power can be saved while keeping the reconfigured cost low. GA and EWA produces higher power savings and involves smaller re-configuration costs than LFA.

D. Sleep Mode of Operation

Most power-aware routing schemes were developed for IP-over-WDM networks where core nodes consist of an electronic core router and/or an OXC. However, in 2009, Bathula and Elmirghani [200] reduced power consumption of an OBS network by turning a selected set of core nodes into sleep mode at random intervals. To be able to route traffic and ensure QoS requirements during these intervals, they developed an Energy

Efficient Routing (EER) heuristic. Their results indicate that a 40% increase in power-efficiency can be obtained by allowing nodes to sleep and routing traffic using EER at the cost of a slight increase in request blocking and end-to-end delay, in comparison to a OBS network without sleep mode of operation.

Most recently, Yang *et al.* [108], [201] showed that sleep-mode-enabled burst switches consume less power than electronic core routers. Certain components of these sleep-mode-enabled burst switches can sleep (i.e., they are in a low power-consuming state) while waiting for the next burst. According to Yang *et al.* [108], [201], to efficiently manage the individual elements, the nodes have to be provisioned with a sleep-wake controller. Although inclusion of an additional controller seems to increase power consumption initially by 1.3 times, a drastic reduction of operational power consumption is attained by allowing elements of core nodes to sleep. Kang *et al.* proposed burst assemble [202], [203] and wake transition decision-making [204] algorithms which maximize power savings of sleep-mode-enabled burst switches by allowing components to sleep for longer durations.

In [203], the authors found that a substantial amount of power can be saved in a sleep-enabled OBS network if traffic shared self-similar characteristics. It was also noted that provisioning larger bursts would allow core node elements (e.g., line cards) to remain in a sleep state for longer durations, resulting in reduced power consumption. By increasing the burst assemble time threshold from 0.01 ms to 1 ms, an extra 10% of power can be saved when traffic exhibits high self-similarity. In comparison to EPS networks, OBS consumes 5% to 35% less power [203]. The proposed Dynamic Time-Based Assemble (DT-BA) algorithm in [202] adjusts the burst assemble time or length according to the nature of traffic to maximize sleeping time of core node elements. In another important study [204], Kang *et al.* proposed fixed-time and fixed-length sleep-awake algorithms to reduce power consumption by minimizing unnecessary transitions between different working states. The two algorithms achieve a maximum combined power saving of 30%.

E. Limitations of Power-Aware Networking

Prior to implementing the switch-off/sleep mode approach on a network, a number of uncertainties need to be resolved. As pointed out in [176] and [205], elements that are switched off or are in sleep mode lose their presence, literally “falling off” the network, unless the network state is frequently monitored [206]. This could lead to transitory network instabilities and reduced reliability. To solve this issue, a proxy is introduced to perform the tasks of the switched-off or sleeping devices. The devices could then move from a low power mode to an active mode when they either receive a wake-up signal from the proxy device or after a pre-configured time elapses.

To switch devices between different operating modes, routers need to process and make controlling decisions instantaneously. Else, the switching delay between different operating modes would result in traffic loss and QoS degradation. Although available commercial routers do not possess the ability to control the operating state of individual devices, recent developments in router technologies [207] and emerging 802.3az

standards that demand a faster transition time between modes (a minimum wake-up time of 3 s in a 10 Gbps link) [13] make it more likely that future devices can quickly adapt to traffic variations.

Nevertheless, the inclusion of additional electronic controlling and monitoring circuitry is likely to elevate power consumption of the core routers [108], [201]. Furthermore, when a device switches between different operating modes, it also experiences a transition period. According to [177] and [206], the device consumes a considerable amount of power during this transition period and, thus, overall reduction in power is much less than anticipated.

Many of the proposed schemes increase power efficiency either by switching off the whole device [178], [181], [182] or by switching off only certain elements of the device [108], [201]. In [208], an interesting approach is proposed which could resolve some of the uncertainties involved in applying power-aware networking schemes in the backbone network. The authors exploited two well-known features where decoupling physical elements of a device from its virtual functionalities and resources, allows the latter (virtual) feature to be migrated onto other active elements of the same device. This indicates that a device with multiple modules can de-activate some modules and transfer their work load to residual modules within the same device. The proposed mechanism [208] allows components/elements (e.g., line cards) of a core router to be switched off selectively without incurring service interruptions. Allowing only modules to be switched off negates the likelihood of a node (i.e., a core router) falling off the network, as in the case of [178], thereby ensuring its presence. The ability to carry out line-card transitions with total IP transparency is considered to be the most innovative part of this proposed scheme. This concept has its similarities with the novel idea introduced in [209], in which migration of virtual routers from one physical router to another is performed. The proposed concept, known as Virtual Routers on the Move (VROOM), reduces power consumption of the core network by shutting down some of the routers.

