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Value optimization of survivable multilayer IP/MPLS-over-WSON networks

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Abstract Network operators are willing to provide a range of services in the hope of maximizing their profits: from the highly available connectivity services for key business customers to the unprotected or even best effort services for residential customers. These services are being provided through IP/multiprotocol label switching (MPLS) over wavelength-switched optical networks (WSON) networks. Such multilayer network enables the application of optimal load balancing between the packet and the optical layer, optimizing both the cost of the packet layer and the utilization of the WSON. To provide highly available services, redundant network resources need to be added to the network providing survivability against failures; generally speaking, the higher the survivability degree, the higher both the capital and the operational expenditures (CAPEX and OPEX, respectively) of the network. In this work, we design networks to meet specific availability objectives considering single failures in optical links, IP/MPLS nodes, and optoelectronic ports. The benefits of the designed networks are evaluated from an economic perspective defining costs and revenues models and using Net Present Value as a metric to evaluate future cash flows after an investment. To this end, CAPEX and OPEX, including power consumption and maintenance, and penalties as a consequence of service level agreement breaches are considered. Exhaustive numerical results on several reference network scenarios demonstrate how the value of the network can be maximized by tuning availability objectives.

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1 Introduction

The hard competition in the telecommunications market is currently forcing the network operators to provide tailored services for a wider range of client profiles to attract new customers in the hope of maximizing network profitability. With the objective of increasing bandwidth and number of service demands while minimizing the costs, intelligent interworking strategies between IP/MPLS networks and a photonic mesh infrastructure based on WSON are usually applied to efficiently aggregate the various bandwidth granularities (see e.g. [1,2]). Since WSON provides physical connections to heterogeneous network services for residential and business customers, it is usually planned as a standalone network. On top of it, the IP/MPLS-based client networks are then deployed and need to be properly planned to meet specific requirements. It means that service differentiation is often achieved on a service level agreements (SLA) basis, i.e., business traffic is usually associated with strict SLAs, which include service availability, in contrast to residential traffic usually served as best effort. At the same time, since the price that clients are willing to pay for those services is decreasing, a reduction in the capital expenditures (CAPEX) and the operational expenditures (OPEX) needs to be attained. It is critical then to perform a detailed analysis of the profitability of any network investment project. In finance, the Net Present Value (NPV) is the most extended criterion to compare investments [3]. Indeed, NPV allows comparing long-term investments as it measures the generated cash flows in present value terms, relating revenues, OPEX, and CAPEX.

In this paper we focus on the maximization of the NPV in survivable IP/MPLS-over-WSON multilayer networks. To achieve it, we deal with the service availability objectives to reduce CAPEX and, since service availability involves also operational costs, with the maintenance strategy and energy consumption to reduce OPEX.

1.1 Related work

Different recovery schemes can be used to provide the required network availability, such as protection and restoration. For multilayer networks, special recovery schemes can be designed, e.g., authors in [4] present a tutorial of multilayer recovery schemes. In this regard, in [5] we propose the *joint* approach consisting in over-dimensioning backbone IP/MPLS nodes and applying lightpath and connectivity restoration. Such joint approach is compared with the traditional *overlay* approach (which consists of duplicating backbone IP/MPLS nodes), resulting in CAPEX savings ranging from 13 to 24% including both IP/MPLS and optical layers. It is worth mentioning that both the joint and the overlay approach have been designed in such a way that the entire amount of traffic affected by any single optical link, IP/MPLS node, or optoelectronic (OE) port failure can be recovered, providing thus the highest availability.

Other works previously studied the impact of network availability on the cost or revenues of the network, e.g., [6–9]. Authors in [6] present models to estimate CAPEX and OPEX in optical networks. Event-driven operational costs, such as repair, are quantified using an activity-based approach. Authors in [7] evaluate the impact of protection schemes and the availability of network components on the OPEX of optical networks. The failure reparation problem to find the number of employees and their locations so to minimize their associated costs and the penalties that should be paid for un-restored services is presented. In another similar study for access networks [8], the authors compare several network architectures in terms of CAPEX and OPEX. Finally, authors in [9] address revenues maximization from the perspective of the SLA penalties, since SLA breaches represent large revenue losses for network operators.

Regarding the OPEX, one of the main components (and the one where more effort is nowadays concentrating) is the cost due to the power consumption. A number of models for the estimation of the power consumption can be found in the literature (e.g., [10–12]) which can be classified into three categories as follows: analytic, experimental, and theoretical energy models. An in-depth survey of energy models can be found in [13]. Experimental and theoretical models do not provide detailed energy consumption of each subsystem or component, but rather, they describe a high-level perspective on the energy consumption of the node as a whole at the expense of granularity and accuracy. In addition, existing analytic models do not consider future energy aware architectures whose energy consumption varies with node types/sizes and traffic load.

1.2 Contributions

A very interesting property of the joint approach presented in [5], in contrast to the overlay one, is that the network availability can be reduced removing redundant OE ports and decreasing spare switching capacity of IP/MPLS nodes.

In view of that, the work in [5] is extended in the present paper by designing the IP/MPLS layer for reduced network availability objectives.SLA penalties as a consequence of reducing availability are considered, and the expected traffic lost is computed for each network design. Regarding OPEX, two operational costs are considered and the models to compute them are presented: energy consumption and maintenance costs, where the maintenance optimization problem (MOP) is proposed to minimize maintenance costs while meeting a double-failure probability threshold.

The contribution of this work is hence multifold: (i) a greedy randomized adaptive search procedure (GRASP)-based heuristic algorithm [14] is proposed to design IP/MPLS networks meeting a reduced network availability objective. The benefits of different network availability objectives are evaluated in terms of CAPEX; (ii) since the design of the network alternatives highly impacts the OPEX, models to compute the energy consumed and the maintenance costs are afterward proposed; (iii) as a consequence of network availability, reduction penalties due to SLA breaches need to be considered for the sake of a fair comparison; (iv) NPV is proposed and used to compare the designed alternatives, relating revenues, including SLA penalties, CAPEX, and OPEX.

In addition, our proposals can be easily extended to any other multilayer network technology, such as Optical Transport Network over WSON.

