Energy-efficiency of protected IP-over-WDM networks with sleep-mode devices

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Abstract. Recently, the need for energy-efficient and sustainable capacity growth has become stringent for telecommunication networks and great efforts have been produced to reduce their power consumption. Optical technologies based on Wavelength Division Multiplexing are well-recognized as a promising solution for greening the future Internet. One relevant approach to achieve such power savings consists in aggregating traffic flows in few network links, so that power can be saved by switching-off some unused network devices. However, the need to ensure network resiliency against link and/or node failures imposes that still the resources reserved to protect connections become available immediately after a failure occurs. Therefore, a possible solution is to set some devices into low-power sleep-mode, so that they can be rapidly re-activated and provide fast connection recovery.

In this paper we focus on the power-efficiency of protected IP-over-WDM networks and provide a comprehensive comparison of four different protection strategies, namely Shared-Link, Shared-Path, Dedicated-Link and Dedicated-Path Protection (SLP, SPP, DLP and DPP respectively) in a sleep-mode scenario. In the proposed design strategies we assume that low-power sleep-mode is enabled for devices used for protection. Mathematical models for a power-aware design with sleep-mode are proposed for the four protection strategies. We show that relevant power savings (up to about 60%) can be obtained for all the protection strategies by setting protection devices into sleep-mode.

Keywords: IP-over-WDM networks, power-awareness, sleep-mode, shared, dedicated, link, path protection

1. Introduction

In the last few years, new high data-rate telecom services, such as Video on Demand (VoD), file-sharing and teleconferencing, are playing an increasingly important role in our everyday life. Thus, telecom network operators must increase network capacity to cope with the Internet traffic growth, which is envisioned [14] to be around 40% in the coming years, corresponding to a growth factor of 1000 in about 20 years. Such traffic growth is also causing a rapid increase in the overall network energy consumption, which is undesirable since the current energy footprint of the ICT sector is already a substantial amount of the global electricity requirements in the world.

Therefore, a new energy-efficient strategy for network management needs to be investigated in order to jointly reduce the impact of Operational Expenditures (OpEx), mainly related to power consumption, and Capital Expenditures (CapEx), i.e., the deployment of network equipment. Optical networks based on Wavelength Division Multiplexing (WDM) have been widely studied and many solutions have been proposed to drastically reduce their power consumption [2,4,5], mainly because they enable a substantial reduction of Electronic/Optical (EO) and Optical/Electronic (OE) signal-conversion operations. For this reason optical networks are universally recognized as the key enabler for future green communication networks.

Another critical issue in network design and operation is the network resilience to failures. When provisioning network capacity, operators reserve additional (protection) resources, which can be exploited in case devices
failures occur along the currently used (i.e., working) resources. Protection strategies can be coarsely classified in two main categories, i.e., dedicated and shared protection. In the former case a specific subset of the protection resources is exclusively dedicated to each established connection, whereas in the latter scenario protection resources (i.e., protection paths) can be shared by two or more working paths, provided that the different connections which share the same protection resources do not share resources also in their working paths. In current mode of operation redundant devices are usually powered-on regardless if they are used or not. In the energy-efficient scenario analyzed in this paper some network elements can be set into a low-power (sleep) mode when they are idle, so that the overall consumed power can be reduced. In such a scenario a trade-off between minimization of protection resources and minimization of power consumption arises, as in the former case operators tend to equally distribute traffic over the network, while in the latter case traffic flows are typically aggregated to switch-off or set into sleep-mode as many devices as possible (i.e., traffic grooming is preferred) [16, 17].

In this context, we perform a power-aware protected network design to minimize the power consumption considering the possibility of setting devices into low-power mode as a promising solution to achieve substantial power savings in resilient IP-over-WDM (IPoWDM) networks.

Research interest in the energy-efficiency of protected optical networks is relatively recent and only few contributions on this topic have already appeared in the literature. In [11], authors provide an integer linear programming (ILP) formulation to propose an energy-aware design strategy in WDM networks with dedicated protection resources which can be set into sleep-mode. Moreover, in [9] a more scalable heuristic approach is proposed to solve the same problem, whereas in [3] the power consumption issue is investigated for the shared protection case. Furthermore, energy-efficiency in protected WDM networks has been also studied under dynamic traffic conditions, for dedicated [6] and shared [1] protection cases. However, in most of these papers the power consumed by devices in sleep-mode is neglected, leading to a substantial underestimation of the protection resource power, and the analysis is always performed without considering traffic grooming (i.e., entire-wavelength connections are considered), thus neglecting its effects and energy-benefits.

In this paper we extend our previous work [13] by providing an ILP formulation for a power-aware design of IPoWDM networks where low-power sleep-mode devices are used for backup lightpaths provisioning. With respect to [13] we include the cases of Shared-Link and Shared-Path Protection (SLP and SPP, respectively) and provide a comprehensive comparison, in terms of energy-efficiency, of these protection strategies with the Dedicated-Link and Dedicated-Path Protection cases (DLP and DPP, respectively).

