Wavelength Defragmentation for Seamless Migration

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Abstract

Dynamic traffic in optical networks leads to spectrum fragmentation, which significantly reduces network performance, i.e., increases blocking rate and reduces spectrum usage. Telecom operators face the operational challenge of operating non-disruptive defragmentation, i.e., within the make-before-break paradigm when dealing with lightpath rerouting in wavelength division multiplexed (WDM) fixed-grid optical networks.

In this paper, we propose a make-before-break (MBB) Routing and Wavelength Assignment (RWA) defragmentation process, which provides the best possible lightpath network provisioning, i.e., with minimum bandwidth requirement. We tested extensively the models and algorithms we propose on four network topologies with different GoS (Grade of Service) defragmentation triggering events. We observe that, for a given throughput, the spectrum usage of the best make-before-break lightpath rerouting is always less than 2.5% away from that of an optimal lightpath provisioning.

Keywords: Wavelength Defragmentation, Seamless Defragmentation, Make-Before-Break Rerouting, Routing and Wavelength Assignment, Fragmented Network, Network Reconfiguration.

1 Introduction

Software Defined Optical Networks (SDONs) can facilitate automation of complex network operations that result in the flexible deployment of new services in order to meet changing application requirements [1]. Due to the fact that the lightpaths are set up and torn down more frequently in SDONs, they are likely to become fragmented. This fragmentation leads to the circumstance in which new requests face a higher blocking probability even though there is enough capacity to satisfy a demand. Spectrum defragmentation operations can reduce lightpath blocking probabilities from 3% [2] up to 75% [3].

A threefold increase expectation for IP traffic by 2021 [4] is also an evidence of the need for an efficient use of the resources in optical networks. Therefore, it is important to regularly reroute the established connections in order to optimize the usage of network resources.

While network reconfiguration is used to refer to different problems, e.g., bandwidth (spectrum) defragmentation in elastic optical networks [5, 6] or capacity recovery in fragmented Multi-Protocol Label Switching (MPLS) networks by rerouting Label Switched Paths (LSPs) [7, 8], we focus on wavelength defragmentation problem in this study.

Wavelength defragmentation, consists of three phases [9]: *(i)* decide when to conduct a defragmentation [10]; *(ii)* design a new lightpath provisioning with a given optimization objective (e.g., minimum bandwidth requirement) for a given traffic pattern, to ensure the most seamless migration possible; and *(iii)* migrate from the current lightpath fragmented provisioning to the new optimized one, as seamlessly as possible. The focus of our paper is primarily on the third phase, while its difficulty depends on the previous ones. This study deepens the previous study [11] on the characteristics of a fragmented optical network and the difficulty to defragment it with the paradigm of make-before-break. In particular, we investigate the deterioration of the GoS (Grade of Service, i.e., the number of granted requests) until we reach a steady state, i.e., a worst case scenario for defragmentation with dynamic traffic. We also examine the impact of topology connectivity and the percentage of shortest paths in optimal provisioning on the ease of make-before-break defragmentation.

In the context of wavelength defragmentation, a defragmentation scheme that requires no disruption corresponds to an make-before-break (MBB) reachable wavelength provisioning, i.e., such that we can move from a fragmented wavelength provisioning to an optimized one with the make-before-break process. Within that context, optimized provisioning is such that it drastically reduces bandwidth requirements, ideally with the smallest possible number of reroutings. Deciding whether there exists an MBB defragmentation from a current fragmented provisioning to an optimized pre-computed one by rerouting on-going connections one after the other can be done in polynomial time [12]. An MBB defragmentation can be defined using a *Move-To-Vacant* (MTV) algorithm, i.e., sequentially choosing a connection, finding a new path using spare resources and then switching the connection to its new path. The process goes on until the new state of the network satisfies the desired constraints, e.g., overall usage of resources or no vacant path is found for any of the demands [13].

In the wavelength defragmentation problem studied in this paper, we aim to find an optimal provisioning for a set of lightpaths such that it can be reached from the current fragmented provisioning with no disruptions (MBB).

The paper is organized as follows. Section 2 is devoted to literature review on wavelength defragmentation and Routing and Wavelength Assignment (RWA) provisioning algorithms. In Section 3, we propose a defragmentation framework in order to investigate the make-before-break wavelength defragmentation problem. Section 4 proposes a nested decomposition optimization algorithm, called WDF_NCG (Wavelength DeFragmentation - Nested Column Generation), that computes the minimum bandwidth RWA provisioning that is reachable with make-before-break. Section 5 describes the details of the WDF_NCG algorithm, which adopts a nested decomposition scheme. Therein, we also propose two other algorithms, one for reducing the size of the dependency graph that records the rerouting ordering of the connections, and one to speed up the restoration of the feasibility conditions at each iteration of the WDF_NCG algorithm. Extensive numerical results are presented in Section 6.

2 Literature Review

We first review the studies on WDM network defragmentation, and then the recent work on RWA provisioning as our proposed algorithms for wavelength defragmentation will borrow some of their ideas.

Note that there are also many references on spectrum or flexible reconfiguration, and in particular on defragmentation, in the context of the Routing and Spectrum Allocation (RSA) problem for flexible optical networks [14, 15]. We omit them as there are not relevant for the WDM network defragmentation problem studied in this paper, as well as for the models and algorithms we propose.

2.1 WDM Network Defragmentation

Network defragmentation can be defined as the process of finding out when and how to migrate to a new configuration with a minimum number of disruptions [9]. Network defragmentation may be required in an optical network due to a change in traffic demand, a failure in the network, a change in the network topology or some maintenance operations [16]. Every network defragmentation process consists of three phases as described in the introduction.
For the first phase, i.e., when to trigger a defragmentation, several performance metrics [9] exist, e.g., the average length (number of links) of the lightpaths, the capacity of the alternative routes, the denial of a new incoming connection.
The second phase consists in building an optimized lightpath provisioning. We review in Section 2.2 the key models and algorithms of the literature. An alternate option would be to directly build the best possible optimized provisioning that can be reached without any disruption. While this has been studied a lot with heuristics, which do not provide any information on how far is their solution from the best possible one, we are aware of only one study with an exact model and algorithm in the context of layer 2 (MPLS) defragmentation, i.e., [7].
The third phase that defines the order of the rerouting so that the migration is completely seamless or as seamless as possible, has been studied with different objective functions, e.g., minimizing the total number of disruptions [17], minimizing the maximum number of concurrent disruptions [12, 18], minimizing disruption time [17] and minimizing defragmentation costs [19]. A comparison of the first two objective functions can be found in [20].

Seamless WDM network defragmentation mean make-before-break defragmentation and we can create it in two different ways. The first way, i.e., the 2-step way as discussed above, is as follows: given the fragmented provisioning and the optimized one, define the best rerouting order so as to define a seamless migration if one exists, or the most seamless possible one. The second way, i.e., a progressive method, is to reroute one connection at a time with, e.g., a MTV algorithm, in order to minimize the bandwidth requirements, until we cannot reduce them further. Drawback of the 2-step way is that very often, no incentive is considered for reducing the number of reroutings when computing the optimized provisioning. Consequently, it often leads to an optimized (e.g., smaller bandwidth requirement or less blocking) provisioning at the expense of a larger number of connections to reroute. Drawback of the progressive way is that it is often considered with the help of heuristics and therefore no information is available on how far is the resulting provisioning from an optimized (MBB) one.

Seamless wavelength defragmentation has been studied in [21]. They propose a heuristic based on greedy randomized adaptive search procedure (GRASP). Their GRASP algorithm returns the best MBB provisioning that can be found within the limit of a given number of iterations. Other authors consider wavelength defragmentation with the minimum number of disruptions, i.e., minimum lightpath disruptions. An Integer Linear Programming (ILP)-based wavelength defragmentation solutions for optimizing wavelength resource utilization with minimal optical path disruptions during the migration process is proposed in [22]. They evaluate their method under a computation time limitation of 10 minutes. The proposed approach can improve the resource efficiency of 20% on sample metro networks Japan Photonic Network (JPN) with 48 nodes, 91 bidirectional links and 100 lightpaths. Different heuristics are proposed in [23] to minimize the disruptions of system resources (transmitters/receivers) while migrating between two given configurations. They define a benefit associated with each lightpath, e.g., transmission delay or number of conflicts with old lightpaths. They propose different heuristics based on the benefit of a lightpath, e.g., using the same benefit or updating the benefits of remaining unestablished lightpaths. They compare the performance of their heuristics according to the computational times and the number of resource disruptions. The heuristic using the number of conflicts as the benefit of a lightpath yields the minimum number of disrupted transceivers.

All reviewed papers in the literature (except [22]) study heuristics and the largest size instances solved so far are related to a NSFNET network with 16 nodes, 25 links and 140 lightpaths [23], and the GEANT2 network (33 nodes, 46 links and 1,000 lightpaths) [21].