The reminder of this paper is organized as follows. Section 2 presents a heuristic algorithm to reduce the CAPEX of a given network, removing spare network components, while meeting a network availability objective. After the designed network is put into operation, costs derived from power consumption and from maintenance need to be considered. Section 3 presents a model to compute the power consumed by the designed networks. Moreover, an integer linear programming model to minimize maintenance costs while ensuring a given double-failure probability is provided. To compare among network alternatives, the NPV formula is presented in Sect. 4. Using these models, each network is compared in Sect. 5 in terms of costs and value. Finally, Sect. 6 concludes the paper.

2 Multilayer network design for reduced availability objective

One of the advantages of the joint approach with respect to the overlay one is that the objective of network availability (A) can be decreased with respect to the full availability (100%) and adapted accordingly to the network operator specific requirements, e.g., five 9's (99.999%). As a consequence of lowering the availability objective, a number of spare network components can be not deployed, thus decreasing both network CAPEX and OPEX. In this section we review network availability computation and propose a heuristic algorithm able to effectively lower A up to a given objective threshold.

2.1 Network availability computation

Generally speaking, availability A is the probability that a system will be found in the operating state at a random time in the future. Unavailability (U) is the probabilistic complement of the availability ($U = 1 - A$). Steady-state availability can be expressed as a function of the mean time to failure (MTTF) and the mean time to repair (MTTR), as:

$$A = \frac{\text{MTTF}}{\text{MTTF} + \text{MTTR}} \tag{1}$$

Nevertheless, when several components can fail (recall that in this work we consider failures in optical links, OE ports, and IP/MPLS nodes, each with different MTTF and MTTR), it is not easy to compute the overall availability of a system using (1). Accordingly, we compute network availability by means of the expected loss of traffic (ELT), i.e., the amount of traffic expected to be lost as a consequence of failures in the network in a time period Δt, e.g., 1 year [15].

To this end, the following notation is used:

Sets:

V	Set of IP/MPLS nodes.
D	Set of demands, index d.
F	Set of single-failure scenarios, index f.
P_r	Set of redundant ports in the given network.
$D(f)$	Subset of D with the demands affected by scenario f.

Parameters:

c_i	Cost of network component i.
U^f	Unavailability of the network component in scenario f.
b_d	Bandwidth of demand d (Gbps).
ζ_d^f	1 if demand d can be recovered under failure scenario f, 0 otherwise.

Using the defined notation, ELT can be computed as:

$$\text{ELT} \cong \Delta t \cdot \sum_{f\in F} \sum_{d\in D(f)} \left(1 - \zeta_d^f\right) \cdot b_d \cdot U^f \tag{2}$$

Note that when only single failures are considered, the value obtained is a lower bound of ELT. However, the accuracy of (2) is very high when the unavailability of network components U^f is very low, i.e., MTTR must be short enough compared with MTTF so that the double-failure probability ($U{*}U$) can be neglected in (2). In this regard, Sect. 3 designs network maintenance for a given MTTR objective while meeting double-failure probability objectives.

The network availability is thus defined as follows:

$$A = 1 - \frac{\text{ELT}}{\Delta t \cdot \sum_{d\in D} b_d} \tag{3}$$

2.2 Heuristic algorithm

With the aim of designing networks for a give availability objective, we start from networks designed to ensure total single-failure connection recovery under the joint approach [5] and remove as much spare network components (spare OE ports and extra switching capacity) as possible, while meeting the availability objective. To this end, we develop a heuristic algorithm based on the GRASP meta-heuristic. The constructive phase of the GRASP heuristic (Table 1) consists in trying to remove spare network components from the network without decreasing network availability beyond the given threshold. At the beginning, a candidate list is built containing all the spare components in the network. Let us define the relative quality of the spare network component i, $q(i)$, as the amount of bandwidth per monetary unit that i can recover. Then, $q(i)$ can be computed as:

$$q(i) = \frac{1}{c_i} \cdot \sum_{f\in F} \sum_{d\in D(f)} \delta_d^f(i) \cdot b_d \cdot U^f, \tag{4}$$

where $\delta_d^f(i)$ is 1 if demand d uses network component i under failure scenario f, 0 otherwise.

For each element in the candidate list, its relative quality is computed and the list is sorted in increasing order with respect to those values. At each iteration, the algorithm builds a restricted candidate list (RCL) which only contains a subset of elements in the candidate list. Those elements with null relative quality, i.e., they do not recover bandwidth from any failure as a consequence of previous iterations of the algorithm, are removed from the RCL, from the network, and added to the current solution S. If element i is a port node, that port is removed from the IP/MPLS node where it is installed; if it is an IP/MPLS node itself, its switching capacity is reduced. Next, one element is selected at random from the RCL. The element is removed from the network, and the availability is recomputed and checked against the objective. In the case network availability, computed using (3), is lower than the objective, the spare element is returned

Table 1 Greedy randomized constructive algorithm

INPUT *network*, D, A, α
OUTPUT S

```
S ← Ø
Initialize the candidate set: Q ← P_r U V
evaluate the quality q(i) for all i ∈ Q using (4)
if availability(network, D) < A then
    return S
while Q ≠ Ø do
    q^min ← min{q(i)|i ∈ Q, ifeasible}
    q^max ← max{q(i)|i ∈ Q, ifeasible}
    RCL ← {i ∈ Q|q(i) ≤ q^min + α(q^max − q^min)}
    if (RCL= Ø) then break
    for each element i in RCL do
        if q(i) = 0 then
            Remove element i from the network
            RCL = RCL\{i}
            S = SU{i}
            if element i is a port then Q = Q\{i}
    end for
    Select an element i from RCL at random
    Remove element i from the network
    if availability(network, D) < A then
        Give back element i to the network
        i not feasible
    else
        S = SU{i}
        if element i is a port then Q = Q \ {i}
        re-evaluate the quality q(i) for all i ∈ Q using (4)
end while
return S
```

to the network, and it is labeled as not eligible in the next iteration.

Once a feasible solution S is built, a local search phase is used to find the optimal solution S' within the neighborhood $N(S)$, i.e., the set of feasible solutions that can be reached from S by a move. We define a move as an exchange between a spare element j not in S and another element i in S, such that $c_j > c_i$ while keeping the network availability under the objective. Here, a first-improving strategy is implemented; that is, the first feasible exchange is performed.

