Off-line Survivable Impairment-aware Routing and Wavelength Assignment

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1 Introduction

Physical impairments caused by noise and signal distortions affect the quality of an optical signal. The effect of physical impairments becomes more significant with an increase in distance and bit rates. In order to minimize the bit error rate (BER), an optical signal may need to be regenerated after a certain distance. This is mainly achieved through re-amplification, re-shaping, and re-timing, which are collectively known as *3R regeneration.* In order to guarantee a certain BER, system vendors offer a certain level of optical signal-to-noise ratio (OSNR) at the output of a system. In a system where signal power levels are low enough that nonlinearities can be neglected, OSNR is an important parameter to measure the quality of an optical signal [12].

It is customary to place amplifiers at several points along a fiber link in order to overcome fiber losses. The segment of a link between two consecutive amplifiers is known as a *fiber span.* However, optical noise is added by each amplifier along a fiber. This noise is referred to as *Amplifier Spontaneous Emission (ASE).* ASE degrades the OSNR and is reflected in that measure. In practice, vendors generally provide bounds on the length of a transparent (non-regenerated) path and number of spans in order to ensure an acceptable level of OSNR [13].

1.1 Figure of Merit (FoM)

The following formula can be used to compute OSNR.

$$\frac{1}{OSNR} = \sum_{j=1}^{H} \frac{2hvRN_{sp.j}}{P_{in,j}} \tag{1}$$

where h is Planck's constant, v is the frequency of the input signal, R is the optical bandwidth, $P_{in,j}$ is the input power (W) at amplifier j, $N_{sp.j}$ is the noise figure of amplifier j, and H is the number of spans.

If the net gain of a fiber link is unity, i.e., each amplifier is placed/tuned in such a way that it exactly cancels out the loss of its preceding span, then the noise figure of a link is the sum of the noise figures of its spans [12]. The noise figure of a system is usually given in (dB). However, in order to add the noise figures of each span to obtain that of a link, the values should be changed to linear units using the following formula [12], which we refer to as the *Figure of Merit (FoM).*

$$FoM = \sum_{j=1}^{H} 10^{\left(\frac{L_j}{10}\right)}, \tag{2}$$

where L_j is the fiber loss of span j in dB (it is the same as the noise figure of amplifier j when the gain of the amplifier is one).

The FoM value of a given fiber link is not directly proportional to its length, instead it depends mainly on the number of spans and the distance covered by each span. For example in Figure 1, let the fiber loss per km be 0.25 dB/km. Using Eq. 2, the FoM value of the scenario in Figure 1 (a) is 3300, while it is 1897 for that of Figure 1 (b).

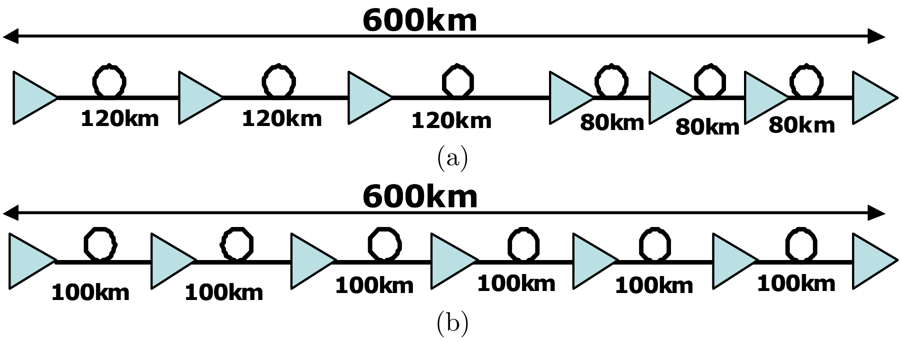

Figure 1: An example that shows how the placement of amplifiers along a given fiber link affects its FoM value.

1.2 Regenerators

Back-to-back optical transponders can be used not only to add/drop traffic but also to regenerate optical signals. Thus, regeneration can also be considered as an add/drop since the signal is added/dropped from the optical layer [12]. The *impairment threshold* of a lightpath is the maximum length (measured in FoM) that can be traversed by the lightpath without regeneration. After this length, the quality of the signal drops below the acceptable level. The impairment threshold of a lightpath depends on the type of transponder (interface) used for regeneration. Figure 2 shows some transponders and their specifications for a 10 Gb/s data rate.

A given wavelength can be regenerated under two scenarios: (1) when regeneration is required so that the impairment threshold is not exceeded, and

10Gb/s Interfaces (Transponders)	Dispersion tolerance (ps/nm)	OSNR (dB, 0.1nm)	FoM Threshold	Relative Cost estimate
DWDM XFP	1600	20	600	1
NRZ	2000	18	1000	4
NRZ with EDC	40000	15	1900	6

Figure 2: Different types of interfaces (transponders) and their specifications.

(2) when traffic carried by the wavelength is added/dropped. We refer to the former as *'true' regeneration*, while to the latter as *add/drop regeneration*.