While network defragmentation with a minimum number of disruptions is certainly of interest in the context of the Internet, most optical network carriers only consider seamless WDM network defragmentations due to the Service Level Agreements with their customers. Consequently, our objective is to investigate how to build the minimum MBB bandwidth lightpath provisioning for a given defragmentation event, with an exact algorithm.

2.2 Routing and Wavelength Assignment

In order to design an efficient wavelength defragmentation algorithm, it is important to review the best models and algorithms for the RWA provisioning, i.e., defining routes and assigning wavelength to these routes [24]. Studies on RWA provisioning differ in their assumptions and objective functions. The most common objective functions are the maximization of the GoS or equivalently minimizing the blocking rate (max-RWA) [25, 24] and the minimization of the required bandwidth (min-RWA) [26, 27]. RWA has also been widely studied for static (the entire set of connections is known in advance) and dynamic cases (a lightpath is set up for each connection request as it arrives) [24, 28]. It has been shown in the literature that static RWA is NP-complete [29].

While many heuristics have been proposed to solve the RWA problem [30], significant progress has been made with exact algorithms, allowing to solve exactly the RWA problem for large instances, i.e., networks with up to 90 nodes and 150 wavelengths, and traffic between all node pairs [24].

3 WDM Network Defragmentation Problem: Our Framework

We present here an overview of the WDM network defragmentation framework we use in order to investigate the MBB wavelength defragmentation problem. It includes three steps, which are detailed below.

3.1 WDM Network Defragmentation Framework

We assume we are given a WDM optical network, and that the input of our WDM network defragmentation framework is a demand given by a set of connections. Each connection, if granted, is to be provisioned by a lightpath, i.e., the combination of a route and a wavelength, the same one (so-called continuity constraints) all the way from the source to the destination. The framework we propose is as follows.

Initialization:

Compute a maximum GoS RWA provisioning, i.e., grant the largest possible number of connections.

Step 1: Dynamic RWA Provisioning

Repeat

Free the resources of each terminating connection.

Grant each new incoming connection if there are spare resources to provision it, and else deny it.

Until a wavelength defragmentation is triggered

Step 2: Trigger Defragmentation
When the deterioration of the GoS reaches a given threshold, trigger defragmentation.
Let RWA^{FRAG} be the resulting RWA provisioning.

Step 3: Conduct Defragmentation
Step 3.1. Compute RWA^{OPT}, a minimum bandwidth RWA provisioning
Step 3.2. Initialize $\text{RWA}^{\text{MBB-OPT}}$, an MBB reachable RWA provisioning with RWA^{OPT}
If $\text{RWA}^{\text{MBB-OPT}}$ is MBB reachable from RWA^{FRAG}
Reroute one request at a time with the MBB technique
Return to **Step 1**
Else
Identify some rerouting deadlocks (i.e., conflicting rerouting order such as k needs to be rerouted before k' and vice-versa)
Recompute a minimum bandwidth RWA provisioning with the deadlock avoidance constraints
Let $\text{RWA}^{\text{MBB-OPT}}$ be the new optimized RWA provisioning
Return to **Step 3.2.**

Figure 1 illustrates our WDM network defragmentation framework. For every incoming request, we check whether there are available spare resources to grant it, even if it means routing it on a longer route. In other words, we search for the shortest lightpath that is available considering the current spare resources. If no spare resource is available, the connection is denied, otherwise it is granted. Better granting proactive algorithms are possible, especially when information is available on the future/forecast traffic, but as this is not the focus of this study, we use the simplest rule for granting connections. Hence, for every new connection request we solve a dynamic max-RWA problem. For every ending connection, the resources used by the corresponding lightpath are freed and made available for future traffic.

3.2 Triggering of the Wavelength Defragmentation

While it goes beyond the scope of this paper to investigate the best way to trigger wavelength defragmentation, we made sure that the way we choose did not facilitate or worsen the wavelength defragmentation, especially under the make-before-break paradigm.

Different performance metrics have been proposed in the literature, see, e.g., [9] for a recent survey on them. We decided to use the Grade of Service (GoS) as the triggering event and, as we will see in the numerical results (see Section 6), we use different threshold GoS values, from restrictive ones (e.g., a GoS decrease of 5%) to more permissive ones (up to 50%). We also observe that, without wavelength defragmentation, the stabilization of the GoS is reached at various levels, depending on the network topologies (all experiments were done with uniform traffic), see Section 6.

3.3 min vs. max RWA provisioning

Throughout the WDM network defragmentation framework, we deal with two variants of the RWA problem: Dynamic Max-RWA in the dynamic provisioning phase and Static Min-RWA in the wavelength defragmentation phase. We briefly remind their definitions in what follows.

3.3.1 Static Min-RWA

In static RWA, the set of requested connections D is known. The objective function is to grant all connection requests while minimizing the bandwidth requirements over a multigraph

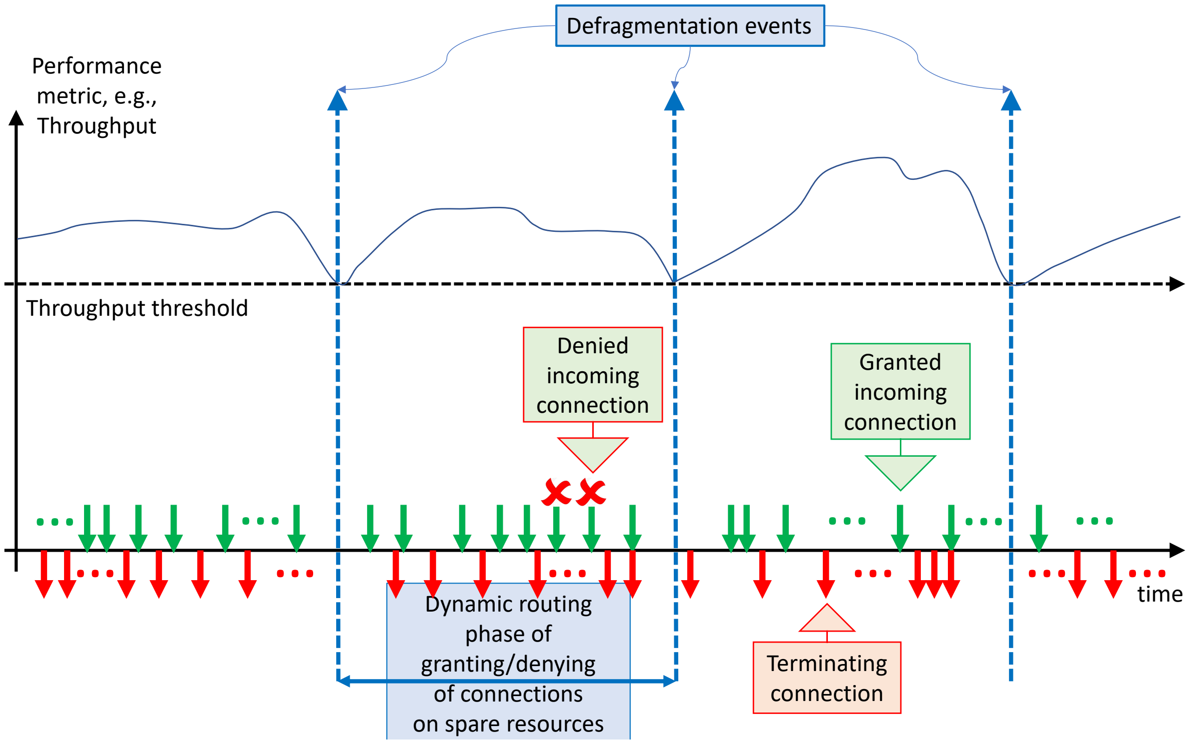


Figure 1: WDM Network Defragmentation Process

$G = (V, L)$ with V (indexed by v) and L (indexed by ℓ) representing the set of nodes and links of G, respectively. $D = (D_{sd})_{(v_s,v_d)\in\mathcal{SD}}$ defines the number of requested unit lightpaths for every node pair with traffic, i.e., $(v_s, v_d) \in \mathcal{SD} \subseteq V \times V$. Each granted connection unit is assigned a lightpath (p, λ) where p is a routing path and λ is the selected wavelength among the set of available wavelengths Λ. No two lightpaths using the same link can share the same wavelength (under the assumption of a single directional fiber in each direction for connected node pairs).

3.3.2 Dynamic Max-RWA

In the dynamic max-RWA problem, the objective function is to grant the largest possible number of connections (GoS) or equivalently to minimize the blocking rate. The set of demands are not known in advance. There is a set of legacy (i.e., on-going) connections D^{LEGACY} routed on a multigraph $G = (V, L)$ and a set of new incoming demands D^{NEW}. We need to assign available lightpaths to D^{NEW} such that no wavelength conflict occurs. Interested reader may refer to, e.g., [24] for detailed formulation in both dynamic and static cases of RWA. In the particular case of one new incoming connection to provision at a time, the dynamic max-RWA problem amounts to searching for an available shortest path connecting the two endpoints of the connection.