The remainder of this paper is organized as follows. In Section 2 we describe the IPoWDM network architecture considered in the paper, whereas in Section 3 the different components contributing to total power consumption are shown. In Section 4 the different protection strategies are described and the corresponding ILP formulations, used to carry out the power-aware design of protected IPoWDM networks, are discussed in Section 5. The obtained numerical results are shown and discussed in Section 6. Finally, the conclusion is drawn in Section 7.

2. IP-over-WDM network model

In this paper we consider a network architecture where IP routers are interconnected through optical fiber links which optically transmit the signal exploiting the WDM technique. Several network elements are needed to support a connection among the routers within IPoWDM networks (see Fig. 1). The electronic signals are generated by the IP routers and then converted into the optical domain by the WDM transponders, thus a wavelength channel (i.e., a lightpath) is initiated. The parallel lightpaths \( \lambda_s \) are then multiplexed into the same optical fiber link (note that in this work we consider single-fiber links) through an optical multiplexer and transmitted towards the next IP router, where wavelengths are first demultiplexed and then OE converted by WDM transponders. Along the fiber links, signals are optically amplified via Erbium Doped Fiber Amplifiers (EDFAs), which are typically placed with

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1 We assume a sleep mode state for devices such that the activation of the idle devices can be readily accomplished and they can be properly configured in case of failure.
Fig. 1. IP-over-WDM network architecture. (Colors are visible in the online version of the article; http://dx.doi.org/10.3233/JHS-130463.)

an 80 km span. Two more EDFAs are usually deployed at the edges of the WDM link as booster and pre-amplifier, respectively. Note that in this paper we do not consider optical switching, i.e., network nodes are not equipped with Optical Cross Connects (OXC), since we assume that signal switching is accomplished in the electronic layer through IP routers.

3. Power contributions

Based on the network architecture described above, in our study we consider the following power consumption contributions.

Electronic processing. This contribution arises when traffic is electronically processed by IP routers. The power consumption of electronic processing is assumed to be composed of two components, on the line of [15]. (1) A fixed power consumption that accounts for basic node operations (e.g., network control, electronic switch matrix, cooling, etc.). It amounts to $P_0 = 2401$ W for a 16-slot rack with a total capacity of 2240 Gbit/s. (2) A traffic-dependent power consumption is also due, according to the number of lightpaths initiated or terminated in the node. It accounts for the power consumption of slot-cards and port-cards and is assumed to be $P_t = 437$ W for every 40 Gbit/s channel. We assume that the router fixed (traffic-independent) power contribution is always due, i.e., we do not consider its consumption in sleep-mode. This is because in the considered case studies (see Section 6) every node is source and/or destination of at least one connection request. Moreover, we assume that the variable (traffic-dependent) contribution is negligible when devices (slot and port cards) are in sleep-mode.

WDM transponders. These elements are transmitter/receiver devices and their consumption is evaluated according to [10]. The power consumption for 40 Gbit/s transmitters and receivers is estimated to be equal and amounts to $T_a = T_a = 79.4$ W for devices in active state, i.e., when they are actually transmitting or receiving data. Whereas, their consumption in sleep-mode (e.g., when they are used for protection paths) is much lower, namely $T_i = T_i = 9.84$ W, basically accounting for only the lasers and photodiodes consumption. Indeed the time required to power-on optical devices is much longer than that needed to activate the electronic side of transponders, e.g., needed for Forward Error Correction (FEC) and drivers, so that the WDM (optical) side of transponders must be maintained into the active state.

WDM links. Their consumption is mainly due to EDFAs, and is considered as independent of the amount of carried traffic. However, it is related to the physical length of the optical fiber link, as one EDFA is deployed every 80 km and consumes $L_0 = 55$ W [15]. Moreover, when a certain WDM link does not carry any working paths, it can be set to sleep-mode (the corresponding power consumption is neglected in this work, i.e., $L_i = 0$).

Table 1 summarizes the aforementioned power contributions.

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2Note that considering a case study (i.e., a traffic matrix) where one or more IP routers are only used as intermediate nodes for connections (i.e., they are not the generating or receiving node for any connection) a more detailed evaluation should be performed for the power consumption of IP routers in sleep-mode. Indeed, in this case, we should consider various components (forwarding engine, switching matrix, control etc.) and also the fact that different components have different wake-up times. Thus only a subset of such components can be set in sleep-mode. However, this detailed analysis is kept as future work.

