Reliability Differentiation in Energy Efficient Optical Networks with Shared Path Protection

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***Abstract*—Energy and resource efficiency are two contrasting objectives to optimize in dynamic and survivable optical networks. Known solutions for improving the energy efficiency include the use of the shared path-protection (SPP) mechanism and of a low power consuming mode (i.e., sleep) for protection resources. On the other hand, resource efficiency can be improved by introducing the concept of Differentiated Reliability (DiR) which can be combined with SPP in order to match the level of provisioned protection resources to the reliability requirements for each specific demand.**

This paper assesses the energy efficiency of the DiR concept combined with SPP and sleep mode support. A multi-objective optimization algorithm is proposed with the intent of jointly optimizing the energy and resource efficiency when dynamically establishing lightpaths with specific reliability levels. Simulation results show that when the proposed multi-objective cost function is properly tuned, not only the SPP-based DiR approach reduces the blocking probability but it is also able to save power for any network load. By enabling sleep mode additional power savings can be achieved at low loads, leading to an overall saving of up to 25%.

I. Introduction

Energy saving is gaining importance in WDM networks as a way to reduce the capital expenditures of network operators. Strategies for reducing the power drained by the optical layer of survivable WDM networks mainly resort to techniques for turning off the unused devices and for sharing the devices as much as possible. The former technique can be enabled by the introduction of a *sleep mode* option in the equipment. Since the devices deployed for protection are unused most of the time (e.g., in absence of failures), they can be set to sleep and promptly re-activated when the recovery is triggered. Sleep mode for protection was proposed in [1]–[3] and is able to save significant amount of power especially at low loads, when the planning [1], [4] and the dynamic management [5] of survivable WDM networks with path protection is properly optimized. The path protection technique concerns the possibility to share protection resources among different connections, i.e., by using *shared path protection* (SPP) mechanism. Energy-efficient planning of static networks with SPP have been addressed in [6], [7]. Both techniques (i.e., sleep mode and SPP) can been exploited together [8], [9] for enhanced power saving.

When applying such energy-saving techniques in dynamic WDM networks, the drawback is a possible degradation of the network performance in terms of blocking probability [10]. This is due to the fact that the minimization of power consumption and the minimization of resource utilization are conflicting objectives, which need to be balanced so that power saving can be achieved without compromising the other network performance. For instance, the routing of the protection path for a lightpath may span on a large number of links which are shared and used only for protection, leading to a low power consumption but to a poor resource utilization in the long run.

To overcome this issue, this paper considers the concept of *Differentiated Reliability* (DiR) [11], which enables connections to have different reliability levels. In DiR the protection path need not be always available for any possible link failure scenario, resulting in a significant reduction of the resource utilization and thus blocking probability [12]. However, the impact of DiR on the power consumption of the network is still unclear. Initial finding [13] indicates that power saving up to about 20% are achievable when a static WDM network is planned in an energy-efficient way with DiR support compared to the conventional dedicated path-protection scheme. However, to the best of authors' knowledge, the tradeoff between energy efficiency and blocking probability in the presence of DiR has not been addressed yet.

The objective of this paper is two-fold. First of all, the DiR concept is applied to a dynamic WDM network with the objective of jointly optimizing energy efficiency, resource utilization, and offered reliability performance beyond the requested level (referred to as reliability excess). This requires the search for the best compromise between these contradictory objectives. In addition, the DiR technique is combined with SPP mechanism and sleep mode support, for enhanced power saving. The impact of the different energy saving techniques are assessed to offer insights on the most suitable solutions for energy saving and performance.

For this purpose, an algorithm is proposed for the dynamic selection of the working and protection paths with corresponding wavelengths, while ensuring the requested reliability level for each connection demand. Such algorithm is based on a multi-objective cost function, which accounts for these different optimization objectives in a flexible way. Moreover, a comprehensive comparison of the energy-saving techniques (e.g., DiR, SPP, and sleep mode) is carried out to assess their power saving and blocking probability, under different tuning of the multi-objective cost function.

