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Power consumption reduction through elastic data rate adaptation in survivable multi-layer optical networks

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Abstract Network survivability requires the provisioning of backup resources in order to protect active traffic against any failure scenario. Backup resources, however, can remain unused most of the time while the network is not in failure condition, inducing high power consumption wastage, if fully powered on. In this paper, we highlight the power consumption wastage of the additional resources for survivability in IP/multi-protocol label switching (MPLS) over dense wavelength division multiplexing multi-layer optical networks. We assume MPLS protection switching as the failure recovery mechanism in the network, a solution interesting for current network operators to ensure fast recovery as well as fine-grained recovery treatment per label switched path. Next, we quantitatively show how elastic optical technologies can effectively reduce such a power consumption by dynamically adjusting the data rate of the transponders to the carried amount of traffic.

Keywords Multi-layer · DWDM · Survivability · Elastic · Energy efficiency

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1 Introduction

IP/multi-protocol label switching (MPLS) over dense wavelength division multiplexing (DWDM) multi-layer optical network architectures are promising solutions to bridge the bandwidth gap between client packet data flows and the ultra-high-capacity lightpaths enabled by recent developments of optical transmission systems and advanced modulation formats. That is, transmission equipment at 100 Gb/s is commercially available to date, and research efforts are already targeting 400 Gb/s and 1 Tb/s [1]. To efficiently exploit such capacities, multi-layer optical networks allow the grooming of lower speed client flows onto available lightpaths. In this way, intermediate IP/MPLS routers between lightpaths electrical termination points can be offloaded compared to pure opaque networks, reducing router capacity requirements, and thus network capital expenditures (CAPEX).

With these high capacities, any failure (e.g., fiber cut, transponder or node failure) can lead to catastrophic data losses. These data losses also have associated big economic losses for operators due to the high downtime costs when serving certain kinds of clients. Hence, survivability becomes of paramount importance in the design and operation of multi-layer optical networks. Specifically, network operators seek to equip the minimum additional capacity in nodes and links to make the network survivable against any possible failure scenario, in view of the recovery mechanism that will be employed during network operation.

In this work, we focus on IP/MPLS over DWDM multi-layer optical networks, survivable against any single link failure scenario using IP/MPLS protection switching. This solution is interesting for current network operators because: (1) fast label switched path (LSP) recovery below 100 ms can be achieved [2]; (2) recovery is entirely performed at the MPLS layer and there is no need for still immature optical control plane solutions; (3) recovery can be performed with LSP granularity, allowing differentiated LSP recovery based on classes if desired. In contrast, note that optical recovery is performed with whole lightpath granularity, thus forcing all carried LSPs in a failed lightpath to be equally recovered.

We target the design of survivable multi-layer optical networks over a Single Line Rate (SLR), Mixed Line Rate (MLR) or an Elastic DWDM optical layer minimizing the total network CAPEX. This design entails significant resource overprovisioning to fit the desired survivability under the highest load period during the day (the peak traffic). On this overprovisioned network design, we then quantify the power savings that Elastic can achieve against fixed SLR and MLR optical layer technologies by adapting the data rate of the transponders (TXPs) to the carried traffic at any time, which translates into network operational expenditures (OPEX) savings.

It is worth mentioning, that some works can be found in the literature highlighting the energy savings that Elastic transmission technologies can achieve against SLR or MLR scenarios (e.g., see [3–5]). However, they mainly focus on the optical layer alone, where lightpath protection (either 1+1, 1:1 or shared protection) and restoration is employed for survivability purposes. Conversely, our work targets multi-layer IP/MPLS over DWDM optical networks, where both layers are jointly optimized for survivability against any link failure scenario through IP/MPLS protection switching at minimum CAPEX. Next, in such a today's realistic network scenario, we quantify the power consumption reduction that Elastic technologies can yield to network operators.

2 Survivable IP/MPLS over SLR/MLR/Elastic DWDM multi-layer optical networks

When adopting SLR to implement the DWDM layer of multi-layer optical networks, all TXPs operate at the same data rate, which cannot be changed dynamically. We assume for SLR that TXPs run at 100 Gb/s with coherent Polarization Division Multiplexing Quadrature Phase Shift Keying (PDM-QPSK). Conversely, TXPs at different data rate coexist in MLR, allowing to better adjust the DWDM layer capacity to the carried traffic, while lowering the number of expensive high-capacity TXPs. We assume for MLR TXPs running either at 10 Gb/s with On–Off Keying (OOK), 40 Gb/s with partial Differential Phase Shift Keying (pDPSK) or 100 Gb/s with coherent PDM-QPSK. TXPs in MLR are also fixed and cannot change their data rate dynamically. Conversely, elastic TXPs show the capability to modify their data rate, adjusting it to the traffic they are supporting. As a short-term viable Elastic technology, we use bandwidth variable TXPs that run either at 25, 50, 75 or 100 Gb/s with coherent PDM-QPSK by adapting the symbol rate to 7, 14, 21 or 28 Gbaud, respectively [6]. This technology is compliant with the 50 GHz ITU-T grid.

