A Power Consumption Sensitivity Analysis of Circuit-Switched Versus Packet-Switched Backbone Networks☆

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Abstract

While telecommunication networks have historically been dominated by a circuit-switched paradigm, the last decades have seen a clear trend towards packet-switched networks. In this paper we evaluate how both paradigms (which have also been referred to as optical bypass and non-bypass, respectively) perform in optical backbone networks from a power consumption point of view, and whether the general agreement of circuit switching being more power-efficient holds. We consider artificially generated topologies of various sizes, mesh degrees and—not yet previously explored in this context—transport linerates. We cross-validate our findings with a number of realistic topologies.

Our results show that circuit switching is preferable when the average node-to-node demands are higher than half the transport linerates. However, packet switching can become preferable when the traffic demands are lower than half the transport linerate. We find that an increase in the network node count does not consistently increase the energy savings of circuit switching over packet switching, but is heavily influenced by the mesh degree and (to a minor extent) by the average link length. Our results are consistent for uniform traffic demands and realistic traffic demands.

A key take-away message for other research on power saving solutions in backbone networks is that the ratio between the average demand and the demand bitrate has considerable effect on the overall efficiency, and should be taken into account.

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1. Introduction

Electricity consumption in telecommunication networks is an important issue — The worldwide electricity consumption of telecommunication networks (which includes operator networks, office network equipment, and customer premises network access equipment) has been estimated to be 330 TWh in 2012, accounting for 1.7% of the total worldwide electricity consumption in the same year [2]. While it can be argued that this number in itself is relatively small, it is non-negligible and increasing at a rate of 10% per year. Moreover, its relative contribution to the total worldwide electricity consumption is increasing as well (from 1.3% in 2007 to 1.7% in 2012). With the foreseen traffic growth in communication networks [3], this trend is not likely to halt soon. As such, the interest to improve the energy-efficiency of telecommunication networks is a hot research topic, and is of importance for economic (reducing the energy cost), technical (reducing the associated heat dissipation) and environmental (reducing the carbon footprint) reasons.

The electricity consumption in backbone networks is expected to rise considerably — The major part of the power consumption in the telecommunication operator networks is currently attributed to the wired aggregation & access networks and mobile radio networks. The backbone networks, in contrast, are estimated to account (in 2012) for only about 8% of the total operator network consumption (which includes the wired aggregation & access, mobile radio and backbone networks) [4]. However, the energy consumption in wired access networks is proportional to the number of connected subscribers, while the consumption in the backbone network is proportional to the traffic volume [4]. With the expected increase of traffic volume, high growth rates in the backbone's energy consumption are expected (potentially even overtaking the access networks' consumption [5]). For this reason, it is important to react timely to the energy issue of backbone networks.

Circuit switching has been identified, so far, as more energy-efficient than packet switching — In response, there is a growing body of research literature on reducing the energy consumption in backbone networks. Among the approaches proposed are the introduction of sleep modes, energy-aware routing protocols, energy-aware network design, optical bypassing of power-hungry Internet Protocol (IP) routers, and dynamic rate adaptation. A thorough survey is available in [6]. However, in the last decades, the telecommunication industry has seen a shift from circuit-switched networks to packet-switched networks. There has been some earlier research into the power consumption of circuit switching versus packet switching (briefly discussed in Section 2). The general agreement seems to be that circuit switching has a lower power consumption than packet switching.

However, we think that the picture is not so clear-cut — Most works point out the benefits of circuit switching over packet switching in terms of power consumption. These benefits depend however on the investigated network scenario. For example, looking at Fig. 4 of [7], the x-axis depicting "Average of random traffic demand" starts from 20 Gbps/node pair, while the capacity of a single Wavelength Division Multiplexing (WDM) channel is set to 40 Gbps. The missing range 0–20 Gbps/node is expected to show that the packet-switched networks can be less power consuming than the circuit-switched networks, as preliminarily indicated in our earlier work [8] and by Bianco et al. in [9].

Contributions of this paper — In this paper we extensively compare circuit and packet-switched IP-over-WDM networks with respect to their power efficiency. We consider circuit switching in the context of optical circuits, in contrast to the more traditional opto-electronic circuit switching such as in SONET/SDH and OTN. We focus on the comparison of circuit switching and packet switching in terms of inverse power efficiency (W/Gbps), leaving the more complex hybrid solutions aside. The inverse power efficiency is the power (in Watts) required to transport a uniform demand of 1 Gbps (lower values indicate more efficient operation). Note that circuit switching and packet switching in this context has also been referred to as optical bypass (or transparent switching) and non-bypass (or opaque switching) respectively. The four key contributions of our paper with respect to the existing body of research are as follows.

- In addition to considering the mesh degree and network size (in terms of the number of nodes and average physical link length), we evaluate the influence of the channel linerate on the power efficiency of circuit switching versus packet switching, a parameter which to our knowledge has previously not been assessed.

- We particularly look at network scenarios where packet switching is preferable from a power consumption point of view. This aspect has to the best of our knowledge not been addressed in the previous literature (cf. [7], as mentioned above).

- We study the (inverse) power efficiency of both switching paradigms under increasing traffic demand. We show that the power efficiency of packet switching in sparsely-connected networks is almost independent of the traffic demand, whereas for circuit switching the power efficiency improves with increasing traffic.

- We find that a higher node count does not necessarily make circuit switching more preferable. In highly meshed networks the node count does not influence the relative savings of circuit switching over packet switching at all. Our results show that the mesh degree, the demand/linerate ratio and the physical link length are critical parameters.

All in all, our results provide a better insight into the trade-off of the power efficiency of circuit switching versus packet switching.

Organization of this paper — We briefly discuss related work in Section 2. After outlining the network architecture (Section 3) we provide details on our methodology for calculating the network power consumption (Section 4). In Section 5 we introduce the different set of topologies, traffic matrices and transport linerates that we will consider. Using the result from our dimensioning tool, we show in Section 6 that (a) indeed packet switching can be the preferable option with respect to power consumption below certain traffic demand bitrates, (b) that this crossover point is essentially determined by the ratio of the traffic demand over the linerate, and (c) to a minor extent also by the mesh degree.

This paper is an extended version of our earlier work [1]. It includes a more elaborate introduction (Section 1) and related work (Section 2), a more formal description of our dimensioning algorithm (Section 4.2), a validation of our results with demands based on actual traffic measurements from the Abilene topology (Section 6.5), an assessment of plausible real-life demand/linerate ratios (Section 6.2), a short cross-validation with the results from Shen and Tucker (Section 6.4), and a sensitivity analysis to a more detailed IP power consumption model (Section 6.6). Moreover, we have now considered 100G linerate technology and dropped the 2.5G linerates (see Table 1), and considered different regeneration reaches for the different linerates (see Table 1).