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II. SYSTEM MODEL AND DIR CONCEPT

This section presents the assumptions used to model the wavelength division multiplexing (WDM) network under exam, and then it provides a detailed description of the DiR concept. This work considers a generic WDM network with a mesh topology, where wavelength conversion is not available. It is assumed that only single-link failures may occur in the network, i.e., the probability that two or more links are down at the same time is considered to be negligible [14]. It is also assumed that a link failure disrupts demands in both directions of propagation.[1] The WDM network is modelled as a graph $\mathcal{G}(\mathcal{V}, \mathcal{E})$, where $\mathcal{V}$ represents the set of nodes and $\mathcal{E}$ the set of unidirectional links. Each link $(m, n) \in \mathcal{E}$ is characterized by two parameters: the set of wavelengths Λ and the value of the link failure probability $(P_f(m, n))$. For example, assuming single link failures and a uniform distribution of faults among all the links, the link failure probability is: $P_f(m, n) = |\mathcal{E}|^{-1}, \forall (m, n) \in \mathcal{E}$, where $\sum_{(m,n)\in\mathcal{E}} P_f(m, n) = 1$.

Demands are assumed to arrive randomly at the network nodes and they must be served as they are received. Each demand consists of one lightpath that needs to be provisioned between two nodes, with a given level of reliability. A demand is blocked when the network does not have enough resources for setting up the lightpath with the requested level of reliability. The reliability level is modelled in terms of *Maximum Conditional Failure Probability* (MCFP). The MCFP level represents the maximum acceptable probability that, upon a link failure, the connection will not survive. The protection scheme must satisfy this value for each demand. The possibility of assigning a MCFP value different from zero to each specific demand allows a differentiation of the provisioned level of reliability, known as the DiR concept [12].

In this work, shared path protection (SPP) is considered for protecting lightpaths affected by a single link failure. With SPP, protection resources (i.e., wavelengths) can be shared among different working lightpaths provided that they are link-disjoint. When demand d requests a reliability level $MCFP^{(d)} = 0$, the demand is provisioned with shared resources along a link-disjoint path to be 100% survivable against any single fault. For a less stringent level of MCFP (i.e., $0 < MCFP^{(d)} \leq 1$), protection need not be available for every possible link failure scenario.

Notice that, thanks to the DiR concept, two working paths having a link in common can also share protection resources if the shared link belongs to the set of unprotected links of either one of the two working paths. Similarly, it is also possible to have a working path completely unprotected provided that its path failure probability satisfies the requested MCFP level.

Fig. 1 illustrates an example of SPP-based DiR or SPP-DiR. In the figure, the links in the network are bidirectional and can accommodate two wavelengths for each direction of propagation. Assume a uniform link failure distribution, i.e., $P_f(m, n) = \frac{1}{7}\ \forall (m, n) \in \mathcal{E}$. Three demands need to be provisioned at different time instants. Demand d_1 arrives first and requires $MCFP^{(d_1)} = 0$. The selected working path is $C-B$. The protection path is $C-E-B$. Then, demand d_2 arrives with $MCFP^{(d_2)} = 0$. The selected working path is $D-E-A$. The protection path is therefore $D-C-B-A$. Finally, demand d_3 arrives and requires $MCFP^{(d_3)} = \frac{1}{7}$. This MCFP level allows demand d_3 to be protected on any link but one. Taking advantage of this possibility, it is possible to route the working path along $D-E-B$ and set link $D-E$ as unprotected. The protection path for d_3 is $D-C-B$ and is used only in the case of the failure of link (E, B). As shown in the example, protection resources on link (C, B) are shared between demands d_2 and d_3 even though their working paths are not link-disjoint. Notice that if demand d_3 would have required a higher reliability level, i.e., $MCFP^{(d_3)} < \frac{1}{7}$, such demand would have been blocked due to the lack of available wavelengths in the network.

[1] This work can be extended to account for node failures, by ensuring node disjointness.

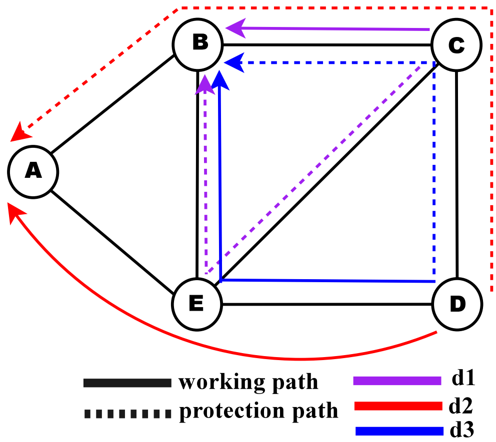

Figure 1. An example of a SPP-based protection scheme with DiR.

