Regenerator Predeployment in CN-ROADM Networks With Shared Mesh Restoration [Invited]

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***Abstract*—We have studied the resource requirements and capacity of a continental-scale backbone network supporting shared mesh restoration (SMR) and service velocity (a rapid provisioning method). Network simulations of wavelength routing by colorless, nondirectional reconfigurable optical add/drop multiplexers (CN-ROADMs) show that performance depends on the routing scheme (minimum distance or minimum regenerator) and on whether or not regeneration is limited to a selected subset of sites. Comparing SMR with dedicated protection, we find that up to 27% fewer regenerators are required for the shared mesh case, while capacity is increased by approximately 40%. Regenerator site concentration and minimum-regenerator routing provide the best results.**

***Index Terms*—Optical fiber communications; Optical fiber networks; reconfigurable optical add/drop multiplexer (ROADM); Shared mesh restoration; Wavelength-routed networks.**

I. Introduction

The deployment of reconfigurable optical add/drop multiplexers (ROADMs) has reduced the operational cost of optical networks by enabling remote configuration of optical bypass for wavelength channels [1]. Further improvement in network operation efficiency can be achieved by deploying colorless and nondirectional ROADMs (CN-ROADMs), which enable any transponder or regenerator to serve any wavelength on any fiber route [1–6]. The introduction of CN-ROADMs in backbone and metro networks can enable shared mesh restoration (SMR) at the optical layer [1–3]. The flexible interconnection between add/drop ports and internode fibers of CN-ROADMs enables efficient predeployment of transponders and regenerators to support the service velocity (SV) concept of rapid service provisioning, where new lightpaths are remotely provisioned without requiring visits (i.e., truck rolls) and manual operations (e.g., changing fiber jumpers) at any intermediate nodes [7]. CN-ROADMs also support recovery from network failures without the need for manual intervention. In particular, the predeployed regenerators at intermediate nodes can be shared across multiple backup paths to maximize the efficiency of SMR in CN-ROADM-based SV networks.

In [7], we proposed SV algorithms to determine the timing and location of regenerator predeployments for rapid provisioning of unprotected connections in a continental-scale backbone network in which all nodes are eligible to be regeneration sites. We introduced a constraint-aware SV algorithm that virtually eliminated negative effects of intranode wavelength contention in CN-ROADMs, achieving resource utilization nearly identical to that of contention-free ROADMs. In [8], we showed that by concentrating regeneration sites to a limited subset, the number of idle regenerators needed to support SV was reduced by 60%.

In this paper, we study the problem of regenerator predeployment in a CN-ROADM network *with SMR* and compare this to one with dedicated protection paths. We evaluate the costs and benefits of SMR with regenerator site concentration by conducting Monte Carlo simulations of quasi-static traffic growth in a backbone network. We propose a heuristic algorithm for selection of concentrated regeneration sites for both minimum-distance (MD) routing and minimum-regenerator (MR) routing schemes. We analyze the latency and regenerator statistics associated with working and backup paths for the network with selected regeneration sites. We also compare the regenerator counts, working and reserved wavelength-kms, and sharing of regenerators along backup paths, for cases with and without regenerator site concentration. A preliminary version of this work was published in [9].

This paper is organized as follows: Section II describes SMR in CN-ROADM networks, including the routing methods used. Section III explains the heuristic algorithm for regeneration site concentration. Section IV presents the

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network model and simulation methods. Section V discusses the design results including concentrated regeneration sites, latency and regeneration statistics, and network simulation results. Section VI is the conclusion of this paper.

II. Shared Mesh Restoration in CN-ROADM Networks and Routing Schemes

The optical network consists of CN-ROADM nodes in which the end-point transponders are routed through a client-side cross connect, while the regenerators are directly connected to two distinct add/drop banks to allow same-wavelength regeneration as shown in Fig. 1 [7]. Wavelength recoloring during regeneration is not considered for the following reasons. First, wavelength continuity is preferred today for simplicity of network management. Second, we did not see significant gain in performance by allowing regenerators to recolor wavelength in a previous study [7]. In this network, each protected connection is assigned two paths—a working path and a backup path that is both link and node disjoint from the working path. Upon failure of the working path, the network switches to the backup path. In SMR, the CN-ROADM nodes enable sharing of wavelengths and regenerators among backup paths whose working paths do not fail simultaneously. As we show in this paper, this sharing in SMR provides substantial improvements in resource utilization compared to dedicated $(1 + 1)$ protection.

We study two schemes for routing of protected connections. In the first, MD routing, a single pair of physically minimum distance working and diverse backup paths is selected for each source–destination (s-d) pair. For the second scheme, MR routing, all possible pairs of working and backup diverse paths that use the minimum combined number of regenerators are considered when site concentration is performed. After site concentration is complete, reachable MR routes are selected for each s-d pair. The MD routing option ensures minimum latency on the working path, an important consideration for some services, while the MR routing provides the lowest hardware (regenerator) cost.