F. Summary of Power-Aware Networking Approaches

To provide an overview of this section, we summarize the relevant findings in Table V. Studies that fall under each subsection are categorized in Table V according to the respective power-related objective and optimization technique used. The outcomes of these studies are also briefly explained.

Traditionally, the backbone network is over-provisioned to cater to peak traffic demand of the future. Hence, devices often remain underutilized during low traffic periods. Our review reveals that power-aware networking shows great potential in reducing power consumption, especially during low traffic periods. Solutions developed using power-aware networking increase resource utilization and reduce device use.

To offer significant reduction in power consumption, network devices should operate in multiple states. Past studies highlight that an effective monitoring mechanism is essential to allow devices to switch between different operating states without causing network instabilities. In developing power-aware net-

working schemes, greater effort needs to be put into minimizing re-configurations, network disruptions, and state transitions. Two solutions that have been introduced to prevent network instabilities, when implementing power-aware networking in the backbone network, are proxy methods and switching off individual modules rather than the device as a whole.

VI. LOAD-ADAPTIVE APPROACHES

Depending on the application, population, and time, traffic between nodes (i.e., connection requests) demand different capacities. Today, in most backbone networks, lightpaths are established using a Single Line Rate (SLR) (i.e., single link rate) that takes a distinct value between 50 Mbps (i.e., Optical Carrier OC-1) and 40 Gbps (OC-768) [22], [210]. To enable more traffic connections to be carried by lightpaths at an envisioned line rate of 100 Gbps, advanced modulation formats and digital processing techniques are currently being developed [210], [211]. As repeatedly mentioned in [22], [212]–[216], backbone networks that rely on SLR show poor resource utilization and consume more power [22], [212], [217]. For example, if the selected line rate is 2.5 Gbps and 9 Gbps of traffic needs to be transported between a pair of nodes, multiple transponders and lightpaths are needed. On the other hand, if the selected line rate is 40 Gbps, transponders are underutilized and bandwidth of the lightpaths is wasted.

A closer look at the rated power consumption values of network devices in [28] reveals that low-capacity devices (or devices running at low operational speeds) consume less power. However, high-capacity devices consume less power per bit of transmitted traffic and, thus, offer a volume discount [5], [45]. To reduce power consumption then, it is preferable to deploy a minimum number of network devices with capacity that matches the actual need. For example, 9 Gbps of traffic transiting between a node pair can be served via a single 10 Gbps transponder, instead of using four 2.5 Gbps transponders.

To increase resource utilization and fully exploit the volume discount offered by high-capacity devices, Mixed Link Rate (MLR) and Adaptive Link Rate (ALR) strategies can be adopted in heterogeneous backbone networks [21], [29], [177], [212]–[216]. These approaches were first used in Ethernet networks [213], [214] and are slowly progressing toward backbone networks [177]. Unlike with SLR, a backbone network employing MLR may serve each traffic connection using a different line rate. However, line rates have to be selected from a discrete set of line rates (e.g., OC-48 (2.5 Gbps), OC-192 (10 Gbps), and OC-768 (40 Gbps)), and thus offer less flexibility. Alternatively, if the backbone network is employing ALR, the line rate can be tuned according to the actual demand.

In Fig. 9, we present a simple example of a backbone network using load-adaptive techniques (MLR or ALR). A core node is represented by a circle whose illustrated size is proportional to the traffic capacity served by that node and the line rates assigned to traffic connections originating from the node. The dotted lines represent links that are lightly loaded and solid lines indicate links that are highly utilized. Basically, the load-adaptive technique allows the capacity of the nodes to be dynamically adjusted according to the demand. In comparison