4 A Nested Decomposition Wavelength Defragmentation Algorithm

In this section, we assume that an optimized RWA provisioning, called RWA^{OPT}, is available. We then aim at designing a model (called WDF_MBB) and an algorithm (called WDF_NCG) that will modify RWA^{OPT} as little as possible so that it can be reached with make-before-break from RWA^{FRAG}, the current fragmented RWA provisioning.

One of the key elements of the WDF_NCG algorithm is the so-called dependency graph. It is introduced in the next section. The second key element is the computation of a RWA provisioning subject to rerouting deadlock avoidance constraints. Consequently, we reviewed all the previous scalable mathematical models for RWA and selected the most relevant one for designing the WDF_MBB model, see Section 4.3. Section 4.4 describes the WDF_NCG algorithm, which is an iterative algorithm alternating solution of the WDF_MBB model and identifying rerouting deadlocks with the dependency graphs, until reaching a minimum bandwidth MBB reachable RWA provisioning.

4.1 Dependency Graph and Lightpath Rerouting Order

In order to define the order in which the lightpaths can be rerouted, we build the so-called dependency graph $G_{\text{D}} = (V_{\text{D}}, L_{\text{D}})$, introduced in [31], between the fragmented (RWA^{FRAG}) and the optimized (RWA^{OPT}) provisionings at the end of each defragmentation interval (see Figure 2(c)). A dependency graph is a directed graph that represents the dependence between rerouted requests. Node and link sets of the dependency graph are defined as follows.

$$\begin{aligned} V_{\text{D}} &= \{\pi = (p, \lambda) : \pi \text{ is a lightpath in } \text{RWA}^{\text{FRAG}}\} \\ L_{\text{D}} &= \{(\pi, \pi') : \pi' \text{ needs to be rerouted before} \\ &\qquad \pi \text{ in order to reach } \text{RWA}^{\text{OPT}} \text{ with MBB}\}. \end{aligned}$$

In other words, each link (π, π') defines the order of migration between two lightpaths, when a lightpath π' needs to be rerouted before another lightpath π in order to perform an MBB rerouting.

Figure 2 illustrates an example on how to build a dependency graph. As mentioned before, dependency graph is built based on two different provisionings. In Figure 2(a) a fragmented provisioning (RWA^{FRAG}) with 29 used links is represented while Figure 2(b) shows an optimized provisioning (RWA^{OPT}) for the same set of demands with 21 used links. Figure 2(c) is the dependency graph built based on the provisionings presented in Figures 2(a) and 2(b). Every link in the dependency graph shows one dependency and the right order of rerouting lightpaths. For example, lightpath π_1 in RWA^{OPT} is routed over blue wavelength and has three links ($v_3 \to v_6$, $v_6 \to v_5$ and $v_5 \to v_4$) in common with lightpath π_4 in RWA^{FRAG}. This means that lightpath π_4 needs to be rerouted first in order to make room for lightpath π_1 in RWA^{OPT}. In other words, lightpath π_1 cannot be rerouted before lightpath π_4 is rerouted. This dependency (also rerouting order) is represented by a link from vertex π_1 to vertex π_4 in the dependency graph. Table 1 shows all the dependencies in this migration. There is one link in the dependency graph for every dependence presented in Table 1. It should be mentioned that lightpath π_7 has the same wavelength and the same path in both RWA^{FRAG} and RWA^{OPT}, hence, it has no dependency and does not appear in the dependency graph.

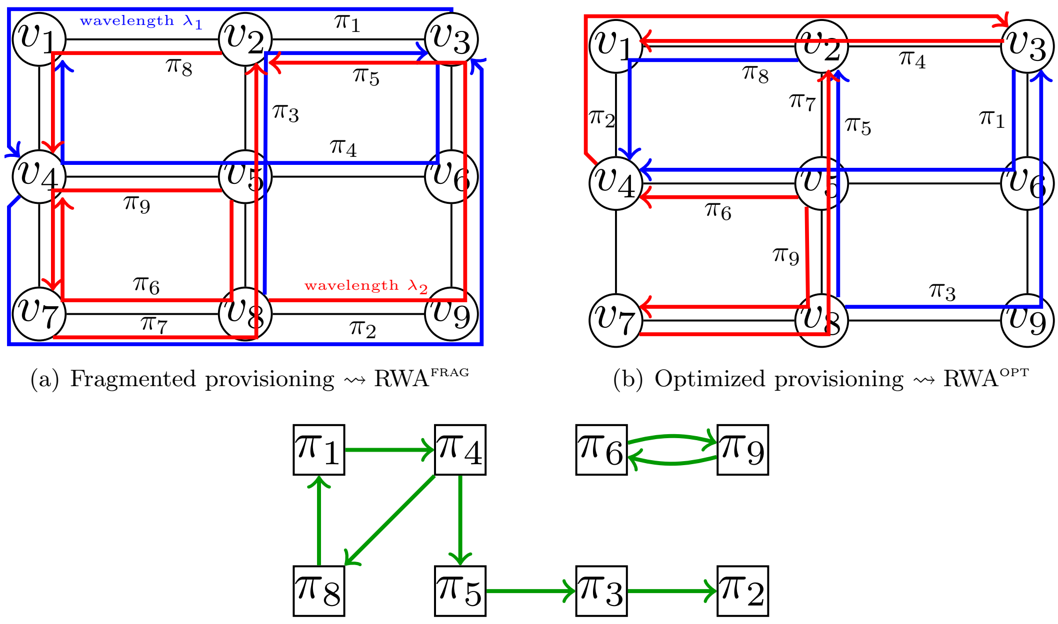
We use Algorithm 1 to build the dependency graph ($G_{\text{D}} = (V_{\text{D}}, L_{\text{D}})$) between RWA^{FRAG} and RWA^{OPT}.

For a given lightpath, denote by π_i^{frag} and π_i^{opt} the lightpath in the fragmented and in the optimized provisioning respectively.

After building the dependency graph, we need to determine the rerouting order of the lightpaths. Since the path and the bandwidth required for the lightpaths with no dependency (no outgoing link), i.e., lightpath π_2 in Figure 2(c), are already available in RWA^{OPT}, they are first rerouted. After each rerouting, at least one link in the dependency graph is removed and it might result in one or more lightpaths with no dependency, e.g., lightpath π_3 can be rerouted since π_2 is rerouted and it has no other dependencies. Lightpath π_5 can also be rerouted after lightpath

Table 1: List of dependencies

Lightpath	Rerouting dependence(s)	Common links
π_1	π_4	$v_3 \to v_6$, $v_6 \to v_5$, $v_5 \to v_4$
π_2	-	-
π_3	π_2	$v_8 \to v_9$, $v_9 \to v_6$, $v_6 \to v_3$
π_4	π_5	$v_3 \to v_2$
	π_8	$v_2 \to v_1$
π_5	π_3	$v_8 \to v_5$, $v_5 \to v_2$
π_6	π_9	$v_5 \to v_4$
π_8	π_1	$v_2 \to v_1$, $v_1 \to v_4$
π_9	π_6	$v_5 \to v_8$, $v_8 \to v_7$



(a) Fragmented provisioning $\rightsquigarrow$ RWA$^{\text{FRAG}}$

(b) Optimized provisioning $\rightsquigarrow$ RWA$^{\text{OPT}}$

(c) Dependency graph for RWA$^{\text{FRAG}} \to$ RWA$^{\text{OPT}}$

Figure 2: An Example of Dependency Graph

Algorithm 1 Dependency Graph Builder

Input: Network Topology, RWA$^{\text{FRAG}}$, RWA$^{\text{OPT}}$

Output: Dependency Graph $G_{\text{D}} = (V_{\text{D}}, L_{\text{D}})$

$V_{\text{D}} \leftarrow \emptyset$; $L_{\text{D}} \leftarrow \emptyset$

for $\forall$ lightpath π_i^{opt} with a different routing than π_i^{frag} **do**

  $V_{\text{D}} \leftarrow V_{\text{D}} \cup \{\pi_i\}$

for every link $\ell \in L$ **do**

  for every lightpath π_i^{opt} using link ℓ **do**

    if there is a lightpath π_j^{frag} using link ℓ such that $\lambda_{\pi_i^{\text{opt}}} = \lambda_{\pi_j^{\text{frag}}}$ **then**

      add arc (π_i, π_j) to L_{D}

Return $G_{\text{D}} = (V_{\text{D}}, L_{\text{D}})$

π_3 is rerouted. For the remaining lightpaths, since they are involved in a circuit (a rerouting deadlock), they all have dependencies and rerouting each one requires at least one disruption. As seen in the dependency graph (Figure 2(c)), there are 2 circuits, one involving π_1, π_4 and π_8 and the other involving π_6 and π_9. Hence, if we want to build an MBB provisioning, we need to identify the circuits and prevent them from occurring again. Since maximal link disjoint circuits are easily identifiable once we have computed strongly connected components, we will proceed with the computation of strongly connected components, using the algorithm of Tarjan [32].