1.3 Types of Nodes

Up to now, we have only considered physical impairments associated with links. However, equipment at the nodes also add noise and contribute to signal distortions. The FoM value associated with a node depends on the type of node, which in turn depends on how wavelengths are added/dropped at the node. In early wavelength division multiplexing (WDM) networks, optical-to-electrical-to-optical (O-E-O) conversion of wavelengths was frequently required, regardless of whether these wavelengths were dropped or were passing through a node. These O-E-O conversions had to be minimized in the network since the O-E-O devices are quite costly and require significant power. This led to the development of Optical Add/Drop Multiplexer (OADM) technology to locally add/drop individual or groups of wavelengths, while the rest are optically passed through without O-E-O conversions. However, most early OADM systems are fixed in that the wavelengths that are added/dropped at a given node are not reconfigurable, thus restricting network reconfigurability in response to new service demands and traffic patterns [1].

In order to provide flexibility, dynamically Reconfigurable Optical Add/Drop Multiplexers (ROADMs) are introduced. ROADMs simplify the planning process for DWDM-based networks by allowing the addition, removal, or modification of one or more wavelength channels within a network automatically, with minimal user intervention. Whereas in fixed OADM systems, the network tuning process is performed manually and requires considerable equipment, traffic management, and personnel [18]. The downside of ROADMs is that they are costly.

1.3.1 Fixed OADM nodes

Fixed OADM nodes usually consist of the following equipment.

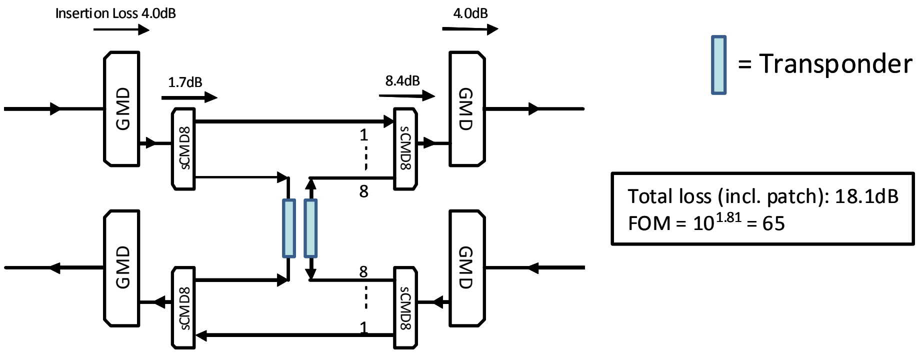

Figure 3: A GMD-based fixed OADM node.

Channel Mux/Demux (CMD): The CMD is a 4-port or 8-port mux/demux filter that feeds into one of the nine ports on the Group Mux/Demux (GMD). Both types of CMDs can coexist on the same line to offer anywhere between 36 and 72 wavelengths on the DWDM system.

Group Mux/Demux (GMD): The GMD provides a second stage mux/demux capability and supports nine CMD filters capable of offering a total of up to 72 wavelengths. The GMD provides a communications infrastructure in order for a node to interface with other nodes and elements within the node.

Figure 3 shows a typical GMD-based fixed OADM node.

1.3.2 Nodes with Reconfigurable OADMs (ROADMs)

In general, there are two types of ROADMs [6]: two-degree and multi-degree, where the degree refers to the numbers of DWDM fibers entering and exiting the ROADM node. This refers to traffic moving in one direction only. In practice, pairs of fibers are generally used with each set carrying traffic in an alternate direction, so there would be twice as many fibers entering and exiting the ROADM as its degree.

The key enabling technology in ROADM configuration is the Wavelength Selective Switch (WSS). This is an advanced fiber-optic module that can be used under software control to dynamically select individual wavelengths from multiple DWDM input fibers and switch these to a common output fiber, or individual wavelengths on a common input fiber can be selectively switched to any of multiple output fibers. Figure 4 shows a typical ROADM node with a WSS.

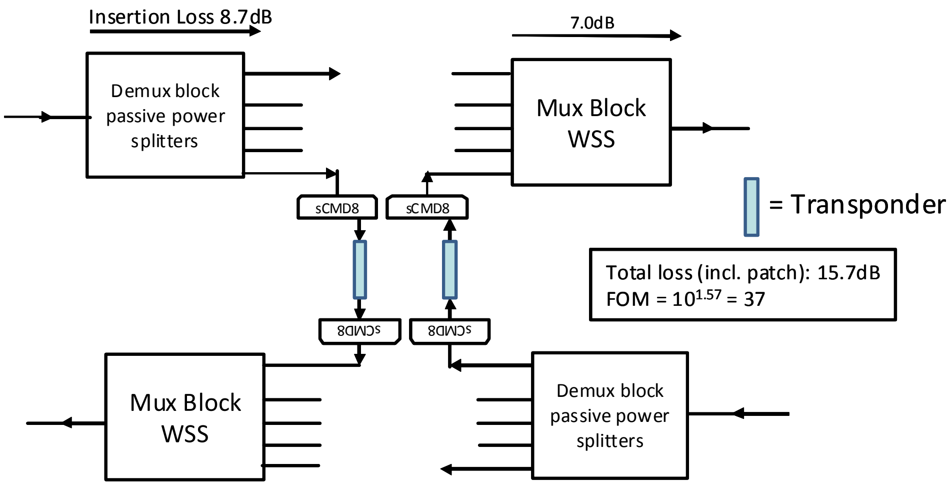

Figure 4: A ROADM node with a Wavelength Selective Switch (WSS).