Table 1 DWDM layer technology details

Rate (Gb/s)	Modulation format	Reach (km)	Cost (c.u.)	Power (W)
SLR				
100	PDM-QPSK	1,200	6	350
MLR				
10	OOK	3,000	1	50
40	pDPSK	1,600	3	75
100	PDM-QPSK	800	6	350
Elastic				
25	PDM-QPSK	1,200	6	189
50	PDM-QPSK	1,200	6	207
75	PDM-QPSK	1,200	6	255
100	PDM-QPSK	1,200	6	350

Table 1 details the transparent reach, TXP cost (in normalized cost units) and power consumption of the SLR, MLR and Elastic technologies, extracted from [6,7]. Note that given the presence of OOK signals and dispersion management in MLR networks the reach of 100Gb/s signals is lower than in Elastic scenarios [8].

Taking SLR as a benchmark, MLR allows a network operator to reduce CAPEX by deploying cheaper lower data rate TXPs (at 10 and 40 Gb/s) when the traffic to carry would underutilize a 100 Gb/s one. Moreover, these TXPs have an additional impact on the OPEX during network operation, since they consume less power. In turn, Elastic TXPs can tightly adapt their operational data rate to the carried traffic at any moment, allowing to reduce the power consumption of the overprovisioned capacity in the network, and so the OPEX. For instance, unused elastic TXPs equipped for backup routes can be set to the minimum data rate in the non-failure scenario. Moreover, TXPs supporting primary routes and dimensioned for the peak traffic can follow the daily traffic fluctuations, saving power during low traffic periods. Regarding their cost, as the architecture of an Elastic TXP is closely related to that developed for 100 Gb/s PDM-QPSK [6], we decide to set its cost equal to the cost of a fixed TXP at 100 Gb/s. Although the (limited) increased complexity of elastic interfaces compared to fixed-rate technologies initially tends to drive the cost of the Elastic TXP above the 100 Gb/s one, possible economies of scale argue in favor of considering the same cost value.

3 Survivable network design approach

This section presents the survivable multi-layer network design approach used in this paper. Specifically, we follow

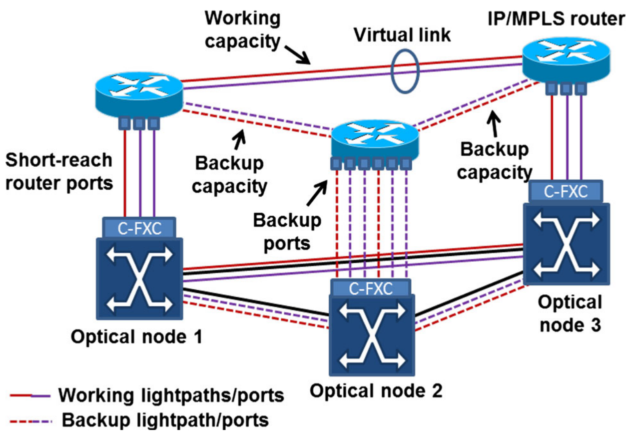

Fig. 1 Survivable multi-layer optical network design example

a 2-step network design approach based on Integer Linear Programming (ILP). We assume the predicted traffic matrix and the transparent DWDM layer topology already given. In the IP/MPLS layer, we assume a router co-located with every optical node in the DWDM layer. Moreover, we assume virtual links at the IP/MPLS layer between all router pairs that can be connected over the DWDM layer with a feasible transparent lightpath at any of the available data rates (i.e., with a physical distance shorter or equal than the maximum transparent reach of the signal). Any virtual link can be composed of multiple lightpaths.

The objective of this approach is to design an IP/MPLS over SLR/MLR/Elastic DWDM optical network carrying the predicted peak traffic matrix, so that all packet flows are survivable under any single link failure through IP/MPLS protection switching with the minimum CAPEX. This entails a joint optimization of the packet flow primary and backup routes over the IP/MPLS layer, together with the Route Wavelength and Rate Assignment (RWRA) of all lightpaths required in all virtual links to make the network survivable under any single link failure. Figure 1 shows an example of the design. As in [9], we assume that optical nodes are equipped with a client-side Fiber Cross-Connect (C-FXC) that enables router ports to be dynamically assigned to optical transponders, thus allowing the reutilization of router ports during failure scenarios.

An optimization like this based on ILP cannot be solved in realistic times even for small problem instances, as already pointed out in [10] in a multi-layer IP/MPLS over SLR Wavelength Switched Optical Network (WSON) scenario. Thus, we solve it in 2 steps: (1) Unprotected network design (primary packet flow routes and virtual link lightpaths) minimizing the total network CAPEX; (2) Joint optimization of the extra capacity to make the network survivable to all link failure scenarios with minimum CAPEX (backup routes of affected packet flows in each failure scenario, and additional lightpaths that may be required between routers to allocate such flows, which can be reused by different affected flows in different failure scenarios). Both steps use the same core ILP formulation, where packet flow primary routes and lightpaths set up for them in Step 1 are inserted as inputs in Step 2.

3.1 Core ILP formulation

We model the DWDM layer as an undirected graph $G = (N, E)$, where N is the set of optical nodes and E the set of optical fiber links, each carrying W wavelengths. We denote as R the set of feasible data rates of the TXPs, and as T_{r} the transparent reach of the signal at rate $r \in R$. Moreover, P denotes the set of all paths over G, being P^r the set of feasible paths over G at bit rate $r \in R$. That is, $\forall p \in P^r$, $Pl_{\mathrm{p}} \leq T_{\mathrm{r}}$, where Pl_{p} is the physical length of $p \in P^r$. Regarding the IP/MPLS layer, it is also represented as an undirected graph $G' = (N, L)$, where N is the set of IP routers co-located with the underlying optical nodes and L the set of IP virtual links. Note that we use the same terminology to refer to either the IP router or optical node in the same location (they are co-located). Furthermore, $\omega(n)$ denotes the set of IP virtual links adjacent to router $n \in N$. Without loss of generality, we assume that at most I lightpaths can be allocated per virtual link. Moreover, P_l^r denotes the set of feasible paths over G eligible to allocate virtual link $l \in L$ at bit rate $r \in R$, that is, $P_l^r \subseteq P^r$.