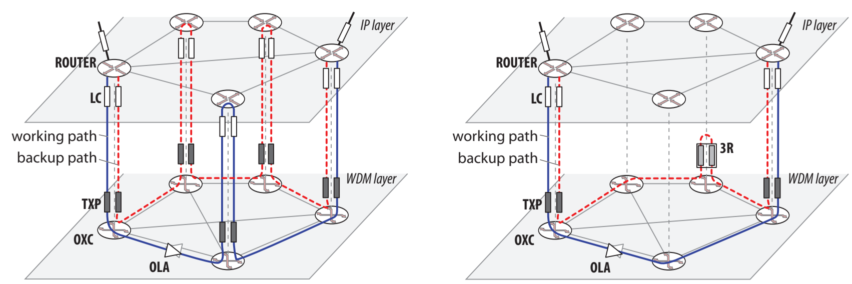
2. Related work

A decent set of recent papers has focused on the energy-efficiency in optical backbone networks. Some of them have also investigated the differences between the circuit and packet switching paradigms, identified respectively as bypass and non-bypass architectures, in the context of optical networks. In this section, we only focus on the works tackling the case of either establishing a bypass only between a source and target of a traffic demand (circuit switching), or establishing no bypass at all (packet switching).

In [7] Shen and Tucker exploited the concept of lightpath-bypass to perform a power-minimized optical network design, based on Integer Linear Programming (ILP) formulations and heuristics. They distinguish non-bypass (packet switching), direct bypass (circuit switching), as well as an intermediate hybrid solution called multi-hop bypass. A similar problem was addressed in our previous work [8], where simulations and an analytical model were used for the power consumption evaluation of bypass and non-bypass scenarios. In the line with these studies, an analytical model based on expectation values has been also developed by Aleksić and Van Heddeghem in [10], where different variations of the optical bypass strategy are evaluated under different mesh degree scenarios, i.e., from a ring up to full-mesh topologies. Capital Expenditure (CapEx) minimized and power minimized networks designed with an ILP and a genetic algorithm have been considered by Bianco et al. [9]. A bypass and non-bypass architecture (differing by traffic grooming, placement of transponders and (non-)existence of Optical Cross-Connects (OXCs)) in IP-over-WDM are distinguished. Finally, in [11], Aleksić performed a power consumption evaluation of switching and routing elements to compare the circuit and packet switching paradigms, but the analysis is limited to the node level.

Most of these works do not consider the effect of the adoption of different transport linerates on the energy-efficiency of the packet and circuit switching paradigms. In this paper, we extend the above earlier works by analyzing the joint impact of both the mesh degree and different linerates on the energy-efficiency of both switching paradigms. We assess under which conditions each switching paradigm represents the most energy-efficient solution.

3. Network architecture: circuit switching vs. packet switching



(a) Packet switching (b) Circuit switching

Figure 1: The packet-switched and circuit-switched network architectures considered in this paper, showing both the bidirectional working path (solid lines) and backup path (dashed lines) under a 1+1 protection scheme. (LC = Line Card, TXP = Transponder, OXC = Optical Cross-Connect, OLA = Optical Line Amplifier, 3R = 3R regenerator)

The general architecture of the network is shown in Fig. 1 on an example of a 5-node topology (IP/Multiprotocol Label Switching (MPLS) and WDM layers). In the *IP/MPLS layer*, a core router is equipped with line cards, providing one or more ports with short reach interfaces. We assume (differently from [11]) that IP routers have to be present in the backbone network under the circuit switching paradigm, since they exchange the IP traffic with other networks (metro, access) attached to them [12]. The buffers located in the router's line cards are used only at the end nodes of the optical circuits. The granularity of the linerates of the interfaces differs: the access or client-side traffic connects to the router using 1-Gbps interfaces, and the core network side interfaces are either 10-Gbps, 40-Gbps or 100-Gbps interfaces (which we refer to as 10G, 40G and 100G). Note that, depending on the traffic demand bitrate, one or more interfaces can be required per demand.

In the *WDM layer*, long reach transponders with the same capacity as the IP/MPLS layer line cards provide a WDM optical signal, which is switched using an OXC towards the correct physical link. A mux/demux (included in the OXC) aggregates up to 40 channels on a fiber. For each physical link, we assume an unlimited number of fibers to be available. A booster and pre-amplifier (included in the OXC) amplify all channels in a fiber pair respectively upon leaving and entering a node. An Optical Line Amplifier (OLA) is placed every 80 km, and amplifies all channels in a fiber pair. For lightpaths longer than the regenerator span, which depends mainly on the tranponder reach (see Table 1), the signal is switched by the OXC to pass through a 3R regenerator.

The way that traffic demands traverse the network is different in packet switching and circuit switching. Under the *packet switching paradigm*, all the traffic in a node—i.e., not only the originating and terminating, but also the transit traffic—is processed at the router in the IP/MPLS layer, as shown by the solid line in Fig. 1a. This provides the opportunity to groom traffic, that is bundling traffic belonging to demands from different sources that are destined to the same outgoing link. As a result, the transport channels (wavelengths) are filled more efficiently.

Under the *circuit switching paradigm*, traffic demands traverse the network over a single IP hop, since dedicated optical circuits are set up from the source IP/MPLS node to the target node, as shown by the solid line in Fig. 1b. This allows the transit traffic to remain in the optical domain and thus bypass the IP router. For this reason such architectures are often referred to as *optical-bypass* architectures. However, depending on the ratio between the traffic demand bitrates and the channel capacity (i.e., linerate), lightpaths might not be optimally used. For a given set of demands, this might result in a higher number of channels required compared to packet switching.

In both switching cases, we assume a 1+1 protection scheme at the IP layer. Under this scheme, a backup path (dashed line in Fig. 1) is simultaneously routed over a link-disjoint physical path with respect to the primary one, so that if the working path fails, the traffic can be instantaneously switched over to the backup path.

4. Network dimensioning and power consumption calculation

The intention of our paper is to calculate the power consumption of a set of network topologies given a set of traffic matrices, and this considering both a circuit-switched architecture and a packet-switched architecture. Thereto, we need to specify what power consumption values we consider for the various equipment outlined above, and how we will dimension the network given a certain traffic matrix.

4.1. Power consumption model

The power consumption values assumed for each equipment type described earlier in Section 3 are listed in Table 1. All values are taken from [8] (whose goal was to collect and present representative power consumption values for backbone equipment), with the exception of the 40G coherent and 100G coherent transponder values which are based on [13]. The transponder reach, which determines the placement of 3R regenerators, is taken from [14].

The power-per-port values for the IP router include both the power consumed by the line card and the basic node (i.e., shelves, switch fabric, routing engine,

Table 1: Power consumption values (source: [8], [13])

Equipment	Power cons.	Inv. pow. eff.
IP/MPLS 1G-port	10 W	10 W/Gbps
IP/MPLS 10G-port	100 W	10 W/Gbps
IP/MPLS 40G-port	400 W	10 W/Gbps
IP/MPLS 100G-port	1000 W	10 W/Gbps
OLA (per fiber pair, 80 km span)	110 W	-
Transponder 10G non-coherent, reach 3000 km	50 W	5 W/Gbps
Transponder 40G coherent, reach 2500 km	167 W	4 W/Gbps
Transponder 100G coherent, reach 1200 km	389 W	3.9 W/Gbps
3R regenerator xG	$2 \cdot$ transponder xG	-
OXC, 40 ch., with degree d_f	150 W + $d_f \cdot$ 135 W	-

power supply, internal cooling and remaining minor components). We assume the power-per-port value fixed and independent of the load (but not of capacity!), as the power consumption of present-day IP routers when idle and under full load are very similar [13, 15]. This also implies that the influence on the power consumption of buffering and table look-up associated with packet switching is negligible.