1.4 Survivability

Since WDM networks transport large amounts of data, failure of lightpaths can be costly. Hence, survivability, which is the ability to restore communication after failure is indispensable in WDM networks. In this paper, we assume a single-link failure model, since single link failures are the most common types of failure [15]. In this model, only a single link is assumed to fail at a time. For single-link failures, it is sufficient to have link-disjoint primary and backup lightpaths so that the backup lightpath takes over when a link fails in the primary lightpath.

2 Related Work

Most of the related work in the literature focuses on the placement of regenerators for unprotected lightpaths. For these studies, the objective can be of two types: minimizing the total number of regenerators [8][11] and minimizing the total number of nodes where regenerators are placed (i.e., regenerator nodes) [3][4][10][16][17]. Since regenerators are active elements and require maintenance, it may be desirable to minimize the number of places where they are placed. Thus, minimizing the number of regenerator nodes is aimed at reducing the operational expenditure (OPEX). On the other hand, minimizing the total number of regenerators reduces the capital expenditure (CAPEX) since regenerators are costly. In addition, it will also reduce the OPEX since regenerators, which generally use O-E-O conversions, have a high power consumption.

Depending on how requests arrive, the traffic can be modeled as on-line (dynamic) [10][16][17] or off-line (static) [3][4]. In an on-line traffic model, the requests are unpredictable and arrive over time; whereas, in an off-line traffic model, the requests are known beforehand and do not vary over a large time scale. A *lightpath* is a simple path between two nodes on a given wavelength. Most previous studies assume that each lightpath requires a single wavelength [3][4][16][10][17]. However, traffic to and from different nodes can be aggregated in a single wavelength using technologies such as synchronous optical network (SONET)/synchronous digital hierarchy (SDH) over WDM. In this paper, a lightpath refers to a connection (which may require less than the capacity of a single wavelength) between two pair of nodes, and a wavelength can carry multiple lightpaths.

Unlike most previous studies, we not only consider impairments associated with links, but also nodal impairments. In addition, we take into account the types of nodes, i.e., the type of a node determines the FoM value associated with it. We also note that a wavelength is regenerated whenever a traffic is added/dropped from it at the source and destination nodes of its lightpaths.

In Section 3, we show that the survivable impairment-aware routing problem, which minimizes the total number of regenerators placed in the network is NP-hard. Subsequently, we provide an exact integer linear programming (ILP) formulation. Since the exact ILP does not scale well, we provide a simple but heuristic approach. We study the performance of this approach in Section 4 using the SURFnet network. Finally, we conclude in Section 5.

3 Survivable Impairment-aware Routing and Wavelength Assignment

In this section, we give a formal definition of the survivable impairment-aware routing and wavelength assignment problem and provide algorithms for solving it. We assume that there is no wavelength conversion. Thus, each lightpath should use the same wavelength in all of its links. We also assume that the same type of interface is used everywhere in the network. The transponders are assumed to be bidirectional, thus one transponder suffices for both directions of signal flow between the source and destination nodes of a request. For each request, a pair of transponders are needed at its source and destination nodes, one for the primary and another for the backup lightpaths. If a lightpath is regenerated at an intermediate node, two transponders are needed, one on either side.

Problem 1 *Given are an optical network* $G(\mathcal{N}, \mathcal{L}, W)$*, where* $\mathcal{N}$ *is the set of nodes,* $\mathcal{L}$ *is the set of links and* W *is the number of wavelengths per link, and a set* $\mathcal{F}$ *of* F *requests. Associated with each link* $(u, v) \in \mathcal{L}$ *is an FoM value* $r(u, v)$*. Also associated with each node* $u \in \mathcal{N}$ *is an FoM value* $r(u)$*. The FoM threshold is* Δ*. The* ***survivable impairment-aware routing and wavelength assignment (SIRWA)*** *problem is to minimize the total number of regenerators (transponders) needed in the network so that (1) each request is assigned a pair of disjoint paths and corresponding wavelengths; (2) the same wavelength is used* *on all the links of a lightpath; (3) the capacity of each wavelength in a link is not exceeded; and (4) for any lightpath, the impairment values between regenerator nodes should not exceed the FoM threshold.*

Theorem 1 *The SIRWA problem is NP-hard.*

We provide a proof based on the *impairment-aware path selection* problem, where given a sparse regeneration network (i.e., a network wherein only a few nodes have regeneration capacity), an impairment threshold, and a request between two pairs of nodes, the problem is to find a feasible simple path for the given request. The impairment-aware path selection problem is proved to be NP-hard [7].

As explained in Section 1.2, we have two scenarios that lead to the regeneration of a given wavelength: add/drop regeneration (i.e., when traffic is added/dropped from the wavelength), and 'true' regeneration (i.e., when the FoM value since last regeneration exceeds the threshold).

Proof. *Instance*: A given wavelength and a set of requests that can all fit in this wavelength.

In this instance, the number of add/drop regenerators is fixed, i.e., twice the total number of distinct source and destination nodes. Hence, the objective reduces to minimizing the number of 'true' regenerations. A decision problem related to the given instance of the SIRWA problem is described as follows:

Question: Is it possible to feasibly route all requests with at most K 'true' regenerations?