3With respect to [10] we neglect some contributions, i.e., local oscillators and digital signal processor, as they are needed for the 100 Gbit/s coherent technology, and client-side, which is already considered in the traffic-dependent electronic processing contribution.
Table 1

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Power consumption in ACTIVE state</th>
<th>Power consumption in IDLE state</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic-independent (basic node)</td>
<td>$P_0 = 2401$ W [15]</td>
<td></td>
</tr>
<tr>
<td>WDM transponders</td>
<td>40 Gbit/s transponder</td>
<td>40 Gbit/s transponder</td>
</tr>
<tr>
<td>WDM links</td>
<td>$L_0 = 55$ W</td>
<td>$L_i = 0$ for one EDFA [15]</td>
</tr>
<tr>
<td>Electronic processing (slot &amp; port cards)</td>
<td>$P_t = 437$ W [15]</td>
<td>$P_t = 0$</td>
</tr>
</tbody>
</table>

4. Protection strategies

In this paper we compare four different protection strategies from the power consumption point of view, namely Dedicated-Link, Dedicated-Path, Shared-Link and Shared-Path Protection (DLP, DPP, SLP and SPP, respectively). Note that in this work, the protection strategies are intended as performed at the IP-flow level, i.e., we reserve backup resources for protection by considering every connection, generated at the IP layer, separately and independently from the others.

In dedicated protection strategies (DLP and DPP), protection resources are exclusively reserved for the different connections. Therefore, in these cases, a high amount of redundant resources is employed to protect all the connections. Here we assume that dedicated protection is a 1:1 protection, i.e., for each traffic flow transmitted over a working path, we only reserve the capacity in a protection path, which does not carry traffic until the failure occurs. On the other hand, in shared protection cases (SLP and SPP), redundant capacity reserved for protection can be shared by two or more different connections, as long as the working paths protected through the same resources are link (or node) disjoint. In these cases, redundant resources are efficiently exploited, though shared protection strategies can only be used when a single-link (or node) failure is allowed at the same time.4

Furthermore, for the link protection cases, every link connecting two nodes A and B is protected reserving the capacity along an alternative route which connects A to B. Instead, in the path protection strategies, the whole end-to-end working path is protected by reserving backup capacity along a node-disjoint (and, consequently, link-disjoint) path.

In Fig. 2 we show how two connections are routed over the working paths $w_1$ and $w_2$ and how the protection resources $p_1$ and $p_2$ are reserved in the four cases.

For the DLP case we show in Fig. 2(a) two connection requests which are routed along the working paths C-A-B-D ($w_1$) and E-A-B ($w_2$), respectively. For sake of clarity, in Fig. 2(a) we only show the resources ($p_1$ and $p_2$) reserved to protect link A-B used by both $w_1$ and $w_2$. We assume that the two connections are protected independently. For instance, if link A-B fails, the traffic belonging to the two connections is routed over two routes (A-E-B and A-F-B for $p_1$ and $p_2$, respectively), both starting in node A and ending in node B.

In Fig. 2(b) we show two connections protected according to the DPP strategy. Protection paths and working paths of a same connection are node-disjoint (except for source and destination nodes). Note that if two (or more) protection paths use the same physical link (e.g., link E-B in Fig. 2(b)), the protection capacity reserved on this link is the sum of the capacity required by the two (or more) connections (i.e., $C_{EB} = C_{p1} + C_{p2}$), since protection resources are exclusively dedicated to every request.

When protection resources are shared among the different connections, significant savings can be obtained in terms of protection capacity (and consequently, devices power consumption). In the SLP and SPP cases (shown in

4The single-point failure condition is sometimes expressed as a relation among the Mean Time To Recover (MTTR) from a link (or node) failure and the Mean Time Between Failures (MTBF, i.e., the average elapsed time between two consecutive failures), that is, $MTTR \ll MTBF$. 


Fig. 2. Different protection strategies under analysis. (a) Dedicated link protection, (b) dedicated path protection; (c) shared link protection and (d) shared path protection. (Colors are visible in the online version of the article; http://dx.doi.org/10.3233/JHS-130463.)

Fig. 2(c) and (d), respectively, if two (or more) protection paths use the same link (e.g., link A-F in Fig. 2(c) and link E-B in Fig. 2(d)), the capacity reserved on these links is calculated as the maximum of the capacity required by the two demands. However, the two working paths \( w_1 \) and \( w_2 \) shown in Fig. 2(c) and (d) cannot be protected if a concurrent failure of, e.g., links A-B and E-F occurs (for sake of clarity, in Fig. 2(c) we only show the resources \( p_1 \) and \( p_2 \) reserved to protect links A-B and E-F used by connections \( w_1 \) and \( w_2 \), respectively).