The power consumption value used for the OXC includes a fixed overhead (150 W) and OXC degree variable part (135 W) that accounts for the switching, mux/demux stages as well as pre- and booster-amplifiers. The OXC degree d_f is defined as the number of network-side bidirectional fiber ports, assuming that all fiber ports are added/dropped at the tributary side (i.e., towards the IP/MPLS layer).

In addition to the total power consumed by the devices listed in Table 1, we assume that an equal amount of overhead power is consumed for site cooling and power supply losses, i.e., the Power Usage Effectiveness (PUE) is equal to 2[1].

In Section 6.6 we also consider a more accurate IP power model than the above capacity-proportional 10 W/Gbps. In the more accurate power model we account for the actual required IP fabric card shelves, line card shelves, slot cards and port cards. The reason we *do not* use the more accurate model by default is that it introduces some anomalous behavior in the power saving charts, as we will show in Section 6.6, thereby somewhat obscuring the general trends.

4.2. Dimensioning and power consumption calculation

To calculate and evaluate the power consumption for a given network topology and traffic matrix, for both the packet and circuit-switched architectures, we use a custom Java-based dimensioning tool.

[1]Note that recently deployed high-capacity data centers with a focus on energy efficiency show much lower PUE values, such as Google claiming to have reached an annualized average PUE across all their tracked data centers of 1.14 by the end of 2011 [16]. However, this is not yet commonplace for telecom operators, with one national operator stating (in private) that '... 1.8–2.0 as an average is not an unreasonable assumption'.

Table 2: Notation used in the network dimensioning

	Symbol	Description
Parameters	$G = (V, E)$	directed physical supply network with nodes V and supplied physical links E
	$H = (V, L)$	directed logical supply network with nodes V and supplied logical links L
	C	capacity (bitrate) of a lightpath
	S	length of a span between two OLAs (in kms)
	R	length of a span between two 3R regenerators (in kms)
	W	number of wavelengths per fiber
	D	a Traffic Matrix (TM)
Variables	f_{ij}^{ab}	whether the traffic demand originated at node $a \in V$ and targeted to node $b \in V$ traverses the logical link from $i \in V$ to $j \in V$, $f_{ij}^{ab} \in \{0, 1\}$
	y_l	number of lightpaths established on the logical link $l \in L$, $y_l \in \mathbb{Z}_+$
	z_e	number of fibers installed on the physical link $e \in E$, $z_e \in \mathbb{Z}_+$
	x_i	number of ports (equal to the number of transponders) installed at each node $i \in V$, $x_i \in \mathbb{Z}_+$

The pseudo-code of the network dimensioning algorithm is given in Alg. 1. The notation used in the description of the network dimensioning method is defined in Table 2 with parameters being input to the algorithm, and variables being output of the algorithm. The general steps in dimensioning the network and calculating the power consumption are as follows.

1. First, the traffic D is routed over the physical supply network G with the constraints of the assumed switching paradigm determining also the lightpaths to be established and the number of ports to be installed at the node. For the packet-switched architecture, this means that we consider the logical supply network H (i.e, the IP topology) identical to the physical supply network G, and that traffic over the same physical link $e \in E$ can be groomed. For the circuit-switched architecture, this means that we consider the logical supply network H to be a full-mesh, and no grooming is possible. To achieve 1+1 protection at the IP layer (see Fig. 1), the two shortest link-disjoint physical paths between the source and target nodes are calculated using a minimum cost flow algorithm, where we assume the

Algorithm 1 Pseudo-code of the network dimensioning and power calculation

Require: G, H, C, S, R, W, D, protectionScheme
Ensure: f_{ij}^{ab} for each $(i, j) \in V \times V$ and $(a, b) \in V \times V$, x_i for each $i \in V$, y_l for each $l \in L$, z_e for each $e \in E$

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1: (f_ij^ab, y_l, x_i) = routeTraffic(D, G, H, C, protectionScheme);
2: z_e = assignWavelengths(y_l, W, first-fit)
3: evaluatePower(x_i, y_l, z_e, S, R);
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overall path length, expressed in number of hops, as cost.

2. Then, the wavelength assignment takes place determining also the number of fibers installed at each physical link z_e. This is done in a first-fit fashion [17], meaning that the algorithm finds the first free wavelength/fiber pair that is available on the physical path between source and target nodes.
3. Eventually, the total power of all devices installed in the network is counted using the values from Table 1.
   - IP routers and transponders installed at each node $i \in V$ are determined based on the number of ports x_i.
   - OXCs installed at each node $i \in V$ are determined based on the number of fibers z_e. Because of the dimensioning tool constraints, we generalized on the OXC power consumption and calculate an average OXC power consumption value based on the average node degree of the network.
   - The number of necessary OLAs at each physical link $e \in E$ is determined by its length, length of the span S and the number of installed fibers z_e.
   - The number of necessary 3R regenerators at each logical link $l \in L$ is determined by the length of its constituting physical links $e \in E$, and the length of the regenerator span R.

5. Case-studies - network scenarios

We will evaluate the power consumption under both a packet-switched and a circuit-switched architecture, and this for a number of different (a) network topologies, (b) traffic matrices, and (c) linerates. This will allow us to do a power consumption sensitivity analysis on an extensive set of parameters.

5.1. Topologies

To understand the influence of the connectivity degree and network size (in terms of number of nodes and average physical link length) on the power consumption, we consider a number of *artificially generated topologies*, ranging from minimally meshed (ring) up to maximally meshed (full-mesh) networks, see Table 3. For each of these variations we consider networks with the number of nodes N equal to 10, 15, 25, and 33.

To be able to cross-validate our results based on artificial topologies, we also consider four *realistic networks*: the Spanish Telefónica I+D (TID) network model (forecasted potential topology for the year 2020 [18]), the DICONET pan-European Géant network [19], the well-known U.S. NSF network ('us-nobel' at http://sndlib.zib.de/) [20], and the slightly smaller U.S. Abilene network[2][20].

[2] The Abilene topology available from sndlib [20] has been slightly modified to represent a survivable network, as required for supporting the 1+1 protection scheme. Thereto, the node ATLAM5 has been removed; all traffic originating from and destined to ATLAM5 has been allocated to the only node it was connected to, i.e., ATLAng.

Table 3: Topologies considered in this study

Topology	Number of nodes N	Number of bidir. links L	Avg. node degree $\overline{d}$	Mesh degree M	Link length (avg) [km]
ring	10	10	2	0.22	250
ring	15	15	2	0.14	166
ring	25	25	2	0.08	100
ring	33	33	2	0.06	75
half-mesh	10	23	4.5	0.50	250
half-mesh	15	53	7	0.50	166
half-mesh	25	150	12	0.50	100
half-mesh	33	264	16	0.50	75
full-mesh	10	45	9	1.00	250
full-mesh	15	105	14	1.00	166
full-mesh	25	300	24	1.00	100
full-mesh	33	528	32	1.00	75
TID	33	53	3.21	0.10	(52.4)
Géant	34	54	3.18	0.10	(753)
NSF	14	21	3.00	0.23	(1087)
Abilene	11	14	2.55	0.26	(1004)

They are also listed in Table 3.

For all of the networks, the IP supply topology H is taken identical to the WDM supply topology G under the packet switching paradigm. All links are bidirectional.