For $K = 0$, the question reduces to: is it possible to feasibly route each request using only add/drop regenerations? In this scenario, the source and destination nodes of the given requests are the only regeneration nodes. In other words, the network has a sparse regeneration capacity. By solving the decision problem, each request will be assigned feasible primary and backup lightpaths using only the existing regeneration network. However, this is equivalent to solving the NP-hard impairment-aware path selection problem. ■

We first provide an exact integer linear programming (ILP) formulation, followed by a simpler but efficient heuristic approach. We convert node weights to link weights by adding half of the FoM values of its end points to obtain the modified FoM of the given link, i.e. $r(u,v) = r(u,v) + \left(\frac{r(u)+r(v)}{2}\right)$. The source and destination nodes of a request are assumed to have an FoM value of zero for the given request.

3.1 Exact ILP

Indices, constants, variables:

$f = 1, \ldots, F$	ID of the lightpaths in the network.
$w = 1, \ldots, W$	ID of the wavelengths in the network.
$\mathcal{N}$	The set of nodes in the network.
$\mathcal{N}(u)$	The set of neighboring nodes of node u.
$\mathcal{L}$	The set of links in the network.
B_w	The capacity of wavelength w.
B_f	The bandwidth requirement of request f.
$a_{f,w,u,v,t}$	is 1 if the primary lightpath of request f uses wavelength w at link (u, v) after being regenerated at node t.
$b_{f,w,u,v,t}$	is 1 if the backup lightpath of request f uses wavelength w at link (u, v) after being regenerated at node t.
$\gamma_{f,w,t,u}$	is 1 if the primary lightpath of request f uses wavelength w and regenerated at node t and at node u, in that order.
$\tau_{f,w,t,u}$	is 1 if the backup lightpath of request f uses wavelength w and regenerated at node t and at node u, in that order.
$x_{u,w}$	is 1 if wavelength w is added/droped at node u.

Objective:

Minimize the total number of regenerators.

$$Minimize : \sum_f \sum_w \sum_t \sum_u (\gamma_{f,w,t,u} + \tau_{f,w,t,u}) + \sum_u \sum_w x_{u,w}$$

Constraints:

Disjointedness constraint:

The primary and the backup lightpaths of a request should be link-disjoint.

$$\sum_t \sum_w (a_{f,w,u,v,t} + a_{f,w,v,u,t} + b_{f,w,u,v,t} + b_{f,w,v,u,t}) \leq 1 \quad f = 1, ..., F;\ \forall (u, v) \in \mathcal{L}.$$

Wavelength Constraint:

The bandwidth requirement of lightpaths using a given wavelength of a link should not exceed the capacity of the wavelength.

$$\sum_f \sum_t B_f (a_{f,w,u,v,t} + a_{f,w,v,u,t} + b_{f,w,u,v,t} + b_{f,w,v,u,t}) \leq B_w \quad w = 1, ..., W; \forall (u, v) \in \mathcal{L}.$$

Flow Conservation constraints:

The primary and backup lightpaths of a given request should originate at its source node.

$$\sum_w \sum_{v \in \mathcal{N}(s_f)} a_{f,w,s_f,v,s_f} = 1 \text{ and } \sum_w \sum_{v \in \mathcal{N}(s_f)} b_{f,w,s_f,v,s_f} = 1 \quad f = 1, ..., F.$$

At intermediate nodes:

If a given node u is not the source or the destination node, then the flow related to the primary/backup lightpath that enters u has to leave it, where $\gamma_{f,w,t,u} = 1$ for the primary and $\tau_{f,w,t,u} = 1$ for the backup path if it is regenerated, and $\gamma_{f,w,t,u} = 0$ for the primary and $\tau_{f,w,t,u} = 0$ for the backup path if it is not.

$$\begin{aligned}
&\sum_{v \in \mathcal{N}(u)} (a_{f,w,u,v,t} - a_{f,w,v,u,t}) = \gamma_{f,w,t,u} \qquad \text{and} \\
&\sum_{v \in \mathcal{N}(u)} (b_{f,w,u,v,t} - b_{f,w,v,u,t}) = \tau_{f,w,t,u} \\
&f \ = 1, ..., F; w \ = 1, ..., W; \forall u \in \mathcal{N} \backslash \{s_f, d_f\}; \forall t \in \mathcal{N} \backslash \{u\}.
\end{aligned}$$

If a lightpath is regenerated at node u, the last regenerator node in the new segment should be node u, and not any other node.

$$\begin{aligned}
&\sum_{v \in \mathcal{N}(u)} a_{f,w,u,v,u} - \sum_{t \in \mathcal{N} \backslash \{u\}} \gamma_{f,w,t,u} \ = 0 \ \text{ and} \\
&\sum_{v \in \mathcal{N}(u)} b_{f,w,u,v,u} - \sum_{t \in \mathcal{N} \backslash \{u\}} \tau_{f,w,t,u} \ = 0 \\
&f \ = 1, ..., F; w \ = 1, ..., W; \forall u \in \mathcal{N} \backslash \{s_f, d_f\}.
\end{aligned}$$

Simple path constraints:

The lightpaths should not contain loops.