TABLE V
SUMMARY OF RESEARCH ON POWER-AWARE NETWORKING

Focus	Optimization technique	Study	Power-related objective	Outcome
Power-aware network design	ILP/MILP	[180]	To select the most power-efficient router configuration.	An appropriate router combined with power-aware routing offers power savings.
		[185]	To investigate the power consumption of four different energy profiles.	Cubic energy profile consumes the least amount of power. On-off profile consumes the most.
		[186]	To investigate the power consumption of three different energy profiles.	Devices with idle energy profile consume less power, are commercially available, and have less impact on link utilization.
Power-aware routing	MILP	[179, 187]	To reduce the number of line cards in use.	Proposed three algorithms. Demonstrate that by re-configuring routes on the IP and physical layers more power can be saved.
	Heuristics	[188]		The proposed algorithm can switch off 60% links.
		[122]	To switch off as many fiber links as possible.	Achieves power efficiency between 80% and 100%.
	MILP and Heuristics	[181]		Reduces power consumption by 35% while guaranteeing resilience against link failures.
	MILP and Heuristics	[178, 189, 190]	To selectively switch off nodes and links.	The proposed algorithm can switch off 50% core nodes and 30% links.
	Heuristics	[191]		The combination of MUP routing algorithm and TP-FF wavelength assignment scheme offers considerable power savings.
	MILP	[182]	To route and assign wavelengths to minimize device use.	The proposed 'switch-on' scheme is more power-efficient in comparison to available 'switch-off' schemes.
	MILP and Heuristics	[192]		The proposed LBC routing algorithm combined with LCW wavelength assignment scheme offers between 85% and 95% increase in power efficiency.
	Heuristics	[194]	To reduce the use of network devices and minimize reconfiguration cost.	The developed model, based on random graph theory, produces power savings even with few reconfigurations allowed.
	MILP	[193]		The VTLR routing scheme reduces power consumption and minimizes re-routings.
MILP and Heuristics	[195, 198]		GA and EWA produce higher power savings and incur lower re-configuration cost than LFA.	
Power-aware networking solutions for OBS networks	Heuristics	[108, 201–203]	To use sleep-mode of operation to reduce power consumption of burst switches.	Proposed burst assemble and wake decision-making algorithms and novel router architectures offer power savings in OBS networks.
Limitations of power-aware networking	N/A	[176, 205, 206]		Suggest that switched-off devices will lose their presence in the network. A "proxy" is introduced to perform the tasks of the switched-off or sleeping devices.
		[13, 207]	To propose solutions to the identified drawbacks of power-aware networking.	Emerging technologies and advancements can enable power-aware networking.
		[208, 209]		Only allows modules of a device to be switched off, while the device remains switched on and tasks are performed by residual modules.

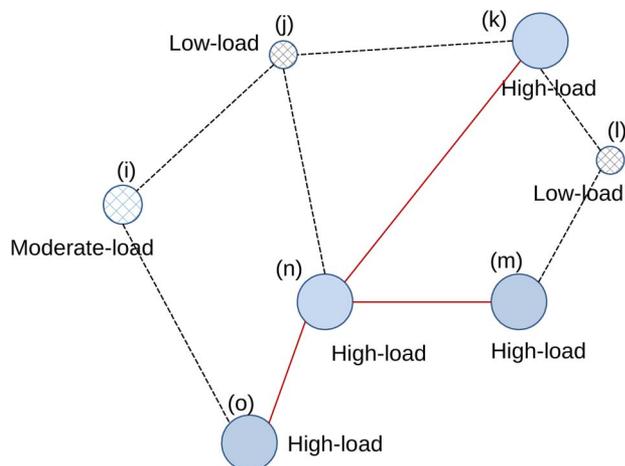


Fig. 9. A backbone network using load-adaptive techniques: The size of each circle is proportional to its capacity and line rate; the dotted and solid lines indicate light and heavy loaded links, respectively.

to Fig. 8, instead of the low-load nodes (nodes j and l) being turned off, they will continue to work at a lower speed or capacity maintaining their presence in the network.

A. Mixed Line Rate (MLR)

At present, the backbone network can support a maximum line rate of 40 Gbps [22]. Following technological advancements, 100 Gbps and 400 Gbps line rates are soon to be a reality in the near future [22]. Considering the heterogeneous nature of traffic demands, multiple line rates should co-exist in the same backbone network. To this end, several studies have investigated the possibility of adopting MLR in backbone networks [21], [22], [29], [45]. In [21], MLR was shown to minimize network cost compared to a network using SLR. However, as demonstrated in many studies [21], [22], [29], [218], co-propagating lightpaths at different line rates induces non-linear effects (e.g., Cross Phase Modulation (XPM), etc.) on each other which impair signal quality. Consequently, high-capacity lightpaths assigned a faster line rate need to be frequently regenerated after every few hundred kilometers. To increase the transmission reach of lightpaths in MLR-based backbone networks, dispersion management techniques, mixed-modulation formats, and channel input power management schemes have been proposed [21], [218], [219].