The SPP-DiR problem is a variation of the SPP problem, which is known to be NP-hard [15]. For this reason an energy aware SPP-DiR heuristic for routing the working and protection paths and for the selection of the protection wavelengths is proposed.

III. ENERGY-AWARE SPP-BASED DIR

The Energy-Aware SPP-DiR algorithm aims at finding for each demand d a pair of working and protection paths $(w^{(d)}, b^{(d)})$ able to satisfy the wavelength continuity constraint and the $MCFP^{(d)}$ requirement while keeping both the number of used resources and the energy consumption at a minimum.

Let $\lambda_w^{(d)}, \lambda_b^{(d)} \in \Lambda$ be the wavelengths that are chosen for the working and protection paths of d, respectively. Let $H_w^{(d)}$ be the set of links that are in the working path of d. Let $H_b^{(d)}$ be the set of links that are in the protection path assigned to d. Let $H_u^{(d)} \subseteq H_w^{(d)}$ be the set of working links of d that are unprotected, i.e., upon the failure of a link in $H_u^{(d)}$ demand d is permanently disrupted. Let $MCFP^{(d)}$ be the minimum reliability degree requested by d. Let D be the set of demands that are already established in the network. Let $\hat{d}$ be an arriving demand. Demand $\hat{d}$ is accepted and inserted in D if all the following constraints are satisfied:

- *link-disjointness*: i.e., the working and the protection path must be link-disjoint, i.e.,

$$H_w^{(\hat{d})} \cap H_b^{(\hat{d})} = \{\emptyset\}; \tag{1}$$

- *protection sharing*: a protection wavelength cannot be shared by multiple demands if they share the same (protected) working link, i.e.,

$$\forall d \in D, d \neq \hat{d}: \begin{cases} (H_w^{(d)} \setminus H_u^{(d)}) \cap (H_w^{(\hat{d})} \setminus H_u^{(\hat{d})}) \neq \{\emptyset\} \\ H_b^{(d)} \cap H_b^{(\hat{d})} = \{\emptyset\} \ \vee \ \lambda_b^{(d)} \neq \lambda_b^{(\hat{d})}; \end{cases} \tag{2}$$

- *MCFP requirement*: the conditional failure probability guaranteed to demand $\hat{d}$ does not exceed the $MCFP^{(\hat{d})}$ required by $\hat{d}$, i.e.,

$$P_f^{(\hat{d})} = \sum_{(m,n) \in H_u^{(\hat{d})}} P_f(m,n) \leq MCFP^{(\hat{d})}. \tag{3}$$

If any of the above constraints cannot be satisfied, demand $\hat{d}$ is blocked. Notice that the protection paths of demands $\hat{d}$ and $d \in D$ are allowed to share a wavelength $\lambda_b^{(\hat{d})} = \lambda_b^{(d)}$, i.e., only if the following constraint is satisfied:

$$(H_w^{(\hat{d})} \cap H_w^{(d)}) \subseteq (H_u^{(\hat{d})} \cup H_u^{(d)}). \tag{4}$$

The selection of the routing and wavelength for $\hat{d}$ (i.e., $w_i^{(\hat{d})}$, $b_j^{(\hat{d})}$ and $\lambda_{b_j}^{(\hat{d})}$) is jointly optimized for the number of resources used, the power consumption, and the excess of reliability[2]. The cost function, $C_{i,j,k}^{(\hat{d})}$, is a linear combination of these three quantities weighted with coefficient γ for the resource cost, coefficient η for the power consumption, and a unitary coefficient for the excess of reliability.

$$C_{i,j,k}^{(\hat{d})} = \gamma \cdot \left(|H_{w_i}^{(\hat{d})}| + |H_{b_j}^{(\hat{d})}| - |H_{s_{(i,j,k)}}^{(\hat{d})}| \right) + \eta \cdot \left(P_{w_i} + P_{b_{(j,k)}} \right) + \left(MCFP^{(\hat{d})} - P_{f_{(i,j,k)}}^{(\hat{d})} \right). \tag{5}$$

