An Efficient Regenerator and Wavelength Assignment Approach for $1+1:1$ and $1:1:1$ Protected Lightpath Services

Gangxiang Shen[1], **Chuanjun Wu**[2], **and Jixiong Dong**[2]

[1]School of Electronic and Information Engineering, Soochow University, Suzhou 215006, China
[2]Huawei Technologies, Shenzhen 518129, China

Abstract— We develop a waveplane-based regenerator placement algorithm for $1+1:1$ and $1:1:1$ protected lightpath services. Results indicate that the algorithm can significantly reduce the number of required regenerators and used wavelengths compared to a simple shortest-path routing algorithm.

1. INTRODUCTION

Signal regeneration is expensive because it requires a pair of transponders. Thus, minimizing signal regeneration is an important topic for the design of optical transport networks. A comprehensive survey on signal regeneration planning has been performed in [1], in which most of the studies are found to focus on planning for unprotected lightpaths. Few are dedicated to the protected services such as $1+1$ or $1:1$ services, not mentioning the services ensured with dual-failure recovery [2] such as $1+1:1$ and $1:1:1$ ones.

Network connections ensured with dual-failure recovery are important for many users that need the connections to support mission-critical services such as financial and military applications. $1+1:1$ and $1:1:1$ protection types provide good survivability for services through establishing three lightpaths between each pair of source and destination nodes. For the $1+1:1$ service, in addition to $1+1$ protection which provides a pair of "working" and "first protection lightpaths," one more protection path (called "the second protection lightpath") is also reserved in case that both the first two paths fail simultaneously. Here colon":" means that the protection resources on the second protection path can be shared. $1:1:1$ protection is similar to $1+1:1$ protection. The only difference is that the protection resources of the first protection lightpath of a $1:1:1$ service is also allowed to be shared (note that protection resources can only be shared in the same categories; the protection resources of a first protection lightpath and a second protection lightpath cannot be shared).

For the first time, we jointly consider the lightpath routing, wavelength assignment, and regenerator placement (RWA-RP) problem for the $1+1:1$ and $1:1:1$ services. We develop an efficient waveplane-based approach that integrates the steps of lightpath routing, wavelength assignment, and regenerator placement to optimize the total numbers of required regenerators and used wavelengths.

2. RELATED CONCEPTS

Waveplane: A *waveplane* is defined as a virtual topology that is copied from a physical topology [3]. A physical topology that supports a certain number (w) of wavelengths on each fiber link can be split into w waveplanes. A node on a waveplane is defined as *wavenode*, and a link on a waveplane is defined as *wavelink*. Each wavelink corresponds to a wavelength and the wavelength indexes of all the wavelinks on a common waveplane are the same.

Regenerator placement threshold: To decide where to place necessary regenerators, we introduce an important parameter called *regenerator placement threshold*. Whenever the signal quality of a lightpath is below a predefined threshold, we place a regenerator at the nearest previous node. We may estimate the signal quality based on an accurate analytical model or a simple criterion such as physical distance. We can also use some criteria lying between the above two extremes to consider a rough optical signal-to-noise ratio (OSNR) (which is simply calculated based on the accumulated amplifier noise), or even simpler, the number of traversed optical transmission section (OTS) hops (as each OTS hop corresponds to an amplification span). Without losing generality, we use the number of traversed OTS hops as a decision criterion for regenerator placement in this paper.

3. CONDITIONS OF $1+1:1$ AND $1:1:1$ PROTECTION RESOURCE SHARING

For each $1+1:1$ service, the first protection lightpath is assigned with dedicated protection resources, while the second protection lightpath is allowed to share protection resources in the same category subject to a certain link-disjoint condition. In this paper, protection resources include *protection wavelengths* and *regenerators* on protection lightpaths. We take Fig. 1 as an example to explain the condition of protection resource sharing on the second protection lightpath. Assume there are two $1+1:1$ services with each including a working path (represented as Wi, where i is service index) and two protection paths (represented as Pij, where j is protection path index). The protection resources on the second protection paths of the two services can be shared only if the condition $\overline{(W1 \otimes W2) \cdot (P11 \otimes P21)} \cdot \overline{(W1 \otimes P21) \cdot (P11 \otimes W2)}$ is satisfied, where the symbol $\otimes$ denotes two paths are joint (or overlap) on some link(s) and $\bar{X}$ represents a "NOT" operation of X. Thus, $W1 \otimes W2$ means that working paths *W1* and *W2* are joint, and $(W1 \otimes W2) \cdot (P11 \otimes P21)$ means that the working and first protection paths of the two services are *pairwise joint*, and finally $\overline{(W1 \otimes W2) \cdot (P11 \otimes P21)} \cdot \overline{(W1 \otimes P21) \cdot (P11 \otimes W2)}$ implies that the working and first protection paths of the two services are not pairwise joint in any way. As long as the two services are not pairwise joint in their working and first protection routes, any dual-failure would not trigger simultaneous restorations on their second protection lightpaths. Rather, at most one second protection lightpath would be triggered to use sharable protection resources, which therefore ensures 100% dual-failure recovery.