From the power consumption point of view, sharing backup capacity enables power savings due to lower protection resources deployment. However, as we will show in Section 6, the possibility of setting backup resources into sleep-mode substantially reduces the amount of additional energy resulting from the adoption of dedicated protection strategies, since the power consumed by sleep-mode devices is much lower than that required for active devices. As an example, consider devices deployed in link E-B of Fig. 2(b) and (d). Assuming that the two connections \( w_1 \) and \( w_2 \) require an entire 40 Gbit/s wavelength each, the only difference, in terms of power consumption, between the DPP and SPP cases is given by the WDM transponders consumption, as both electronic processing and EDFAs contributions are negligible when such devices are in sleep state (see Table 1). In this case the WDM transponders power contribution for backup resources in link E-B is equal to \( 2 \cdot (T_i + R_i) \approx 40 \) W in the DPP case and \( (T_i + R_i) \approx 20 \) W in the SPP case, since in the latter case the capacity of only one wavelength is reserved and shared by \( p_1 \) and \( p_2 \). Therefore, the gain of 20 W per link obtained in the SPP case is low in comparison to the total power consumed by the same resources to transmit the two (working) connections over one link. Indeed the consumption due to active WDM transponders is \( 2 \cdot (T_a + R_a) \approx 320 \) W,\(^5\) therefore enabling sleep-mode for protection resources would lead to a lower percentage saving in the SPP case with respect to the DPP one.

5. ILP model for power-aware design of protected networks

We now formally state the problem of power-aware design of protected IPoWDM networks, which we model by means of four ILP flow-based formulations for the four protection strategies under comparison. The input

\(^5\) Note that, to evaluate the total consumption due to transmit two working wavelengths over one link, we should also include the traffic-dependent electronic processing and the EDFAs contributions, which would make the overall consumption much higher than 320 W.
5.1. Shared Link Protection (SLP)

Variables. The variables are basically the same for all the four protection strategies (minor changes will be specified in the following). For the SLP they are defined as follows:

- \( w_{mn} \) (binary): is equal to 1 if the working path of request \( r \in R \) uses link \((m, n) \in A\), otherwise it is equal to 0;
- \( p_{xy}^{mnr} \) (binary): is equal to 1 if traffic of request \( r \in R \) routed on the working path \((m, n) \in A\) is protected using link \((x, y) \in A\), otherwise it is equal to 0;
- \( h_m \) (binary): is equal to 1 if any working path traverses node \( m \in N \), otherwise it is equal to 0;
- \( k_{mn} \) (binary): is equal to 1 if any working path traverses link \((m, n) \in A\), otherwise it is equal to 0;
- \( j_{xy} \) (binary): is equal to 1 if link \((x, y) \in A\) is used only for protection paths, otherwise it is equal to 0;
- \( \sigma_{mn} \) (integer): number of wavelengths used for working paths in link \((m, n) \in A\);
- \( \pi_{xy} \) (integer): number of wavelengths used for protection paths in link \((x, y) \in A\).

Objective function

\[
\text{minimize } \left\{ \sum_{m \in N} P_0 h_m + 2 P_t \sum_{(m, n) \in A} \sigma_{mn} + L_0 \sum_{(m, n) \in A} A_{mn} k_{mn} + L_i \sum_{(x, y) \in A} A_{xy} j_{xy} + \left( T_a + R_a \right) \sum_{(m, n) \in A} \sigma_{mn} + \left( T_i + R_i \right) \sum_{(x, y) \in A} \pi_{xy} \right\}.
\]

Constraints

\[
\sum_{n \in N} w_{mn} - \sum_{n \in N} w_{nm} = \begin{cases} 1, & m = s_r, \\ -1, & m = d_r, \\ 0, & \text{otherwise} \end{cases} \quad \forall m \in N, r \in R,
\]

\[
\sum_{y \in N} p_{xy}^{mnr} - \sum_{y \in N} p_{yx}^{mnr} = \begin{cases} w_{mn}^r, & x = m, \\ -w_{mn}^r, & x = n, \\ 0, & \text{otherwise} \end{cases} \quad \forall x \in N, (m, n) \in A, r \in R,
\]

\[
p_{xy} = 0 \quad \forall (m = x, n = y) \in A, r \in R,
\]

\[
h_n \geq \sum_{r \in R} \sum_{m \in N} \frac{(w_{mn}^r + w_{nm}^r)}{M} \quad \forall n \in N,
\]

\[
\frac{1}{M} \sum_{r \in R} w_{mn}^r \leq k_{mn} \leq \sum_{r \in R} w_{mn}^r \quad \forall (m, n) \in A,
\]
The objective is to find the minimum total power consumed by the IPoWDM network. The total power consumption consists of five contributions:

(i) The term within round brackets is the electronic processing consumption, which is formed by the basic-node consumption and the traffic-dependent consumption due to slot and port cards (the factor 2 is needed as, for each link \((m, n)\), the slot and port cards consumption must be accounted for both nodes \(m\) and \(n\)).

(ii)–(iii) The second and third terms account for power consumed by EDFAs in active and idle links, respectively.

(iv)–(v) Finally, the fourth and fifth terms evaluate the consumption due to transmitters/receivers in active and sleep states.