In an SLR-based backbone network, every transponder works at the same line rate of 10 Gbps, 40 Gbps, or 100 Gbps. As a result, when network traffic is high, a 10 Gbps SLR employs a large number of transponders, consuming more power. On the other hand, if network traffic is low, a significant amount of power is consumed unnecessarily by power-hungry transponders of a 100 Gbps SLR. However, if MLR is used in place of SLR, transponders of both low and high line rates can be employed according to the actual traffic demand, reducing power consumption and increasing transponder utilization. However, signal degradation is critical in MLR-based backbone networks and, thus, high-capacity lightpaths may often need the service of a regenerator. Consequently, as shown in [22], when network traffic is high or when core nodes in the network are

located far apart, a 100 Gbps SLR consumes less power than MLR [22]. While an SLR network designed to minimize power consumption also reduces network cost, an energy-minimized MLR network would not necessarily minimize network cost [22].

Under dynamic traffic demands, line rates have to be frequently adjusted in an MLR network. As a result, lightpaths would have to be removed and reinstated using different line rates on a frequent basis. However, to reduce both re-configuration cost and network disruptions, established lightpaths should remain intact when network traffic upgrades from one state to another. In [45], the authors investigated how this can be achieved in an MLR network while reducing cost and power consumption. The study uses an MILP-based optimization scheme to find the optimum line rates that can serve different traffic connection requests. The maximum number of disruptions allowed between the current and ensuing state is assigned a value between 5 and 40. Power consumed is recorded against increasing network traffic. By allowing more disruptions to occur, the study shows that MLR is able to adjust line rates more efficiently, thereby reducing power consumption. As such, by allowing 5 disruptions at a network traffic capacity of 250 Gbps and 40 disruptions when traffic capacity rises to 375 Gbps, power consumption can be reduced by 4% and 6%, respectively, in comparison to zero disruptions.

B. Adaptive Line Rate (ALR)

The ALR technique was first introduced by Nordman *et al.* [215] as a method of reducing power consumption of Ethernet network interface cards (NICs). The authors in [213] and [214] then developed a number of practical algorithms to test and validate power savings offered by ALR. By changing the Ethernet line rate according to the link utilization factor, ALR allows network devices to work at a lower clock speed, when network traffic is low, and consume much less power. Although most research on ALR is still at an experimental stage, Zhang *et al.* [220] succeeded in developing an ALR-enabled NIC. Thus, it is fair to believe that ALR-enabled backbone network devices would become commercially available in the near future.

ALR is commonly realized using the Optical Orthogonal Frequency Division Multiplexing (O-OFDM) technique. ALR can be applied to backbone networks using O-OFDM-based SEON [130], and existing power-related results available for SEON networks are impressive. The experiments in [130] and [221] demonstrate that a tunable O-OFDM-based backbone network significantly reduces the need for transponders and wavelengths. Due to such power-saving benefits, SEON networks are frequently compared against SLR and MLR techniques. In an example comparison of SLR, MLR, and ALR techniques shown in Fig. 10, 50 Gbps of traffic travels from node i to node j . If a single line rate of 10 Gbps is used, then a total of 5 lightpaths would be established. If MLR is used, then 2 lightpaths with different line rates can serve the traffic demand. On the other hand, with ALR, a single lightpath that has a variable capacity between 0 and 100 would accommodate the 50 Gbps traffic demand between the two nodes.

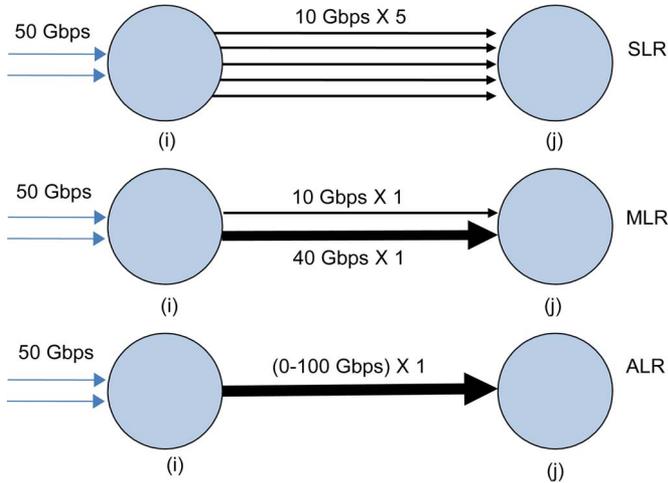


Fig. 10. Rates assigned by SLR, MLR, and ALR techniques when transporting 50 Gbps of traffic from node i to j .