The first term in (5) gives an estimation of the resources (that is number of links on which wavelengths are to be reserved) needed to provision $\hat{d}$ on $w_i^{(\hat{d})}$ and $b_j^{(\hat{d})}$ using wavelength $\lambda_{b_j}^{(\hat{d})} = \lambda_k$ for $b_j^{(\hat{d})}$. Shared resources are accounted by subtracting the number of protection links in which the protection wavelength is shared, i.e., $|H_s^{(\hat{d})}|$, with $H_s^{(\hat{d})} \subseteq H_b^{(\hat{d})}$. The second term accounts for both the power consumption of $w_i^{(\hat{d})}$ and $b_j^{(\hat{d})}$, i.e., P_{w_i} and P_{b_j} (see Sec. IV). Finally, the third term includes the excess of reliability defined as the difference between the required $MCFP^{(\hat{d})}$ level and the value of $P_{f_{(i,j,k)}}^{(\hat{d})}$ computed as in (3) for the specific triplet $w_i^{(\hat{d})}$, $b_j^{(\hat{d})}$, and $\lambda_{b_j}^{(\hat{d})} = \lambda_k$.

[2] Note that the choice of for the wavelength of the working path has no impact on the cost function.

Algorithm 1 Energy-Aware SPP-based DiR

$\mathcal{G}(\mathcal{V}, \mathcal{E})$: network topology;
$\hat{d}$: lightpath demand;
$W^{(\hat{d})}$: set working paths for $\hat{d}$ sorted for hop length;
$B^{(\hat{d})}$: set protection paths for $\hat{d}$ sorted for hop length for path $w_i^{(\hat{d})}$;
Initialization: $\widetilde{C} = -1$;
for each path $w_i^{(\hat{d})} \in W^{(\hat{d})}$ **do**
  Let $\Lambda_{w_i}^{(\hat{d})}$ be set of continuous wavelengths for $w_i^{(\hat{d})}$;
  if $\Lambda_{w_i}^{(\hat{d})} \neq \emptyset$ **then**
    for each $b_j^{(\hat{d})} \in B^{(\hat{d})}$: $H_w^{(\hat{d})} \cap H_b^{(\hat{d})} = \{\emptyset\}$ (Eq. (1)) **do**
      Let $\Lambda_{b_i}^{(\hat{d})}$ be the set of continuous wavelengths for $b_j^{(\hat{d})}$;
      if $\Lambda_{b_i}^{(\hat{d})} \neq \{\emptyset\}$ **then**
        for each $\lambda_k \in \Lambda_{b_i}^{(\hat{d})}$ **do**
          if $w_i^{(\hat{d})}, b_j^{(\hat{d})}, \lambda_k$ satisfy Eqs. (2) and (3) **then**
            Compute cost $C_{i,j,k}^{(\hat{d})}$ (Eq. (5));
          end if
        end for
      end if
    end for
  end if
end for
Select $w_i^{(\hat{d})}$, $b_j^{(\hat{d})}$ and λ_k : $\widetilde{C} = \min_{i,j,k}\{C_{i,j,k}^{(\hat{d})}\}$;
if $\widetilde{C} \neq -1$ **then**
  Return $w_i^{(\hat{d})}$, $b_j^{(\hat{d})}$, λ_k, $\Lambda_{w_i}^{(\hat{d})}$;
else
  Block $\hat{d}$;
end if

