Consolidation strategies of provisioning oriented optical networks[1]

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Fast provisioning capabilities enabled by signalling intelligence and automated switching flexibility are becoming fundamental features of Next Generation Networks based on optical transport. Throughout the recent years numerous research and development projects, standardisation activities, and a large number of publications have been devoted to fast provisioning enabled optical networks. However, in the related research activities less attention has been paid to network state evolution during the provisioning process.

The main scope of the paper is, based on a three-phase network development lifecycle, to define different consolidation strategies in order to improve the performance of provisioning oriented optical networks. The proposal is motivated by the inherent lack of capacity efficiency of optical channel provisioning processes.

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1. Introduction and motivations

Recently, the hardly predictable and permanently increasing data traffic of IP services and broadband applications has become the largest traffic component in transport networks. The major market changes, e.g. the pay-as-you-grow preference of providers, and the layered structure of the players on the service market (content providers, network service providers and transport service providers) led to significant difficulties in modelling and forecasting services and traffic growth. This evolution disabled the traditional approach based on forecast driven off-line design and pre-configuration of network resources. The implementation of the Next Generation Network concept [1], i.e., the realisation of a unified all-IP

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service platform will strengthen these trends in the foreseeable future.

Transport networking under uncertain capacity demands requires either inefficient over-dimensioning of network resources or intelligent configuration flexibility to follow unexpected changes in the traffic pattern. Both strategies are capable of preventing early saturations of some transport systems that would lead to network bottlenecks and, ultimately, blocking of transport capacity requests. Reduction of the effect of demand uncertainty has been studied in the context of many network technologies, such as in case of leased line services networks [2], ATM networks [3] and survivable mesh-based transport networks [4-6].

Provisioning oriented optical networks are optical networks with enough intelligent flexibility to automatically serve optical channel requests arriving spread in time and space to the network. The intelligent control and management functions are based on the Automatically Switched Optical Network (ASON) or the Generalized Multiprotocol Label Switching (GMPLS) concept. The strategies, presented in the paper, can be realized applying either the GMPLS or the ASON concept with centralized or distributed UNI implementation [7, 10].

Throughout the recent years numerous research and development projects like IST Next Generation Optical Network for Broadband in Europe (NOBEL) [8] and Multi-Partner European Test Beds for Research Networking (MUPBED) [9], standardisation activities e.g. OIF's UNI specification [10] and a large number of publications have been devoted to fast provisioning enabled optical networks. However, in the related research activities less attention has been paid to network state evolution during the provisioning processes.

The re-optimization phase has already been part of the lifecycle of traditional TDM networks, where the amount of reserved capacities was optimized by periodically re-grooming the traffic [11].

The re-optimization of optical networks has been studied widely in research works. These works differ in the applied measures of the reconfiguration, in the algorithms, how the reconfigured network state can be achieved and in the relation between the current and the reconfigured network state. The applied measures can be divided into two basic classes. The first class contains measures that consider the re-optimization of occupied network resources, e.g. minimize average hop-numbers of connections [12], the number of occupied wavelengths [13], the number of occupied physical links [13], the average propagation delay over a lightpath [14] or the maximum link load [14]. At the same time the second class of measures describe the number of changes necessary to reach the optimal network state from the current one. Various types of changes may be considered according to the network model, e.g. the number of wavelength changes [13], the number of wavelength path changes [12], the mean number of disrupted transceivers or the maximum instantaneous number of disrupted transceivers [15].

The algorithms can be assorted into methods giving exact results, e.g. linear [4, 12-14, 16-17] or non-linear programming methods, and methods giving approximate results, e.g. genetic algorithms [14, 18], or Lagrange decomposition [19].

Finally, in terms of the relation between the current and the reconfigured network state one can distinguished direct approaches, where the new network configuration is independent from the current one, partial reconfiguration approaches and local search approaches. A detailed summary of measures and algorithms can be found in [20].

[21] was among the first publications that raised the lightpath re-optimization issue in mesh optical networks. The authors published a more comprehensive description of the problem and their related achievements recently in [22]. In these studies [21, 22] the re-optimization was carried out in a live OEO network. The presented work covers the re-optimization of optical mesh networks where shared (backup) path protection is used. The main focus of the paper is on the algorithmic considerations of lightpath re-optimization. The savings yielded by optimal re-arrangement are also demonstrated by numerical examples in both networks with static infrastructure and traffic churn and networks with growing infrastructure. Rearrangement strategies and algorithms are given both for backup path re-optimization and complete re-optimization, which involves working and backup paths, as well.

The main motivations for rerouting/reconfiguration in optical networks mentioned in [23] are resilience, i.e. rerouting in failure cases, and congestion easing, i.e. rerouting of already accommodated requests to make room for new ones. This work studies the rerouting/reconfiguration process itself and puts emphasis on finding the proper sequence of rerouting and resolving the dependencies that block a potential rerouting sequence.

In [24] the author shows some situations, relating to the size of the modules, when the re-optimization of the network is unnecessary and only the incremental design can give nearly the same good result.

The next research paper that must be mentioned is [25]. In this work the authors compare four re-optimization strategies for span-restorable mesh survivable networks. The defined strategies differ in their objective functions and they are given both for backup path and complete re-optimization. The applied network model was an OOO network with wavelength conversion and with static demands.