For illustrative purposes, Fig. 1 plots the evolution of network unavailability using the proposed constructive algorithm when applied to a network designed for $A = 100\%$. As shown, CAPEX can be decreased by removing some components from the network, reducing its availability to 99.9999% (six 9's), 99.999% (five 9's), or 99.99% (four 9's).

The next section considers the networks in operational phase and proposes models to compute the OPEX. In particular we compare the networks designed using the overlay and the joint approaches described in [5] and the family of networks resulting from the reduced availability algorithm seen above.

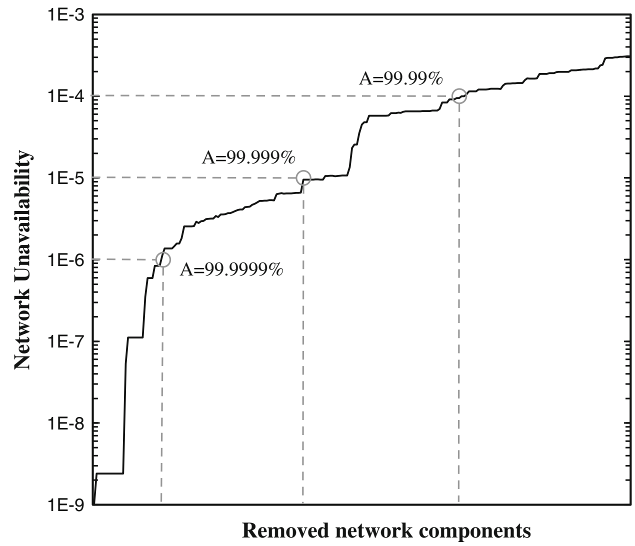


Fig. 1 Network unavailability evolution versus removed network components

3 Putting networks into operation

A number of costs need to be considered regarding in-operation network efficiency evaluation. Here, we focus on two key aspects: power consumption and maintenance.

3.1 Power consumption model

In our model, the power consumption of an IP/MPLS node consists of a fixed part, due for the device to stay on, and a variable part, dependent on the traffic load, due to the active OE ports. The energy model is illustrated in Fig. 2. The fixed part is the power consumed by the node base system, basically the switching matrix, the control circuitry, the CPUs and memories, accounting for a great part of the total power consumption [12,16]. The greater the node, the more complex is its circuitry, and so its energy requirement increases. Moreover, since faster ports require lower energy per bit than slower ports [17], we differentiate the power consumption of the ports by using different values for the variable power consumptions of the actual ports installed in the nodes. In our model, when there is no traffic on an OE port, the power consumption of the corresponding port is taken as percentage of its maximum consumption (accounting for periodic *hello* messages, OSPF-TE LSAs, etc.) [18]. According to our model, the fixed consumption of the node is always present,

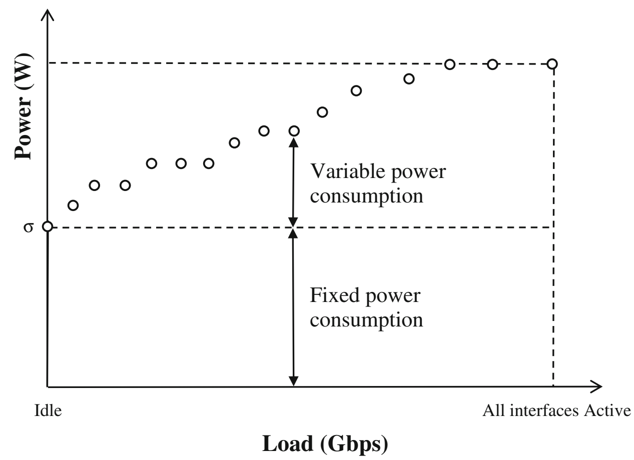


Fig. 2 Model of IP/MPLS node power consumption as a function of the load

even with no load, i.e., the per-node sleep mode is not considered. As a result, the total node energy consumption depends on the node switching matrix capacity, on the actual OE ports installed and on the traffic load.

We use the following notation:

Sets:

RT	Set of node classes, index c. Each class defined by a switching capacity and a number of slots where OE ports can be installed.
PT	Set of OE port bit-rates, index k.
$p(i)$	Set of OE ports of IP/MPLS node i.

Parameters:

B_j	Bit-rate of OE port j(Gbps).
b_j	Traffic load transmitted through OE port j (Gbps).
$\sigma_c(i)$	Fixed power consumption of a class c node i(W).
$\pi_k(j)$	Variable power consumption (W/Gbps) of port j with bit-rate k.
η	Percentage of power consumption of an idle port.
$\rho_k(j)$	Percentage of power consumption of port j of bit-rate k. 100% if $b_j > 0$, η otherwise.

The total node power consumption $P(i)$of IP/MPLS node i is thus given by the sum of the fixed power consumption of the base system and the variable power consumptions of the ports, depending on the current traffic distribution:

$$P(i) = \sigma_c(i) + \sum_{j \in p(i)} \pi_k(j) \cdot \rho_k(j) \cdot B_j \tag{5}$$

Table 2 provides the values used in this work, in line with those in [10,17]. As previously commented, (5) and values in Table 2 reflect the fact that: (i) the larger the node, the larger the fixed power consumption; (ii) the faster the OE ports, the lower the variable power consumption, since they consume smaller energy-per-bit than slower ones.