Similarly to [10] we define the mesh degree M of a network as the ratio of the average node degree of the network under consideration, $\overline{d}$, and the node degree of a full-mesh network having the same number of nodes as the considered network, i.e., d_{mesh} =N−1, so we get $M = \frac{\overline{d}}{d_{mesh}}$. The half-mesh networks have a mesh degree of $M = 0.5$, so the average desired node degree is calculated as $\overline{d} = \frac{N-1}{2}$. To generate these half-mesh networks we (a) start from a ring network with the required number of nodes N and number of links $L_{ring} = N$, (b) then calculate the number of links to add in order to have the desired[3] average mesh (and node) degree, and (c) eventually add these links distributed evenly across the ring (connecting the most-distant nodes, based on the hop count, first). Note that the number of links in such a half-mesh network is given by $L = L_{ring} + N \cdot \frac{\overline{d}-2}{2} = N \cdot \frac{N-1}{4}$.

For the physical link lengths, which influence the power consumption of the OLAs and 3R regenerators, we assume that each of the generated networks covers a geographical area with a diameter of 800 km (which is comparable to a country-sized network such as Germany), or a circumference of approximately

[3] Note that, depending on the number of nodes and the requested degree, the theoretical number of links to add might be a fractional number. So we round this value up or down to the closest integer to get a practical (i.e., integral) number of links to add. As a result, the actual degree of the network might differ slightly from the requested one.

2,500 km. The physical link lengths are then taken to be 2,500 km divided by the number of links in a ring network. For the half-mesh and full-mesh networks we take all other physical links to have the same length, even if this is topologically unrealistic (Table 3).

5.2. Traffic matrices

For each topology, we generate traffic matrices with *uniform demands*, i.e., an identical demand between each node pair. We consider a range of uniform node-to-node demand values, starting at 1 Gbps, and stepwise increasing up to 220 Gbps. The upper limit of our range is determined so that demands are at least higher than twice our largest considered linerate, which is 100G (see Section 3).

Furthermore, for a subset of topologies we also consider more *realistic demand* types. These include random demands, gravity demands, and demands based on actual traffic measurements; similar as for the uniform demands, the demands were scaled to span a large range of actual demands. More details are given in Section 6.5, where we perform a sensitivity analysis on the demand type.

5.3. Linerates

As noted in Section 3 we consider three different transport linerates: 10G, 40G and 100G. This affects the IP interfaces and transponders.

6. Results and observations

In this section we compare the power consumption of packet switching (PS) and circuit switching (CS) architectures, evaluated over the artificially generated topologies (from ring to full-mesh) and cross-validated with the realistic topologies[4].

For this evaluation we use three metrics: the absolute total power consumption (kW), the inverse power efficiency (W/Gbps), and the relative power consumption savings of CS over PS (%). The inverse power efficiency is the power (in Watt) required to transport a uniform demand of 1 Gbps (lower values indicate more efficient operation). The relative power consumption savings of CS over PS are calculated as $100 \times \frac{\text{Power}_{\text{PS}} - \text{Power}_{\text{CS}}}{\text{Power}_{\text{PS}}}$, and give a clear indication which switching paradigm is more power-efficient; positive values indicate that CS is preferable, negative values indicate that PS is preferable.

As this section is rather dense in content, an overview of the findings in this section is given in Table 4, with forward references to the relevant subsections.

[4]Note that a useful extension would be to find the optimum topology (through optimization), instead of comparing given topologies under different conditions. This is however considered out of scope.

Table 4: Overview of our findings. Key findings in bold

	Finding	Section
General	Sparser topologies consume more	6.1
	(Inv.) power efficiency improves with increasing demands, except for PS in sparse topologies	6.1
	Higher demands favor CS	6.1
d/l ratio	High demand/linerate ratios favor CS, low demand/linerate ratios favor PS	6.2
	CS is always preferable for demands higher than half the channel linerate	6.2
	There are reasons for real-life networks to operate with demand/linerate ratios (far) above 1	6.2
Network size	**Networks with more nodes do not necessarily result in larger relative savings of CS over PS**	6.3
	Longer link lengths result in reduced savings for CS	6.3
Mesh degree	Savings of CS over PS decrease with increasing mesh degree	6.4
	The above behavior is not applicable at low demand/linerate ratios	6.4
Demand type	Realistic traffic has a smoother savings profile	6.5

6.1. General observations

Sparser topologies consume more — From Fig. 2(a) and (b) we see that sparser topologies (i.e., more ring-like) consume more power than more meshed topologies. This is due to longer paths needed both in the PS and CS.

(Inv.) power efficiency improves with increasing demands, except for PS in sparse topologies — Fig. 2(c) and (d) show the inverse power efficiency, i.e., the power (in Watt) required to transport a uniform demand of 1 Gbps. We see that the power efficiency of PS (dashed lines) is almost independent of the traffic demand in ring-like networks, whereas in highly-meshed topologies its efficiency gradually improves with increasing traffic. CS (solid lines) behavior is similar to the latter irrespective of the mesh degree.

6.2. Influence of the demand/linerate ratio

To get a clear understanding of when CS is more power-efficient than PS (or vice versa), we plot in Fig. 3 the power consumption savings of CS over PS. Positive values indicate that CS is preferable, negative values indicate that PS is preferable. For a fair comparison between the different channel linerates, we plot this metric against the ratio of the average demand bitrate over the channel linerate. For a ratio equal to 1, the average demand bitrate is equal to the linerate.

High demand/linerate ratios favor CS, low demand/linerate ratios favor PS — Fig. 3 shows that increasing demand/linerate ratios lead to higher savings of CS over PS. Low demand/linerate ratios always make PS the preferable paradigm. The reason is that, for low demands, PS can groom traffic into the available capacity of the linerates, whereas for CS low demands result in a lot of unused

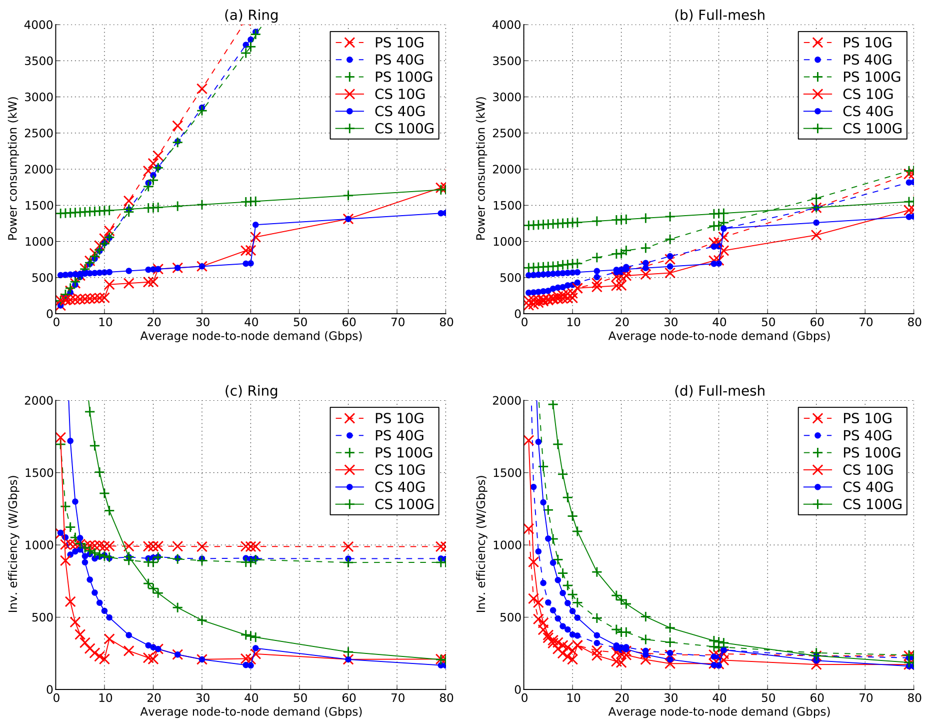

Figure 2: The total power consumption and inverse power efficiency of a 15-node ring and full-mesh topology with increasing node-to-node traffic demand. The packet-switched (PS) paradigm shows an overall linear behavior, whereas the circuit-switched (CS) paradigm shows a stepwise behavior whenever the traffic demand becomes a multiple of the channel capacity. The power efficiency of PS in sparsely-connected networks is almost independent of the traffic demand, whereas for CS the power efficiency improves with increasing traffic.