Nedevschi *et al.* [177] compared the amount of power consumed by networks utilizing the sleep mode of operation (discussed in Section V) and those using ALR. Their results indicate that enabling sleep mode offers higher power savings under bursty traffic environments as power consumption can be reduced during idle times between bursts. However, when the traffic load is low, the ALR technique offers more power savings. Nedevschi *et al.* conclude that a combination of the two techniques could provide the best configuration in the context of power efficiency. Analyzing the results obtained in [222] and [223], in which the authors developed a hybrid network by incorporating the abilities of sleep mode of operation and ALR, we are likely to agree with Nedevschi *et al.*'s conclusion. In a similar vein, the authors of [224] successfully formulated a hybrid network using ALR (referred to as rate-adaptive scaling (RS) in their study) and sleep mode of operation (referred to as sleep-state-exploitation (SSE) in their study). In developing this hybrid network, the authors also considered time-related parameters incurred by a data packet that travels in the network. Although the hybrid network proposed in [224] was tested for resource utilization, its power consumption has yet to be examined.

In [216], the authors compared the power efficiency of backbone networks utilizing power-aware-routing (which allows more links to remain asleep) and rate-adaptive techniques (which is similar to ALR). The authors point out that if rate-adaptable devices consume a substantial amount of power at the start-up (i.e., instantaneous power at activation), then power-aware routing is a more power-efficient strategy. However, if devices consume relatively low power at the start, then higher power savings are offered by rate-adaptive techniques.

In [212], Klekamp *et al.* compared MLR and reach/rate-adaptive (i.e., ALR) techniques. Using the actual German50 network, projected line rates for 2010 and 2020, and power consumption values of core network devices (both IP and WDM), the authors conducted a heuristic-based experiment. Two different routing schemes (hierarchical and flat) were also used. The obtained results indicate that both MLR and ALR consume an equal amount of power at the IP layer. On the

contrary, MLR consumes less power at the WDM layer than the reach/rate-adaptive technique. In separate studies [217], [225], Klekamp *et al.* performed a similar experiment on the USA66 network. The results mirror that of [212] and demonstrate that MLR consumes approximately 15% less power in comparison to the reach/rate adaptive technique in the dense-WDM (DWDM) layer of the network. Furthermore, it is noted that both capital expenditure and power consumption are more dominantly controlled by network devices in the IP layer. While MLR is more effective in reducing power consumption of the DWDM layer, the reach/rate adaptive method greatly reduces the number of used transponders and fibers in the network. However, the cost associated with reach/rate adaptive networks is higher in comparison to MLR networks, as the former employs expensive rate-adaptive transponders.

Vizcaino *et al.* also extensively studied the differences in power consumption among O-OFDM, MLR, and SLR approaches. Considering a static traffic environment, Vizcaino *et al.* [226] demonstrated that MLR and O-OFDM techniques both consume a similar amount of power and outperform SLR. Despite these similarities, O-OFDM elastic networks offer power consumption improvements over MLR networks that utilize 100 Gbps line rate. Taking a step further, Vizcaino *et al.* in [227] developed energy-aware heuristic algorithms to efficiently allocate resources under static and dynamic traffic environments for O-OFDM elastic networks and WDM networks employing SLR and MLR techniques. The proposed heuristics when tested on a large-sized network (e.g., GÉANT2 network) under a static traffic environment show that O-OFDM networks consume 37.5% and 50% less power in comparison to MLR and SLR, respectively. Similarly, when the three techniques were tested under a dynamic traffic environment, the O-OFDM network consumed approximately 50% and 100% less power in comparison to MLR and SLR. A similar pattern was also observed for the service blocking ratio, with the O-OFDM network sustaining the least amount of blocking and the SLR network incurring a higher blocking ratio.

Though SLR, MLR, and ALR have been comparatively analyzed in terms of power efficiency and transponder cost in many previous studies, their effects on path protection or network resilience were only studied in [228]. The most widely adopted approach in assuring network resilience is reserving resources on two non-overlapping routes for working and protection paths by considering peak traffic demands. Consequently, resilient networks consume more power than unprotected networks. In [228], Lopez *et al.* attempted to identify the most power-efficient solution between resilient networks adopting SLR, MLR, and ALR approaches, where ALR is achieved by implementing O-OFDM-based SEON. The main objective of the study was to measure the increase in power efficiency of SLR, MLR, and ALR-based networks by dynamically adjusting transponder capacities (traffic awareness) in the protection paths according to hourly variability of the network traffic. Evaluating the results in [228], we observe that SEON networks can save up to 27% of power when network traffic is high. Within the range of tested traffic loads, ALR outperforms SLR and MLR by consuming the least amount of power. Between MLR and SLR networks, MLR consumes less power at low