The focus of the present paper is different from that of the listed works. The adapted approach here is closer to [26], where some practical preferences of a network operator are taken into account, as well. In a previous paper [27] we have already identified and demonstrated the inherent lack of capacity efficiency of provisioning processes by numerical examples. This has justified the insertion of consolidation into the lifecycle of provisioning oriented optical networks. The introduced papers [21-22, 25] deal with the measure of the re-optimization of the network, i.e. what must be reconfigured, the complete network or only the protection paths, beside different objective functions. The present paper defines some new re-optimization strategies, which take also into consideration the frequency of re-optimization. To make it easier to understand, a general formulation is given to the description of consolidation strategies. The introduction of the new strategies is connected to such real network situations, where the application of these strategies can guarantee better efficiency. These contributions can serve with new information to the research area.

Section 2 gives a brief overview on the efficiency issues of the network configurations evolved in real time provisioning processes and discusses an approach to operate and maintain provisioning oriented optical networks with improved efficiency. Section 3 introduces a formulation, which can be suitable to the general description of consolidation strategies. Then Section 4 shows some useful strategies for the consolidation of a highly saturated network and a network that serves optical channel requests with high reliability requirements. Finally, the presented work is summarized and concluded in Section 5.

2. Lifecycle of Provisioning Oriented Optical Networks

Fast provisioning of permanent optical channels, that is, soft permanent optical channel services [28] can be interpreted, as follows. Due to the traffic changes of client services the clients generate optical channel requests spread in time and space. Based on the distributed signalling and switching intelligence of optical network nodes, routing and wavelength allocation (RWA) is solved on-line, and the appropriate network elements are configured to accommodate the optical channel requests. Once an optical channel is set up to accommodate a request it remains unchanged, assuming a simple incremental traffic model.

2.A. Traditional lifecycle

During the lifetime of a provisioning oriented network, basically, there are two repetitive phases:

Provisioning phase: arriving requests are served sequentially. This process may lead to the saturation of some network resources; in that case extension of network capacity is needed.

Network capacity extension phase: additional resources are designed and installed to remove/prevent network bottlenecks.

The aim of the provisioning process is to set up optical lightpaths by means of performing on-line decisions and configuration actions while minimizing blocking probability on the given limited network resources. The decisions cover both path selection and wavelength assignment.

The basic two-phase cycle leaves the configuration and setup of network resources unchanged, thus, the capacity efficiency of the network is determined by the applied provisioning process, i.e. it may strongly depend on the random arrival sequence of optical channel requests.

In case of on-line provisioning the capacity demands are not known in advance; therefore, because of the sequential service of the arriving optical channel requests the decisions made during the provisioning process are sub-optimal. In other words, the accommodation of the current request is optimal in the given network state, but not for the whole provisioning process.

2.B. Lifecycle with consolidation

With the extension of the lifecycle the overall network performance can be improved. When network saturation requires actions from the operator, before or even instead of installing new resources, a consolidation process can be activated. During the consolidation process limited rearrangement and reconfiguration of the network is performed to improve capacity efficiency. This may free some network resources. If the consolidation does not result in enough idle resources the network capacity should still be extended by installing new network elements.

The consolidation phase should be repetitive since the requests arriving after a consolidation phase are served according to sub-optimal decisions, again.

This extension of network phases results in a three-phase lifecycle (see Fig. 1.) including:

Provisioning phase,

Consolidation phase,

Network capacity extension phase.

The basic idea behind consolidation is that configuration decisions based on the knowledge of a certain group of optical channel requests (already in the network) is definitely more efficient than those resulted from a given realization (sequence) of the provisioning process.

A more optimal resource allocation may be obtained by performing a ‘traditional’ network design including all demands currently being served. A sequence of reconfiguration actions is then needed to set up the obtained optimal network state. But the trade-off between the increase of capacity efficiency and the extent of rearrangements should be considered in the process.

The extent of rearrangements can be restricted according to the types and amount of changes, as well. For example, having a network configuration with predefined routes, the routing can be left unchanged, and only the wavelength assignment is modified.

An important problem is to identify when the consolidation process needs to be triggered. The simplest approach is that consolidation is executed after fixed time intervals. Another approach can be to trigger consolidation by the change of some network parameters, e.g. the amount of the free capacities in the whole network.

The frequency of reconfiguration is likely to have an impact on the amount of changes and the computational complexity of the optimised solution. Thus, one must find a trade-off between the frequency of the reconfigurations and the amount of required changes. These problems will be explained in detail in Chapter 4.

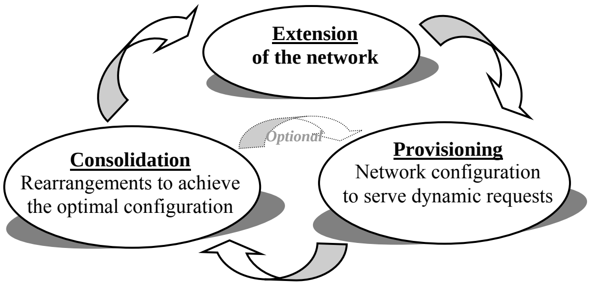


Fig. 1. Major networking processes in a provisioning oriented optical network

The gain in efficiency due to consolidation can also be considered as the sub-optimality of the provisioning process. The measure of this kind of sub-optimality can be evaluated according to a simple theoretical upper bound, if the operation of the provisioning mechanism is known. Assuming that the set of sequential demands is known in advance, an upper bound concerning the achievable capacity efficiency can be obtained by means of applying traditional off-line design (see Fig. 2).