4.2 Identification of Avoidable Disruptions: Reducing the Number of Circuits in the Dependency Graph

In this section, we propose an algorithm in order to check whether it is possible to break some of the circuits without adding cuts and compromising the optimal solution by finding new lightpath(s) for one or some of the connections. Figure 3 represents an example of removing a circuit by finding a new lightpath for π_1. As seen in Figure 3(c), there is a circuit involving π_1 and π_2 while migrating from the fragmented provisioning (Figure 3(a)) to the optimized provisioning (Figure 3(b)). If we can find a new lightpath for one of these connections without creating new circuits, then a seamless migration will be possible. As seen in Figure 3(d), a new lightpath can be assigned to lightpath π_1 that not only does not create a new circuit but also breaks the circuit between π_1 and π_2. It should be mentioned that it is also possible to find a new lightpath for π_2 and get the same results, e.g., changing the wavelength of π_2 from blue to red on the same path in Figure 3(d) returns the same result that is an MBB provisioning.

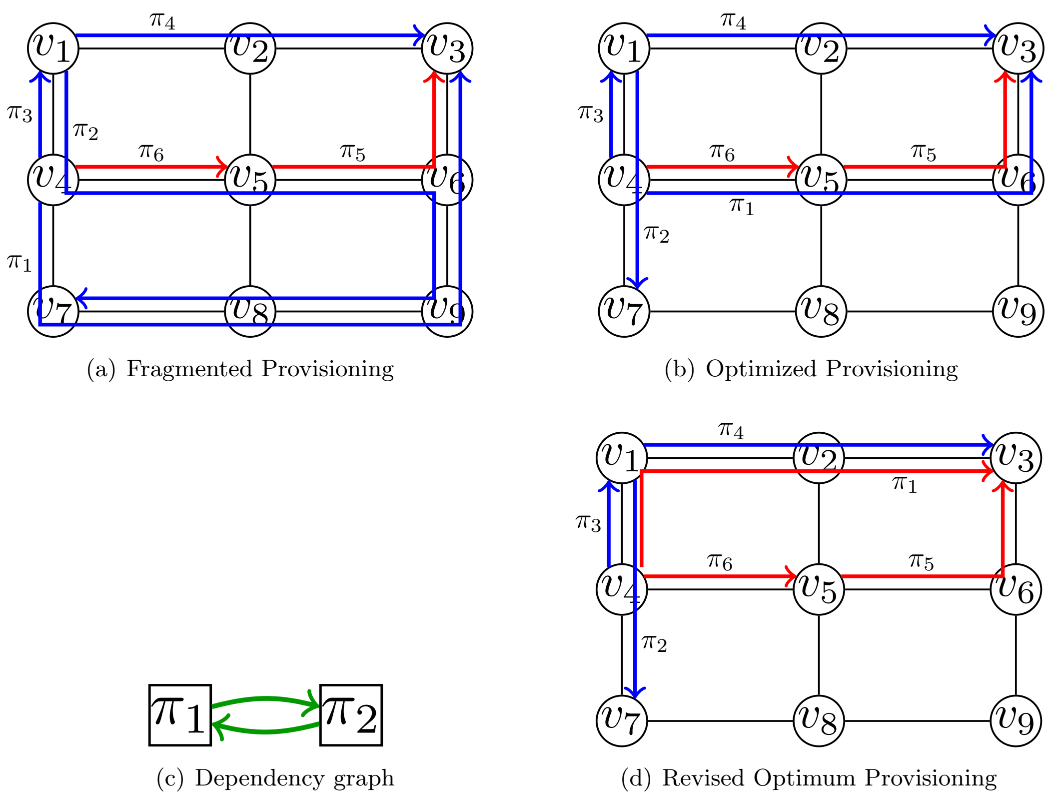


Figure 3: Preprocessing Operation

In Algorithm 2, after building the dependency graph G_D and finding the set C of Strongly Connected Components (SCCs), we try to find for each lightpath involved in a SCC a new lightpath, of the same length, that allows the break of a circuit in the SCC and eventually make it acyclic. If such a new lightpath is found for a given connection request, we use it and update G_{D} accordingly. We repeat this process until G_{D} becomes acyclic or we can no longer find any new lightpath helping to break circuits. If there are no more circuits, it means that an MBB provisioning has been found. But, finding no lightpaths to be rerouted while there are still some circuits shows that Algorithm 2 cannot break any other circuits and so that a seamless migration is not yet possible.

It should be mentioned that the nodes in G_{D} are prioritized based on their in-degree (the number of arcs ending in each node). The reason is that having higher in-degree for a given lightpath π shows that more lightpaths are dependent on π and it can contribute to more circuits.

Algorithm 2 Preprocessing Algorithm

Input: Dependency graph G_{D}

Input: $G_\lambda = (V, L_\lambda) \subseteq G = (V, L)$ where L_λ is the set of links which are not used in any lightpath using λ, for $\lambda \in \Lambda$.

Output: New wavelength assignment for some lightpaths involved in circuits

Find the strongly connected components (SCCs) of G_{D}
Build the list Π of lightpaths, i.e, the set of nodes in G_{D}, involved in the SCCs
Sort Π by non-increasing in-degree in G_{D}
for every node (lightpath) $\pi = (p, \lambda) \in \Pi$ such that $p : v_s \rightsquigarrow v_d$ **do**
    for every $\lambda' \in \Lambda$ **do**
        $\hat{p} \leftarrow$ shortest path from v_s to v_d in $G_{\lambda'}$
        if $\hat{p} \neq \emptyset$ and $|\hat{p}| \leq |p|$ **then**
            Check if changing π to $(\hat{p}, \lambda')$ creates new circuits in G_{D}
            if no new circuit is generated **then**
                Set $\pi = (\hat{p}, \lambda')$; Update G_λ and $G_{\lambda'}$
                Go to step 1
return Set of lightpaths

4.3 WDF_MBB Model

As seen in Section 2.2, RWA problem has been widely studied and there are several exact solution schemes in the literature including compact and decomposition formulations. Although the compact formulations are not scalable, real size instances can be solved exactly using decomposition methods, e.g., column generation technique. According to the recent RWA studies [24], the most efficient decomposition is to generate wavelength plans (i.e., set of pairwise link disjoint lightpaths using the same wavelength) using a path formulation, followed by a link formulation in order to guarantee the optimality of the linear relaxation of the model.

In order to avoid the use of a link formulation, which is computationally costly to solve, we propose to use a nested decomposition scheme. We first establish the so-called master problem of the decomposition scheme, called WDF_MBB model. We will next discuss its detailed solution in Section 5.

The WDF_MBB model relies on the concept of wavelength configurations, where a configuration γ corresponds to a wavelength plan, for a given wavelength λ. While in the RWA decomposition models, configuration (i.e., wavelength plan) can be defined for a generic wavelength and therefore do not have any symmetry issues (the wavelength assignment is done a posterior), this is unfortunately not possible here in order to be able to express the rerouting deadlock avoidance constraints.

Model WDF_MBB requires one unique set of decision variables z_γ for $\gamma \in \Gamma$. Each variable z_γ allows or not the selection of configuration γ in the optimal RWA provisioning output.

Each configuration $\gamma \in \Gamma$ is formally defined by the following parameters:

$B^\gamma =$ bandwidth requirement of configuration γ, as expressed by the number of links used in γ for routing some connections

$a^\gamma_{sd} =$ number of lightpaths for node pair (v_s, v_d) in configuration γ

$a^\gamma_\pi = 1$ if lightpath π is used in configuration γ, 0 otherwise.