In addition, F denotes the set of possible fiber link failure scenarios, where $f = 0$ represents the non-failure scenario. The binary parameter α_{fp} equals to 1 if feasible path $p \in P$ is available in failure scenario $f \in F$; 0 otherwise. Finally, D denotes the set of bidirectional connection requests offered to the network, h_d the traffic demand (in Gb/s) requested by $d \in D$ and s_d and t_d its source and destination nodes, respectively. Binary parameter β_d^f equals to 1 if connection d is affected under failure scenario f and thus can be rerouted; 0 otherwise. Concerning costs, C_{RP} is the cost of a router port at fixed data rate B (in Gb/s) and C_{TXP}^r the cost of a long-haul transponder at data rate $r \in R$.

This being said, the decision variables of the formulation are the following:

x_{ild}^f:	Binary; 1 if request d is routed on lightpath i of virtual link l under failure scenario f; 0 otherwise.
y_{ilr}^f:	Binary; 1 if lightpath i of virtual link l is used at rate r under failure scenario f; 0 otherwise.
z_{ilpw}:	Binary; 1 if lightpath i of virtual link l is allocated on path p with wavelength w; 0 otherwise.
TXP_{ilr}:	Binary; 1 if a TXP at rate r must be equipped for lightpath i of virtual link l; 0 otherwise.
$\mathrm{RP}(n)$:	Integer; number of router ports needed at node $n \in N$.

And the formulation finally is:

$$\text{minimize} \quad C_{\mathrm{RP}} \sum_{n \in N} \mathrm{RP}(n) + 2 \sum_{l \in L} \sum_{i} \sum_{r \in R} C^r_{\mathrm{TXP}} \mathrm{TXP}_{ilr} + \mu \sum_{f \in F} \sum_{l \in L} \sum_{i} \sum_{r \in R} r y^f_{ilr} \tag{1}$$

subject to:

$$\sum_{l \in \omega(n)} \sum_{i} x^f_{ild} = 1 \quad d \in D, n \in \{s_d, t_d\}, f \in F \tag{2}$$

$$\sum_{l \in \omega(n)} \sum_{i} x^f_{ild} \le 2 \quad d \in D, n \in N \backslash \{s_d, t_d\}, f \in F \tag{3}$$

$$\sum_{l' \in \omega(n), l' \neq l} \sum_{i} x^f_{il'd} \ge \sum_{i} x^f_{ild} \quad d \in D, n \in N \backslash \{s_d, t_d\}, l \in \omega(n), f \in F \tag{4}$$

$$\sum_{d \in D} h_d x^f_{ild} \le \sum_{r \in R} r y^f_{ilr} \quad l \in L, i \in \{1, \ldots, I\}, f \in F \tag{5}$$

$$\sum_{r \in R} y^f_{ilr} \le 1 \quad l \in L, i \in \{1, \ldots, I\}, f \in F \tag{6}$$

$$\sum_{p \in P^r_l} \sum_{w} \alpha_{fp} z_{ilpw} \ge y^f_{ilr} \quad l \in L, i \in \{1, \ldots, I\}, r \in R, f \in F \tag{7}$$

$$\sum_{p \in P} \sum_{w} z_{ilpw} \le 1 \quad l \in L, i \in \{1, \ldots, I\} \tag{8}$$

$$\sum_{l \in L} \sum_{i} \sum_{p \in P : e \in p} z_{ilpw} \le 1 \quad e \in E, w \in \{1, \ldots, W\} \tag{9}$$

$$x^0_{ild} - x^f_{ild} \le \beta^f_d \quad d \in D, l \in L, i \in \{1, \ldots, I\}, f \in F \backslash \{0\} \tag{10}$$

$$x^f_{ild} - x^0_{ild} \le \beta^f_d \quad d \in D, l \in L, i \in \{1, \ldots, I\}, f \in F \backslash \{0\} \tag{11}$$

$$\sum_{r \in R} r y^f_{ilr} \le \sum_{r \in R} r \mathrm{TXP}_{ilr} \quad l \in L, i \in \{1, \ldots, I\}, f \in F \tag{12}$$

$$\sum_{r \in R} \mathrm{TXP}_{ilr} \le 1 \quad l \in L, i \in \{1, \ldots, I\} \tag{13}$$

$$\sum_{d \in D} \sum_{l \in \omega(n)} \sum_{i} h_d x^f_{ild} \le B \cdot \mathrm{RP}(n) \quad n \in N, f \in F \tag{14}$$

Additional constraint for MLR DWDM layer:

$$\sum_{f \in F} y^f_{ilr} \le |F| \cdot \mathrm{TXP}_{ilr} \quad l \in L, i \in \{1, \ldots, I\}, r \in R \tag{15}$$