In [27] a more detailed description of the traditional and the three-phase lifecycle is given.

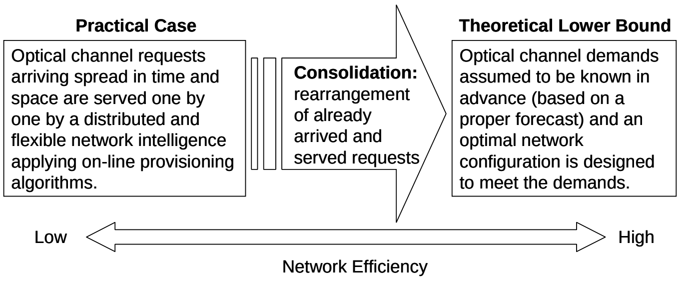


Fig. 2. Inefficiency of on-line provisioning

3. Formalization of the consolidation phase

This chapter shows a formulation of the general description of consolidation strategies. In the provisioning phase each optical channel request, which can be served, gets a path and a wavelength. Based on this concept the consolidation can be realized as the transformation of the path and wavelength allocation. The result of this transformation is the optimal allocation. However the input cannot be described so simply, because it contains multiple parameters. The first parameter is the sub-optimal allocation of the paths and wavelengths coming from the provisioning phase.

The second parameter of the transformation is the objective function, which determines what the optimal solution of the reconfiguration is. The objective function may require more parameters, as well. These parameters can belong to three groups:

Parameters controlling the paths of the demands (e.g. to minimize the amount of reserved capacities)

Parameters controlling the wavelength allocation (e.g. to minimize the number of used wavelengths)

Special parameters that depend on the applied provisioning strategy (e.g. the served demands must not overachieve their reliability requirements significantly).

The effect of the different parameters can be weighted in the objective function.

The further parameters of the transformation concern the strategy of the consolidation. The two main questions in relation to consolidation are that when the consolidation should take place and what should be reconfigured. More precisely, what kind of network attribute triggers the consolidation process and what the measure of the consolidation is. Based on this approach, two new parameters are needed, one to describe the triggering attribute and another one to define the measure of the reconfiguration.

Besides, a last parameter must still be introduced to describe the restrictive conditions coming from the applied provisioning strategy, e.g. an optical channel demand with high reliability requirement must not be interrupted for a long time.

Thus the consolidation can be interpreted as the following transformation:

$$Consolidation(All_{curr}, Obj, Tri, Mea, \mathrm{Re}\,s) \rightarrow All_{opt}$$, where

All_{curr} : current path and wavelength allocation before the consolidation

All_{opt} : optimal path and wavelength allocation

Obj : objective function

Tri : network attribute that triggers the consolidation process (the simplest case is when the interval between the consolidation processes is fixed)

Mea : reconfiguration measures allowed

$\mathrm{Re}\,s$: parameter to describe the restrictive conditions

The next chapter shows how some different consolidation strategies can be interpreted by this formulation and what these parameters of the transformation mean in practice.

4. Consolidation strategies

In this chapter some basic strategies are introduced to the consolidation of two networks having different features. In the first case the network is highly saturated and in the second one the demands have high reliability requirements. In both cases an unavailability threshold based provisioning strategy [29] is used. This provisioning strategy is a kind of shared protection. This means, that protection paths can share capacity, to decrease the amount of required resources, if their working paths are disjoint. This provisioning strategy completes the shared protection with end-to-end reliability guarantees for the connections in the presence of multiple simultaneous failures. The complexity of the computations of this problem is eliminated by introducing the concept of sharing unavailability, defined as the probability that a shared backup resource is activated and thus becomes unavailable to a demand. The extent of allowed sharing is determined by introducing a threshold on sharing unavailability. Shared (backup) path protection is combined with this threshold to propose an on-line provisioning strategy.

In the experiment of the current study an L1VPN (Layer 1 Virtual Private Network) [30] with 9 nodes, 16 links, 9 wavelength/link was used over a theoretical Hungarian optical network topology for accommodating a certain random demand sequence. The 9 wavelengths belong to one VPN; the consolidation is applied only to this network segment. In this case the extension of the network capacities can be made easily by adding 1-2 wavelengths to the VPN. To implement the on-line provisioning a simulator has been developed. After each 10 demand arrivals until 40 demands a snapshot is taken of the network state and resource consumption yielded by the proposed provisioning oriented network development lifecycle is compared against the output of the ILP (Integer Linear Programming) design process performed with the data of the respective snapshot. The ILP formulation of the consolidation phase can be found in Annex A. This is the formulation of the strategy, when all of the arrived demands are consolidated. For a specific consolidation strategy the formulation must be completed with further constraints. These constraints are introduced next to the definition of the strategies. To support the observations, all of the cases are simulated with 6 random sequences of demands and confidence intervals are calculated, which can be found in Annex B.

4.A. Consolidation of highly saturated networks

The first network example is a highly saturated network. In this case the problem is that there are only few free capacities for the reconfiguration of the demands. The solution of the problem is that only some reconfiguration actions can be made during a consolidation phase. The obvious way is that only few demands are re-optimized during a consolidation phase. On the other hand it also can be reached if the network is not allowed to move far from the optimal ILP solution. Based on the first approach one reconfigures only those demands that arrived after the previous consolidation process. Although after the consolidation the allocation of paths and wavelengths will not be optimal, the number of reconfigured demands in a consolidation process will be lower and this number can be decreased even more with more frequent consolidation.