We now express the WDF_MBB model that computes the minimum bandwidth RWA provisioning subject to deadlock avoidance constraints as identified in the dependency graph. Since the number of circuits in a directed graph can be exponential, we do not introduce all possible circuits. Using Tarjan's algorithm, we identify the strongly connected components (SCCs). While a SCC can contain several circuits, we add only one circuit per SCC in order to control the number of constraints, i.e., the circuit that includes all nodes of the SCC.

$$\text{Minimize:} \quad \sum_{\gamma \in \Gamma} B^\gamma z_\gamma \tag{1}$$

$$\text{Subject to:} \quad \sum_{\gamma \in \Gamma_\lambda} z_\gamma \leq 1, \qquad \lambda \in \Lambda \tag{2}$$

$$\sum_{\gamma \in \Gamma} a^\gamma_{sd} z_\gamma \geq D_{sd}, \qquad (v_s, v_d) \in \mathcal{SD} \tag{3}$$

$$\sum_{\pi=(p,\lambda) \in c} \sum_{\gamma \in \Gamma_\lambda} a^\gamma_\pi z_\gamma \leq |c| - 1 \qquad c \in C \tag{4}$$

$$z_\gamma \in \{0, 1\}, \qquad \gamma \in \Gamma. \tag{5}$$

Constraints (2) ensure that we select at most one configuration for each wavelength λ. Constraints (3) enforce the demand constraints, with the left-hand side term computing the number of demand units provided by each configuration, and then summing over all configurations. Constraints (4) guarantee that the provisioning will not contain any of the circuits $c \in C$. Constraints (5) define the domains of the variables.

4.4 WDF_NCG Algorithm

In order to find an MBB provisioning, we propose an iterative process presented in Algorithm 3. This process starts with building a dependency graph G_{D} for migrating from a fragmented provisioning (RWA$^{\text{FRAG}}$) to an optimized provisioning (RWA$^{\text{OPT}}$). Tarjan's algorithm is used in order to find the set of circuits C (strongly connected components) in G_{D}. Algorithm 2 helps us break some of the circuits. If C is empty, it means that a seamless migration has been found. Otherwise, one constraint corresponding to each circuit $c \in C$ is added to WDF_MBB. The solution of WDF_MBB is the updated RWA$^{\text{OPT}}$ that does not contain any of the circuits found in previous iterations due to deadlock avoidance constraints. However, it may contain some new circuits. Hence, the dependency graph is generated, set of circuits are found and Algorithm 2 tries to reduce the number of circuits in C. This process goes on until the set of circuits C is empty.

Algorithm 3 WDF_NCG Algorithm

Input: RWA^{FRAG}, RWA^{OPT}
Output: make-before-break RWA^{OPT}

Build dependency graph G_{D} (Algorithm 1).
Find the set of circuits C in G_{D} (Tarjan's Algorithm).
Reduce the number of circuits C (Algorithm 2).
while C is not empty **do**
    Update RWA^{OPT} by solving WDF_MBB
    Build dependency graph G_{D} (Algorithm 1).
    Find the set of circuits C in G_{D} (Tarjan's Algorithm).
    Reduce the number of circuits C (Algorithm 2).
return RWA^{OPT}

5 Solution the WDF_MBB Model: A Nested Decomposition Wavelength Defragmentation Model

We first discuss the details of the solution process for the WDF_MBB model with a nested decomposition algorithm in Section 5.1. We next discuss in Section 5.2 an algorithm in order to speed up the feasibility in WDF_MBB model after the addition of new rerouting deadlock avoidance constraints.

5.1 Nested Column Generation

The WDF_MBB model proposed in Section 4.3 has an exponential number of variables, and therefore is not scalable if solved using classical ILP (Integer Linear Programming) tools. Indeed, we need to use column generation techniques in order to manage a solution process that only requires an *implicit* enumeration of the wavelength configurations (interested readers may refer to Chvátal [33]). Column generation method allows the exact solution of the linear relaxation of model (1)-(5), i.e., where variables $z_\gamma \in \mathbb{Z}^+$ are replaced by $z_\gamma \geq 0$, for $\gamma \in \Gamma$. It consists in solving alternatively a restricted master problem (the WDF_MBB model in Section 4.3 with a very limited number of columns/variables) and the pricing problem (generation of a new wavelength configuration) until the optimality condition is satisfied (i.e., no wavelength configuration with a negative reduced cost). In other words, when a new wavelength configuration is generated, it is added to the current restricted master problem only if its addition implies an improvement of the optimal value of the current restricted master problem. This condition, indeed an optimality condition, can be easily checked with the sign of the reduced cost, denoted by $\overline{\text{COST}}$, see (6) for its expression (the reader who is not familiar with linear programming concepts is referred to [33]), of variables z_γ.

Once the optimal solution of the LP (Linear Programming) relaxation ($z^\star_{\text{LP}}$) has been reached, we solve exactly the last restricted master problem, i.e., the restricted master problem of the last iteration in the column generation solution process, using a branch-and-bound method, leading then to an ε-optimal ILP solution ($\tilde{z}_{\text{ILP}}$), where $\varepsilon = (z^\star_{\text{LP}} - \tilde{z}_{\text{ILP}}) / z^\star_{\text{LP}}$. Branch-and-price methods can be used in order to find optimal solutions, if the accuracy (ε) is not satisfactory, see, e.g., [34].

In order to solve WDF_MBB, we design a nested column generation algorithm in which each pricing problem is solved by column generation itself. In other words, the master problem comprises all generated wavelength configurations. Each wavelength configuration is a set of feasible link disjoint paths and first level pricing problem is responsible for generating such configurations.

Each wavelength configuration (first level) pricing problem can be viewed as a second level master problem and a set of second level pricing problems. Each second level pricing problem generates a path for a given node pair $(v_s, v_d) \in \mathcal{SD}$. The objective in the second level master problem represents the cost of the wavelength configuration in the current pricing problem. We now present the second level master and pricing problems.

We first introduce the set of variables:

$\beta_p^{sd} = 1$ if path p is used in the wavelength configuration under construction, 0 otherwise.

Note that γ is omitted in the sequel in order to alleviate the notations (e.g., $B^\gamma \rightsquigarrow B$). Let Π_λ^c be the set of lighpaths in c using λ.

$$\min \quad \overline{\text{COST}}^{\text{CONFIG}} = B - u_\lambda^{(2)} - \sum_{(v_s,v_d)\in\mathcal{SD}} \sum_{p\in P_{sd}} \beta_p^{sd} u_{sd}^{(3)} - \sum_{c\in C} \sum_{(v_s,v_d)\in\mathcal{SD}} \sum_{p\in P_{sd}:\pi=(p,\lambda)\in\Pi_\lambda^c} u_c^{(4)} \beta_p^{sd} \quad (6)$$

subject to:

$$\sum_{(v_s,v_d)\in\mathcal{SD}} \sum_{p\in P_{sd}} \delta_\ell^p \beta_p^{sd} \leq 1 \qquad \ell \in L \quad (7)$$

$$\sum_{p\in P_{sd}} \beta_p^{sd} \leq D_{sd} \qquad (v_s, v_d) \in \mathcal{SD} \quad (8)$$

$$\sum_{(v_s,v_d)\in\mathcal{SD}} \sum_{p\in P_{sd}} \sum_{\ell\in L} \delta_\ell^p \beta_p^{sd} \leq B \quad (9)$$

$$\beta_p^{sd} \in \{0,1\} \qquad (v_s, v_d) \in \mathcal{SD},\ p \in P_{sd}, \quad (10)$$

where δ_ℓ^p is equal to 1 if link ℓ belongs to path p.

Constraint set (7) assures that selected paths are link disjoint. Thanks to constraint set (8), no more than D_{sd} is granted for every node pair $(v_s, v_d) \in \mathcal{SD}$. Constraint set (9) determines the number of used links in current configuration. Observe that for a path $p \in P_{sd}$, $\sum_{\ell\in L} \delta_\ell^p$ is the length of path p.

In order to generate a path between a given node pair $(v_s, v_d) \in \mathcal{SD}$, we find the path with minimum cost in the second level pricing problem:

$$\min \quad \overline{\text{COST}}^{\text{PATH}} = -u_{sd}^{(3)} - \sum_{\ell\in L} \delta_\ell u_\ell^{(7)} - u_{sd}^{(8)} - u^{(9)} \sum_{\ell\in L} \delta_\ell. \quad (11)$$

If the output path is equal to one of the paths involved in a circuit using wavelength λ, then $-u_c^{(4)}$ needs to be subtracted from the reduced cost.

Since $u_{sd}^{(3)}$ and $u_{sd}^{(8)}$ are constant values for a given node pair, objective (11) can be rewritten as

$$\min \quad \overline{\text{COST}}^{\text{PATH}} = -\sum_{\ell\in L} \delta_\ell u_\ell^{(7)} - u^{(9)} \sum_{\ell\in L} \delta_\ell \quad (12)$$

and will need to be adjusted with the constant terms $(-u_{sd}^{(3)} - u_{sd}^{(8)}\ (-u_c^{(4)}))$, before checking his sign. Note that $-u_c^{(4)}$ refers to checking whether the output path is equal to one of the paths involved in a lightpath using wavelength λ as explained previously. As $u_\ell^{(7)}$ and $u^{(9)}$ come from inequality constraints that are "$\leq$", and as we have a minimization problem, those dual values are both non-positive. We can then assign a non-negative weight $-u_\ell^{(7)} - u^{(9)}$ to each link and use a polynomial-time algorithm, e.g., Dikjstra's algorithm, to find a weighted shortest path for a given node pair for solving the second level pricing problems.