Algorithm 1 aims at computing the routing of both the working and protection paths, and at selecting the protection resources for each arriving demand $\hat{d}$. The route of the working path (i.e., $w^{(\hat{d})}$) is selected within a set of pre-computed candidates $W^{(\hat{d})}$. For path $w^{(\hat{d})}$, the route of the protection path (i.e., $b^{(\hat{d})}$) is selected among a number of pre-computed candidates $B^{(\hat{d})}$. First, the algorithm checks the wavelength availability for the working path by starting from the first path in $W^{(\hat{d})}$, $w_1^{(\hat{d})}$. If the same wavelength is not available on all the links of $w_1^{(\hat{d})}$, the path is discarded and the next path in $W^{(\hat{d})}$ is considered. Otherwise a link-disjoint protection paths in $B^{(\hat{d})}$ is considered (i.e., satisfying the link disjoint constraint in Eq. (1)). For each link-disjoint path in $B^{(\hat{d})}$, $b_j^{(\hat{d})}$, the resource availability is checked. First the set of available continuous wavelengths ($\Lambda_{b_i}^{(\hat{d})}$) is computed, then each $\lambda_k \in \Lambda_{b_i}^{(\hat{d})}$ is checked. If λ_k is already used for protection purposes by other protection paths the protection sharing constraint (Eq. (2)) is checked. If satisfied and if the MCFP requirement (Eq. (3)) is met, then the triplet w_i, b_j, and λ_k is a feasible solution and the value of $C_{i,j,k}^{(\hat{d})}$ is computed (Eq. (5)). Among all the feasible solutions, the one at minimum cost $C_{i,j,k}^{(\hat{d})}$ is selected. If a feasible solution is not found, then the lightpath demand $\hat{d}$ is blocked. Finally, the wavelength for the working path $\lambda_w^{(\hat{d})}$ is selected within the set of available wavelengths $\Lambda_{w_i}^{(\hat{d})}$ using the first-fit strategy. The computational complexity of Algorithm 1 is $O[|W^{(\hat{d})}||B^{(\hat{d})}||D||\Lambda||\mathcal{V}|^3]$. The number of provisioning demands, $|D|$, can be upper bounded by $O[|\mathcal{E}||\Lambda|]$, leading to an overall complexity of $O[|W^{(\hat{d})}||B^{(\hat{d})}||\mathcal{E}||\Lambda|^2|\mathcal{V}|^3]$.

IV. Sleep Mode and Power Model

For higher energy efficiency, sleep (i.e., idle) mode can be enabled at the optical layer. The optical devices that are unused are turned off and disconnected from the WDM and the electrical network. Optical devices used only for protection purposes are set in idle state and they consume a (possibly) low amount of power to ensure that they can be promptly activated at any moment.

For a WDM network operating at 40 Gb/s, the optical devices draining power are: OXC controllers (150 W at each node) [16], in-line amplifiers (155 W + 55 W $\times$ 80 km) [17], transmitters and receivers. A transmitter and receiver include drivers (2×9 W), laser (6.6 W), photodiode and transimpedance amplifier (2×0.4 W), ADC (2×2 W), and management (20% of the overall power) [3]. When supporting sleep mode, the drivers and the ADC of the transmitter for the protection can be set to idle, leading to a saving of 26.92 W. Similarly, if sleep mode is enabled and a link is supporting only protection paths, the in-line amplifiers along the links are set to idle, leading to a negligible amount of power.

In the cost function $C_{i,j,k}^{(\hat{d})}$ in Eq. (5), the total power consumed by a working (P_w) and a protection (P_b) path is the sum of the power drained by the devices traversed by each path (i.e., transmitters and receivers, OXC controllers, and amplifiers) according to the operational state (active vs. idle vs. off) that would be enabled after the connection is established.

V. Numerical Results

The performance of the proposed energy-aware SPP-based DiR algorithm is assessed with a custom-built event-driven simulator. The evaluation is carried out on the Pan-European topology (COST 239) [18], which consists of 11 nodes and 52 unidirectional links with 16 wavelengths per link.

The link failure probability is derived using a uniform distribution of failures, that is $P_f(m,n) = \frac{1}{52}\ \forall (m,n) \in \mathcal{E}$. Demands are assumed to arrive in the network following a Poisson process. Established lightpaths are assumed to have an exponentially distributed duration, whose average value is set to 1. It is also assumed that detailed link status information is promptly disseminated throughout the network so that each node controller can execute the proposed algorithm with updated information. Also, the latency for reserving the network resources is considered negligible.

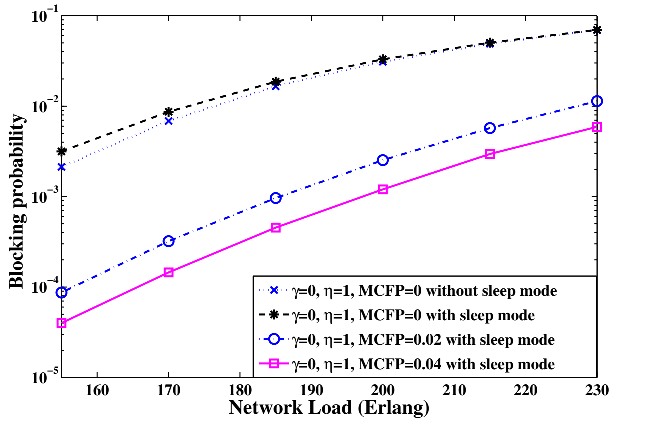

Figure 2. Blocking probability versus offered network load when minimizing power consumption.