At the source node, there should not be a flow associated with any of its incoming links.

$$\sum_{w} \sum_{v \in \mathcal{N}(s_f)} \sum_{t} (a_{f,w,v,s_f,t} + b_{f,w,v,s_f,t}) = 0 \qquad f \ = 1, ..., F.$$

In addition, any flow that exits the source node, other than the one originating at the source node, should explicitly be set to 0.

$$\sum_{w} \sum_{v \in \mathcal{N}(s_f)} \sum_{t \in \mathcal{N} \backslash \{s_f\}} (a_{f,w,s_f v,t} + b_{f,w,s_f v,,t}) = 0 \qquad f \ = 1, ..., F.$$

Similarly, for any intermediate node, there can at most be one flow of the primary or backup lightpath entering the node.

$$\begin{aligned}
\sum_{w} \sum_{v \in \mathcal{N}(u)} \sum_{t} a_{f,w,v,u,t} \ &\leq \ 1 \text{ and} \sum_{w} \sum_{v \in \mathcal{N}(u)} \sum_{t} b_{f,w,v,u,t} \ \leq 1 \\
\forall u \ &\in \ \mathcal{N} \backslash \{s_f\}; f \ = 1, ..., F.
\end{aligned}$$

Impairment constraints:

The FoM of any transparent segment (i.e., that of the links and the nodes) should not exceed the threshold,

$$\sum_{w}\sum_{u}\sum_{v\in\mathcal{N}(u)} r(u,v)(a_{f,w,u,v,t}+a_{f,w,v,u,t}) \leq \Delta$$
$$\forall t \in \mathcal{N}; f \ = 1,...,F; w \ = 1,...,W.$$

Add/drop Regenerations:

If traffic is added/dropped at a given node, then there is regeneration.

$$\sum_{f\in\{f|s_f=u\}}\sum_{v\in\mathcal{N}(u)} (a_{f,w,u,v,u}+b_{f,w,u,v,u}) \leq F\cdot x_{u,w} \qquad \forall u \in \mathcal{N}; w \ = 1,...,W.$$

3.2 Heuristic Approach

The exact ILP does not scale well even for small sized networks as the SURFnet network considered in Section 4. The complexity of the problem can be reduced by limiting the number of paths that are considered. Thus, we now propose a two-phase heuristic approach that makes use of a precomputed set of paths to solve the SIRWA problem.

3.2.1 Phase 1: Precomputed Paths

In the first phase, K pairs of (shortest) disjoint paths are pre-computed for each request (using an algorithm given in [9]), and the solution will be selected from these pairs of paths using an ILP formulation. In this phase, the objective is to minimize the number of transponders required for adding/dropping the wavelengths. It is based on the assumption that putting lightpaths that originate or end at a given node in the same wavelength minimizes the total number of transponders needed. This approach has also an additional advantage in that the total number of wavelengths used is minimized, since it tends to aggregate traffic in a smaller number of wavelengths.

Indices, constants, variables:

$P_{f,k} = \{P_{f,k,1}, P_{f,k,2}\}$ for $k = 1, \ldots, K$	A set of precomputed pairs of disjoint paths for request f.
$\alpha_{f,k,w}$	is 1 if the k^{th} disjoint path pair is selected and the primary lightpath uses wavelength w; 0 otherwise.
$\gamma_{f,k,w}$	is 1 if the k^{th} disjoint path pair is selected and the backup lightpath uses wavelength w; 0 otherwise.
$a_{f,k,l}$	is 1 if the primary of the k^{th} disjoint path pair uses link l; 0 otherwise.
$b_{f,k,l}$	is 1 if the primary of the k^{th} disjoint path pair uses link l; 0 otherwise.

Objective:

Minimize the total number of regenerators.

$$\text{Minimize} \qquad \sum_u \sum_w x_{u,w}$$

Constraints:

For each request, only one pair of disjoint paths is selected.

$$\sum_k \sum_w \alpha_{f,k,w} = 1 \text{ and } \sum_k \sum_w \alpha_{f,k,w} = 1 \quad \text{for } f = 1, \ldots, F.$$

The primary and backup paths should be from the same pair.

$$\sum_w \alpha_{f,k,w} = \sum_w \gamma_{f,k,w} \quad \text{for } f = 1, \ldots, F; k = 1, \ldots, K.$$

The capacity of each wavelength on each link should not be exceeded.

$$\sum_f \sum_k B_f(a_{f,k,l}\alpha_{f,k,w} + b_{f,k,l}\gamma_{f,k,w}) \leq B_w \qquad \text{for } \forall l \in \mathcal{L}; w = 1, \ldots, W.$$

There is add/drop regeneration whenever traffic is added/dropped.

$$\sum_{f \in \{f | s_f = u \text{ or } d_f = u\}} \sum_k (\alpha_{f,k,w} + \gamma_{f,k,w}) \leq F \cdot x_{u,w} \text{ for } \forall u \in \mathcal{N}; w \ = 1, ..., W.$$

In the given ILP formulation, the primary and backup lightpaths of a request can be on different wavelengths. However, assigning the same wavelength to the primary and backup lightpaths of a request not only simplifies the ILP formulation by providing symmetry, but it also reduces the number of transponders needed since the primary and backup lightpaths share starting and end points.

3.2.2 Phase 2: Rerouting Lightpaths

In phase 1, the objective is to reduce the number of transponders needed to add/drop the given set of requests at their source and destination nodes. However, some of the lightpaths obtained in phase 1 may not be feasible, thus requiring the placement of extra regenerators. Algorithm *Reroute* tries to minimize the additional number of regenerators by rerouting lightpaths that are infeasible. Let $\mathcal{P}$ be the set of requests that need extra regeneration. A request needs extra regeneration if its primary or backup lightpath has an infeasible segment (i.e., its FoM value exceeds Δ) in the current setup. Let $\mathcal{N}_w$ be the set of regenerator nodes for wavelength w in the network.