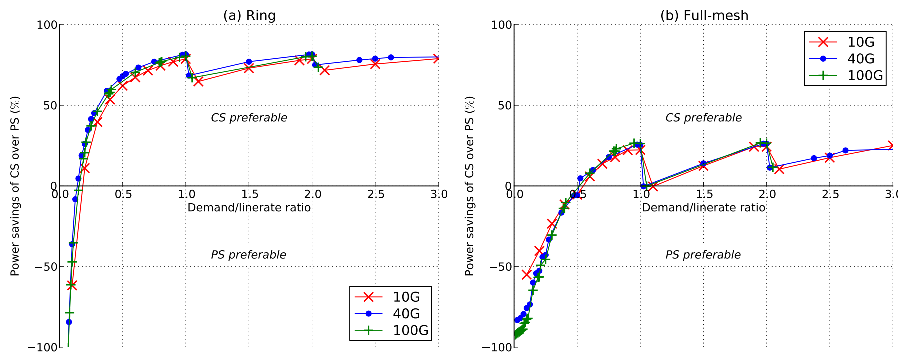

Figure 3: Power savings of CS over PS mapped to the ratio of the demand bitrate over the channel linerate (15-node topology). The savings show a stepwise behavior around integral multiples of this ratio (i.e., the savings suddenly drop when the node-to-node traffic demands surpass the channel linerate). The ratio's transition window where CS becomes more preferable than PS is relatively small and relatively independent of the channel linerate (especially for highly-meshed networks, where it is fixed at 1/2).

capacity. Both Fig. 3(a) and (b) also clearly show a stepwise behavior around integral multiples of this ratio. This behavior originates from the stepwise behavior of the power consumption of the CS architecture (shown in Fig. 2(a)). The CS savings increase until the demand reaches the channel capacity (as there is an increasing usage of the channel capacity), and then suddenly drops when the demands surpass the channel capacity (thereby requiring an extra WDM channel).

CS is always preferable for demands higher than half the channel linerate — Fig. 3 also indicates that there is a rather narrow transition window of the demand/linerate ratio where CS becomes more preferable than PS. In sparse networks (Fig. 3(a)) PS is the preferable option up to about demands being 1/10 to 1/5 of the channel linerate. In highly connected networks (Fig. 3(b)), the crossover window is much smaller, and PS is the preferable option for demands being up to half the channel linerate, independently of the utilized transmission technology. The reason that the crossover point is at half the channel linerate is because once a node-to-node demand is larger than half of the channel linerate, there is no free capacity left to groom another demand onto the same channel, and a separate channel is required for each demand.

There are reasons for real-life networks to operate with demand/linerate ratios (far) above 1 — Now that we have identified the demand/linerate ratio as an important parameter, the question naturally ensuing from this observation is which demand/linerate ratios are common in real-life networks. Unfortunately, we could not find reliable data on this issue. In [21], Fisher et al. state:

> In backbone networks, pairs of routers are typically connected by mul-

tiple physical cables that form one logical bundled link[5] [Doverspike et al., 2010] that participates in the intradomain routing protocol. (...) Link bundles are prevalent because when capacity is upgraded, new links are added alongside the existing ones, rather than replacing the existing equipment with a higher capacity link. (...) Bundled links are also necessary when the aggregate capacity of the bundle exceeds the capacity of the fastest available link technology. In today's backbone networks, a vast majority of links would be bundled, with bundles consisting of two to approximately twenty cables, a majority between the two extremes.

Note that link bundles of 'two to twenty cables' (with 'cables' corresponding in this context to wavelengths or channels) imply a demand/linerate ratio of 2–20 as well. The range for this ratio in Fig. 3 (and later figures) is only up to 3. The referenced work (Doverspike et al. [22]) does mention a third driver for link bundling, which is resilience and consequently network stability. If one of the component links fails, the bundled link remains up and a failure-driven topology update is not required. Unfortunately, [22] does not provide actual data (such as link bundle counts for real operators) to ground their—otherwise plausible—claims. In [23], the availability of bundled links (referred to as 'parallel paths') are an important premises for one of the proposed energy-saving solution, but no actual data or references are given that give insight to what extent this is actually the case in current backbone networks. On the contrary, the work admits that splitting IP traffic demands over multiple parallel paths "is a strong assumption, as multi-path routing is normally not enabled in today's routers. MPLS allows this kind of traffic engineering, but the label switched paths (LSP) are not frequently reconfigured today, either." In an expert interview with a large national operator, we were informed that the choice of implementing a link through either multiple smaller capacity interfaces or through a single overprovisioned interface is largely governed by an economic (i.e., cost) decision. Both options were feasible, i.e., operation with a demand/linerate ratio above as well as below 1 exists. Actual data was unfortunately not available. Summarized, the information above suggests that there are some good reasons for real-life networks to operate with demand/linerate ratios (far) above 1, and that this is at least done in some cases. This would imply that a CS architecture is more desirable than a PS architecture from a power consumption point of view.

6.3. Influence of the network size (number of nodes and physical link lengths)

Fig. 4 shows the power consumption savings of CS over PS for networks with different number of nodes (the network with N=25 has been omitted for clarity). The subfigures (a) to (d) correspond to an increasing mesh degree. Fig. 4(b) represents a mesh degree M=0.1, and contains in addition two realistic

[5] Link bundling is also referred to under various other umbrella terms such as link aggregation, link bonding, link teaming and port trunking. The IEEE 802.1AX-2008 standard uses the term 'link aggregation'.