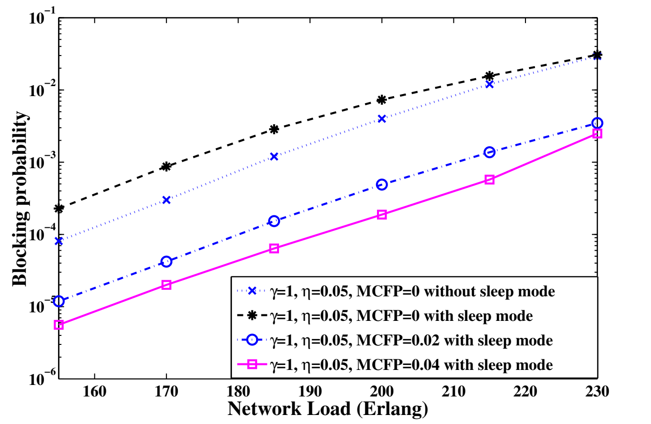

Figure 3. Blocking probability versus offered network load when minimizing power consumption and then resource utilization.

Demands are uniformly distributed among all node pairs. Unless otherwise specified, each demand is assigned the same reliability requirement $MCFP = MCFP^{(d)} = 0.02,\ \forall d$. With this value and in the network topology under consideration, each demand may be able to have up one working link that is unprotected ($|H_u^{(d)}| = 1,\ \forall d$). The number of candidate routes for each working path and for each protection path of a given candidate working path is set to 5 ($|W^{(d)}| = |B^{(d)}| = 5,\ \forall d$), which are computed using K shortest path routing [19]. Simulation results are collected to achieve a confidence interval of 6% or better with 90% confidence level. The performance of enabling DiR and sleep mode is assessed in terms of average blocking probability and time-averaged power per established lightpath.

The average blocking probability as a function of the load is evaluated in Figs. 2-4. In Fig. 2, the cost function is tuned for minimizing the power consumption, i.e., $\gamma = 0,\ \eta = 1$. The impact of the MCFP level and sleep mode is assessed. Two insights can be gained. First, the blocking probability slightly increased when enabling sleep mode. The reason is that, for the working lightpaths, in the presence of sleep mode the cost function forces the selection of longer paths (i.e., to set as much as possible resources in sleep mode) rather than shorter ones but without sleeping links. In turn, this leads to a higher resource utilization and thus higher blocking. Second,

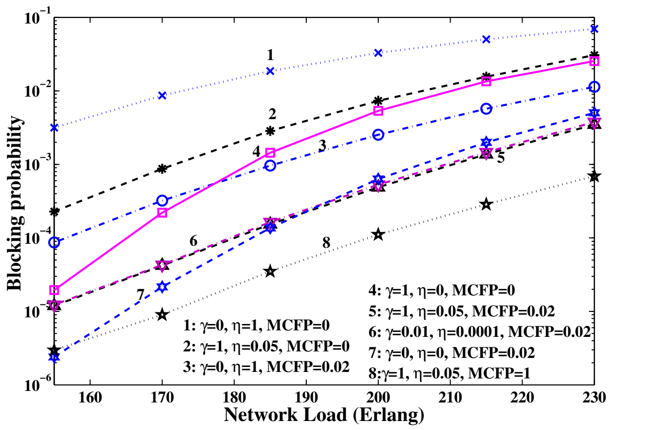

Figure 4. Blocking probability versus offered network load for different combinations of the cost coefficients.