5.2 Re-Establishment of a Feasible RWA Provisioning

We propose Algorithm 4 in order to overcome the infeasibility while obtaining ILP solution, due to the addition of the deadlock avoidance constraints.

Algorithm 4 Building a feasible ILP solution

Input: A feasible LP solution: A set of configurations Γ_{LP}
Output: A feasible ILP solution: A set of configurations Γ_{ILP}

$\Gamma_{\text{ILP}} = \emptyset$.
Sort configurations in LP based on their LP value.
for $\lambda \in \Lambda$ **do**
    Choose a configuration γ with max LP value.
    $\Gamma_{\text{ILP}} = \Gamma_{\text{ILP}} \bigcup \{\gamma\}$
Update Γ_{ILP} by removing lightpaths related to overfilled demands (longest lightpaths). See Constraint (3).
Update Γ_{ILP} by removing lightpaths violating the circuit constraints (longest lightpaths).
Build the set of unfulfilled demands (D_{uf}).
while D_{uf} is not empty **do**
    Choose a demand $d \in D_{uf}$
    if It is possible to find a lightpath π satisfying circuit elimination constraints **then**
        Assign π to d ; $D_{uf} \leftarrow D_{uf} - \{d\}$
    else
        Find the busiest configuration γ
            i.e., with the maximum number of lightpaths
        Free up the shortest path for d in γ by removing a
            set of lightpaths related to a set of demands D_r
        $D_{uf} \leftarrow D_{uf} - d$; $D_{uf} \leftarrow D_{uf} \bigcup D_r$
return Γ_{ILP}

6 Computational Results

6.1 Traffic and Network Data Sets

We use four different networks, whose key characteristics (number of nodes and links, average node degrees) are described in Table 2, see [24] for their references.

Table 2: Main characteristics of the networks

Networks	$\|V\|$	$\|L\|$	Avg. node deg.	# wavelengths
USA	24	88	3.7	75
GERMANY	50	176	3.5	130
NTT	55	144	2.6	42
CONUS	60	158	2.6	30 & 50

Table 3: Statistics for the Characteristics of the Strongly Connected Components (SCC) in the Dependency Graphs

Networks	GoS Reduction	# of nodes in SCC/AVG degree (# Links/# Nodes) SCC #1	SCC #2	SCC #3	SCC #4	SCC #5	SCC #6	SCC #7	SCC #8	SCC #9	# SCCs
NTT	10%	282 2.20	3 2	2 1	2 1	1 0					589
	15%	251 2.23	3 1.33	1 0							581
	20%	318 2.28	3 3.33	2 3	1 0						445
	25%	170 2.46	6 1.83	3 2	3 1.67	3 1.33	2 6.50	2 3	2 1.50	1 0	542
USA	5%	529 2.13	1 0								412
	10%	506 2.11	2 3	1 0							387
	15%	428 2.11	3 6	2 3	2 1	1 0					413
GERMANY	5%	1,062 2.43	1 0								775
	10%	544 2.16	3 2	3 2	2 2.5	1 0					1,190
	15%	175 1.65	5 1.60	3 2	2 2	2 1.50	2 1.5	2 1.50	2 1	1 0	1,453
	20%	20 1.50	10 1.40	5 1.60	3 2	2 1.50	2 1	1 0			1,413
	25%	16 2	1 0								1,446
CONUS	25%	249 2.73	9 2.25	7 2.33	4 2	1 0					469
	30%	153 2.31	9 2.44	4 2	2 1	1 0					504
	35%	184 2.64	2 4	2 3	2 1	1 0					444

6.2 Generation of Fragmented RWA Provisionings

In order to generate a RWA provisioning, we use the framework described in Section 3. The first initial provisioning corresponds to the RWA provisioning obtained in [24], with the objective of maximizing the Grade of Service (GoS), i.e., the number of granted requests. We then use a dynamic RWA process with ADD and DROP requests, using a random generator such that the probability of ADD and DROP is the same, i.e., 0.5. Source and destination of the ADD and DROP requests are selected at random.

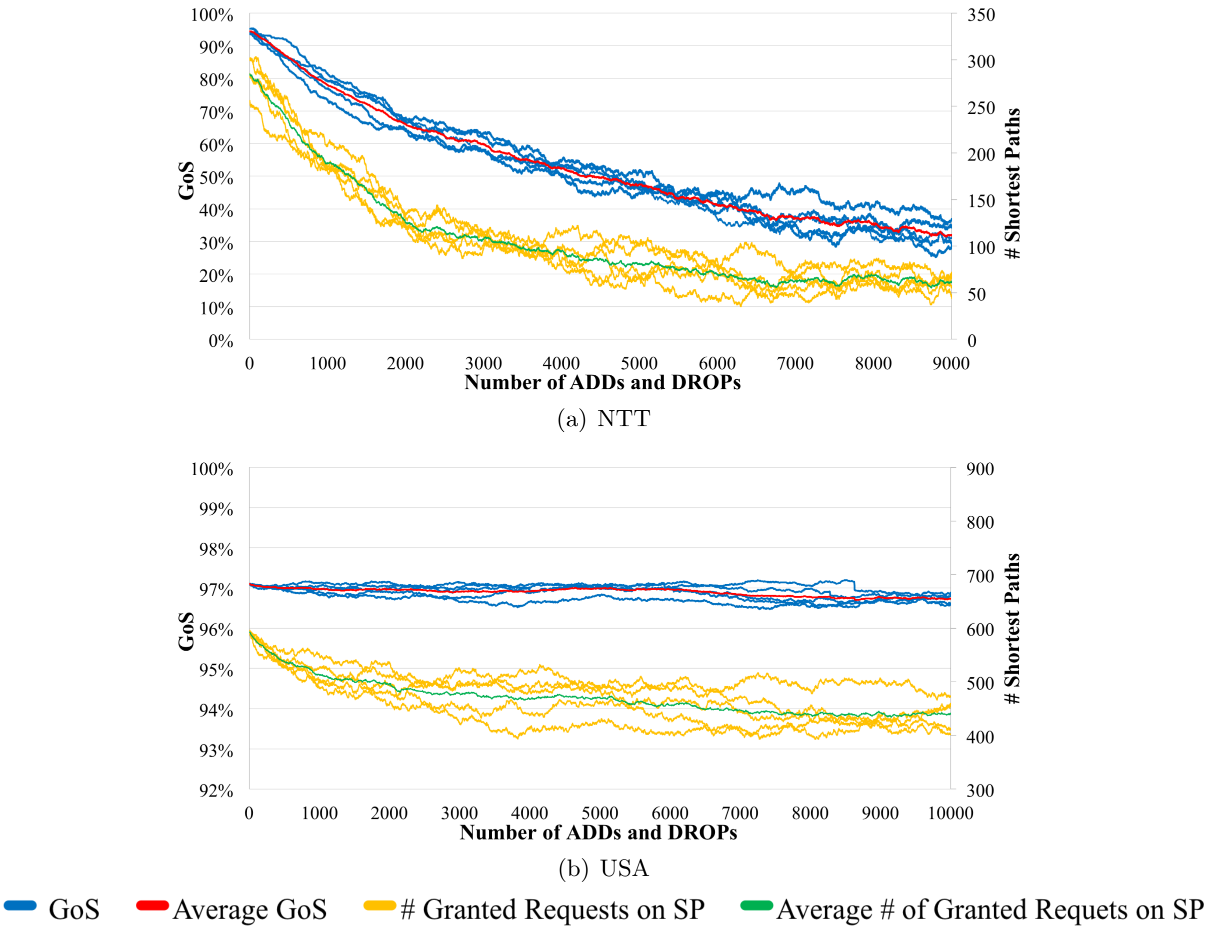
We report the GoS behavior for two networks in Figure 4, where the GoS (left vertical axis) is expressed in % and the right vertical axis reports the number of shortest paths. We plot two sets of curves, the top ones (blue curves) are each associated with one random dynamic traffic and the red curve is the average of the five individual dynamic RWA curves. The second set of curves (bottom ones) corresponds to the number of granted requests on a shortest path (be aware that for a given node pair, there may exist several shortest paths). Again, we have 5 individual curves (orange ones) and one additional curve (green curve) that represents their average.

We observe that the steady state takes a variable number of ADD and DROP requests before reaching a steady state, depending on the networks. In addition, the steady state is reached for different values of GoS. USA (Figure 4(b)) network has a larger GoS value than NTT (Figure 4(a)) in its steady state. An explanatory factor is the average node degree of the networks, see Table 2. Indeed, USA has a higher average node degree, and consequently is more connected. This leads to more options for establishing a lightpath for incoming requests, with the length of routes increasing more slowly. Behavior of the number of requests routed on a shortest path follows the behavior of the GoS decrease, as expected. As the GoS decreases, the network becomes more fragmented and, as a result, fewer shortest paths are available to grant and route incoming requests.