The algorithm (see Algorithm 1) works as follows. In Step 1, it (randomly) chooses a request f among all the requests in $\mathcal{P}$. In the next steps, it tries to find a feasible pair of disjoint paths using only the existing regenerators. This is done by constructing a new graph on each wavelength. In Step 2, graph G_w represents a graph in wavelength w, which is made up of links that have enough capacity to support graph G, or belong to the disjoint paths of request f. In Step 2b, a new graph G'_w is obtained from graph G_w as follows. Its nodes are the regenerator nodes of wavelength w (including the source and destination nodes of the request), and there is a link between two nodes if they are directly reachable (i.e., without a regenerator). Then in Step 2c, two disjoint paths are computed using Suurballe's algorithm [14] in graph G'_w. These paths are then translated to their equivalent paths in G_w by replacing the links in G'_w with their corresponding subpaths in G_w. If the paths are simple and feasible, they are accepted as a solution. Otherwise, we add regenerators to make the original paths feasible. Adding regenerators, however, may make some of the requests in $\mathcal{P}$ feasible. These paths are removed from $\mathcal{P}$ before continuing to the next iteration.

4 Simulation Results

We have performed simulations on the SURFnet network whose FoM values are given in Figure 5. The traffic matrix is shown in Figure 6. The given traffic represents synchronous digital hierarchy (SDH) data over the WDM network. Each unit of traffic represents one VC4, which is equivalent to 155Mb/s. Each wavelength has a capacity of 10Gb/s (64 VC4s). We assume that the type of transponders used in the network is DWDM XFP (see Figure 2). Thus, the FoM threshold is 600.

We compare our heuristic approach with an on-line sequential approach. In the sequential approach, each request is assigned the shortest link-disjoint pair of paths between its source and destination nodes. Then, the lightpaths are sequentially allocated wavelengths in such a way that a lightpath is assigned to the lowest-indexed wavelength that has sufficient capacity for its traffic. In the sequential approach, 9 wavelengths and a total of 290 XFPs are required for the given traffic matrix. Figure 7 shows the number of wavelengths on each link, and

Algorithm 1 *Reroute*

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1. While $\mathcal{P}$ is not empty, pick a request $f \in \mathcal{P}$. Let its assigned disjoint pair of paths be $\{P_{f,1}, P_{f,2}\}$.
2. For each wavelength $w$, let $B'_{l,w}$ be the residual capacity of wavelength $w$ on link $l$. Let $G_w = (\mathcal{N}, \mathcal{L}_w)$, where $\mathcal{L}_w = \{l \in \mathcal{L} | B'_{l,w} \geq B_f$ or $l \in P_{f,1}$ or $l \in P_{f,2}\}$.
    (a) For any $u, v \in \mathcal{N}_w \cup \{s_f, d_f\}$, let $r_w(P_{u-v})$ be the length of the shortest path (in terms of FoM) between nodes $u$ and $v$ in $G_w$.
    (b) Create graph $G'_w = (\mathcal{N}'_w, \mathcal{L}'_w)$, where $\mathcal{N}'_w = \{\mathcal{N}_w, s_f, d_f\}$ and $\mathcal{L}'_w = \{(u, v) | u, v \in \mathcal{N}'_w$ and $r_w(P_{u-v}) \leq \Delta\}$. Assign a cost of 1 to each link in $G'_w$.
    (c) Find two disjoint paths $P'_1$ and $P'_2$ in graph $G'_w$.
    (d) For $P'_1$ and $P'_2$, find their corresponding paths $P_1$ and $P_2$ in $G_w$.
    (e) If $P_1$ and $P_2$ are simple and disjoint paths:
        i. Assign them to request $f$.
        ii. Remove $f$ from $\mathcal{P}$ and update the residual capacities of all links that belong to the old and new paths of $f$.
        iii. Go to Step 1.
    (f) Else, go to Step 1 for the next wavelength.
3. If all wavelengths are exhausted and no feasible paths are found,
    (a) Place the minimum number of regenerators needed to make $P_{f,1}, P_{f,2}$ feasible.
    (b) Remove $f$ from $\mathcal{P}$.
    (c) Remove all requests in $\mathcal{P}$ whose paths are now feasible.
    (d) Go to Step 1.
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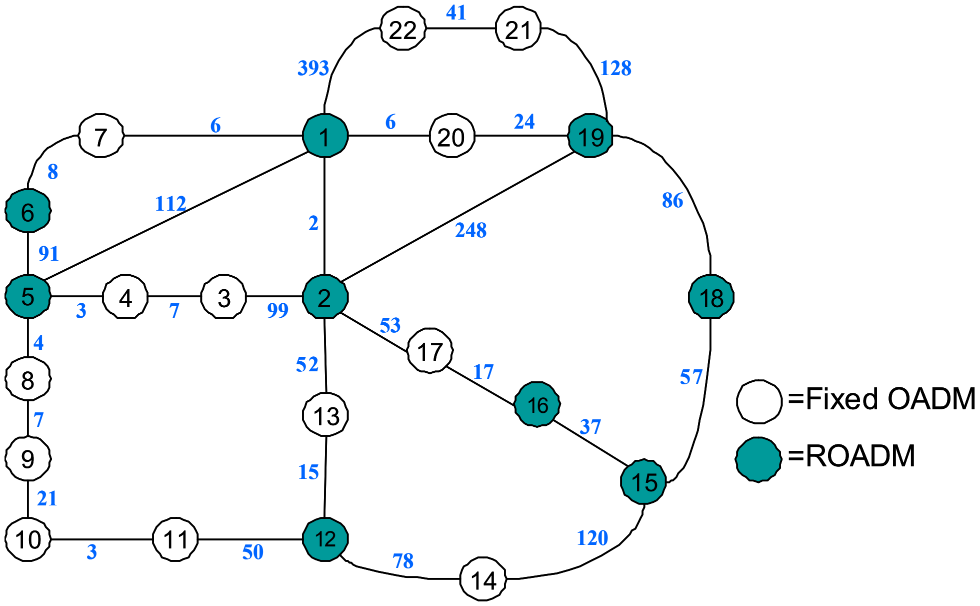
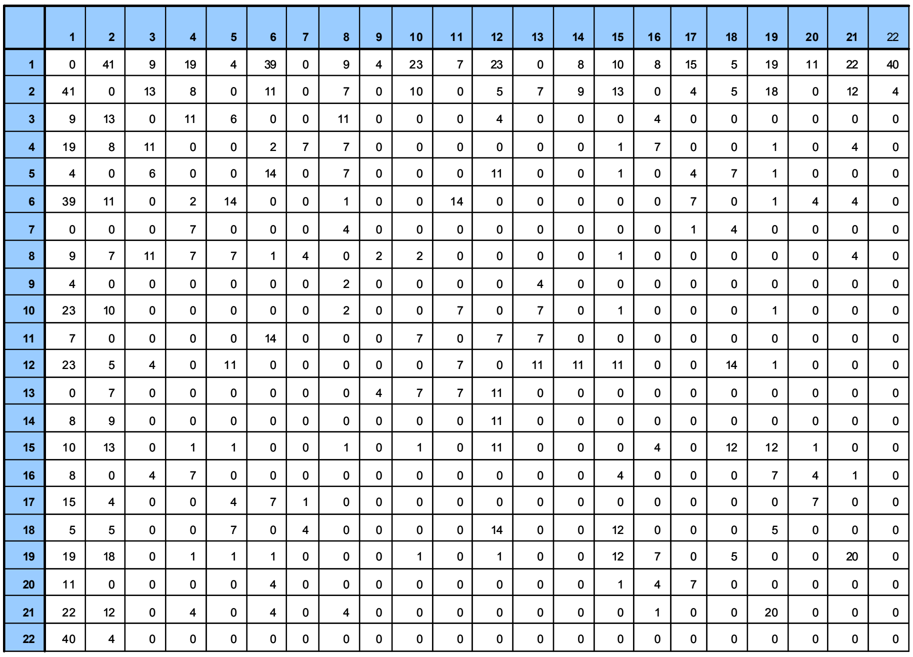