The description of “Consolidate recent arrived demands” and “Consolidate all arrived demands” strategy with the introduced formulation can be found in the first and second column of Table 1. When applying the “Consolidate all arrived demands” strategy one must use the formulation introduced in Annex A. In the “Consolidate recent arrived demands” the $\omega^{\lambda}_{p_w(x)}$ and the $\rho^{\lambda}_{p_p(p_w(x))}$ variables of the demands, which arrived before the last consolidation phase, must be bounded.

Table 1. The *Obj, Tri* and *Mea* parameters of the different consolidation strategies

	Consolidate recent arrived demands	Consolidate all arrived demands	Permanent working path and wavelength	Permanent working path
Obj	Minimize the amount of reserved capacities			
Tri	Consolidation after 10 new demands arrived			
Mea	Reconfiguration of the demands, arrived after the last consolidation phase	Reconfiguration of all arrived demands	Reconfiguration of the protection path and wavelength of all arrived demands	Reconfiguration of the working wavelength and the protection path and wavelength of all arrived demands

The difference between the “Consolidate recent arrived demands” and the “Consolidate all arrived demands” strategies can be seen in Fig. 3. The observation is that the difference between the amount of reserved capacity of the two different consolidation strategies is not so significant, although it increases with the number of arrived demands. After 40 demand arrivals the average difference is 10% before the consolidation and 5% after the consolidation. However, the number of reconfigured demands is significantly lower in case of the “Consolidate recent arrived demands” strategy. Fig. 5B demonstrates the total path and wavelength changes in case of the two different strategies. As it is expected, the “Consolidate recent arrived demands” strategy requires less path and wavelength changes to achieve the optimal solution.

The second solution is that the network is not allowed to move far from the optimal configuration and,

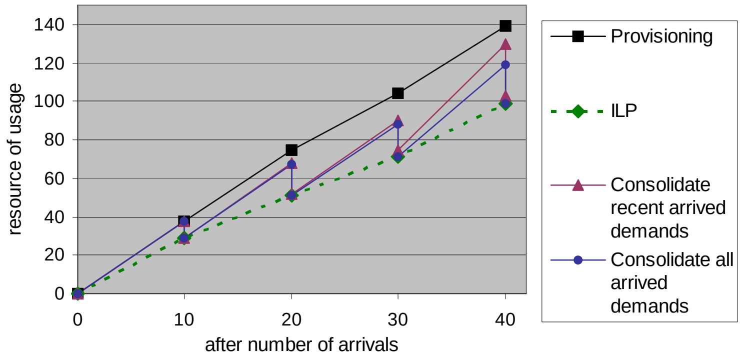


Fig. 3. Amount of reserved capacities when in the snapshot points all of the arrived demands or only the demands arrived after the last consolidation phase are re-optimized

therefore, less reconfiguration actions are needed to reach the optimal allocation. This approach can be realized if the network is consolidated more frequently. In this case the strategy can be defined as the "Consolidate all arrived demands" strategy, but the value of the *Tri* parameter is changed.

Fig. 4 shows the amount of reserved capacities in the optimal case and during the provisioning phase with consolidation activated with different frequencies. The observation is that the deviation of the provisioning process from the optimal solution increases over time, and so does the potential resource utilization gain due to consolidation. But after reconfiguration the network state gets close to the optimal configuration. In case of a "Frequent consolidation" strategy the amount of the used resources is closer to the optimal ILP solution, as can be seen in the case of the CONS(10) curve. In case of a "Rare consolidation" strategy, as in the case of CONS(40), where consolidation is run only at the end of the provisioning process, the resource efficiency gap is larger. This phenomenon can be observed also in Figure 5A, which illustrates the dependence of deviation from the optimal resource usage as a function of the frequency of the consolidation. The CONS(x) refers to the provisioning process with consolidation, where x is the number of demand arrivals in between successive re-optimisation attempts.

Even though every consolidation frequency gives nearly the same result after the arrival of the last demand, the amount of necessary configuration changes are not the same. A "Frequent consolidation" strategy results in a higher number of total path and wavelength changes executed during the consolidation, as demonstrated by Figure 5B. At the same time the average number of configuration changes required per reconfiguration is lower. Intuitively, less changes also means that during the reconfiguration phase less extra