Objective function (1) aims at minimizing equipment installation cost resulting from ports at IP routers and TXPs at optical nodes, as well as the operational data rate of the installed TXPs under any failure scenario (useful in the Elastic scenario). The term μ is a small constant value to prevent that this third term in (1) interferes on the CAPEX minimization goal. Constraints (2)–(4) guarantee that all demands are served. Moreover, they guarantee the continuity of the flows at the IP layer, also ensuring that flows follow one and only one path from source to destination. Constraint (5) ensures that the amount of traffic that any lightpath of any virtual link supports does not exceed the data rate of the associated TXP. Constraint (6) enforces that at most one data rate is assigned to any lightpath of any virtual link under any failure scenario. Constraint (7) guarantees that every active lightpath of any virtual link is assigned to an available feasible path and wavelength. Constraint (8) enforces that at most one path and wavelength is assigned to any lightpath of any virtual link (i.e., static optical layer). Constraint (9) is the wavelength clashing constraint, ensuring that any wavelength in any physical link is allocated to one lightpath at most. Constraints (10) and (11) enforce that only affected connections can be rerouted over the IP/MPLS layer under every failure scenario. Constraints (12) and (13) account for the TXPs that must be equipped in the network, as well as their data rate. Finally, constraint (14) accounts for the number of router ports that must be equipped at each network router. Constraint (15) only applies to the MLR DWDM optical layer scenario, keeping fixed the data rate of TXPs over all failure scenarios.

The presented ILP formulation is generic enough to model SLR, MLR and Elastic DWDM optical layer scenarios. Note that in Step 1, we set $F = \{0\}$, that is, we only focus on the non-failure scenario. Therefore, constraints (10) and (11) do not apply. Once Step 1 is completed, binary parameters β^f_d are computed given the routes of the working traffic at the IP/MPLS layer and the physical lightpaths that support the virtual links carrying traffic (output values of decision variables x^0_{ild} and z_{ilpw}) and are used in Step 2. Moreover, x^0_{ild} values and z_{ilpw} values that equal to 1 are also inserted as constraints in Step 2, thus keeping the working routes and lightpaths supporting those routes fixed, which allows us to know which demands are affected under each failure scenario in advance.

4 Performance comparison

We use the proposed network design approach in the two different backbone network scenarios depicted in Fig. 2, namely, a Pan-European like network of 11 nodes and 18 bidirectional links with average link distance of 525 km (hereafter referred as EON), as well as the Deutsche Telekom (DT) National Backbone network of 12 nodes and 20 bidirectional links with average link distance of 243 km. In both networks, 16 bidirectional wavelengths per fiber link have been assumed.

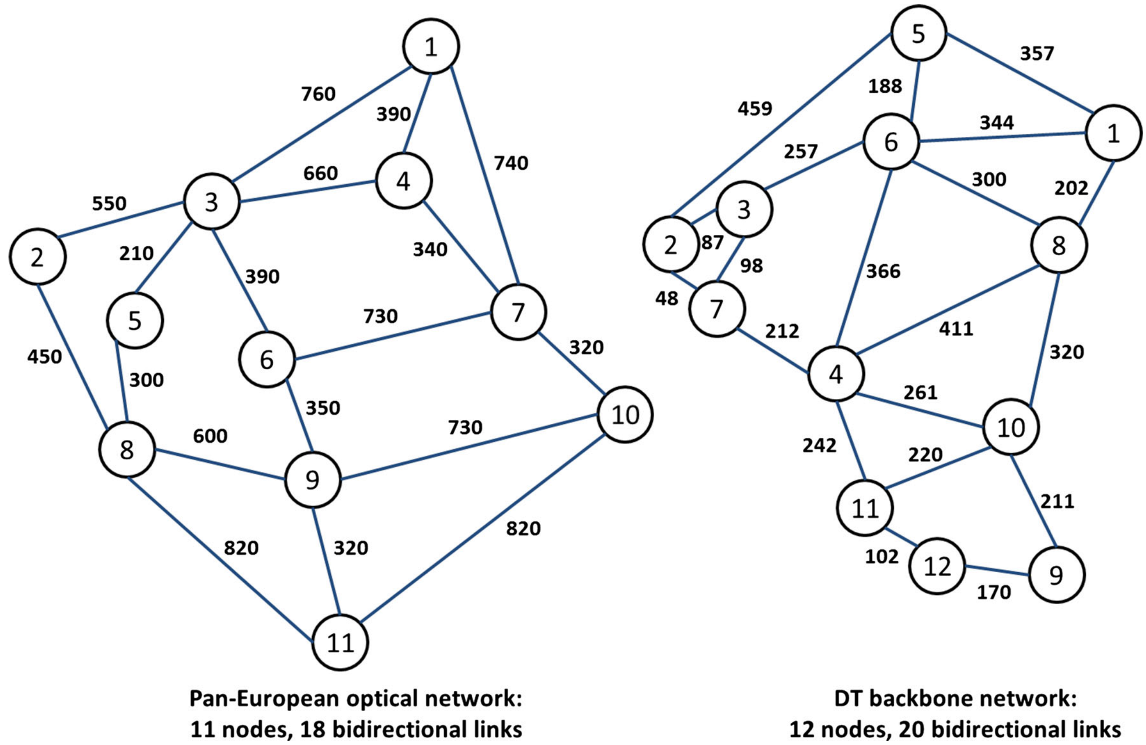

Fig. 2 Backbone network topologies under evaluation (link distances are shown in km)