6.3 Reduction of the Number of Rerouting Deadlocks

6.3.1 Distribution and Sizes of the Strongly Connected Components

As mentioned in Section 2.1, network defragmentation is triggered by the GoS. Table 3 shows the different GoS values we considered. For every GoS value, we computed the Strongly Connected



(a) NTT

(b) USA

Figure 4: Fragmented Networks (GoS)

Components (SCCs) of the dependency graph. Therein, SCC$\#i$ denotes the ith largest SCC, where the size is measured by the number of nodes in each SCC, i.e., the number of lightpaths in the optical network. If they are all of size one, we can conclude that the optimal RWA provisioning is MBB reachable. However, this was the case for none of the data instances as showed in Table 3: each data instance is such that its associated dependency graph has at least one strongly connected component with a size larger than 1.

We observe that most data instances are such that the dependency graph contains only one strongly connected component with more than one node. In addition, the latter component is usually quite large, as in the theoretical results on the distribution and size of strongly connected components in random graphs, see, e.g., [35].

6.3.2 Reduction of the Number of Rerouting Deadlocks

We report in Table 3 the number and sizes of the strongly connected components after applying Algorithm 2. We observe that the number of strongly connected components has significantly increased as a consequence of the drastic reduction of the size of the largest strongly connected components, still on average larger than one. While seamless migration is still not yet possible for most of the cases except for GERMANY (5% and 25%), the number of rerouting deadlocks, as expressed by the number of circuits, and hence the size and the density of the strongly connected components of size larger than 1, has significantly decreased.

Reduction of the size of the biggest strongly connected component for each data instance is

Table 4: Statistics for the SCCs after preprocessing algorithm

Networks	GoS Reduction	# of nodes in SCC vs. AVG node degree (# Links/# Nodes) SCC #1		SCC #2		Other SCCs		# SCCs
NTT	10%	2	2.50	1	0	0	0	874
	15%	20	1.85	1	0	0	0	814
	20%	16	2.25	9	2.00	8	6.17	738
	25%	3	1.67	3	1.67	7	10	722
USA	5%	4	2.00	4	1.75	5	3	932
	10%	24	2.00	1	0	0	0	870
	15%	7	1.57	5	1.20	1	0	834
GERMANY	5%	1	0	0	0	0	0	1,836
	10%	9	1.45	3	2.00	1	0	1,728
	15%	16	1.44	2	1.50	3	1.50	1,621
	20%	5	1.60	2	1.50	3	1	1,446
	25%	1	0	0	0	0	0	1,453
CONUS	25%	5	3.44	4	1.5	3	2	714
	30%	2	1.50	1	0	0	0	667
	35%	2	3	2	1.50	1	0	629

represented in Figure 5.

Figure 6 illustrates the efficiency of using the ordering criterion of Algorithm 2 with respect to the in-degree of the nodes of the dependency graph. Indeed, Figure 6(a) represents the strongly connected component of the USA5% data set, after the first construction of the dependency graph. Therein, we can observe many rerouting deadlocks. Figure 6(b) depicts the largest strongly connected component after applying Algorithm 2, using an arbitrary order of the nodes: the size of the largest strongly connected component has significantly decreased, and we can observe a weaker density with several interconnected circuits. Lastly, Figure 6(c) shows again the largest strongly connected component, this time after applying Algorithm 2 with its current ordering rule for node processing. We can note a very significant reduction of the strongly connected component, now limited to a single circuit, i.e., a single rerouting deadlock.

6.4 Seamless or Almost Seamless Wavelength Defragmentation

We now evaluate the compromise to be made on the minimization of the bandwidth requirement in order to get a seamless, i.e., make-before-break, wavelength defragmentation. As described in Section 4.4, the WDF_NCG algorithm searches for alternate wavelength provisioning when a rerouting deadlock is identified in the dependency graph, and it may result in increasing the bandwidth requirements.

We report the results in Table 5. No data instance requires more than 5 rounds of the iterative process of the WDF_NCG algorithm and six instances are solved in 1 round. NTT with threshold 25% requires the largest number of deadlock avoidance constraints, i.e., 11 additional constraints.

In addition, the WDF_NCG algorithm is also pretty much scalable. All 13 instances are solved in less than 4 minutes, with 6 instances with a computational time less than 1 minute. It should be noted that the time reported in Table 5 (column "Time") is related to calculating

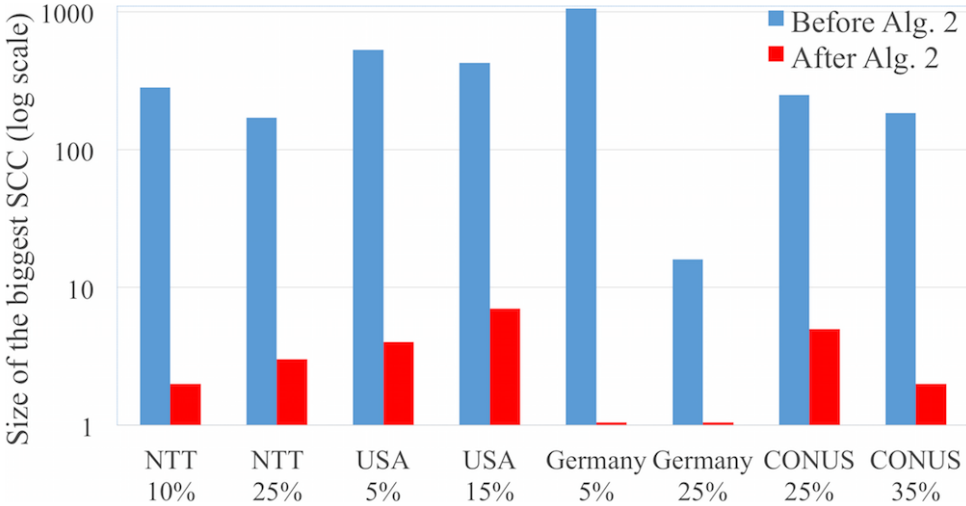


Figure 5: Performance of Algorithm 2: Reduction of the size of the biggest strongly connected component.

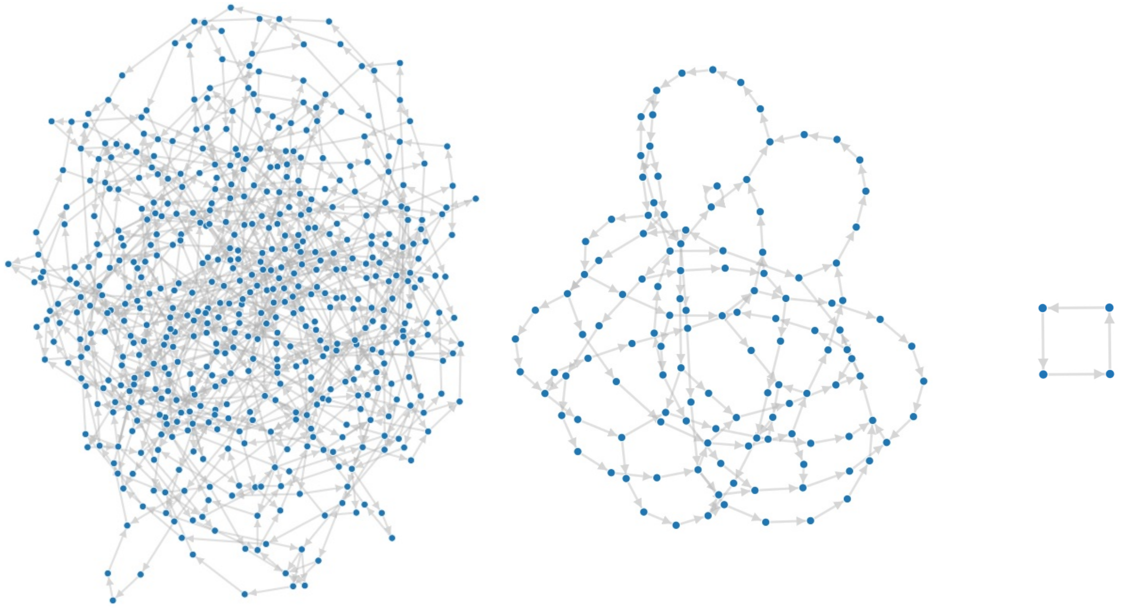
MBB provisioning and does not include the time required for calculating initial RWA^{OPT} that we have reported in column "Min RWA" (time for solving the RWA problem while minimizing the number of used wavelengths).