Figure 5: FoM values of the SURFnet network.

Figure 8 shows the number of transponders needed at each node using our two-phase heuristic approach. It can be seen that both the number of transponders and wavelengths required by our heuristic approach are significantly less than those of the sequential approach. In addition, in our result, all the regenerations in the network are handled using add/drop regenerations, i.e., no extra XFPs are needed for 'true' regenerations. The exact ILP formulation of Section 3.1 could not finish within a reasonable time on this network.

5 Conclusions

In this paper, we have studied the off-line survivable impairment-aware routing and wavelength assignment (SIRWA) problem, where given a network and a set of requests, the problem is to assign link-disjoint primary and backup lightpaths for each request such that the total number of regenerators required in the network is minimized. We have shown that this problem is NP-hard, and provided an exact integer linear programming (ILP) formulation for it. However, since the exact ILP does not scale well for even medium sized networks, we have provided a simpler but efficient heuristic approach. We have performed simulations using a given traffic matrix on the SURFnet network. The simulation results have shown that the number of regenerators and wavelengths required by our heuristic approach are significantly less than those of an on-line



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	0	41	9	19	4	39	0	9	4	23	7	23	0	8	10	8	15	5	19	11	22	40
2	41	0	13	8	0	11	0	7	0	10	0	5	7	9	13	0	4	5	18	0	12	4
3	9	13	0	11	6	0	0	11	0	0	0	4	0	0	0	4	0	0	0	0	0	0
4	19	8	11	0	0	2	7	7	0	0	0	0	0	0	1	7	0	0	1	0	4	0
5	4	0	6	0	0	14	0	7	0	0	0	11	0	0	1	0	4	7	1	0	0	0
6	39	11	0	2	14	0	0	1	0	0	14	0	0	0	0	0	7	0	1	4	4	0
7	0	0	0	7	0	0	0	4	0	0	0	0	0	0	0	0	1	4	0	0	0	0
8	9	7	11	7	7	1	4	0	2	2	0	0	0	0	1	0	0	0	0	0	4	0
9	4	0	0	0	0	0	0	2	0	0	0	0	4	0	0	0	0	0	0	0	0	0
10	23	10	0	0	0	0	0	2	0	0	7	0	7	0	1	0	0	0	1	0	0	0
11	7	0	0	0	0	14	0	0	0	7	0	7	7	0	0	0	0	0	0	0	0	0
12	23	5	4	0	11	0	0	0	0	0	7	0	11	11	11	0	0	14	1	0	0	0
13	0	7	0	0	0	0	0	0	4	7	7	11	0	0	0	0	0	0	0	0	0	0
14	8	9	0	0	0	0	0	0	0	0	0	11	0	0	0	0	0	0	0	0	0	0
15	10	13	0	1	1	0	0	1	0	1	0	11	0	0	0	4	0	12	12	1	0	0
16	8	0	4	7	0	0	0	0	0	0	0	0	0	0	4	0	0	0	7	4	1	0
17	15	4	0	0	4	7	1	0	0	0	0	0	0	0	0	0	0	0	0	7	0	0
18	5	5	0	0	7	0	4	0	0	0	0	14	0	0	12	0	0	0	5	0	0	0
19	19	18	0	1	1	1	0	0	0	1	0	1	0	0	12	7	0	5	0	0	20	0
20	11	0	0	0	0	4	0	0	0	0	0	0	0	0	1	4	7	0	0	0	0	0
21	22	12	0	4	0	4	0	4	0	0	0	0	0	0	0	1	0	0	20	0	0	0
22	40	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 6: The traffic matrix in terms of VC4s.