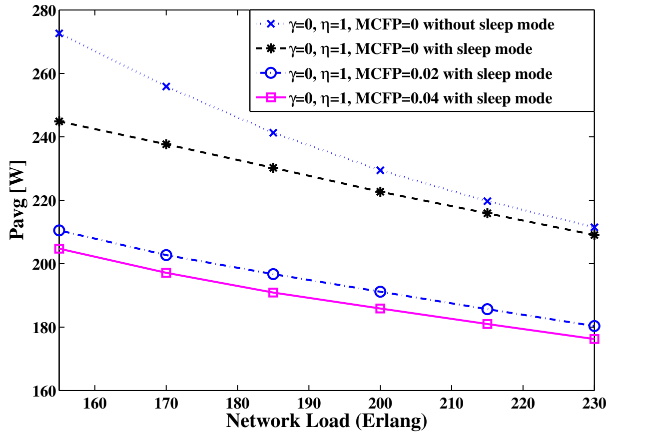

Figure 5. Avg. power per established lightpath versus offered network load when minimizing the power consumption.

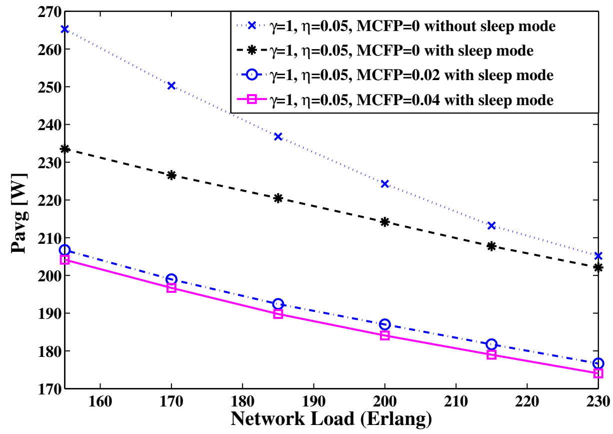

Figure 6. Avg. power per established lightpath versus offered network load when minimizing the power consumption and then the resource utilization.

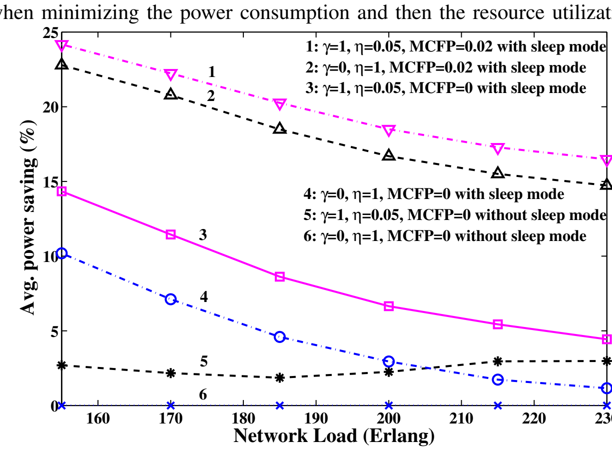

Figure 7. Average power saving versus offered network load.

an improvement of more than one order of magnitude in blocking probability can be achieved when a lower reliability level is requested ($MCFP{=}0.02$). However, if the reliability level is further decreased (e.g., $MCFP{=}0.04$), the marginal improvement reduces.

Fig. 3 shows the value of the blocking probability when the cost function aims at minimizing the power consumption as primary objective and the resource utilization as a secondary objective. By accounting also for the resource utilization, the blocking probability is reduced by more than one order of magnitude with respect to the results for power optimization only (Fig. 2), for all the different scenarios.

Fig. 4 considers different optimization functions. When the primary objective is the resource minimization, the blocking probability slightly improves with respect to the case of minimizing also the power consumption (Fig. 3) but only at low loads. For $MCFP = 0.02$, the difference of blocking probability is modest when changing the cost coefficient γ and η so that resource minimization becomes the primary objective (curves 5 and 6). However, when minimizing the excess of reliability (i.e., $\gamma = 0$, $\eta = 0$), sharing of resources is not incentivized leading to lower blocking probability when the load is low, but higher blocking probability when the load is high.