The flow-conservation constraints are expressed by Eq. (2), where we assume non-bifurcated traffic. The protection links corresponding to every working links are set by Eq. (3). With constraints (4) we impose that working and protection resources are link-disjoint. Through constraints (5) the nodes traversed by any working paths are activated. To activate working links a similar set of constraints is applied in (6), where the variable \(k_{mn}\) is also forced not to assume value 1 in case no working paths traverse link \((m, n)\). Similarly, with constraints (7) sleep-mode links are selected. Note that, for each link \((x, y)\), at most one variable among \(k_{xy}\) and \(j_{xy}\) can be set to 1 and, considering both set of constraints (6) and (7), if there is at least one working path in link \((x, y)\), i.e., \(k_{xy} = 1\), then the corresponding \(j_{xy}\) is set to 0. Finally, constraints (8) and (9) calculate, respectively, the number of working and protection wavelengths to be reserved in every link, whereas constraints (10) impose a threshold for the number of wavelengths which can be used in every link (capacity constraint).

5.2. Shared Path Protection (SPP)

Variables. The variables used in this case are the same as in the SLP scenario, except for variable \(p_{mn}^{r,xy}\), which now becomes \(p_{r,xy}\), as we do not need to protect single links but the whole end-to-end working path of each request. Moreover, an additional variable is needed to evaluate the amount of protection resources to reserve in each link, i.e., to compute the number of paths protected by each link. The newly introduced variable is defined as follows:

- \(p_{r,xy}\) (binary): is equal to 1 if the protection path of request \(r \in R\) uses link \((x, y) \in A\), otherwise it is equal to 0.
- \(z^{r,xy}_{mn}\) (binary): is equal to 1 if, for the request \(r \in R\), the working path traverses link \((m, n) \in A\) and the protection path uses link \((x, y) \in A\), otherwise it is equal to 0.

Objective function. The objective function is expressed as in the previous case.

Constraints. The constraints needed in the SPP case are similar to Eqs (2)–(10), but now we have to consider the change in the flow variable \(p_{r,xy}\). Therefore, we maintain the constraints (2), (5), (6), (8) and (10), and add the

\[\frac{1}{M} \sum_{r \in R} \sum_{(m, n) \in A} p_{mn}^{r,xy} \leq j_{xy} + k_{xy} \leq 1 \quad \forall (x, y) \in A, \quad (7)\]

\[C \cdot \sigma_{mn} \geq \sum_{r \in R} t_{r} \cdot w_{mn} \quad \forall (m, n) \in A, \quad (8)\]

\[C \cdot \pi_{xy} \geq \sum_{r \in R} t_{r} \cdot p_{mn}^{r,xy} \quad \forall (m, n), (x, y) \in A, \quad (9)\]

\[\sigma_{mn} + \pi_{mn} \leq W \quad \forall (m, n) \in A. \quad (10)\]

Note that in this paper we neglect the power contribution due to EDFAs in sleep-mode (i.e., \(L_i = 0\)), but for a more accurate evaluation, it can be computed as in the objective function setting \(L_i \neq 0\).
following sets of constraints:

\[
\sum_{y \in N} p_{xy}^r - \sum_{y \in N} p_{yx}^r = \begin{cases} 
1, & x = s_r, \\
-1, & x = d_r, \\
0, & \text{otherwise}
\end{cases} \quad \forall x \in N, r \in R, (11)
\]

\[
\sum_{n \in N} (w_{mn}^r + p_{mn}^r) \leq 1 \quad \forall r \in R, m \in N | m \neq s_r. (12)
\]

\[
\frac{1}{M} \sum_{r \in R} p_{xy}^r \leq j_{xy} + k_{xy} \leq 1 \quad \forall (x, y) \in A, (13)
\]

\[
w_{mn}^r + p_{xy}^r - 1 \leq z_{mn}^{mnr} \leq w_{mn}^r + p_{xy}^r \quad \forall r \in R, (m, n), (x, y) \in A. (14)
\]

\[
C \cdot \pi_{xy} \geq \sum_{r \in R} t_r \cdot z_{mn}^{mnr} \quad \forall (m, n), (x, y) \in A. (15)
\]

With Eq. (11) the flow-continuity for protection paths is established for each request, whereas constraints (12) impose that they are node-disjoint with respect to the working paths. Moreover, constraints (13) are used to select idle links. Constraints (14) establish whether request \( r \) uses link \((m, n)\) for the working and link \((x, y)\) for the protection path, forcing variable \( z_{mn}^{mnr} \) to be equal to 1 if and only if both \( w_{mn}^r \) and \( p_{xy}^r \) are equal to 1 (i.e., \( z_{mn}^{mnr} = w_{mn}^r \cdot p_{xy}^r \)).\(^7\) Then, for each link, the number of wavelengths used for protection is computed through constraints (15).

5.3. Dedicated Link Protection (DLP)

Variables and objective function. The variables and the objective function considered for the DLP scenario are unchanged with respect to the SLP case.