In the case of MD routing, routes for some s-d pairs may require excess regenerators after site concentration (as discussed below in Section V). On the other hand, no excess regenerators are allowed in the MR routing scheme since the MR constraint is always satisfied.

Once a regeneration site set and associated working/backup paths for each s-d pair have been selected, they are used in an SV simulation [7] to estimate the timing and allocation of regenerator predeployment at each regeneration site, as a function of traffic growth.

III. Regeneration Site Concentration Algorithm

The regeneration site concentration problem is known to be NP-hard [10]. In a previous study [10], a heuristic algorithm was proposed to identify the minimum subset of nodes in a network as concentrated regeneration sites for unprotected traffic. This heuristic algorithm was shown to achieve a lower bound on the size of optimal concentrated regeneration sites [10]. In this study, this heuristic algorithm is extended to identify the concentrated regeneration sites in protected optical ROADM networks for each of the routing schemes, MD and MR routing. The flow chart of the heuristic algorithm is presented in Fig. 2.

The heuristic algorithm starts with a set A of diverse working and backup path pairs satisfying a routing scheme for all s-d pairs in the network. Under MD routing, set A includes a single MD working path and its associated (link and node diverse) backup path for each s-d pair. However, in MR routing, one or more pairs of working and backup paths with a minimum number of combined regenerators are included in set A for each s-d pair, which helps to reduce the total number of regeneration sites [11]. For example,

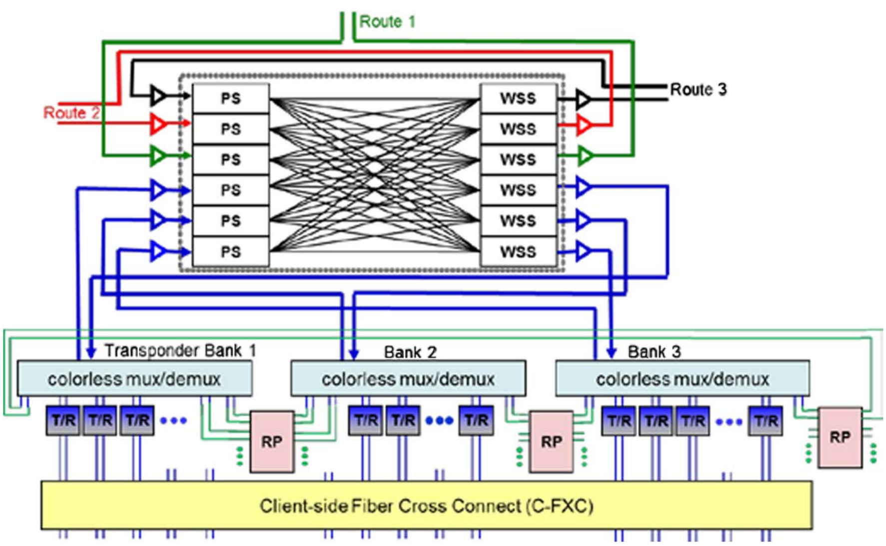

Fig. 1. CN-ROADM architecture with regenerator pools (RPs).

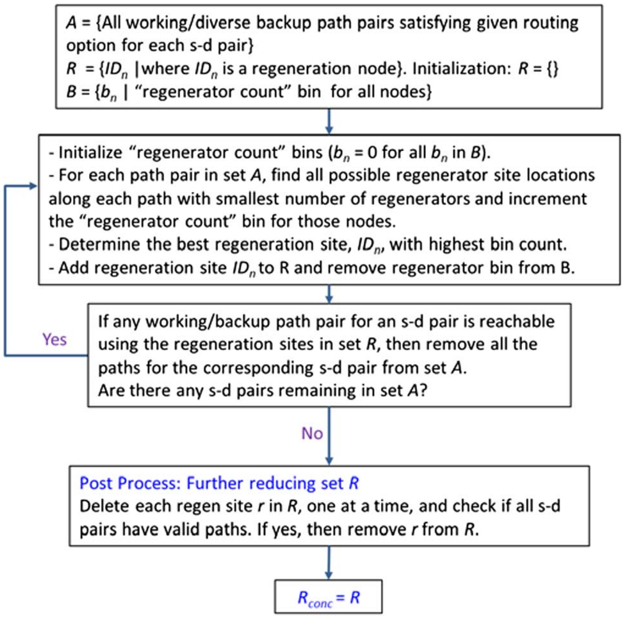

Fig. 2. Flow chart for regeneration site concentration.

let us assume #WR and #BR represent the number of regenerators needed along working and backup paths, respectively. If the minimum number of combined regenerators for a given s-d pair is 3, only the following combinations are included in set A: {WR = 1, BR = 2} or {WR = 0, BR = 3}. Here, we assume that the path requiring a smaller number of regenerators is assigned as a working path. If the working path and the backup path require the same number of regenerators, the shorter path is assigned as a working path.

Two additional sets, namely, set B containing the "regenerator count" bins of nodes in the network and set R representing the regeneration site candidates, are defined. In the beginning, the size of set B is equal to number of nodes in the network, while set R is initialized to the null set.