Regarding the offered traffic characteristics, a peak traffic matrix with 80 randomly distributed bidirectional packet flow requests at 10 Gb/s (50 %), 40 Gb/s (30 %) and 100 Gb/s (20 %) is separately generated for each network, making up a total offered load around 6 Tb/s in both cases. To populate the set *P* of physical paths over *G* onto which virtual link lightpaths are established, only the shortest path between every pair of nodes is contemplated, which allows us keeping the complexity of the model within reasonable limits. Please recall, however, that the core ILP formulation in the proposed approach is generic enough to accept any potential number of physical paths between node pairs. Furthermore, the formulation allows complete freedom when routing demands at the IP/MPLS layer, which enables efficient traffic grooming. As for the network equipment cost details, we take the TXP costs previously presented in Table 1. In addition, we assume router ports at 10 Gb/s with cost 1.1 (i.e., 1 c.u. + 0.1 c.u. as the average processing cost of 10 Gb/s in a router, derived from [11]).

Table 2 depicts the details of the survivable IP/MPLS over SLR/MLR/Elastic DWDM optical network design minimizing CAPEX in the evaluated EON and DT network topologies. This table also shows the number of equipped devices and cost that would only be needed for an unprotected network design (output of Step 1 of the proposed approach), which helps highlighting the amount of resource overprovisioning required to make the network survivable against any single link failure. Such unprotected and survivable scenarios are referred as UN and SURV in the table, respectively. An additional column named Overprov. (%) is also introduced, which quantitatively depicts the percentage of overprovisioned router port and TXP capacity required in every case to make the network survivable. To solve the related ILP problem instances, the CPLEX v12.5 optimization software has been used, setting an optimality gap of 1 and 3 % in Step 1 and 2 of the approach, respectively.

Looking at the results in Table 2, we can identify that SLR and Elastic DWDM layer technologies lead to almost identical total network cost. One might easily expect this, since SLR and Elastic TXPs have identical maximum capacity and transparent reach, so any small difference between them can only be attributed to the optimality gaps of CPLEX. Conversely, focusing on the MLR DWDM layer technology, its cost-effectiveness against SLR and Elastic differs in the EON or DT network scenario. While MLR in EON yields very minor but still appreciable network design cost savings, it leads to slightly increased cost in the DT network. A result like this one can be explained by the smaller transparent reach of the TXPs at 100 Gb/s in MLR compared to SLR and Elastic (i.e., 800 km against 1,200 km [8]), which prevents the establishment of high-capacity lightpaths between far-off nodes, thus demanding more router ports due to the additional hops of the packet flows at the IP/MPLS layer. This effect is not appreciated in the EON

Table 2 Network design: number of equipped devices and cost

Scenario	DWDM layer	Router ports		TXPs @ 10G		TXPs @ 40G		TXPs @ 100G		Elastic TXPs		Overprov. (%)		Total cost (c.u.)	
		UN	SURV	UN	SURV	UN	SURV	UN	SURV	UN	SURV	Ports	TXPs	UN	SURV
EON (11 nodes, 18 links)	SLR	780	1,052	–	–	–	–	84	140	–	–	34.9	66.7	1,362	1,997
	MLR	740	1,020	62	54	42	80	56	94	–	–	37.8	66.3	1,338	1,980
	Elastic	784	1,042	–	–	–	–	–	–	84	140	32.9	66.7	1,366	1,986
DT network (12 nodes, 20 links)	SLR	622	902	–	–	–	–	78	142	–	–	45.0	82.1	1,152	1,844
	MLR	674	978	28	26	36	50	56	103	–	–	45.1	71.6	1,213	1,870
	Elastic	636	902	–	–	–	–	–	–	76	142	41.8	86.8	1,156	1,844

case although having longer links due to its topological characteristics, making nodes to be uniformly better connected among them. Regarding the percentage of overprovisioned router port and TXP capacity to make the network survivable, we see that less overprovisioning in terms of router port capacity than TXP capacity is required, thanks to the reutilization of router ports among in the different failure scenarios enabled by the equipped C-FXCs. In general, we identify that the DT network requires higher capacity overprovisioning to make the network survivable compared to the EON, which again can be attributed to its less favorable topological characteristics.

Taking these network designs, we now quantify the total power consumption of the EON and DT network designs in the non-failure state, that is, the normal state in which the network operates most of the time. Specifically, different offered load values have been considered (100, 75, 50, 25 %) by scaling the load of the original offered demands while keeping demand routes at the IP/MPLS layer fixed (i.e., no dynamic demand re-routing for traffic engineering purposes is contemplated). For the IP layer, works typically assume that routers consume between 10 and 20 W/Gb/s [7], including router processing and line cards. In this work, we decouple the power consumption of the processing, which is traffic dependent, from that of the router port short-reach interfaces, which is traffic independent. For the processing, 10 W/Gb/s is assumed, whereas for each short-reach interface, 56 W is considered [7]. Following the same UN and SURV nomenclature, we differentiate between unprotected and survivable network design energy consumption (i.e., outcomes of Step 1 and 2 of the proposed approach, respectively), which allows us to highlight the power consumption of the overprovisioned resources for survivability purposes, namely, the difference between the power consumption of the SURV and UN network designs. The obtained power consumption results are shown in Tables 3 and 4.