Constraint. The constraints needed in this case are directly retrieved from the SLP case (Eqs (2)–(10)). However, as in the DLP case protection resources are dedicated to connections, the number of wavelengths used in each link for protection (constraints (9) for the SLP case) is now computed as follows:

\[
C \cdot \pi_{xy} \geq \sum_{r \in R} \sum_{(m, n) \in A} t_r \cdot p_{mn}^{mnr} \quad \forall (x, y) \in A. (16)
\]

5.4. Dedicated Path Protection (DPP)

Variables. The variables used in this case are the same as in the SPP scenario, except for variable \( z_{mn}^{mnr} \), which is not needed in this case.

Objective function. The objective function is expressed as in the previous cases.

Constraints. The constraints for the DPP scenario are the same as those used with the SPP strategy, except for constraints (14), which are not needed in this case, and (15), which compute the number of wavelengths used in each link for protection and are modified as follows:

\[
C \cdot \pi_{xy} \geq \sum_{r \in R} t_r \cdot p_{xy}^r \quad \forall (x, y) \in A. (17)
\]

The variables, objective function and constraints used in the four ILP formulations are reported in Table 2 for sake of clarity.

\(^7\)Note that constraints (14) do not apply if only one between \( w_{mn}^r \) and \( p_{xy}^r \) is equal to 1, as in this case we would simply have \( 0 \leq z_{mn}^{mnr} \leq 1 \) (i.e., \( z_{mn}^{mnr} \) is not constrained). However, in this case, variable \( z_{mn}^{mnr} \) will be set to 0 by the minimization of the objective function.


<table>
<thead>
<tr>
<th>Table 2</th>
<th>ILP formulations for the four protection strategies</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Variables</strong></td>
<td>SLP</td>
</tr>
<tr>
<td>( w_{rmn} ), ( p_{min} ), ( h_m ), ( k_{mn} ), ( J_{xy} ) (binary), ( \sigma_{mn} ), ( \pi_{xy} ) (integer)</td>
<td>( w_{min} ), ( p_{xy} ), ( h_m ), ( k_{mn} ), ( J_{xy} ) (binary), ( \sigma_{mn} ), ( \pi_{xy} ) (integer)</td>
</tr>
<tr>
<td>Objective function</td>
<td>( \min \left( \sum_{m \in N} P_0 h_m + 2P_t \sum_{(m,n) \in A} \sigma_{mn} \right) + L_0 \sum_{(m,n) \in A} A_{mn} h_{mn} + L_1 \sum_{(x,y) \in A} A_{xy} j_{xy} )</td>
</tr>
<tr>
<td>Constraints</td>
<td>(2)–(10)</td>
</tr>
</tbody>
</table>

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6. Results

We have tested the four ILP-based power-aware design strategies over the NSFNET network topology shown in Fig. 3, consisting of 14 nodes and 22 single-fiber bidirectional links (links lengths expressed in km are also shown in the figure), where \( W = 20 \) wavelengths are considered for each link direction. We have assumed a non-uniform directed traffic matrix as in [8] where a total amount of traffic of 180 Gbit/s is distributed among 54 source/destination pairs. We tested the four strategies also with the COST239 network topology (see [12] for topology details), considering a traffic matrix where connections are uniformly distributed between node couples, but no significant differences have been found with respect to the NSFNET case study, so in the following we only discuss results obtained in the latter case.

To solve the optimization problems in the different protection scenarios, we used ILOG CPLEX 12.0 solver on a workstation equipped with \( 8 \times 2.00 \text{ GHz} \) processors and with 32 GByte of RAM. With such problem instances (i.e., network size and traffic matrix), in most of the cases results within the 5% of the optimal values are obtained in no more than four hours.

In Table 3 we show the results obtained for the four different protection strategies, for an increasing factor \( f \) equal to 1, 2, 5, 10 and 20 and used to scale the bandwidth required by the connections.\(^8\) The proposed Power-Aware (PA) design strategies, where devices can be set into sleep-mode if they are only used for protection, are compared with the scenarios where protection devices are considered as fully powered-on (“all-ON” in the table).\(^9\) Moreover, we

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Note that when the connections bandwidth is scaled by a factor \( f = 20 \), in the DPP case the network is not able (i.e., the number of wavelengths is not sufficient) to support all the connections establishing both working and protection paths, mainly for two reasons: \( i \) more resources need to be reserved in the dedicated protection case with respect to the shared one; \( ii \) the node-disjoint constraint over working and protection paths in the path protection scenario is more restrictive than the link-disjoint one used in the link protection case.