Table 2 Power consumption of IP/MPLS nodes and OE ports

Switching matrix	5 W/Gbps
100 Gbps port	8 W/Gbps
40 Gbps port	9 W/Gbps
10 Gbps port	9 W/Gbps
1 Gbps port	10 W/Gbps
Idle ports power consumption, η	10%

Finally, the energy cost C_E of a network in a given time interval Δt can be computed as follows, where c_{Wh} is the price of the energy per time unit.

$$C_E = \sum_{i \in V} P(i) \cdot \Delta t \cdot c_{Wh} \tag{6}$$

3.2 Maintenance dimensioning

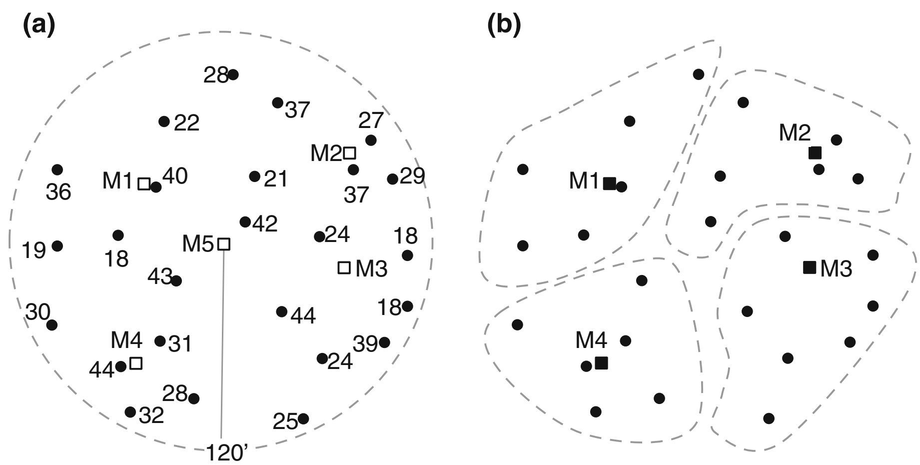
In this section we study the maintenance costs of the IP/MPLS network. As already mentioned, we do not include the WSON costs in the problem assuming, in this case, that the WSON maintenance (optical cables and nodes) is already defined and thus out of the scope of this study. Nonetheless many of the ideas proposed here for the IP/MPLS layer can also be adapted to the optical layer.

We propose a two-level maintenance strategy for the IP/MPLS network. A network operations center (NOC) focuses on alarm surveillance and network monitoring, so that anomalies can be solved to minimize, or even prevent, service cuts. In addition, remote maintenance (i.e., software reconfiguration) can be performed. The size of the NOC can be easily determined as a function of the number of nodes under surveillance.

At the second level, a set of distributed area maintenance centers are in charge of repairing hardware failures. In this case, the number and placement of area maintenance centers, together with some other parameters such as MTTR, need to be carefully studied to keep under control double-failure probability while minimizing maintenance costs. Since OE ports are the hardware elements with the highest failure probability [4], these distributed area centers are mainly devoted to repair this kind of failures by replacing failed elements.

To illustrate why correct area maintenance dimensioning is important, Fig. 3a shows a number of locations containing a number of OE ports to be maintained. Five candidate area maintenance centers, labeled as M1–M5, are positioned. Note that trip times from maintenance center M5 to every location is lower than 120 min. If we assume an MTTR objective equal to 120 min, only one area maintenance center would need to be opened. However, due to the large amount

Fig. 3 Example of area maintenance dimensioning. **a** A set of 25 locations, each containing a number of OE ports, need to be maintained. **b** Four area maintenance centers need to be opened for dual-failure threshold equal to 10-6



of OE ports to be maintained, dual-failure probability would be excessive and then failures could not be repaired within the objective time, e.g., if, while maintenance personnel was traveling to repair a failure in a location, another OE port would fail in a remote location, the time to repair the second failure could rise to approximately 3*MTTR. Therefore, to limit dual-failure probability in two different locations being maintained by a common area center, a threshold is considered in Fig. 3b. As a consequence of the double-failure constraint, four maintenance centers need to be opened.

The area MOP can be formally stated as follows:

Given:

- A network to be maintained, consisting in a set L of locations to be maintained. Each location l contains a number of OE ports $p(l)$,
- a set M of candidate area maintenance centers,
- the driving trip time t_m^l, from area maintenance center m to location l,
- the considered values for MTTF and MTTR of OE ports. Note that OE port unavailability U_p can be computed using (1),
- OE ports reparation time (TR) once in a location, and
- the double-failure probability b threshold that can be assumed. Specifically, b represents the probability threshold of dual failure in two different locations l and l' being maintained by a common maintenance center.

Output:

- Area maintenance centers to be opened,
- the area maintenance center in charge of each location.

Objective: Minimize the number of area maintenance centers to be opened.

The MOP problem can be modeled in terms of mathematical programming. To this end, we define the following decision variables:

x_m Binary. 1 if maintenance center m is opened, 0 otherwise.

x_m^l Binary. 1 if location l is maintained from maintenance center m, 0 otherwise.

y_m^l Real positive. Stores dual failure probability for the pair (m, l).

Then, the MOP problem can be modeled as follows:

$$\text{minimize} \quad \sum_{m \in M} x_m \tag{7}$$

s.t.

$$\frac{1}{|L|} \cdot \sum_{m \in M} \sum_{l \in L} t_m^l \cdot x_m^l \leq \text{MTTR-TR} \tag{8}$$

$$\sum_{m \in M} x_m^l = 1 \quad \forall l \in L \tag{9}$$

$$\sum_{l \in L} x_m^l \leq x_m \cdot |L| \quad \forall m \in M \tag{10}$$

$$\sum_{l \in L} \left(p(l) \cdot x_m^l \cdot U_p \cdot \sum_{\substack{l' \in L \\ l' \neq l}} \left(p(l') \cdot x_m^{l'} \cdot U_p \right) \right) \leq b \quad \forall m \in M \tag{11}$$

$$x_m \in \{0, 1\} \quad \forall m \in M$$

$$x_m^l \in \{0, 1\} \quad \forall m \in M, l \in L \tag{12}$$

The objective function (7) minimizes the number of maintenance centers that need to be opened. Constraint (8) ensures that the mean time to repair a port failure is lower than the specified. Then, the mean trip time must be kept under MTTR-TR. Constraint (9) guarantees that every location is assigned to one maintenance center. Constraint (10), together with the objective function, opens a maintenance center only if there are locations being assigned to it. Constraint (11) makes sure that the probability of double-failure occurrence in ports of two different locations being maintained by the same maintenance center is kept under a given threshold. Note that this constraint is not linear as a consequence of variable multiplication. Constraint (12) defines variables as binary.