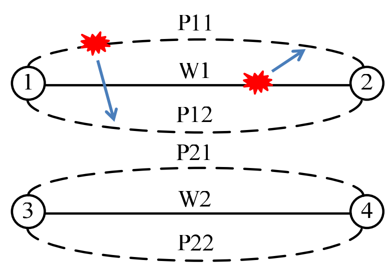

Figure 1: Conditions of protection resource sharing among protection routes.

For the $1:1:1$ service, the protection resources on the first and second protection lightpaths can both be shared among the same categories. The condition of protection resources sharing on the second protection lightpath is the same as that of the $1+1:1$ service, while the condition of protection resources sharing on the first protection lightpath is $\overline{(W1 \otimes W2) \cdot (P12 \otimes P22)} \cdot \overline{(W1 \otimes P22) \cdot (P12 \otimes W2)}$ in the context of Fig. 1.

3.1. Waveplane-based Approach for Wavelength Assignment and Regenerator Placement

We develop a new approach that integrates the steps of lightpath routing, wavelength assignment, and regenerator placement to efficiently establish $1+1:1$ and $1:1:1$ lightpath services. We make such integration possible with the concept of *waveplane*. Fig. 2 shows the flowchart of the approach. We employ a three-step strategy to first establish a working lightpath, then the first protection lightpath, and finally the second protection lightpath. Only if all the three lightpaths are successfully established, can the service be considered successfully established. Take a $1+1:1$ service as an example. We first search for a working route; if succeeded, we then remove all the wavelinks whose physical links traversed by the found working route from the waveplane topologies (i.e., waveplane list (WL)), and then based on the updated topologies, search for the first protection route; if succeeded, then we remove all the wavelinks from the WL topology whose physical links traversed by the found first protection route, and then search for the second protection route. When searching for the second protection route, protection resource sharing (including wavelengths and regenerators) is allowed as long as the sharing conditione laborated in Section 3 is met. If we succeed in all the three route-searching steps, wavelengths and regenerators are assigned to the three lightpaths. In particular,when establishing the second protection lightpath, we should maximally share protection resources.

For a $1:1:1$ service, both the first and second protection lightpaths are allowed to share protection resources. For resource sharing of the second protection lightpath, we follow the same

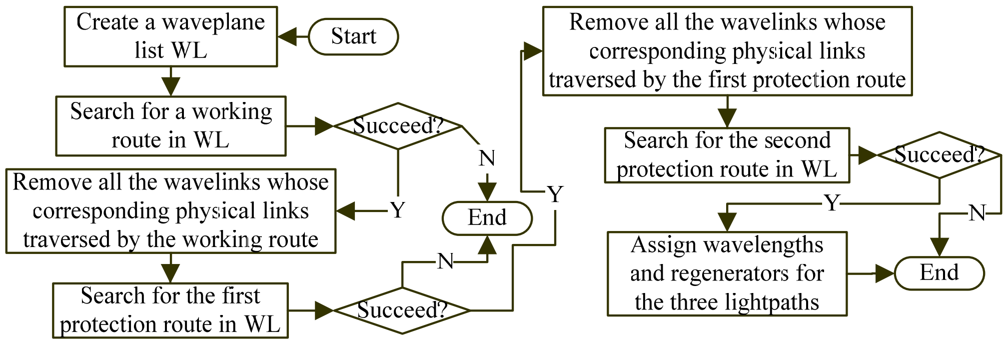

Figure 2: Flowchart of $1+1:1/1:1:1$ service establishment.

steps as in establishing a $1+1:1$ service. For resource sharing of the first protection lightpath, we need to step back after establishing the second protection lightpath; that is, after establishing the service in the way of $1+1:1$, which has ensured maximal sharing of protection resources on the second protection lightpath, without changing the routes of the service (so as not to destroy the resource sharing condition of the second protection lightpath), we release all the used network resources by the first protection lightpath, and reestablish it by allowing its protection resources to be maximally shared with other first protection lightpaths subject to the same sharing condition as for the second protection lightpath.

To cater to different requirements or situations,we can further extend the algorithm in Fig. 2 to incorporate new constraints. For instance, due to the *color* constraint of add/drop port in a ROADM, we may require two or all of the lightpaths of a service to use an identical wavelength. If two lightpaths are required to use an identical wavelength, the algorithm needs to search a route pair for themon a common waveplane. Likewise, if all the three lightpaths are required to use an identical wavelength, three disjoint routes should be searched on the same waveplane.