\(^9\)In other words, in these cases the backup devices consume the same power as those used for working paths, i.e., \( P_t = 437 \text{ W}, T_t = T_a = R_t = R_a = 79.4 \text{ W} \) and \( L_t = L_a = 55 \text{ W} \), for power contributions due to slot and port cards, transmitting and receiving WDM transponders and EDFAs, respectively.
consider as benchmark the case of the unprotected network, where routing of non-resilient connections is carried out in a power-aware fashion.10

We observe that for all the protection strategies, the overall network consumption can be reduced by enabling low-power sleep-mode for protection devices, especially for higher bandwidth requirements (high values of \( f \)), when power savings ranging from \( \sim 39\% \) (SPP case) to \( \sim 59\% \) (DLP case) are obtained. This is due to the high impact of slot and port cards power contribution which increases with traffic. For lower traffic loads, the power advantage obtained with sleep-mode tends to reduce due to the lower amount of electronic processing needed. In any case, for every protection strategy, the power savings obtained using sleep-mode devices are maintained always above the 30% with respect to the corresponding all-ON case.

As expected, the shared protection scenarios have a slightly better behaviour in terms of power requirements with respect to the dedicated ones, since in the SLP and SPP cases less resources need to be reserved for protection paths. Note that in the all-ON scenarios this difference is more evident due to the much higher power contribution provided by protection devices in the dedicated protection scenarios. Considering the SLP and SPP strategies, it can be observed that the results are comparable in terms of power requirements (the difference between the two scenarios is below 1%) and, in general, the SLP scenario slightly outperforms the SPP one. Similar considerations can be drawn for the comparison between the DLP and DPP cases, where 1–2% of difference is observed in the power consumption values; however in this case it is not univocal which one is the best solution.

The negligible difference in the power consumption observed in the various protection strategies with sleep-mode devices is basically due to the fact that the main contribution to the total consumption is provided by the electronic processing (as shown in [7]), which is independent of the protection strategy and whose relative (percentage) impact does not depend on the overall supported traffic. In Fig. 4 we show the percentage of the three contributions (i.e., electronic processing \( P_e \), WDM transponders \( P_t \) and optical fiber links \( P_{\text{links}} \)) over the total power consumption when sleep-mode is assumed for protection devices. In the figure we only show the values for the SLP case, but comparable results can be drawn for the other protection strategies with sleep-mode and also for the unprotected network case. Indeed, the electronic processing contribution is around 70% of the total power consumption in all cases. On the other hand, the WDM transponders relative contributions increases with \( f \) since more wavelengths are needed to support all the traffic. Moreover, in general the power contribution due to links tends to decrease with \( f \), since once a link is utilized for working paths (i.e., its EDFAs are powered-on) its consumption is fixed. In fact, a small increase (in percentage) is observed in \( P_{\text{links}} \) when passing from \( f = 2 \) to \( f = 5 \). This corresponds to the point (i.e., overall traffic) when it is more convenient to power-on more links to support the higher traffic of working paths, rather than performing many grooming operations which require higher consumption due to slot and port cards.

In Fig. 5 we show the three power contributions (electronic processing, WDM transponders and optical fiber links) values in the four protection scenarios for both the sleep-mode and all-ON cases. The most relevant power saving obtained by adopting sleep-mode is observed at the IP-layer (\( P_e \)), especially for higher loads (note that the scale of y-axis is different in the three graphs of Fig. 5).

10In this case, the power-aware design for the unprotected network is performed using the same ILP formulation of Section 5.1, where we do not consider variables \( p_{\text{links}}^{\text{non}} \), \( j_{xy} \) and \( \pi_{xy} \) (i.e., these variables are set equal to zero), and neglect constraints (3), (4), (7) and (9).

Table 3

<table>
<thead>
<tr>
<th>Scaling factor</th>
<th>SLP sleep-mode</th>
<th>SLP all-ON</th>
<th>SPP sleep-mode</th>
<th>SPP all-ON</th>
<th>DLP sleep-mode</th>
<th>DLP all-ON</th>
<th>DPP sleep-mode</th>
<th>DPP all-ON</th>
<th>Unprotected</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f = 1 )</td>
<td>73.791</td>
<td>110.297</td>
<td>73.89</td>
<td>108.054</td>
<td>74.008</td>
<td>120.057</td>
<td>73.89</td>
<td>115.321</td>
<td>73.398</td>
</tr>
<tr>
<td>( f = 2 )</td>
<td>86.469</td>
<td>130.672</td>
<td>86.469</td>
<td>121.974</td>
<td>86.902</td>
<td>148.835</td>
<td>87.301</td>
<td>136.661</td>
<td>85.859</td>
</tr>
<tr>
<td>( f = 5 )</td>
<td>121.365</td>
<td>185.6</td>
<td>121.954</td>
<td>186.406</td>
<td>122.388</td>
<td>232.027</td>
<td>121.817</td>
<td>203.591</td>
<td>120.381</td>
</tr>
<tr>
<td>( f = 20 )</td>
<td>270.23</td>
<td>455.448</td>
<td>270.992</td>
<td>442.877</td>
<td>274.186</td>
<td>662.191</td>
<td>not supported</td>
<td>266.806</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 4. Percentage of the different power contributions over the total power consumption for increasing scaling factor $f$ (the values are depicted for the SLP scenario but no relevant differences are observed with the other protection strategies). Sleep-mode is assumed for protection devices.