The non-linearity of constraint (11) can be solved rewriting it as constraints (13)–(15) and introducing the new variable y_m^l. Then, constraint (13) computes the probability of dual failure for any pair of maintenance center m and location l and stores it in y_m^l. Note that, when a location is not maintained from a given maintenance center, the computation is deactivated. Constraint (14) ensures that the probability of dual failure in the locations assigned to a single maintenance center is kept under the given threshold. Finally, constraint (15) defines y_m^l as a positive integer.

$$p(l) \cdot U_p^2 \cdot \sum_{\substack{l' \in L \\ l' \neq l}} \left(p(l') \cdot x_m^{l'} \right) \leq y_m^l + (1 - x_m^l)$$

$$\forall m \in M, \forall l \in L \quad (13)$$

$$\sum_{l \in L} y_m^l \leq b \quad \forall m \in M \quad (14)$$

$$y_m^l \in Z^+ \quad \forall m \in M, l \in L \quad (15)$$

To compute maintenance costs (C_{M}), we assume the same cost for the NOC and for each of the area centers, which depends on the required number of employees. We consider that four employees with a cost $c_{ManYear}$ are needed for a 24 h per day / 7 days a week service. Then, C_{M} can be computed as:

$$C_{\mathrm{M}} = \left(1 + \sum_{m \in M} x_m \right) \cdot 4 \cdot c_{ManYear} \quad (16)$$

4 Net present value for overall network comparison

In this section, we present a model to compare each of the alternative network designs in economic terms using the NPV expression. NPV calculates the *value* in present time of future cash flows originated by an investment. The methodology consists in evaluating in current time (updated with an interest rate) the value of each of the alternatives. Comparing these results we are able to choose the approach providing the highest profitability. NPV can be computed as follows, where Y is the total time period considered (in years), r is the annual discount rate, $\mathrm{REVENUES}_y$ is the annual income obtained by the commercialization of connectivity, OPEX_y are the annual network operation and maintenance costs, and finally CAPEX is the initial investment, i.e., the capital necessary for the initial network deployment.

$$\mathrm{NPV} = \sum_{y=1}^{Y} \left[\frac{\mathrm{REVENUES}_y - \mathrm{OPEX}_y}{(1+r)^y} \right] - \mathrm{CAPEX} \quad (17)$$

CAPEX costs can be computed from the network design, whereas OPEX costs are computed using equations (6) and (16). Revenues are computed from the traffic matrix. However, part of the traffic could be lost as a consequence of failures, especially when reduced availability approaches are used, and thus, some penalties are applied. To compute the amount of expected traffic lost we use (2) introduced in Sect. 2. Then, the amount of effective revenues for the connectivity service can be computed as follows, where c_{p2p} is the price per hour of a point-to-point connection, and the parameter β is the relative penalty for the lost traffic.

$$\mathrm{REVENUES}_y = \left[\sum_{d \in D} \Delta t \cdot b_d - \beta \cdot \mathrm{ELT} \right] \cdot c_{p2p} \quad (18)$$

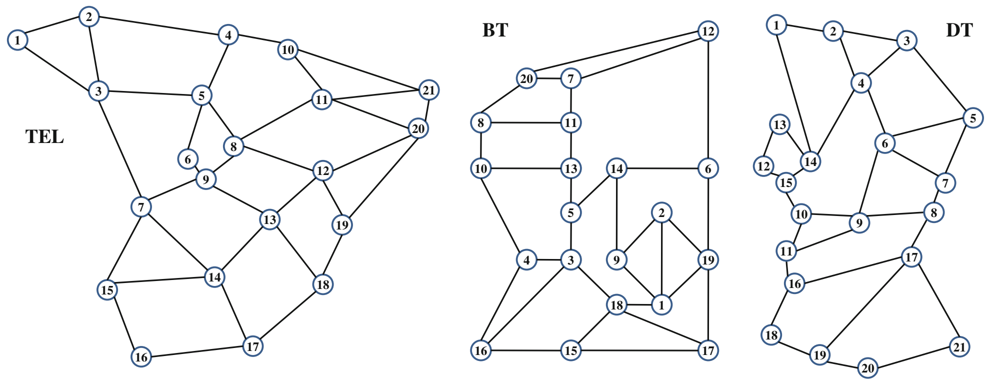
Next section provides interesting numerical results for the different network approaches and models presented.

5 Illustrative numerical results

5.1 Scenario

As previously stated, the main objective of this work is to efficiently address the problem of designing networks meeting a reduced network availability objective and hence reducing the CAPEX and OPEX operators' costs without significantly increasing SLA penalties. In this section, the performance of the approaches (joint and overlay from [5] and reduced availability GRASP-based optimizations presented in this paper)is compared in economics terms on a significant variety of real network topologies. Specifically, we have considered three national optical network topologies with different IP/MPLS topologies on the top (see Fig. 4): the 21-node Spanish Telefónica (TEL), the 20-node British Telecom (BT), and the 21-node Deutsche Telecom (DT).

Aiming at applying the presented approaches and models over a wide range of multilayer networks, on the top of the optical topologies, different IP/MPLS topologies with 40 metro nodes and different number of transit and interconnection nodes are designed. The table in Fig. 4 specifies the location of transit and interconnection nodes (identified by the associated optical node) of each multilayer network. Moreover, the spatial position of metro nodes is characterized by a uniform coverage degree based on the Kolmogorov–Smirnov goodness-of-fit test [19]. A value close to 100% indicates metro nodes uniformly located around every optical node, whereas a low value denotes the presence of areas with high density of metro nodes. Figure 4 also contains the coverage degree of the three networks under study. Regarding traffic,



Net	Transit	Interconn.	Metro Coverage degree	Traffic Mix (National/Interconnection)
TEL	3, 4, 9, 11, 14, 15, 19, 21	6, 8, 20	0.1%	30% / 70%
BT	1, 9, 10, 12, 14, 16, 20	7, 13, 15, 19	30%	40% / 60%
DT	3, 4, 5, 8, 9, 14, 19, 21	6, 7, 10, 13, 20	90%	50% / 50%

Fig. 4 Sample optical network topologies used in our tests: 21-node Spanish Telefónica (*left*), 20-node British Telecom (*center*), and 21-node Deutsche Telecom (*right*). A table with details of the IP/MPLS topologies as well as the IP/MPLS traffic mix is also provided

we assume two types of demands: national, where both metro end nodes belong to the network, and interconnection, where one of the end nodes is outside of the network. The considered traffic mix is also detailed in Fig. 4. As shown, three different multilayer network scenarios are defined, from an unbalanced scenario where 70% of the total traffic is interconnection with only 3 interconnection nodes and several high density metro areas TEL, to the well-balanced scenario with 50% of interconnection traffic, 5 interconnection nodes and near-uniformly metro areas DT.