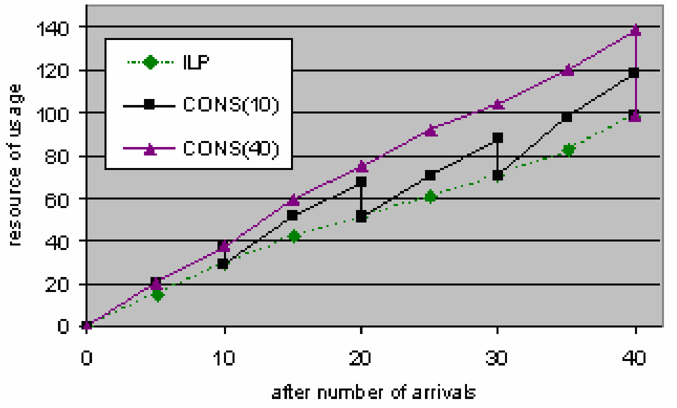
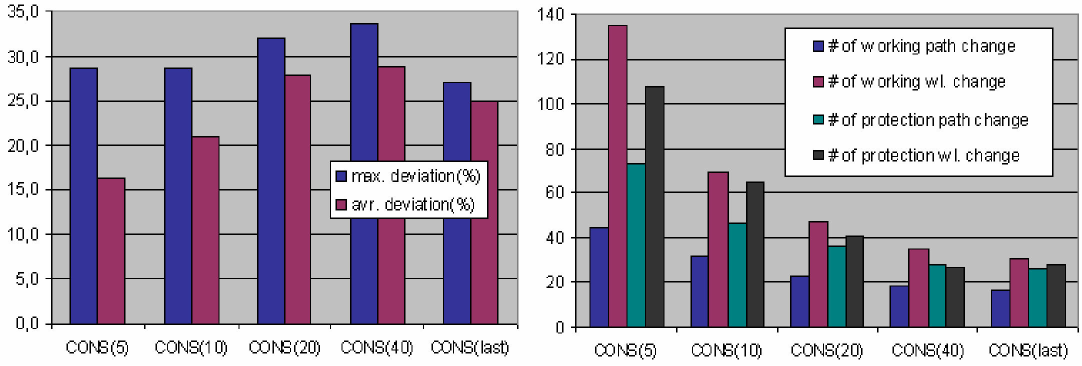


Fig. 4. Amount of reserved capacities in the optimal case and the provisioning case with different consolidation frequencies



A) Maximal and average deviation from the optimal in case solution in the reconfiguration points

B) Total number of path and wavelengths changes of different consolidation strategies

Fig. 5.

capacity (buffer capacity temporarily used in a given reconfiguration sequence) is needed to reach the consolidated network state. As a consequence, in a nearly saturated network consolidation should be triggered more frequently. The opposite of the described phenomenon can be observed if the frequency of consolidation is decreased.

Based on the observations it can be claimed that the best strategy for the consolidation of a highly saturated network is that only the most recently arrived demands are re-optimized and/or the consolidation process is applied frequently. In this case the network may move farther from the optimal solution, but the number of reconfiguration actions stays less.

4.B. Re-optimization of demands with high reliability requirements

The problem with the re-optimization of these demands is that the demands must not be interrupted for a long time, because their reliability requirements may be violated. Therefore, the demands can be reconfigured only a few times. The solution for this problem can be the “Consolidate recent arrived demands” strategy or a “Rare consolidation” strategy because, in the case of these strategies the number, the consolidation phase is activated, is lower, as can be seen in Section 4.A.

Another solution is that only the protection path and wavelength of a demand can be reconfigured. The description of this “Permanent working path and wavelength” strategy can be found in the third column of Table 1. In this case the demand is not interrupted and the reliability requirement is not violated. In the “Permanent working path and wavelength” strategy the $\omega^{\lambda}_{p_w(x)}$ variables for each demand must be bounded. As can be seen in Fig. 6, the amount of reserved capacities is far from the optimal ILP solution and the deviation increases with the number of arrived demands.

To decrease this deviation we may also allow the re-optimization of working wavelengths beside the protection paths and wavelengths. Thus only the working paths stay fixed under the consolidation phases.

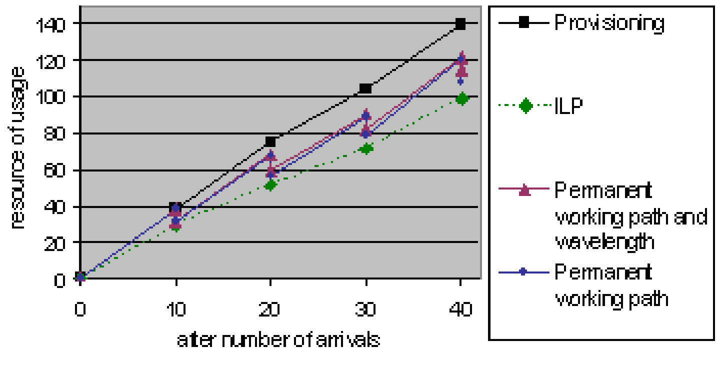


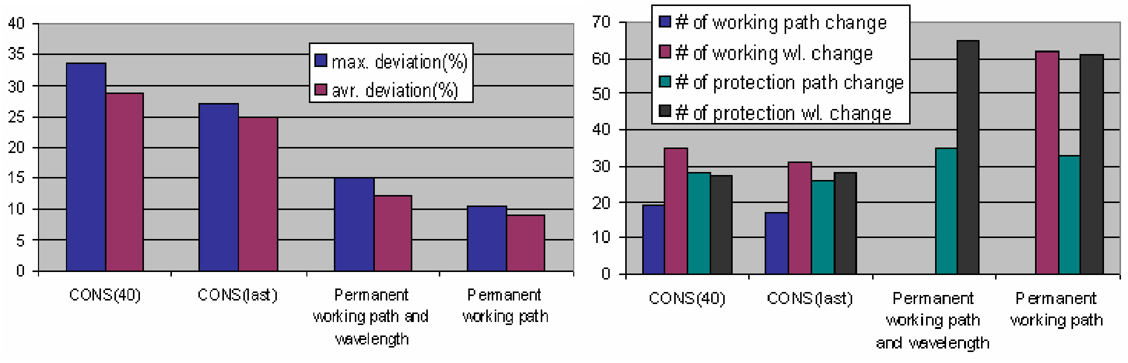
Fig. 6. Amount of reserved capacities if both the working paths and wavelengths or only the working paths of the demands are

The definition of this "Permanent working path" strategy is in the forth column of Table 1. The basis of this approach is that the change of a wavelength requires less management complexity than the reconfiguration of the whole path. The reason of this statement is that the change of a wavelength, besides wavelength continuity, means only the freeing of a wavelength and a reserving another one along a fixed path. Whereas, the reconfiguration of a path is a path search in the space of continuous wavelengths, and the solution of this problem involves more nodes.