Looking at Table 3, the optical layer power consumption with SLR and MLR DWDM technologies remains constant with the offered load in the EON, since TXPs are always operating at the maximum data rate, thus consuming the same. These power consumption values are substantially lower with MLR, though, which benefits from the lower power consumption of TXPs at 10 and 40 Gb/s. In contrast, Elastic adapts the data rate of the TXPs to the traffic they are carrying, saving power in this way. For instance, focusing in the SURV scenario in Table 3, Elastic can reduce the optical layer power consumption of SLR by 10.5 kW for a 100 % offered load, while such a reduction increases to 22.5 kW when the offered load falls to 25 %. These power consumption benefits are maximized in the SURV scenario, since the data rate of all those overprovisioned TXPs for survivability, unused in non-failure conditions, can also be lowered to the minimum power state (running at 25 Gb/s). Regard-

Table 3 EON network power consumption versus offered load (non-failure scenario)

DWDM layer	Load = 25 %		Load = 50 %		Load = 75 %		Load = 100 %	
	UN	SURV	UN	SURV	UN	SURV	UN	SURV
Optical layer								
SLR	29.4	49	29.4	49	29.4	49	29.4	49
MLR	25.9	41.6	25.9	41.6	25.9	41.6	25.9	41.6
Elastic	15.9	26.5	17.3	27.9	21.2	31.8	27.9	38.5
IP layer (router ports)								
SLR	43.7	58.9	43.7	58.9	43.7	58.9	43.7	58.9
MLR	41.4	57.1	41.4	57.1	41.4	57.1	41.4	57.1
Elastic	43.9	58.4	43.9	58.4	43.9	58.4	43.9	58.4
IP layer (processing)								
SLR	33.6	33.6	67.1	67.1	100.7	100.7	134.2	134.2
MLR	32.6	32.6	65.1	65.1	97.7	97.7	130.2	130.2
Elastic	33.7	33.7	67.3	67.3	101	101	134.6	134.6
Total power consumption (IP + optical)								
SLR	106.7	141.5	140.2	175	173.8	208.6	207.3	242.1
MLR	99.9	131.3	132.4	163.8	165	196.4	197.5	228.9
Elastic	93.5	118.6	128.5	153.6	166.1	191.2	206.4	231.5

Table 4 DT network power consumption versus offered load (non-failure scenario)

DWDM layer	Load = 25 %		Load = 50 %		Load = 75 %		Load = 100 %	
	UN	SURV	UN	SURV	UN	SURV	UN	SURV
Optical layer								
SLR	27.3	49.7	27.3	49.7	27.3	49.7	27.3	49.7
MLR	23.7	41.1	23.7	41.1	23.7	41.1	23.7	41.1
Elastic	14.4	26.9	15.6	28	18.9	31.3	23.8	36.3
IP layer (router ports)								
SLR	34.8	50.5	34.8	50.5	34.8	50.5	34.8	50.5
MLR	37.7	54.8	37.7	54.8	37.7	54.8	37.7	54.8
Elastic	35.6	50.5	35.6	50.5	35.6	50.5	35.6	50.5
IP layer (processing)								
SLR	29.9	29.9	59.8	59.8	89.7	89.7	119.6	119.6
MLR	31.2	31.2	62.4	62.4	93.6	93.6	124.8	124.8
Elastic	30.3	30.3	60.5	60.5	90.8	90.8	121	121
Total power consumption (IP + optical)								
SLR	92	130.1	121.9	160	151.8	189.9	181.7	219.8
MLR	92.6	127.1	123.8	158.3	155	189.5	186.2	220.7
Elastic	80.3	107.7	111.7	139	145.3	172.6	180.4	207.8

ing the IP layer, we can see that the power consumption of the router ports remains constant with the offered load no matter which DWDM layer technology is employed, since short-reach interfaces are always operational. This is not the case of the power consumption due to processing, which is clearly influenced by the offered load to the network. Here, the power consumption differences perceived between mechanisms result from the length of the routes at the IP/MPLS layer in hops (i.e., MLR seems to yield slightly shorter routes at the IP/MPLS layer in the EON). Finally, looking at the total power consumption of the IP and optical layers together, we can observe that MLR is the most efficient DWDM layer technology in terms of power consumption for a load of 100 %, but as the offered load starts decreasing Elastic becomes the