The average power consumption (per established lightpath) as a function of the load is evaluated in Figs. 5-8. In Fig. 5, the cost function is tuned for minimizing the power consumption, i.e., $\gamma = 0$, $\eta = 1$. The power consumption per lightpath decreases with the offered network load. The main reason is that the power consumption of load-independent devices (e.g., power consumption of in-line amplifiers, which can be considered independent of the number of amplified working lightpaths) can be shared among a larger number of lightpaths. By introducing the sleep mode, the slope of the curve is reduced, meaning that less power is wasted at low loads for powering scarcely used resources. This results in a power saving of about 10% at low loads. By closely matching the connection reliability level ($MCFP = 0.02$), the power saving can be further improved by 13%. However, there is no significant advantage in further increasing MCFP (e.g., $MCFP{=}0.04$). This limitation is mainly due to the network topology, which is highly connected. Indeed the network connectivity leads to paths with short hop lengths, making it difficult to find protection paths in which more than one link can be unprotected.

Fig. 6 shows the average power consumption per lightpath when the cost function aims at minimizing the power consumption as primary objective and the resource utilization as secondary objective. The curves experience the same trend as in Fig. 5. However, by incorporating the resource cost factor (i.e., setting $\gamma = 1$) in the optimization function, the power

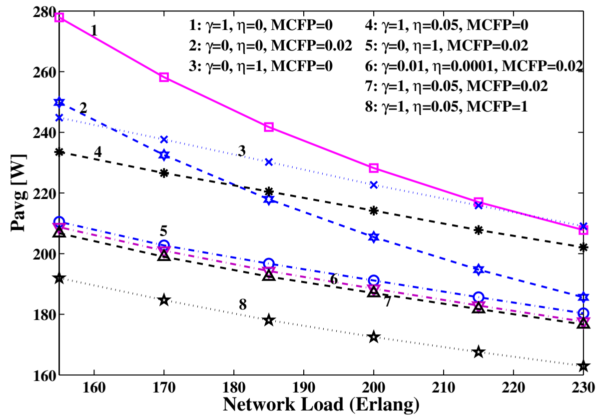

Figure 8. Avg. power per established lightpath versus offered network load, for different combinations of the cost coefficient.

consumption reduces compared to Fig. 5. This unexpected result can be explained by the fact that among the different solutions at minimum power the one using less resources is selected. This at the end ensures that each provisioned demand uses overall less resources, leading to an overall energy saving.

The average power savings of the different cases with respect to the conventional energy-aware SPP (i.e., $\gamma = 0$, $\eta = 1$ and $MCFP = 0$) with sleep mode disabled is assessed in Fig. 7. Sleep mode enables savings up to 10% at low loads, but these benefits rapidly decrease at high loads. A more significant power saving, almost independent of the load, is achievable by introducing DiR. The highest power saving, up to 25%, is achieved by jointly optimizing power consumption and resource utilization ($\gamma = 1$, $\eta = 0.05$, $MCFP = 0.02$) while enabling DiR and sleep mode.

The impact of the selected optimization function on the power consumption is further analyzed in Fig. 8. For $MCFP = 0.02$, minimal differences in terms of power consumption are observed when the coefficient γ and η are varied to minimize either the network power or the wavelength resources used (curves 5, 6, and 7). However, when minimizing the reliability excess (i.e., $\gamma = 0$, $\eta = 0$ and $MCFP = 0.02$) the average power consumption of the lightpath demands is exacerbated compared to other combinations of the cost coefficient. This is because the strategy ignores the sharing of resources and active devices, and thus it selects the paths that match the MCFP level regardless of their hop length and power consumption.

VI. Conclusion

In this paper, the DiR concept has been combined with SPP and sleep mode to enable an energy-efficient utilization of resource in dynamic WDM network, while guaranteeing the required reliability level for each connection. An algorithm for routing working and protection paths, for selecting the corresponding wavelength, and for ensuring the requested maximum conditional failure probability is proposed, which aims at optimizing the weighted combination of power consumption, resource utilization, and reliability excess.

Simulation results show that the energy aware SPP-based DiR is able to improve not only the blocking probability [11] but also the power consumption. Both benefits are achievable when the multi-objective function is tuned to minimize both the power consumption and the resource utilization, which favors the sharing of protection and the minimization of the used resources.

On the other hand, sleep mode enables power saving at low loads but leads to higher blocking probability. However, when sleep mode is combined with the energy aware SPP-based DiR, up to 25% of power is saved while the blocking probability is reduced by up to one order of magnitude even at 98% reliability levels, with respect to the conventional SPP without sleep mode.

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