When applying the "Permanent working path" strategy the $\sum_{\lambda} \omega^{\lambda}_{p_w(x)} \leq 1$ constraint must be used for each working path. As expected, the amount of reserved capacities is lower when applying this strategy (see Fig. 6).

Fig. 7A demonstrates the average and maximum deviance from the optimal solution and Fig. 7B shows the total number of path and wavelength changes. On both figures the results are compared to the results of the "Rare consolidation" strategy and the "Consolidate recent arrived demands" strategy.

The observation is that the two strategies last introduced approximate the optimal solution much better than other strategies (see Fig. 7A). However, to reach the configuration, which is close to the optimal, significantly more reconfiguration actions must be made, than applying the other two strategies (Fig 7B).



A) Maximal and average deviation from the optimal **B) Total number of path and**
wavelengths changes in solution at the reconfiguration points **case of different**
consolidation strategies

Fig. 7.

The conclusion is that if there are enough free capacities in the network, the application of the "Permanent working path and wavelength" or the "Permanent working path" strategy is recommended. Otherwise, if the network is saturated, then the "Rare consolidation" strategy or the "Consolidate recent arrived demands" strategy is proposed. Another potential solution can be a mixed strategy, e.g. only the protection path and wavelength of the most recently arrived demands can be re-optimized. The research of these mixed strategies will take place in the future.

5. Summary and conclusions

The paper proposed a potential approach to design provisioning oriented optical networks. Limited resource efficiency of provisioning strategies due to the on-line nature of the problem was identified and a consolidation stage was introduced in the lifecycle to improve capacity efficiency. Then, a general formulation was given that can describe the different consolidation strategies as a transformation, whose input parameters are the path and wavelength allocation before the consolidation, the objective function, the triggering attributes, the reconfiguration measures allowed and a parameter, which can describe the restrictive conditions that derive from the applied provisioning strategy.

Finally, some useful consolidation strategies were introduced for the consolidation of a highly saturated network and for the re-optimization of demands with high reliability requirements, and their advantages and disadvantages were analyzed by means of simulations. Based on the results obtained it is turned out that different network situations require different consolidation strategies (e.g. "Consolidate recent arrived demands" or "Frequent consolidation" strategy in case of a highly saturated network; "Rare consolidation", "Consolidate recent arrived demands", "Permanent working path and wavelength" or "Permanent working path" strategy in case of a network that serves optical channel requests with high reliability requirements) to achieve the best efficiency.

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ANNEX A

MILP formulation of the optimization problem

To determine the solution with the least amount of capacity usage for the consolidation of the unavailability threshold based provisioning strategy we solve this problem formally as a mixed-integer linear program. The following formulation is based on the notations introduced in [29].

In the formulation the network topology is represented as a directed graph $G(V,E)$ where *V* is the set of nodes and E is the set of links. Links can have two states, they are either operating or failed. Link failures are assumed to be statistically independent, and the link failure probability $FP(e)$ is known for all links $e \in E$.

Each link $e \in E$ corresponds to a pair of fibers, one for each direction of propagation. Without loss of generality, links are assumed to have W wavelength channels on each fiber.

Each OCh demand $x \in X$ requires one wavelength channel between a source node $s \in V$ and a destination node $d \in V$ and has a reliability requirement parameter $0 \le r < 1$ i.e., the maximum accepted probability that demand *x* is disrupted by a failure of any multiplicity in the network. Demands are served from a predefined set of routes, which contains the working paths and the link disjoint backup paths. (Note: the paths are wavelength continuous, therefore we do not have a specific constraint for wavelength continuity in the formulation).

Given:

$V = \{v\}$	Number of nodes in the network
$E = \{e\}$	Number of links in the network
$e(i, j)$	Link originating in $i \in V$ and terminating in $j \in V$
$L(e)$	Length of link $e \in E$
$W = \{\lambda\}$	Number of wavelengths on each fiber
$X = \{x\}$	Set of demands
$r(x)$	Reliability requirement parameter of demand $x \in X$
$P_w(x) = \{p_w(x)\}$	Set of working paths of demand $x \in X$
$P_p(P_w(x)) = \{p_p(p_w(x))\}$	Set of protection paths of demand $x \in X$
$e \in p_w(x)$	Means that $p_w(x)$ contains link $e \in E$
$e \in p_p(p_w(x))$	Means that $p_p(p_w(x))$ contains link $e \in E$
$\Pr(p_w(x))$	Probability that working path $p_w(x)$ is disrupted

$\Pr(p_p(p_w(x)))$	Probability that protection path $p_p(p_w(x))$ is disrupted
$\Pr(e)$	Failure probability of link $e \in E$
q_s	Unavailability threshold

Variables:

$\alpha_{e(i,j)}^{\lambda}$	Link indicator that equals one if the λ wavelength of the link $e(i, j)$ is used by any working path; zero otherwise (binary variable).
$\beta_{e(i,j)}^{\lambda}$	Link indicator that equals one if the λ wavelength of the link $e(i, j)$ is used by any protection path; zero otherwise (binary variable).
$\omega_{p_w(x)}^{\lambda}$	Working path indicator that equals one if the λ wavelength is used by $p_w(x)$; zero otherwise (binary variable).
$\rho_{p_p(p_w(x))}^{\lambda}$	Protection path indicator that equals one if the λ wavelength is used by $p_p(p_w(x))$; zero otherwise (binary variable).