Table 3 Cost of IP/MPLS nodes and OE ports (c.u.)

	Class 1	Class 2	Class 3	Class 4	Class 5
Capacity (Gbps)	160	320	640	1280	2,560
Max. ports	4	8	16	32	64
Cost	3	4.5	6.5	22.5	50.19
	1 Gbps	10 Gbps	40 Gbps	100 Gbps	
Port in IP/MPLS node	0.35	1.25	7.625	20.625	
Port in optical node	0.1	0.25	0.5	4	

5.2 CAPEX studies

Each multilayer network has been planned for six gradually increasing traffic loads, starting from an initial load of 4 Gbps per metro node and with increments of 45% at each step (roughly representing a year-over-year traffic increase). Aiming at providing accuracy, each traffic load has been executed 10 times with randomly generated demands following the above characteristics.

In addition to the networks designed using the overlay and the joint network approaches, three reduced network availability objective networks, designed applying the heuristic algorithm described in Sect. 2 to networks planned using the joint approach, have been considered: six 9's (6×9 s), five 9's (5×9 s), and four 9's (4×9 s).

To compute the network CAPEX, we consider the equipment costs proposed in [5]. Table 3 provides the used costs in cost unit (c.u.) for IP/MPLS nodes and OE ports. Note that, in contrast to the study carried out in [5], the cost of the optical layer is not computed; i.e., only IP/MPLS equipment is here considered. Figure 5 plots CAPEX costs for each of the considered approaches as a function of the offered load. Each load (4 Gbps $* 1.45^{(i-1)}$) is identified by the exponent i. As shown, to provide the highest availability, the overlay and the joint approaches require similar CAPEX (i.e., the differences observed in [5] are due to the cost of the optical layer). However, as soon as the network availability objective is lowered, CAPEX is reduced accordingly. Table 4 presents CAPEX savings on average obtained by implementing each of the approaches with respect to the overlay approach. As shown, relaxing network availability to the yet stringent objective of six 9's, obtained CAPEX savings are as high as 19%. These savings rise to more than 22% for the traditional five 9's network availability objective.

5.3 OPEX studies

Once the designed networks are put into operation, OPEX costs apply which take into account both energy and maintenance costs. Table 5 presents the values of the considered

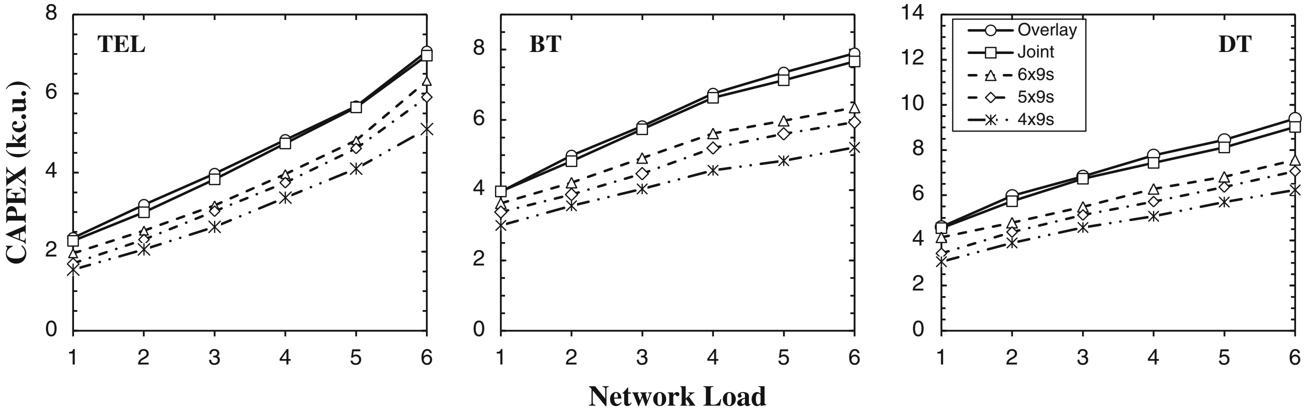


Fig. 5 CAPEX to implement each of the considered approaches as a function of the network load in TEL (*left*), BT (*center*), and DT (*right*) networks

Table 4 CAPEX savings

	Joint (%)	6×9s (%)	5×9s (%)	4×9s (%)
TEL	1.5	17.0	22.9	32.1
BT	1.4	15.7	22.0	30.8
DT	7.3	19.6	27.1	35.2

Table 6 Power consumption reduction

	Joint (%)	6×9s (%)	5×9s (%)	4×9s (%)
TEL	13.7	22.0	25.0	28.0
BT	16.4	26.4	28.8	31.2
DT	17.3	25.9	28.6	31.0

Table 5 Value of OPEX parameters

Time parameter	Value	Param.	Value
OE port MTTF	4E+5 h	$c_{ManYear}$	2.25 c.u.
IP/MPLS node MTTF	1E+3 h	c_{Wh}	5.5×10^{-7} c.u./kWh
OE port TR	10 min		
IP/MPLS node MTTR	12 min		

parameters, where time-related ones (left column in Table 5) are in line with those in [4].