Fig. 5. Increase of power contributions with traffic scaling factor $f$ for the different protection strategies: contributions due to (a) electronic processing ($P_e$), (b) WDM transponders ($P_{tr}$) and (c) links ($P_{links}$). (Colors are visible in the online version of the article; http://dx.doi.org/10.3233/JHS-130465.)
Comparing the proposed Power-Aware design strategies with sleep-mode devices with the unprotected network scenario shown in Table 3, it can be seen that only a small additional power (on the order of 1–2% for every protection strategy) is required to establish protection paths. This small percentage of additional power corresponds to the additional devices in sleep-mode installed for protection purposes.

Moreover, for all the four protection scenarios, we compare the proposed Power-Aware strategies with the Power-Unaware (PU) cost-minimized design. In this PU scenario the objective of the optimization consists of minimizing the number of used wavelengths for both working and protection paths, i.e., we aim at minimizing the cost function \( CF = \sum_{(m,n) \in A} (\sigma_{mn} + \pi_{mn}) \). Note that also in the PU scenarios we consider protected networks. In these cases the total network power consumption is computed \textit{a posteriori}, i.e., after the cost-minimized design has been solved.

In Fig. 6 we show the percentage power saving obtained with the PA strategies with respect to the PU ones. In general, the relative gain tends to decrease for higher loads, where performing traffic grooming in a power-aware fashion is less important (higher-traffic connections leave less flexibility to grooming). In fact, when the design aims at minimizing the number of used wavelengths, connections tend to be groomed together as much as possible, especially when the offered traffic granularity is low, so longer routes are preferred and large amount of power-hungry OE and EO conversions and electronic processing operations are needed. An exception to this behaviour is observed in the DPP case, where the percentage gain of the power-aware strategy compared to the power-unaware one increases with the traffic load. This is due to the fact that in the PU-DPP case a high number of resources is required (since the protection resources are exclusively reserved for each connection and the node-disjointness constraint used in the path protection strategy is much more restrictive than the simple link-disjoint one) and, as the solution tends to jointly minimize the length of working and protection paths, longer working paths are employed with respect to the PA-DPP case, where setting protection devices into sleep-mode makes the power-aware design strategy use shorter working paths and longer protection paths. In other words in the PU-DPP case, on average the number of hops (and, consequently, the number of OE and EO conversions and the amount of electronic processing) of working and protection paths is similar, since the overall number of used wavelengths (for both working and protection paths) is minimized; on the other hand, in the PA-DPP scenario, working paths tend to be shortened at the cost of longer protection paths which can be set into sleep-mode, thus saving power.

Another exception to the previous statement is obtained for the SPP case with \( f = 2 \), when the relative gain of PA strategies with respect to PU ones is higher than the case for \( f = 1 \). This is due to the much higher increase of links power contribution obtained in the PU case with respect to the PA case when passing from \( f = 1 \) to \( f = 2 \). Indeed, in the PU case the \textit{overall} number of used wavelengths is minimized with no interest on performing load balancing of wavelengths over the fiber links; on the other hand, in the PA case wavelengths tend to be aggregated in few links to save power.

![Fig. 6. Percentage power consumption gain obtained with respect to power-unaware strategies for the four protection strategies.](image-url)
In general, the optimal solution in the power-aware cases with sleep-mode emerges out of a trade-off among shortest-path routing (which tends to minimize the number of links traversed by a connection), traffic grooming of connections (which tries to minimize the number of wavelength channels used), and aggregation of protection paths in the same links (which maximizes the number of links which can be put into sleep-mode).

7. Conclusion

In this paper we investigate the power consumption of protected IP-over-WDM networks by comparing four different protection strategies, namely Shared-Link, Shared-Path, Dedicated-Link and Dedicated-Path Protection. We provide four ILP formulations to accomplish a power-aware network design that enables low-power sleep-mode for devices used for backup paths provisioning. We show that for all the protection strategies relevant power savings, up to about 60%, can be obtained by setting protection devices into sleep-mode, and consistent savings can be also reached (up to about 18%, according to the protection strategy and traffic load) with respect to power-unaware design strategies where the cost, intended as number of used wavelengths, is minimized. Moreover, we show that, by employing sleep-mode for protection devices, it is possible to guarantee network resilience for a small (1–2%) additional power expenditure compared to the unprotected network scenario.

In most cases, the differences among the four protection strategies are negligible (below 1%), since the most relevant contribution to the total power consumption is due to the electronic traffic processing performed at the IP layer, which is almost independent of the adopted protection strategy and takes the highest advantage from setting backup resources into sleep-mode, especially for higher traffic. Moreover, also the power consumed at the WDM layer can be significantly reduced when enabling sleep-mode for protection devices.

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References