Objective:

$$\text{Minimize } \sum_{\lambda, e(i,j)} \alpha_{e(i,j)}^{\lambda} + \sum_{\lambda, e(i,j)} \beta_{e(i,j)}^{\lambda}$$

The objective function minimizes the amount of reserved capacities (wavelength * link).

Constraints:

Topology constraints:

Equation (1) ensures that only one working path is assigned to a demand. If the reliability requirement of a demand is higher than what the working path can guarantee, a protection path must be also reserved for the demand. Equation (2) ensures that only one working path is assigned to a demand. The constraint, that one working path can be realized on a wavelength of a link, is guaranteed by Equation (3). Equation (4) ensures the sharing of protection paths and prevents protection paths from sharing a wavelength with any working path. Equation (5) guarantees that the protection path of the demand will be chosen from that protection path set which belongs to the working path of the demand.

$$\forall x \qquad \sum_{p_w(x)} \sum_{\lambda} \omega^{\lambda}_{p_w(x)} = 1 \tag{1}$$

$$\forall x \qquad \sum_{p_p(p_w(x))} \sum_{\lambda} \rho^{\lambda}_{p_p(p_w(x))} \leq 1 \tag{2}$$

$$\forall e, \lambda \qquad \sum_{x} \sum_{p_w(x) | e \in p_w(x)} \omega^{\lambda}_{p_w(x)} \leq 1 \tag{3}$$

$$\forall p_p(p_w(x)), \lambda \qquad \rho^{\lambda}_{p_p(p_w(x))} + \sum_{p_w(x) | p_w(x) \cap p_p(p_w(x)) \neq \{\}} \omega^{\lambda}_{p_w(x)} \leq 1 \tag{4}$$

$$\forall p_w(x) \qquad \sum_{\lambda} \omega^{\lambda}_{p_{w1}(x)} + \sum_{\lambda, p_p(p_{w2}(x)) | p_{w1}(x) \neq p_{w2}(x)} \rho^{\lambda}_{p_p(p_{w2}(x))} \leq 1 \tag{5}$$

Constraints on traffic variables:

Equations (6) and (7) set the value of the variables which show the usage of a wavelength on a link. In Equation (7) the value of K must be higher than the number of the protection paths.

$$\forall e, \lambda \qquad \alpha^{\lambda}_{e(i,j)} - \sum_{p_w(x) | e \in p_w(x)} \omega^{\lambda}_{p_w(x)} \geq 0 \tag{6}$$

$$\forall e, \lambda \qquad K * \beta^{\lambda}_{e(i,j)} - \sum_{p_p(p_w(x)) | e \in p_p(p_w(x))} \rho^{\lambda}_{p_p(p_w(x))} \geq 0 \tag{7}$$

Reliability constraints:

The reliability requirements of each demand are guaranteed by Equation (8), where $UB_{\Pr(p_p(p_w(x)))}$ is an upper bound of $\Pr(p_p(p_w(x)))$.

$$\forall x \qquad \prod_{\forall p_w(x)} \Pr(p_w(x)) * \prod_{\forall p_p(p_w(x))} UB_{\Pr(p_p(p_w(x)))} \leq r(x) \tag{8}$$

The failure probability of working paths and the upper bounds can be calculated in advance, thus the ILP formulation of the constraint is as follows:

$$\sum_{\forall p_w(x),\lambda}\{\ln[\Pr(p_w(x))]*\omega^{\lambda}_{p_w(x)}\}+\sum_{\forall p_p(p_w(x)),\lambda}\{\ln[UB_{\Pr(p_p(p_w(x)))}]*\rho^{\lambda}_{p_p(p_w(x))}\}\le r(x)$$

$\forall x$

In this equation ILP variables are multiplied by one another, which is not feasible in an ILP formulation. For this reason the natural logarithm of the probability values must be taken, where the multiplication is transformed into addition.

$$UB_{u(e,\lambda,y_i)}\le q_s(e,\lambda,y_i) \qquad (9)$$

for each shared resource (e,λ) used by the protection path $p_p(p_w(x))$ of connection demand x and each demand $y_i\in Q(e,\lambda,x)$. The detailed description of the criterion and the variables can be found in [29].

Equation (9) checks that the unavailability threshold is not violated anywhere.

The ILP formulation of the constraint seems as follows:

$\forall p_p(p_w(x)),\lambda$

$$\sum_{p_p(p_w(x)),2|e\in p_w(x),2}\{\ln[1-\Pr(e)]*\rho^{\lambda}_{p_p(p_w(x)),2}\}+(-\ln(1-q_s))*\rho^{\lambda}_{p_p(p_w(x)),1}-L*\rho^{\lambda}_{p_p(p_w(x)),1}\ge -L$$

where $[p_p(p_w(x)),1\cap p_p(p_w(x)),2]\ne\{\}$, i.e. protection paths are not link independent, and $p_w(x),2$ is the working path of $p_p(p_w(x)),2$. "1" and "2" represent two different demands.

$$p_w(x)\cap L(e,\lambda)\ne 0 \qquad (10)$$

for each $e\in p_w(x)$ and the assigned protection wavelength λ. This criterion enforces that no shared resource might be used by two different demands for protection against the failure of the same component.