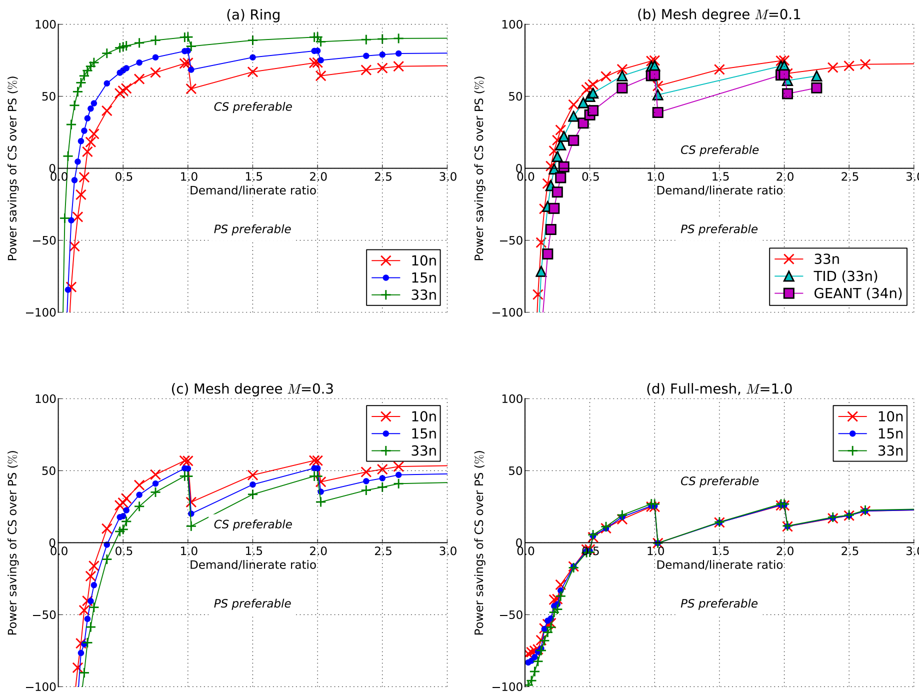

Figure 4: Influence of the node count on the power savings of CS over PS (for linerate = 40G). Only for sparse topologies (i.e., (a) through (c)) the node count has an influence on the savings. While for a ring topology a higher node count leads to more savings, this is not consistently the case for other sparsely meshed topologies. The relatively large deviation of the Géant topology from the general trend is explained in Fig. 5.

topologies that also have M=0.1 (the lowest mesh degree of the 10-node and 15-node topology is higher than 0.1, see Table 3).

Networks with more nodes do not *necessarily result in larger relative savings of CS over PS* — For sparse topologies (Fig. 4(a) through (c)) the node count has considerable influence on the relative savings of CS over PS. For the ring topology, a higher node count makes CS more preferable. This is due to the higher hop count in larger ring networks, which implies a much higher IP-layer contribution, which increases the PS power consumption. This is inline with [7]. However, our results indicate that the above rule cannot be applied universally to all sparse topologies. In Fig. 4(c) a higher node count does not consistently correspond to increased CS savings (the savings for 33-node artificial topology are lower than for the 15-node topology). Moreover, while in Fig. 4(b) the realistic TID network (33 nodes) savings seems to be inline with the 33-node artificial topology, the Géant network (34 nodes) curve is considerably lower. There must be another parameter with substantial influence on power savings.

Longer link lengths result in reduced savings for CS — In order to explore the reason of the above described anomaly, Fig. 5(a) plots, in addition to the 33-node artificial topology (physical link length = 75 km) and the original Géant topology (average physical link length = 753 km), the same Géant topology where all links have been (artificially) set to 75 km. The figure shows that the difference in link length is the reason of the diverging behavior of the original Géant topology from the artificial 33-node topology. The long link length of the original Géant topology increases the number of required OLAs and 3R regenerators and the associated power consumption. As the additional power consumption has a larger relative impact on the CS power consumption, the power consumption savings of CS over PS decrease accordingly. This is also confirmed by Fig. 5(b) where the NSF network (14 nodes, mesh degree $M = 0.2$, average physical link length = 1087 km) is compared with our artificial 15-node $M = 0.2$ topology. When the link lengths are adjusted (either from the artificial topology, or from the NSF network), the savings curves become very similar.

6.4. Influence of the mesh degree

Although we have not focused on the mesh degree yet, it is already clear from the previous figures and discussion that this parameter is of considerable influence on the power savings of CS over PS.

Savings of CS over PS decrease with increasing mesh degree — As shown in Fig. 6, the savings of CS over PS tend to decrease for increasing mesh degree, as adding more edges decreases the hop count and thus more interfaces (i.e., router ports and transponders) can be saved in intermediate nodes of the PS architecture while still performing traffic grooming. On the other hand, for the CS architecture, a higher mesh degree only impacts the OLAs (and eventually, the regenerators) consumption, which constitutes a less relevant contribution in the total consumed power if compared to the power spent by the interfaces. It is useful to remark that this is also confirmed by the data in the study by Shen and Tucker [7]: if we calculate the mesh degree for the three networks considered

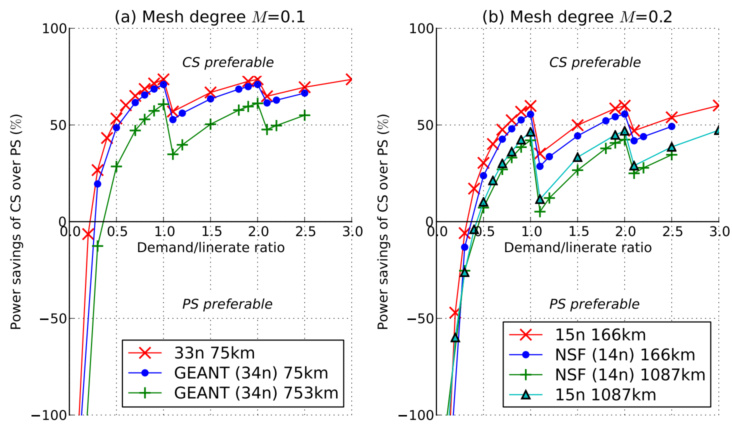

Figure 5: Influence of the average physical link length on the relative savings of CS over PS (linerate = 10G). Longer link lengths result in lower savings, and explain why the savings profile of topologies such as Géant (average physical link length = 753 km) does not correspond very well with our artificial topology of the same node count but much shorter link length.

in [7], then indeed higher mesh degrees correspond to reduced preference for CS (see Table 5).

The above behavior is not applicable at low demand/linerate ratios — An exception to this behavior is obtained for low demand/linerate ratios (i.e., higher channel linerates under low traffic conditions). This is shown in Fig. 7, which plots the savings as a function of the mesh degree for different demand/linerate ratios. In this case, passing from ring to half-mesh topologies has, as previously, a higher benefit for the PS than for the CS solution (i.e., the PS solution benefits from the reduction in IP hops, shown as Effect A in Fig. 7). However, adding further links to the network (i.e., going towards full-mesh topologies), does *not* require more interfaces for the CS solution, but it does for the PS solution. However, there is lower opportunity for traffic grooming, so with high channel linerates interfaces are underutilized, thus causing higher relative power consumption of the PS solution compared to the CS solution (shown as Effect B in Fig. 7).