4. SIMULATIONS AND PERFORMANCE ANALYSES

To evaluate the efficiency of the proposed waveplane-based algorithm, we ran simulations for seven test networks whose topologic information and lightpath demands are shown in Table 1. The numbers of network nodes and links are listed in the second and third columns, respectively. The fourth column is the total number of lightpath demand units required between node pairs. The maximal number of wavelengths on each fiber link is assumed to be 80 in all the test networks. The threshold number of OTS hops for regenerator placement is assumed to be ten for all the test cases. In addition, because the performance of the proposed algorithm is closely related to the establishment sequence of lightpath demand units, we implemented a multi-iteration process [4] to find the minimum number of required regenerators. Specifically, we shuffled the lightpath demand units and generated 50 random demand unit lists. For each of the lists, we ran the proposed waveplane-based algorithm shown in Fig. 2 to find the total numbers of required regenerators and used wavelengths. Finally, we compare the results of the 50 iterations to choose a design that requires the smallest number of regenerators and wavelengths as our final solution.

Table 1: Test networks.

Networks	**Nodes**	**Links**	**Optical channel units**
1	20	40	100
2	55	90	174
3	30	55	200
4	35	70	256
5	40	70	233
6	45	90	90
7	50	100	220

Table 2: Numbers of required regenerators and used wavelengths (x, y, z: regen #, wave #, unserved lightpath unit #).

Networks	**1 + 1 : 1**		**1 : 1 : 1**	
	Shortest	**Waveplane**	**Shortest**	**Waveplane**
1	15, 76, 0	9, 49, 0	9, 57, 0	0, 30, 0
2	394, 80, 30	379, 80, 8	296, 80, 18	317, 78, 4
3	103, 80, 35	6, 80, 37	11, 80, 22	2, 80, 27
4	128, 80, 42	7, 66, 42	10, 76, 42	3, 61, 42
5	98, 80, 79	2, 80, 78	5, 80, 78	5, 80, 78
6	144, 80, 74	42, 80, 60	64, 80, 61	31, 80, 67
7	192, 80, 30	37, 80, 35	46, 80, 30	30, 80, 35

To evaluate the efficiency of the proposed algorithm, we compare the results of the waveplane-based algorithm ("Waveplane" in short) and the algorithm simply based on shortest physical routing ("Shortest" in short) in terms of regenerator and wavelength numbers. The algorithm based on shortest physical routing finds the working, first, and second protection paths simply based on the physical topology (not considering the waveplane topology). Table 2 shows the results of the two schemes for two different service types. Each triple (x, y, z) means that x regenerators and y (never greater than 80) waveplanes are required to establish all (except z units) of the services. For the $1+1:1$ service, the second protection lightpath is required to use the same wavelength as that of either working or the first protection lightpath, while for the $1:1:1$ service, all the three lightpaths are allowed to use different wavelengths.

We can see that the waveplane-based algorithm requires much smaller numbers of regenerators than those of the "shortest" algorithm. Moreover, it is found that the waveplane-based algorithm can successfully serve more traffic demands (under the constraint of 80 wavelengths on each fiber link) than the "shortest" algorithm (please compare value z in each triple between the two algorithms). Also, comparing the numbers of used waveplanes (wavelengths), we see that the proposed waveplane-based algorithm has smaller numbers of used waveplanes. For example, for the $1+1:1$ service in test case 4, the proposed algorithm requires only 7 regenerators versus 128 regenerators by the "shortest" algorithm, and uses only 66 wavelengths versus 80 wavelengths by the "shortest" algorithm. For the $1:1:1$ service, the proposed algorithm requires only 3 regenerators versus 10 regenerators by the "shortest" algorithm, and uses only 61 wavelengths versus 76 wavelengths by the "shortest" algorithm. The reason of better performance of the proposed algorithm is as follows: Under the waveplane-based strategy, the wavelength-continuity constraint is always ensured if a route is found on a certain waveplane; however, for the algorithm based on the shortest physical routes, in addition to placing regenerators, we have to consider wavelength collision and place wavelength converters if required. Given a limited number of wavelengths on each fiber link, more wavelength resources are consumed with the increase of lightpath demand, which leads to more wavelength collisions and therefore needs more wavelength converters (regenerators). Finally, comparing the results of the $1+1:1$ and $1:1:1$ services, because the latter allows the first protection lightpath to also share protection resources, we can see that much fewer regenerators and used wavelengths are required to serve all the demand units.

5. CONCLUSION

We proposed a waveplane-based lightpath routing, wavelength assignment, and regenerator placement algorithm for the $1+1:1$ and $1:1:1$ lightpath services. By comparing the numbers of required regenerators, used wavelengths, and unserved lightpath demand units, we show that the proposed waveplane-based algorithm is efficient to significantly outperform the algorithms imply based on shortest physical routes. In addition, allowing the first protection lightpath to also share protection resources in the $1:1:1$ protection mode can further improve protection resource utilization.

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