Figure 6 illustrates the power consumed by the designed networks. Interestingly, great power consumption savings can be obtained by implementing the joint approach with respect to the overlay approach, as a consequence of IP/MPLS node duplication of the latter. Additional savings can be obtained by relaxing network availability. Table 6 presents the average power consumption reduction obtained by implementing each of the approaches with respect to the overlay approach. We observe that the reductions range between more than 13% (joint approach) and more than 31% (4 × 9's approach); we also note that with the traditional five 9's network availability objective, and a saving of more than 25% is obtained. In summary, great energy savings are obtainable when passing from the overlay to the joint

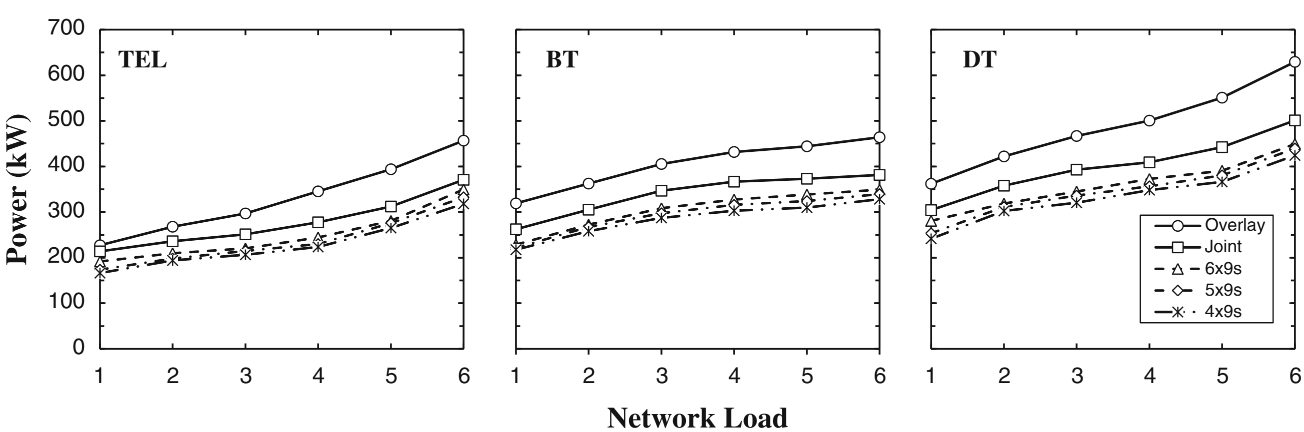


Fig. 6 Power consumption of the considered approaches as a function of the network load in TEL (*left*), BT (*center*), and DT (*right*) networks

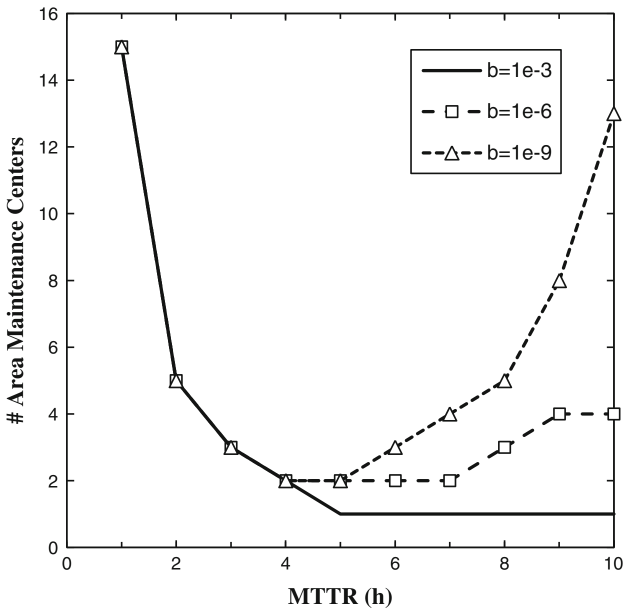


Fig. 7 Number of area maintenance centers to open as a function of the MTTR objective

approach, with the 6/5/4 × 9s approaches adding further significant energy savings.

Regarding maintenance costs, the MOP model was implemented in iLog-OPL and solved by the CPLEX v.12.2 optimizer [20] on a 2.4 GHz Quad-Core machine with 8 GB RAM memory. Firstly, it is worth studying the influence of both the required MTTR and the double-failure probability b threshold over the number of area maintenance centers that need to be opened. Figure 7 shows the number of maintenance centers that need to be opened for the TEL network, where the plots represent different values of b. When the double-failure probability is high ($>10^{-3}$), the number of area maintenance centers decreases when MTTR is increased, reaching its minimum for MTTR equal to 5 h. Note that this is in line with the results in [7]. However, when the required value of b is low (10^{-6}) or very low (10^{-9}), the number of maintenance centers cannot reach the minimum since the double-failure threshold would be exceeded. Even worse, increasing MTTR increases unavailability of the network components, and as a consequence, the number of required area maintenance centers will be higher. The same conclusions can be also applied to BT and DT networks. Without loss of generality, hereafter, we use 10^{-6} for the double-failure probability threshold.

Table 7 Value of NPV-related parameters

Parameter	Value
Δt	365 ∗ 24 h
β	2
Y	10 years
r	5%

Table 8 NPV relative gains

	Joint (%)	6 × 9 s (%)	5 × 9 s (%)	4 × 9 s (%)
TEL	62	121	132	149
BT	54	106	125	134
DT	56	118	126	132

5.4 NPV comparison

It is important to compare the alternatives in terms of the NPV, since CAPEX and OPEX costs are only partial indicators. Table 7 shows the value of the parameters used for the NPV comparison, where the price of the connectivity service, β, has been selected to reach the break-even point (NPV = 0) after 5 years for each network under the overlay approach, assuming MTTR = 2 h.

We have studied the influence of MTTR on the NPV for the networks designed above. As shown in Fig. 8, choosing four

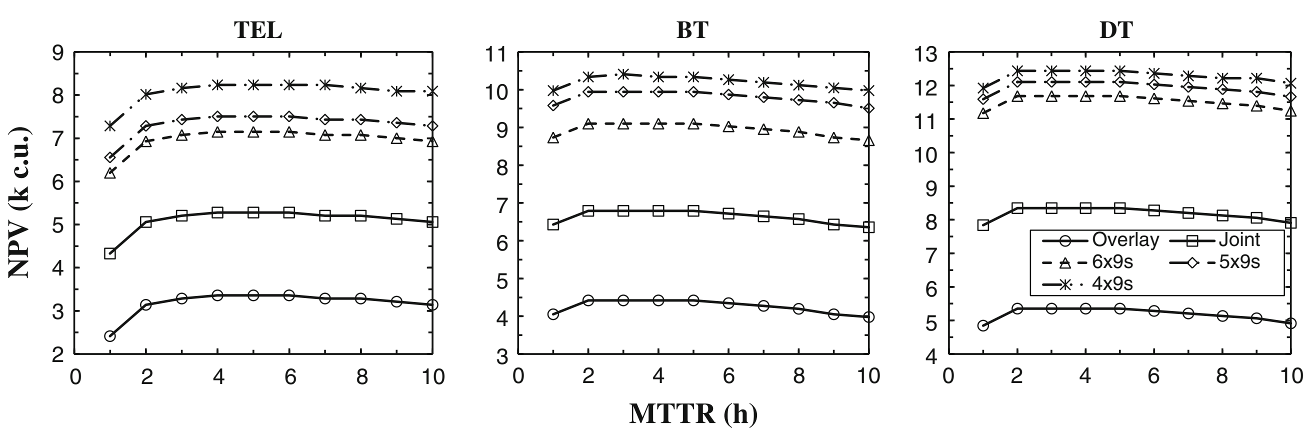


Fig. 8 NPV against MTTR for medium network loads ($i = 3$) in TEL (*left*), BT (*center*), and DT (*right*) networks