TABLE VI
BROAD COMPARISON OF SLR, MLR, AND ALR APPROACHES

Focus	SLR	MLR	ALR/Elastic/SEON/Rate adaptive techniques
Function	Every lightpath is assigned the same line rate.	Each lightpath has the ability to select its speed from a set of discrete values.	Each lightpath has the ability to select its speed from a set of continuous values.
Power-related comparison vs SLR		MLR is more power-efficient at low network traffic volumes and when traffic volume is not an integer multiple of the selected SLR. [22,29,226,228]	ALR is more power efficient than SLR at all volumes of network traffic. [227, 228]
Power-related comparison vs MLR	When network traffic volume is high and SLR is 100 Gbps, SLR consumes less power than MLR as a result of reduced regeneration. [22, 29, 227, 228]		The IP-layer of the backbone network consumes less power [212, 217, 225] with ALR than with MLR, ALR is more power efficient when experimented with static or dynamic network traffic models. [227, 228]
Power-related comparison vs ALR	SLR consumes more power than ALR at all traffic volumes. [22, 29, 227, 228]	The WDM-layer of the backbone network consumes less power with MLR. [212, 217, 225]	
Other drawbacks	Low transponder and lightpath utilization. High power consumption, especially when network traffic is high.	Excessive use of regenerators by high-capacity lightpaths increases power consumption.	Requires expensive, power-hungry bandwidth-adaptive long-reach transponders and add/drop multiplexers.

traffic loads. However, a 100 Gbps SLR consumes much less power than MLR at higher traffic loads which is consistent with the results of [22].

C. Summary of Load-Adaptive Approaches

Studies that examined load-adaptive approaches are summarized in Table VI and categorized according to the specific technique examined (i.e., SLR, MLR, and/or ALR). A comparison of network power consumption using these three techniques is presented, with the outcomes of the comparison briefly explained. The key drawbacks of SLR, MLR, and ALR are also highlighted.

In summary, to reduce bandwidth waste and exploit volume discount on power consumption of high-capacity transponders, traffic needs to be served using appropriate line rates by employing either MLR or ALR. The key conclusion that we draw from the reviewed literature is that MLR and ALR techniques consume less power than SLR. However, power consumption of MLR-based networks is affected by regenerator power consumption at high network traffic volumes. Hence, it is vital to develop new algorithms to assign an appropriate line rate to each lightpath depending on the actual traffic requirement. Although findings reveal, overall, that ALR consumes less power, it is important to recognize that these results have been obtained using approximated power consumption values

for bandwidth-adaptive long-reach transponders and add/drop multiplexers which are in the early stage of development.

VII. ADOPTING THESE APPROACHES IN REAL NETWORKS

In Sections III–VI, we discussed the solutions developed by academic scholars utilizing different approaches. In this section, we survey how these proposed solutions are currently adopted by carriers/operators, vendors, and research bodies to increase power efficiency of backbone networks. We begin our survey by describing important research projects, that are funded by network operators and/or device manufacturers, and their findings. In no particular order, we demonstrate the critical role played by our four approaches in these projects and provide examples of their application in devices and technologies.

A. Approaches Adopted in Industrial Research Projects

To explore solutions to the increasing power consumption of backbone networks, UC Santa Barbara’s Institute for Energy Efficiency convened a two-day technology roundtable in February 2013, bringing together 27 industry leaders representing vendors (e.g., Cienna, Juniper, Cisco, Infinera), service providers (e.g., Verizon, Sprint, Deutsche Telekom), research institutes (e.g., GreenTouch by Alcatel Lucent, Infinetics Research), government laboratories (e.g., Energy

Sciences Network), and academics [229]. At the end of the two-day roundtable discussions, the participants identified several key advancements that could be exploited in reducing backbone network power consumption. These advancements include integrating optical and electronic technologies at device and component levels (as discussed under network redesign), using optical switching and optical bypass strategies (as discussed under both network redesign and traffic engineering), and making network systems' power consumption proportional to traffic load by adjusting routing paths and increasing device utilization (as discussed under network re-design), among others. The participants argue that load-adaptive approaches, such as gridless architecture (i.e., SEONs) and the use of high-speed line rates, cannot produce high power savings, even in another ten years, due to the non-linear Shannon limit of fibers.