It is interesting to point out that for the full-mesh case the power consumption of PS and CS are *not* equal (i.e., CS over PS savings are not zero), as one might incorrectly expect. The link disjoint backup paths always require two hops in

Table 5: Calculating the mesh degree for the 3 networks considered in [7] confirms the finding that higher mesh degrees correspond to reduced preference for CS

Topology [7]	Reported CS over PS saving [7]	Mesh degree
6 nodes, 8 links	25% savings	0.53
15 nodes, 21 links	40% savings	0.20
42 nodes, 43 links	45% savings	0.09

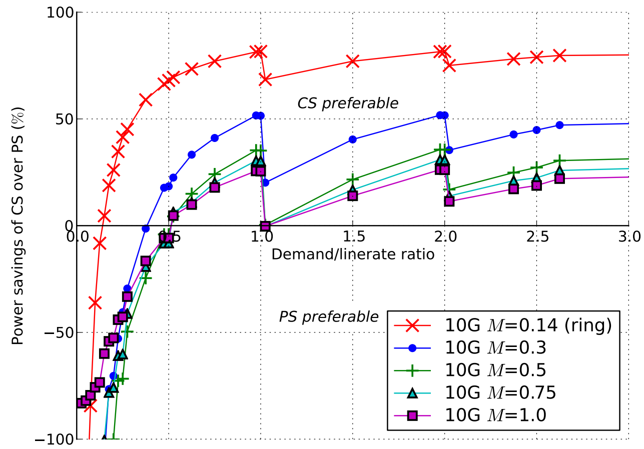

Figure 6: Influence of the mesh degree on the relative savings of CS over PS (for linerate = 40G, and 15-node topologies). Higher mesh degrees (M) result in lower savings.

both switching paradigms, but the intermediate node requires IP ports under the PS paradigm only, leading to CS being more preferable. However, an exception to this is observed for high linerates (e.g., 100G), combined with low demands bitrate (e.g., 15 Gbps per demand). In this case the opportunity to groom traffic in the PS scenario produces higher power benefits in comparison to the high demands bitrate situation, and thus the CS option is outperformed.

To summarize our finding for the mesh degree: in general, the power consumption advantage of CS over PS decreases with an increasing mesh degree. In other words, for networks with a lower mesh degree (such as ring networks), CS is *more* preferable than it is for fully meshed networks. However, this observation does not necessarily hold for low traffic conditions (i.e., demand/linerate ratio < 0.5) as in that case the effect of underutilized channels in the CS scenario starts to dominate.

6.5. Sensitivity to non-uniform demands

In all of the above scenarios we assumed fully-meshed uniform demands. To see the effect of non-uniform demands on the power savings of CS over PS, we consider in Fig. 8 two additional demand types: (a) a gravity traffic matrix where nearby nodes have larger demands, thus closer resembling real life demands [19], and (b) a random fully meshed traffic matrix where each demand is evenly distributed between -30% and +30% of the nominal demand.

We consider both demand types for two of our network topologies where we have realistic demands available. For the Géant topology the gravity traffic matrix is based on a mathematical model [19]. For the Abilene topology, the traffic matrix is based on actually measured traffic, as made available through sndlib [20]. It was generated by taking the maximum for each demand over the

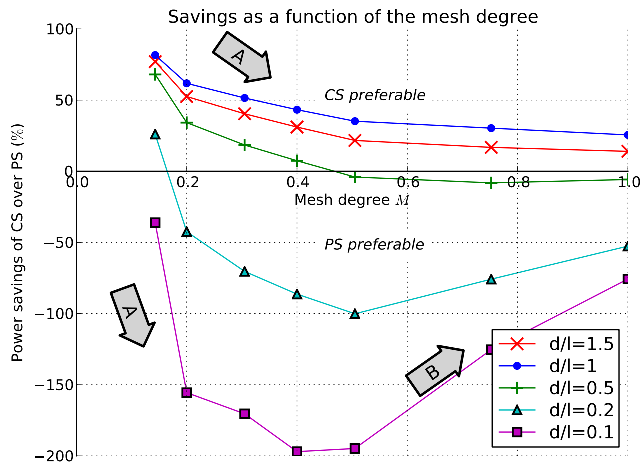

Figure 7: Influence of the mesh degree and the demand/linerate ratio d/l on the relative savings of CS over PS (for linerate = 40G, and 15-node topologies). For low demand/linerate ratios there is an optimum point where PS is favorable. *Effect A:* The PS power consumption decreases with increasing mesh degree, as less IP hops are required. *Effect B:* The PS power consumption increases towards that of the CS solution, because the PS grooming potential decreases with increasing mesh degree.

period 2004-07-01 to 2004-07-31 (per [24]), scaled up to a set of traffic matrices with the average demand bitrate ranging from 1 Gbps to 25 Gbps. As we already noted in Section 5.1, we have removed the ATLAM5 node and moved all its traffic to the ATLAng in order to have a survivable network that can provide 1+1 protection for each traffic demand. Furthermore, since the Abilene traffic data is given as unidirectional traffic, and we only consider bidirectional demands, we have taken the maximum value of node-to-node demands where demands in each direction were different. Finally, we converted the original Mbps demands to Gbps, rounding up to the nearest integer value.

Realistic traffic has a smoother savings profile — While the saving curves associated with uniform demands show the distinct stepwise behavior, the curve is much smoother for random demands and gravity demands. This stepwise behavior originates in the stepwise power profile of the CS architecture, as explained in Section 6.2 and shown in Fig. 2(a). For more realistic traffic, the network's *average* demand/linerate ratio is the result of a mix of different demand values (the demand between each node pair is potentially different). As such the behavior that occurs when a demand is just below or just above the linerate is smoothed out. However, the general trend observed before remains valid: CS is preferable for demands higher than half the channel linerate (on average) also under the gravity and random traffic matrices. This observation holds for both the Géant gravity demands (generated based on a mathematical model), as well as the Abilene realistic demands (which are based on real traffic measurements in the Abilene network). This increases our confidence that our

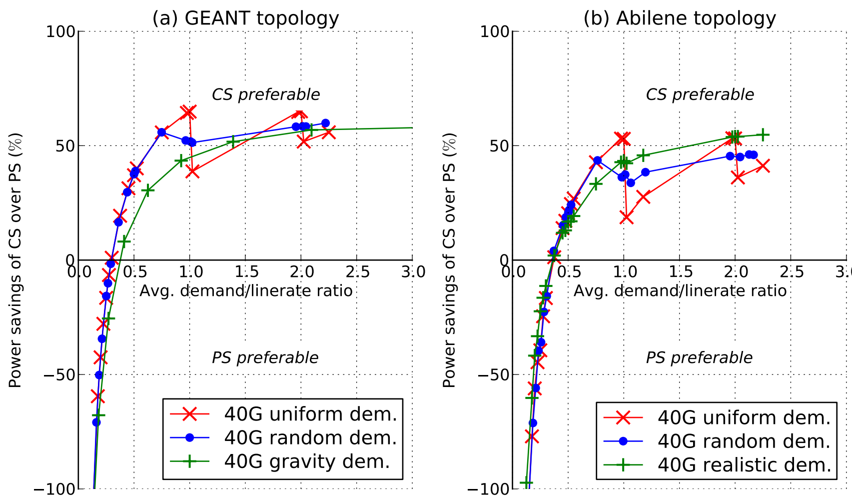

Figure 8: Influence of different demand types on the savings of CS over PS, both for the (a) Géant and (b) Abilene topology (linerate=40G). While uniform demands show a distinct stepwise behavior, more realistic demand sets (i.e., random and gravity demands) smooth out this behavior.

results hold for other real demands as well.

6.6. Sensitivity to a more detailed IP power consumption calculation

In Section 4.1 we modelled the power consumption of IP backbone routers as 10 W/Gbps. The implication of this is that we assume perfect power-proportionality of backbone routers to changes in the required capacity. This is a simplification, as IP backbone routers consist of various building blocks, and a slight increase in capacity might require the addition of a certain component, incurring a significant additional power consumption. For example, Cisco's CRS series consists of fabric card shelves, line card shelves, slot cards and port cards (see [25] for a concise overview).