The ILP formulation of the constraint is as follows:

$$\forall e,\lambda \qquad \sum_{p_p(p_w(x))|e\in p_w(x)}\rho^{\lambda}_{p_p(p_w(x))}\le 1$$

The above formulation gives the solution with the lowest capacity usage for the consolidation of the unavailability threshold based provisioning strategy. Numerical results are presented in the paper.

ANNEX B

In this session you can found the confidence intervals of the numerical results presented in the paper.

The significance level is α = 0.05 and the sample size is 6 in each calculation. The “no cons.” means that the demands are not re-optimized in that case.

Confidence intervals of Figure 3:

	Provisioning	Last arrived demands consolidation	All arrived demands consolidation
10 (before consolidation)	[38.03, 44.96]	[38.03, 44.96]	[38.03, 44.96]
10 (after consolidation)	no cons.	[25.93, 31.07]	[25.93, 31.07]
20 (before consolidation)	[71.57, 84.75]	[69.17, 78.15]	[67.83, 73.17]
20 (after consolidation)	no cons.	[51.19, 57.14]	[49.28, 56.05]
30 (before consolidation)	[103.37, 115.96]	[94.20, 101.12]	[87.56, 90.43]
30 (after consolidation)	no cons.	[75.75, 82.24]	[72.26, 78.40]
40 (before consolidation)	[137.80, 145.86]	[128.78, 131.54]	[114.84, 119.82]
40 (after consolidation)	no cons.	[104.73, 110.26]	[99.00, 99.00]

Confidence intervals of Figure 4:

	CONS(10)	CONS(40)
5	[20.81, 26.51]	[20.81, 26.51]
10 (before consolidation)	[38.03, 44.96]	[38.03, 44.96]
10 (after consolidation)	[25.93, 31.07]	no cons.
15	[48.81, 54.51]	[59.69, 67.64]
20 (before consolidation)	[67.83, 73.17]	[71.57, 84.75]
20 (after consolidation)	[49.28, 56.05]	no cons.
25	[70.60, 74.06]	[90.84, 107.83]
30 (before consolidation)	[87.56, 90.43]	[103.37, 115.96]
30 (after consolidation)	[72.26, 78.40]	no cons.
35	[96.72, 101.95]	[120.09, 137.23]
40 (before consolidation)	[113.84, 116.82]	[137.80, 145.86]
40 (after consolidation)	[99.00, 99.00]	[99.00, 99.00]

Confidence intervals of Figure 5A:

	CONS(5)	CONS(10)	CONS(20)	CONS(40)
Maximal deviation	[26.90, 29.54]	[27.55, 34.05]	[31.46, 39.18]	[32.91, 38.87]
Average deviation	[14.32, 16.37]	[19.35, 21.20]	[27.07, 30.06]	[28.78, 34.55]

Confidence intervals of Figure 5B:

	CONS(5)	CONS(10)	CONS(20)	CONS(40)
# of working path change	[44.93, 54.06]	[31.99, 41.51]	[23.07, 26.42]	[18.78, 21.72]
# of working wl. change	[135.07, 138.42]	[69.96, 77.53]	[46.23, 48.77]	[34.23, 36.77]
# of protection path change	[72.11, 77.88]	[45.70, 53.30]	[35.01, 37.48]	[23.88, 28.12]
# of protection wl. change	[109.05, 116.45]	[64.62, 68.38]	[41.07, 44.42]	[22.16, 26.83]

Confidence intervals of Figure 5B:

	Last arrived demands consolidation
# of working path change	[16.34, 22.14]
# of working wl. change	[29.88, 38.42]
# of protection path change	[25.17, 30.56]
# of protection wl. change	[27.03, 33.69]

Confidence intervals of Figure 6:

	Permanent working path and wavelength	Permanent working path
10 (before consolidation)	[38.03, 44.96]	[38.03, 44.96]
10 (after consolidation)	[30.43, 37.90]	[29.95, 35.38]
20 (before consolidation)	[65.80, 76.53]	[65.81, 74.85]
20 (after consolidation)	[58.20, 65.46]	[55.82, 61.84]
30 (before consolidation)	[87.27, 98.73]	[87.07, 93.26]
30 (after consolidation)	[81.32, 90.01]	[78.04, 85.95]
40 (before consolidation)	[122.46, 131.20]	[119.33, 123.34]
40 (after consolidation)	[117.79, 126.20]	[108.55, 117.11]

Confidence intervals of Figure 7A:

	CONS(40)	CONS(last)	Permanent working path and wavelength	Permanent working path
Maximal deviation	[32.91, 38.87]	[26.48 29.12]	[13.88, 16.34]	[9.32, 11.14]
Average deviation	[28.78, 34.55]	[24.33, 27.11]	[11.21, 13.77]	[8.02, 9.67]

Confidence intervals of Figure 7B:

	Permanent working path and wavelength	Permanent working path
# of working path change	0	0
# of working wl. change	0	[59.12, 67.43]
# of protection path change	[33.45, 39.31]	[31.73, 37.54]
# of protection wl. change	[63.88, 70.31]	[59.67, 66.23]