In 2010, a team of researchers established a partnership with a group of device manufacturers to form the ECONet project [230]. The primary objective of ECONet is to develop novel solutions to reduce power consumption of the Internet by exploiting power-aware networking and load-adaptive operation. The developed solutions and technologies are evaluated using large-scale test-beds at the TELIT test plant and two additional, small-scale test-beds at GRNET and NASK sites with "real-life" testing methodologies and instrumentation, that are usually adopted for evaluating commercial network devices, before putting them into actual production.

The GreenTouch consortium, launched in 2010, provides a platform for innovative researchers, engineers, and technology experts from around the world to develop solutions to increase power efficiency of the Internet, by a factor of 1000, by 2015 [231]. GreenTouch targets the following areas in developing these solutions, which we have previously discussed under network re-design, power-aware networking, and load-adaptive operation:

- reducing power consumption of network devices and components;
- adopting MLR;
- using sleep and low-power-consuming operating modes;
- optimizing the physical topology considering traffic fluctuations.

The GreenTouch white paper issued after three years of project commencement reported that developments in the four areas would improve power efficiency in the year 2020 by 2.7%, 1.2%, 1.8%, and 1.1%, respectively, compared to 2010.

Researchers who are currently involved in Alcatel-Lucent's "green research program," spearheaded by Bell Labs, expect to increase power efficiency of backbone networks by integrating electronic and optical technologies within a single device, optimizing the network architecture, and achieving proportionality between power consumption and minimizing capacity waste [232]. In a separate partnership with the University of Melbourne, Bell Labs explores how traffic grooming affects next-generation backbone networks and investigates how increased traffic volumes could be modulated into high-line rates without increasing power consumption.

In 2008, the International Telecommunication Union (ITU) made recommendations to minimize power consumption of Next Generation Networks (NGNs) [233]. The use of network devices with multiple power modes (e.g., full power, low power, stand-by, and hibernation) was shown to have a great impact on reducing power consumption of both optical backbone and access networks.

B. Approaches Adopted by Vendors and Carriers

To conserve energy, vendors incorporate state-of-the-art optical and electronic technologies to produce high-capacity, low-power-consuming devices.

Cisco plans to tackle increasing power consumption of the Internet with a range of solutions using the novel concepts discussed under the network redesign approach. Each generation of Cisco products consumes less electricity per bit of transmitted data. For example, Cisco-CRS-3 consumes 2.8 nW/bit in comparison to 8 nW/bit consumed by the Cisco CRS-1 core router [25], [26]. Furthermore, each generation of Cisco core routers and products support increased throughput, work at higher speeds, and contain a large number of ports. Thus, more traffic can be transmitted via a smaller number of lightpaths and devices. These CRS routers help AT&T, a Tier 1 carrier in the U.S., to meet growing traffic demands while, at the same time, reducing electricity consumption [234]. In recognition of its outstanding contributions to conserving energy and reducing environmental impact, Cisco was awarded the Supplier Sustainability Award by AT&T in 2012 [234].

Juniper is another top-tier manufacturer that continues to deliver devices that provide increased throughput with high power efficiency, by integrating advanced electronics with optical technology. For example, the Juniper Networks T1600 series core router has a maximum throughput of 1.6 Tbps, supports 10/40/100 Gbps line rates, and performs traffic aggregation while consuming 40% less power than other competitive platforms. At present, Juniper products are utilized by Verizon, another Tier 1 carrier in the U.S., and Japan Inc. (IIJ) to offer higher capacity and reduced power per gigabit of served traffic [235], [236].

Infinera uses the latest technology to produce devices that can consume less electricity and comply with standards such as EU, WEEE, RoHS, and other global environmental regulations. To minimize O-E/E-O conversions and, thereby, reduce power consumption, Infinera integrates hundreds of optical functions into small-form photonic integrated circuits [237]. Lab demonstrations show that Infinera's 400 Gbps Photonic Integrated Circuits (PICs) consume approximately 50% and 80% less power compared to today's 100 Gbps and 40 Gbps PICs, respectively [237].

While most vendors try to minimize power consumption by integrating optical and electronic technologies in their devices, a few others explore traffic engineering, power-aware networking, and load-adaptive operation to search for alternative solutions. Some examples of such efforts are explained below.