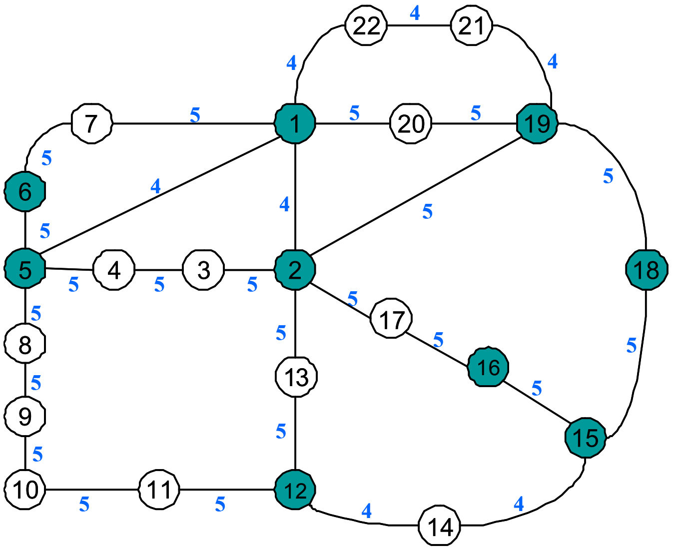
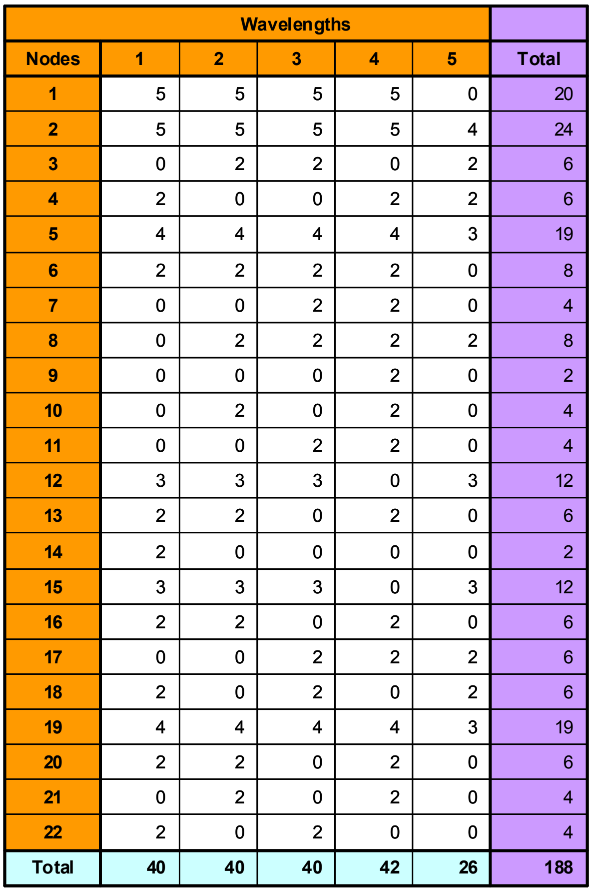


Figure 7: The number of wavelengths needed on each link.



	Wavelengths					
Nodes	**1**	**2**	**3**	**4**	**5**	**Total**
1	5	5	5	5	0	20
2	5	5	5	5	4	24
3	0	2	2	0	2	6
4	2	0	0	2	2	6
5	4	4	4	4	3	19
6	2	2	2	2	0	8
7	0	0	2	2	0	4
8	0	2	2	2	2	8
9	0	0	0	2	0	2
10	0	2	0	2	0	4
11	0	0	2	2	0	4
12	3	3	3	0	3	12
13	2	2	0	2	0	6
14	2	0	0	0	0	2
15	3	3	3	0	3	12
16	2	2	0	2	0	6
17	0	0	2	2	2	6
18	2	0	2	0	2	6
19	4	4	4	4	3	19
20	2	2	0	2	0	6
21	0	2	0	2	0	4
22	2	0	2	0	0	4
Total	**40**	**40**	**40**	**42**	**26**	**188**

Figure 8: The number of filters needed at each node for each wavelength.

sequential approach. Minimizing the number of regenerators will not only lead to a significant reduction in the CAPEX, but also results in a reduced OPEX because of the significant decrease in power consumption and heat dissipation. In addition, the reduced number of wavelengths decreases the operating cost (OPEX) associated with each wavelength.

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