To assess the impact and validity of our 10 W/Gbps simplification, we have also calculated the power consumption and power consumption savings of CS over PS with a more accurate calculation. For each IP node, we determine the required number of fabric card shelves, line card shelves, slot cards and port cards, and multiply this with the associated equipment power consumption values[6].

The result of the more detailed calculation is shown in Fig. 9 and Fig. 10.

We make the following two observations:

[6]We have used the capacity and power consumption data from Table 1 in [8], with the power consumption as follows: fabric card shelf=8100 W, line card shelf=2401 W, 140G slot card=401 W, 14×10G port card=135 W, 3×40G port card=315 W, 1×100G port card=135 W.

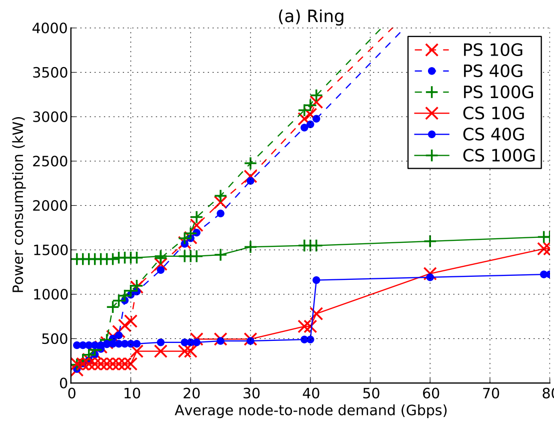

Figure 9: Influence of using more accurate IP power consumption modelling on the total power consumption (15-node topology). The overall shape of the curves is not affected; compare with Fig. 2(a).

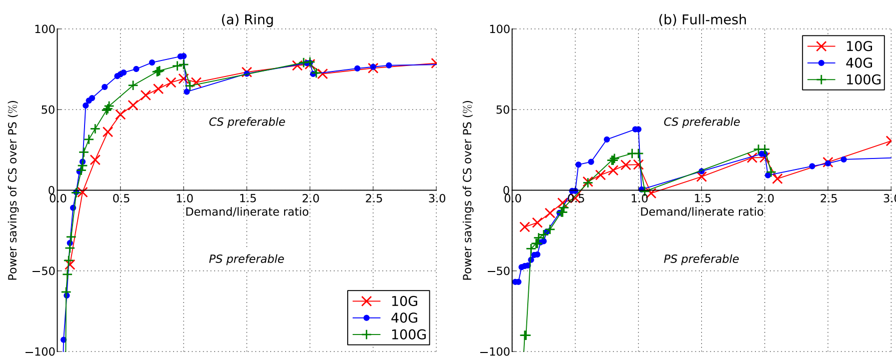

Figure 10: Influence of using more accurate IP power consumption modelling on the power savings of CS over PS (15-node topology). The overall shape of the curves is not affected; compare with Fig. 3.

- As expected, Fig. 9 shows that the power consumption increases in a more stepwise fashion than in Fig. 2(a). For example, for the PS 100G case the increase from an average node-to-node demand of 6 Gbps to 7 Gbps requires in each node a second line card shelf and subsequently a fabric card shelf to connect both line card shelves, which is clearly visible[7].
- The overall shape of the CS over PS savings curves are not affected, as can be seen when comparing Fig. 10 with Fig. 3. While specific capacity requirements might result in unfortunate combinations when comparing CS and PS—such as can be seen in Fig. 10(b) for the 10G architecture at a demand/linerate ratio of 1.1, where the CS architecture suddenly requires an additional fabric card shelve in each of the 15 nodes, while the PS architecture does not—the overall shape of the curve is nearly identical to those which we calculated using the power-proportional 10 W/Gbps approach.

Thus, the general trends and conclusion from the earlier sections are not affected when using the more accurate IP power consumption calculation. On the downside, the more accurate IP power modeling does introduce sudden changes in the shape of the curves that can only be properly explained when looking in detail at the resulting data. Furthermore, the location of these 'jumps' does not necessarily correspond to real-life deployments, as actual equipment deployment depends also on such issues as expected traffic growth [13]. For these reasons, we eventually chose to present our results with the more idealized 10 W/Gbps model, as it more clearly shows the overall behavior of using a CS versus PS architecture.

7. Conclusion and further work

In this paper we extensively compared the power consumption of circuit and packet switching architectures in optical backbone networks. We evaluated the impact of the channel linerate, the network size (both number of nodes and physical link length), demand/linerate ratio and the network mesh degree to assess under which conditions each switching paradigm represents the most power-efficient solution.

We found that, in general, circuit switching is preferable, as fewer power-hungry IP router ports and WDM transponders are needed. This is especially true for networks that use link bundling, i.e., where a node-to-node logical link with a certain capacity is realized using multiple links/interfaces with smaller capacities. We did not find unambiguous data on how common or uncommon link bundling is in backbone networks, but the few sources we were able to find suggest that it is attractive from an operational point of view, and used in at least some cases. However we point out on the top of the related work that for

[7] For the 15-node network, including a PUE=2, the fabric card shelf (8.1 kW) and the line card shelf (2.4 kW) account for $2 \times 15 \times (8.1 + 2.4) = 315$ kW in the sudden jump.

relatively low traffic values—i.e., when the demands bitrate is lower than at least half the channel linerate—the packet switching solution is more power-efficient, thanks to the opportunity of exploiting traffic grooming to better utilize network resources.

Our key finding is that an increase in the network node count does not consistently increase the power savings of circuit switching over packet switching. Instead, these power savings are heavily influenced by the mesh degree and (to a minor extent) by the average physical link length. Increasing the network mesh degree produces higher energy benefits for packet switching than for circuit switching, as more power can be saved in intermediate nodes in the former case. Our main analysis was performed using uniform traffic demands, however we cross-validated our results using more realistic demand sets and found that the key results hold. In fact, more realistic demands remove erratic behavior from the power savings of circuit switching over packet switching that is otherwise observed when the average node-to-node demand bitrate is slightly higher than the transport linerate.

A message to take away by researchers looking into power saving solutions in backbone networks, is that the assumptions made with respect to the average demand bitrate and transport linerates do matter. For example, evaluating a particular solution in a scenario with an average demand of 20 Gbps over either 10G interfaces or 40G interfaces affects the overall network power efficiency beyond just the slight increase in power efficiency associated with 40G interfaces. It is important to be aware of this for a fair evaluation.

While our work already evaluated the circuit switching vs. packet switching paradigm over a wide set of input parameters, there are still a number of interesting inputs to consider for useful further work. First, while our power model accounts for the required equipment capacity, we did assume that the power consumption does not vary for different traffic loads, which is a reasonable assumption for current backbone equipment. However, should the power consumption of future packet switches become more proportional to the load, it is likely that this will influence the outcome of our comparison. Furthermore, we assumed that at each node there is both an IP switch and a WDM switch; this is not always the case in backbone networks, which motivates further investigation of such heterogeneous networks. Finally, our study focussed on two extreme scenarios, being either packet switching or circuit switching. Hybrid solutions—e.g. those that perform a joint optimization of the IP and WDM layer (such as the multi hop bypass solution in [7]), the use of multi-linerate transponders, or hybrid forms of packet and circuit switching—would likely perform optimally under a wider range of traffic/demand linerate ratios. Because of the intention of the current study, this was out of scope. It would however be a useful research topic to compare the impact and optimization potential of such hybrid solutions.

Acknowledgments

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