Fujitsu, a top-tier network device manufacturer, reported in 2010 that their market-leading FLASHWAVE 4500/9500

Multi-service Provisioning Platform (MSPP)/Packet Optical Networking Platform (Packet ONP) meets the standards defined by the Telecommunications Energy Efficiency Ratio (TEER) metric [238]. Furthermore, in 2012, Fujitsu developed two technologies: “flexible optical node” and “spectrum defragmentation technology” which allow the backbone network architecture to be dynamically altered (using power-aware networking), as needed, to increase resource utilization and minimize power consumption by eliminating unnecessary network devices [239].

MRV is another network device manufacturer who ensures that their products adhere to standards defined by the TEER metric [240]. Using traffic engineering and power-aware networking approaches, the MRV LambdaDriver aggregates and transmits outgoing traffic via a reduced number of links and de-activates the under-utilized links to reduce electricity consumption.

Huawei has begun to utilize power-aware networking and load-adaptive operation to develop power-efficient network solutions. In a more recent report, Huawei suggests that, to maximize power savings, a device has to operate in normal, idle, or battery modes as decided by the traffic flow. In collaboration with telecommunication operators from Spain, the United Kingdom, and Germany, Huawei performed a series of successful field trials for the realization of hybrid transport mechanisms, using 10 Gbps, 40 Gbps, and 100 Gbps MLR [241].

Cienna uses their expertise in multi-layer switching, bandwidth sharing, and high line-rate transmission to design and develop next-generation, power-efficient backbone networks. Using experimental results, in 2013, Steve Alexander, the Vice President and Chief Technological Officer of Cienna, demonstrated that MHB grooming is more effective in reducing power consumption than both NB and DB grooming schemes when traffic is transmitted using 10/40/100 Gbps SLR [242]. Cienna’s 10/40/100 Gbps coherent optical interfaces help COMCAST, one of America’s largest Internet service providers, to increase power efficiency by reducing the number of network devices and optical regenerators used [243].

C. Summary of Approaches Adopted in Real Networks

In this section, we presented examples of real-life, industry application of the four main approaches discussed in this survey. Although the academic literature has not provided evidence of the utilization of the four approaches by carriers/operators in real networks, we were able to scour online resources to find evidence of vendors who incorporate one or more approaches in manufacturing their devices and carriers/operators who utilize such devices.

Vendors, operators, and researchers agree that the integration of optical and electronic technologies, which is a concept examined under the network redesign approach, is the most effective method to date in reducing power consumption. As a result, next-generation network devices are produced by heavily integrating electronic and optical components. In addition, traffic engineering is often preferred as a method of increasing device utilization and promoting optical bypass. As discussed

in the section pertaining to this approach in our survey, next-generation core routers are capable of aggregating a large amount of traffic into few lightpaths. Finally, using field trials and experiments, vendors adopt MLR in backbone networks to increase resource utilization and reduce power consumption. To maximize power savings, next-generation devices are designed to operate in multiple power modes.

VIII. CONCLUSION

Reducing power consumption of the backbone network is critical to the growth of the Internet. As of recent, we have observed a surge in the number of studies on reducing power consumption of the backbone network. However, in order to develop new energy-efficient architectures and mechanisms, it is first essential to develop a sound understanding of existing frameworks. This paper aimed to provide a comprehensive review of the literature by examining four main approaches to reducing power consumption in backbone networks.

We categorized the main techniques used in the literature to reduce power consumption of backbone networks into four main approaches, namely, network redesign, traffic engineering, power-aware networking, and load-adaptive operation. We discussed the results of individual studies and compared the potential of their solutions to offer power savings against their inherent limitations. Our survey shows that integrating individual concepts across approaches offers promising results for the generation of power-efficient backbone networks. We finally explained how particular solutions within each approach are currently adopted in real-life projects and devices by device manufacturers and network carriers.

Our survey first showed that, with future advancements in all-optical technologies, OCS, OBS, and OPS networks can be used individually or jointly to increase power efficiency in all-optical backbone networks. It also revealed that hybrid technologies and topological optimization are advantageous in reducing power consumption of next-generation backbone networks. Furthermore, we found that combining waveband grooming and wavelength grooming shows great potential in reducing power consumption at the IP layer as well as the WDM layer of the backbone network. These grooming schemes also support growing traffic demands, without the need to install more equipment and fibers, by increasing bandwidth utilization. In addition, by selectively switching devices between different operating states, we observed that power-aware networking reduces power consumption during periods of low network traffic. Finally, much needed proportionality in the relationship between power consumption and network traffic can be achieved by deploying rate-adaptive networks and transponders with MLR or ALR.

Our survey highlights the current standing of research in the four approaches, the directions in which each area is headed, and which technologies and futuristic concepts might prevail in the future.

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