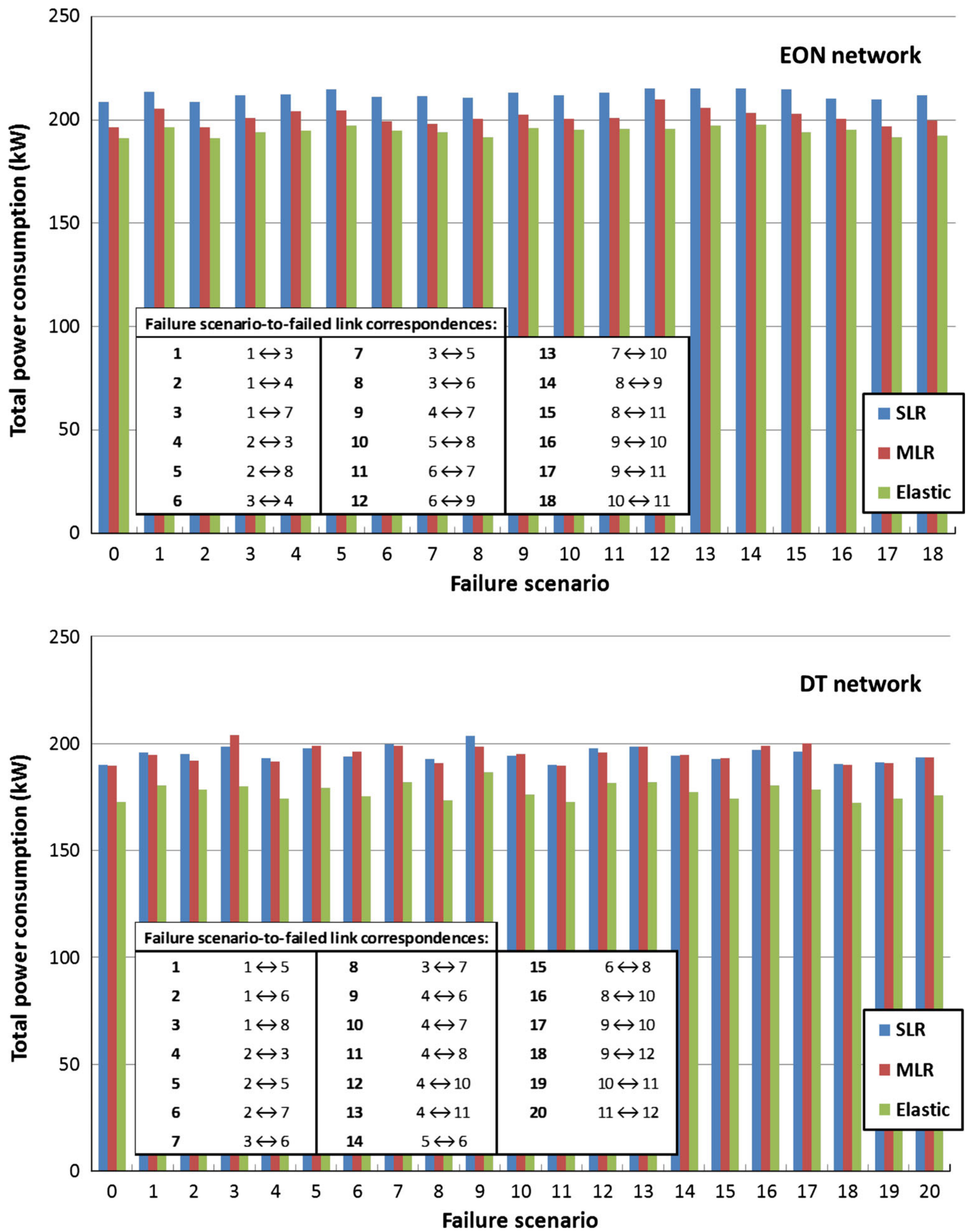

Fig. 3 Total power consumption (in kW) of the survivable IP/MPLS over SLR/MLR/Elastic DWDM optical network depending on the failure scenario and for an offered load of 75 %: EON network (*top*); DT network (*bottom*)

most interesting option, thanks to its capability to adapt the data rate and thus reducing the power consumption of the TXPs.

Similar results but for the DT network are shown in Table 4. Regarding the optical layer power consumption, SLR is the DWDM technology providing the least efficient performance, followed by MLR and Elastic as the most efficient one even with 100 % load. As for the IP layer power consumption due to the router ports, all DWDM technologies remain constant with the offered load as before (short-reach interfaces are always operational). Nonetheless, MLR consumes significantly more in this scenario, due to the large number of ports that the DT network design requires (i.e., as shown in Table 2). Moreover, since the routes at the IP/MPLS layer with MLR are longer in terms of hops, the IP layer power consumption due to processing is also higher. This eventually makes that the total power consumption of the IP and optical layers together in the DT network with MLR becomes significantly higher than Elastic for all offered loads, even for a 100 % offered load.

In addition, we can also compare the power consumption of the additional resources overprovisioned for survivability

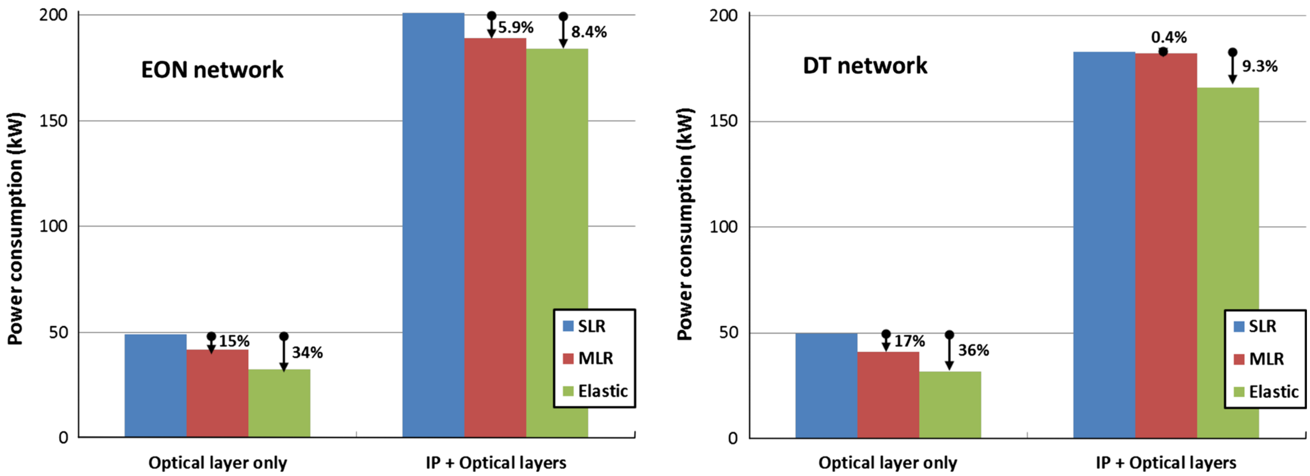

Fig. 4 Daily power consumption (in kW) of the survivable IP/MPLS over SLR/MLR/Elastic DWDM layer design: EON network (*left*), DT network (*right*)