Table 5: Performance of the WDF_NCG algorithm

Networks	GoS Reduction	# Rounds	# Constr.	Time (sec)	Min RWA (sec)
NTT	10%	4	4	203	1,259
	15%	1	1	13	1,291
	20%	4	8	168	1,332
	25%	5	11	202	1,153
USA	5%	3	8	70	619
	10%	2	2	28	450
	15%	1	2	15	534
GERMANY	10%	1	2	11	13,158
	15%	2	4	14	18,027
	20%	1	3	10	18,746
CONUS	25%	3	5	165	2,891
	30%	1	1	83	2,827
	35%	1	2	70	1,069

Table 6 provides the bandwidth requirement and how far it is from minimum bandwidth requirement in order to derive a make-before-break reachable wavelength provisioning. We report the bandwidth requirement for the RWA^{FRAG} right before the defragmentation event, the optimal (RWA^{OPT}) provisioning and the best wavelength provisioning ($\text{RWA}^{\text{MBB\_OPT}}$) that is make-before-break reachable. As seen, the difference between link usage of the MBB and optimal provisionings is less than 1% and even equal to the optimal provisioning except NTT (20%) while the performance of the network in terms of used links is improved in all cases.

Table 7 analyzes the total length of the lightpaths in different provisionings based on the



(a) Before preprocessing

(b) After Algorithm 2 with arbitrary ordering

(c) After Algorithm 2 with specific ordering rule

Figure 6: Largest SCC for USA 5% before preprocessing (6(a)), after applying Algorithm 2 using an arbitrary order of the nodes (6(b)), and after Algorithm 2 with its current ordering rule for node processing (6(c)).

geographical distances presented in [36] for the USA network. As expected, the difference between MBB and optimal provisionings is negligible while the improvement form RWA^{FRAG} to $\text{RWA}^{\text{MBB-OPT}}$ provisioning is over 25%.

Figure 7 compares the percentage of the number of the lightpaths routed over the shortest paths in MBB and RWA^{FRAG} provisionings. As seen in Figure 7, more lightpaths use the shortest paths in $\text{RWA}^{\text{MBB-OPT}}$ than in RWA^{FRAG}. It is as expected based on the higher number of links used in RWA^{FRAG} (Table 6). By migrating from RWA^{FRAG} provisioning to MBB provisioning, more lightpaths are routed over shortest paths, fewer links are used and as the result, the blocking rate is reduced.

6.5 Number of Reroutings vs. Bandwidth Improvement

In this section, we investigate the trade off between the percentage of rerouted lightpaths and bandwidth saving while providing a seamless migration. As illustrated in Figure 8, aiming higher bandwidth savings will result in more rerouted lightpaths. Figure 8 shows that almost all lightpaths need to be rerouted in order to reach the maximum bandwidth saving in NTT network (10%). The same holds for all the networks used in this study.

The seamless solution still gives the network operator the opportunity to decide on the desired saving and/or possible amount of reroutings and come up with the best seamless migration. For instance, Figure 8 shows that if we reroute at most 60% of the lightpaths, then the maximum bandwidth usage will be around 7%.

Table 6: Bandwidth requirement compromise for a make-before-break reachable optimized wavelength provisioning

Networks	Defrag. trigg. event	Bandwdith requirement (number of wavelength links)			RWA^{MBB_OPT} vs. RWA^{OPT}	RWA^{FRAG} vs. RWA^{MBB_OPT}
		RWA^{FRAG}	RWA^{OPT}	RWA^{MBB_OPT}		
NTT	10%	2,907	2,546	2,558	0.47%	12.00%
	15%	3,009	2,645	2,645	0.00%	12.09%
	20%	2,971	2,537	2,600	2.42%	12.48%
	25%	2,920	2,464	2,470	0.24%	15.41%
USA	5%	3,931	2,798	2,814	0.57%	28.42%
	10%	3,691	2,593	2,601	0.31%	29.53%
	15%	3,573	2,545	2,548	0.12%	28.69%
GERMANY	10%	8,347	6,386	6,386	0.00%	23.50%
	15%	7,893	5,984	5,984	0.00%	24.18%
	20%	7,008	5,329	5,329	0.00%	23.96%
CONUS	25%	3,921	3,410	3,424	0.41%	14.51%
	30%	3,746	3,159	3,164	0.15%	15.67%
	35%	3,718	3,039	3,054	0.49%	22.34%

Table 7: Length Reduction for USA

Defrag. trigg. event	Total length of the lightpaths (Length (KM))			RWA^{MBB_OPT} vs. RWA^{OPT}	RWA^{FRAG} vs. RWA^{MBB_OPT}
	RWA^{FRAG}	RWA^{OPT}	RWA^{MBB_OPT}		
5%	2,996,850	2,978,500	4,044,700	0.6%	25.9%
10%	2,761,000	2,751,200	3,709,500	0.3%	25.6%
15%	2,724,200	2,721,450	3,701,550	0.1%	26.4%

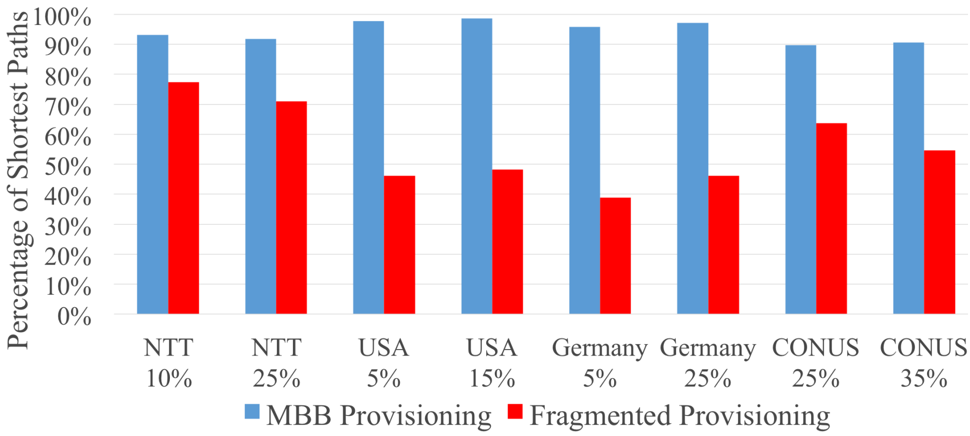


Figure 7: Percentage of Shortest Paths

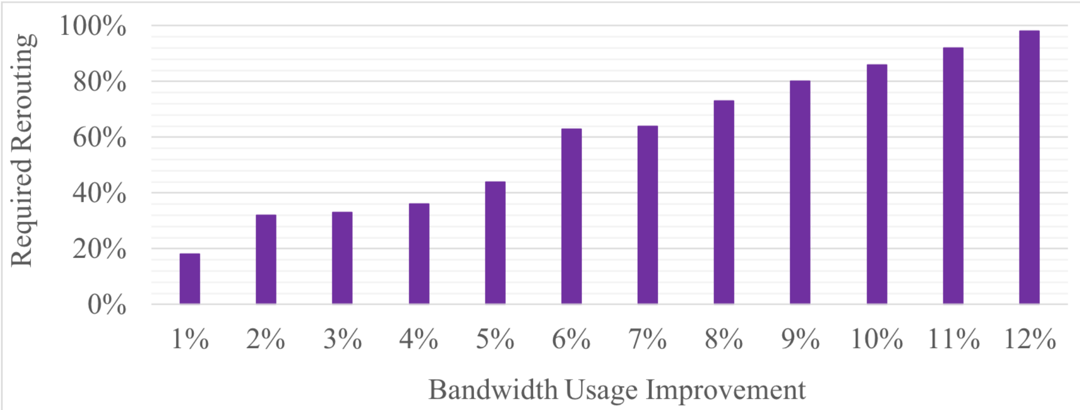


Figure 8: Rerouting vs. Bandwidth Improvement for NTT 10%

7 Conclusions and Future Work

We proposed a very efficient algorithm for obtaining an MBB wavelength optimized provisioning that allows a seamless migration from a fragmented network provisioning to an optimized one. We also proposed Algorithm 2 in order to reduce the number of strongly connected components by identifying avoidable disruptions. Although the number and the size of the strongly connected components for migrating from fragmented provisioning to optimal provisioning might be big, applying Algorithm 2 can efficiently reduce both the number and the size of them and consequently adding simpler and fewer deadlock avoidance constraints. We evaluated our defragmentation framework and algorithms on different real size data sets. The results show that the algorithm can efficiently provide a seamless migration in reasonable time.

Future work should consider investigating the best compromise between number of reroutings and bandwidth savings, as well as the triggering of the defragmentation events. We also plan to generalize the proposed defragmentation techniques to flexible optical networks. While the generalization of the dependency graph is straightforward, the mathematical model and its associated nested decomposition algorithm for a Routing and Spectrum Provisioning (RSA) requires significant adjustments due to the contiguity requirement for frequency slots.

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