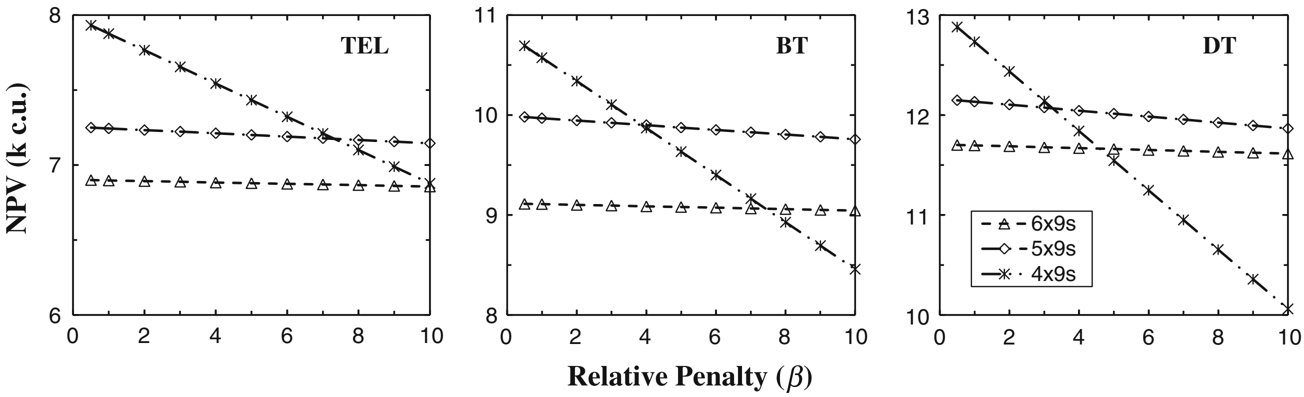


Fig. 9 NPV against β for medium network loads ($i = 3$) in TEL (*left*), BT (*center*), and DT (*right*) networks

Table 9 Relative price of the services

	Joint (%)	6×9 s (%)	5×9 s (%)	4×9 s (%)
TEL	−10.8	−23.4	−25.7	−31.2
BT	−9.3	−20.5	−23.7	−29.6
DT	−10.1	−24.2	−26.7	−30.9

9's for the network availability objective maximizes NPV of every network and for every MTTR when applying the values of Table 5. Note how NPV of networks designed with the overlay approach is clearly lower than that of the joint approach. Additionally, reducing network availability objective to the stringent value of six 9's highly increases NPV. Moreover, regarding MTTR, mean values ranging from 3 to 5 h provide optimal NPV values as a consequence of the reduction in maintenance costs.

Similar to previous comparisons, Table 8 presents on average NPV gains obtained by implementing each of the approaches with respect to the overlay approach. Improvements ranging from 54 to 62% are observed when applying the joint approach. Moreover, reducing the network availability objective, gains as high as 149% can be obtained.

Although networks designed for the four 9's objective provide the highest NPV in Fig. 8, the result would be different when different values for the relative penalty for the lost traffic (β) were applied. To analyze this dependency, Fig. 9 plots networks' NPV as a function of β for MTTR $= 2$ h. As shown, values lower than 3 ensure that the four 9's availability option maximizes network NPV. Only when higher values of β are used, as high as 7 in the TEL network, the traditional five 9's availability option would be the most profitable.

Finally, since specific services could be offered over each designed network and thus SLAs tuned for the specific availability for which the network was designed, Table 9 shows the relative price of the services with respect to the overlay approach such that NPV $= 0$ after 5 years, MTTR $= 2$ h, and $\beta = 0$. As illustrated, prices can be reduced more than 20% as soon as the network availability is reduced to six 9's and more than 30% on average for four 9's availability, enlarging thus the set of services that a network operator can offer.

6 Concluding remarks

To provide full survivability against single failures in optical links, IP/MPLS nodes, and OE ports in IP/MPLS-over-WSON multilayer networks, different approaches consisting in either duplicating IP/MPLS nodes (the traditional overlay approach) or over-dimensioning IP/MPLS nodes (the joint approach) can be followed. However, to provide differentiated services, specific network availability requirements can be added to the IP/MPLS network design. This paper has studied the influence of the required availability on the value of IP/MPLS-over-WSON multilayer networks.

Firstly, a GRASP-based heuristic algorithm was presented to design the network while meeting reduced network availability objectives. In terms of CAPEX, networks designed under the joint and the overlay behave similarly (when no optical layer costs are considered), while networks for reduced availability objective provided savings in the order of 16% even for the stringent six 9's availability.

Secondly, since OPEX needed to be considered in the comparison, models to compute energy and maintenance costs, both of major concern for network operators, were proposed. Networks designed under the overlay approach demonstrated the highest power consumption, since even the joint approach achieved more that 13.7% of reduction. When network availability was reduced, power consumption reduction ranged from 22 to 31.2%.

Third, since reducing network availability would reduce revenues as a result of SLA breaches, the expected loss of traffic as a consequence of failures was also computed. When network alternatives were compared in terms of NPV, including thus not only CAPEX and OPEX but also revenues, high gains were observed. For example, using the joint approaches, the gains raised from 54 to 62%. These gains were almost duplicated as soon as the network availability objective was reduced.

To conclude, a wide range of services can be covered, each with its proper price, deploying networks specifically designed to meet specific availability objectives.

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