in both EON and DT network scenarios, namely, the power consumption differences between UN and SURV network designs. For instance, in the EON network for a 100 % load the overprovisioned capacity at the optical layer consumes 19.6 and 15.6 kW, which is reduced to 10.6 kW in Elastic by setting the data rate of the overprovisioned TXPs for survivability to the minimum power state (i.e., operating at 25 Gb/s). Similar differences are also observed in the optical layer of the DT network. Regarding the IP layer, the power consumption of the overprovisioned router ports is directly proportional to the router port capacity overprovisioning percentages disclosed in Table 2, that is, around 33–38 and 42–45 % of the router port power consumption in the UN scenario with the EON and DT network, respectively.

In Tables 3 and 4, we have only focused on the power consumption of the EON and DT network in the non-failure state, namely, the operational state where the network will remain most of the time. Nevertheless, the interested reader may wonder about the differences in the network power consumption when the network is in failure. To provide answer to these questions, in Fig. 3, we plot the total network power consumption (in kW) when using SLR, MLR or Elastic in the optical layer, under the different failure scenarios in the EON (top bar graph) and DT network (bottom bar graph) scenarios. Please note that the survivable network design has been considered for both networks with an offered load of 75 % of the peak traffic, close to the average offered load along a typical daily traffic profile (e.g., like the one in [6], used later on in this section). Moreover, failure scenario 0 identifies the non-failure scenario in both bar graphs.

Looking at Fig. 3 (top), we observe that the total power consumption in the EON network shows minor variations with the failure scenario, no matter the DWDM layer technology used. Moreover, it is worth highlighting that the lowest power consumption is found for failure scenario 0, namely, the non-failure scenario. This can be expected, since the non-failure scenario typically leads to the shortest routes at the IP/MPLS layer, thus saving on router port usage and IP processing. When comparing SLR, MLR and Elastic, we can also see that the power consumption differences between them remain also quite constant along the failure scenarios, which reflects that the most power-efficient DWDM layer technologies, such as MLR and particularly Elastic, continue yielding power savings even when the network is in failure. Moving to Fig. 3 (bottom), we identify more variation on the power consumption along the failure scenarios, a sign of significantly longer backup routes compared to the primary ones (recall the higher overprovisioning % for the DT network in Table 2). Moreover, more significant power consumption differences between Elastic and MLR than in the EON network are found here, being MLR even less power-efficient than SLR in some failure scenarios.

Finally, the results in Tables 3 and 4 allow us to easily quantify the daily power consumption of survivable IP/MPLS over SLR/MLR/Elastic DWDM networks under a typical daily traffic profile as the one presented in [6]. In such a traffic profile, traffic variations are discretized in 8 periods along a day, where the offered traffic fluctuates among 100 % (11:30 am–19 pm, 22–23 pm), 75 % (9–11:30 am, 19–22 pm, 23–24 pm), 50 % (0–2 am, 7–9 am) and 25 % (2–7 am) of the peak traffic. These results for the EON and DT networks are depicted in Fig. 4.

Looking at Fig. 4 and focusing only on the optical layer, we observe that although MLR achieves significant power consumption reduction against SLR in both EON and DT networks, this one is clearly outperformed by Elastic, which can even double such a reduction (i.e, 34 versus 15 % in the EON network, and 36 versus 17 % in the DT network). Now, if we consider both IP and optical layers together, we can also see that the power consumption benefits that Elastic yield in the optical layer are indeed reflected in the overall network power consumption as well. For instance, by deploying Elastic DWDM technology in the EON network, an overall power consumption reduction of 8.4 % can be archived, whereas this overall power consumption reduction increases to 9.3 % in the DT network. Regarding MLR, it still provides appreciable benefits on the overall power consumption of the EON network (5.9 %), but fails in this endeavor in the DT network, leading to only 0.4 % overall power consumption reduction there, due to its additional router port necessities and longer routes at the IP/MPLS layer.

5 Conclusions

Survivable IP/MPLS over DWDM multi-layer optical networks require significant resource overprovisioning so as to ensure traffic recovery under any failure scenario. Such additional resources consume power even when unused. In this paper, we show how Elastic DWDM layer technologies can effectively decrease the power consumption of the optical layer in such multi-layer optical networks when compared to fixed single/mixed line rate DWDM layer technologies. From the obtained results on two different reference network topologies, we observe that Elastic can yield up to 36 % optical layer power consumption reduction when compared to SLR. This remarkable optical layer power consumption reduction is also translated into a significant 9.3 % overall network power consumption reduction when considering both IP and optical layers together.

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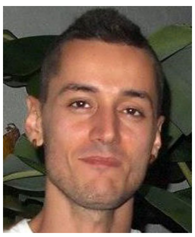

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