Next all the bins in B are initialized to zero. For each path in set A, all possible combinations of regeneration site locations along each path with the smallest number of regenerators are found and the regenerator count bins in B are incremented for each corresponding intermediate node. The node with the highest count bin is added to regeneration site set R. Then, the "regenerator count" bin of the added node is removed from set B.

Subsequently, the original set A of paths is filtered by removing all working/backup path pairs for each s-d pair if that s-d pair is reachable using regeneration sites in set R. The previous steps are repeated until all s-d pairs have at least one reachable working and diverse backup path pair.

Finally a postprocessing step is performed to see whether the set R can be further reduced by cycling through each candidate regeneration site in R and checking whether reachability for all s-d pairs is maintained when the site is removed from set R. For example, a new subset $R^* = R - \{r\}$ is created by removing a regeneration site r that belongs to R. If at least one working and diverse backup path pair for each s-d pair is reachable with R^*, then the set R is redefined as R^*. This process is repeated for all regeneration sites in R. At the end of this step, the set R represents the set of concentrated regeneration sites named as R_{conc}.

Due to the heuristic nature of the algorithm, the above procedure can be repeated multiple times by initializing the candidate regeneration sites R with a random subset of R_{conc}, instead of a null set. This may help in further minimizing the regeneration sites.

In the case of MD routing, there is only a single working and diverse backup path pair for each s-d pair that is reachable with the set R_{conc}, while there can still be one or more choices of path pairs for some s-d pairs in the case of MR routing. To select a single path pair from these multiple choices in the case of MR routing, the following order is considered: 1) a pair with minimum regenerators in the working path is selected; 2) if needed, then a pair with the shortest working path is selected; and 3) a pair with the shortest backup path is selected. The regeneration site set and the selected working/backup paths for each s-d pair are used in the SV simulation [7].

IV. Network Model and Simulation Method

In this simulation, we have used the CORONET CONUS network topology with 75 nodes and 99 links as shown in Fig. 3 [12]. The transmission systems are assumed to support 88 wavelengths per fiber link with an all-optical reach of 2000 km. The traffic model used in the SV simulation is quasi-static, where the demands arrive randomly but persist indefinitely. We adopted a nonuniform traffic matrix in which the population of each city determines its probability to be used as a source or destination. In addition, the simulation includes the capability to overbuild individual fiber links when they exceed 60% wavelength fill, up to a maximum of three fiber pairs per link [7,8]. Fiber link overbuild improves the number of demands that can be served before

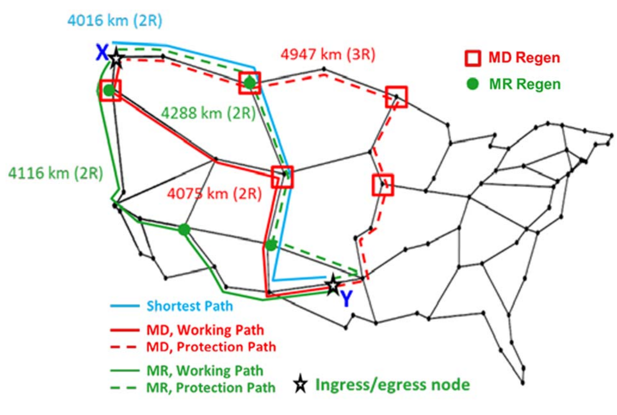

Fig. 3. CORONET network topology and routing examples (squares, regeneration sites for MD; circles, regeneration sites for MR).

network blocking (e.g., blocking due to lack of continuous wavelength along the fiber links of a path) occurs. The number of add/drop banks at each node is set equal to the number of fiber link pairs to support up to 100% add/drop capacity. Also, for each link overbuild, an add/drop bank is added at the two end nodes of the link. In our simulations, the total number of transponders preprovisioned at each node is proportional to the population of the city and equally distributed among the add/drop banks.

We initialized the network by predeploying two regenerators at each regeneration site at the start of SV simulation. For each new protected demand received, the regenerators are put in service along the working path and are reserved along the backup path to be used after a link failure. After the protected demand is routed, a constraint-aware SV algorithm checks to see whether more regenerators need to be predeployed to satisfy future demands and also identifies the regeneration sites for installation [7]. If needed, regenerators are added in groups of at least four at each identified site to minimize truck rolls. The constraint-aware SV algorithm takes into consideration the intranode wavelength contention in each CN-ROADM node while allocating regenerators and assigning wavelengths [7].

The network is designed to support single link failures for SMR. The network resources, including wavelengths and regenerators, are allowed to be shared among backup paths if the working paths do not share any links. The placement of regenerators at regeneration sites along a working path is determined by allowing the optical signal to travel as far as possible before being regenerated. The regenerators in each backup path are flexibly placed to maximize sharing of regenerators but without increasing the number of regenerators.

For SMR with SV simulation, we considered four scenarios: 1) MD routing with all nodes as regeneration sites (MD-All), 2) MR routing with all nodes as regeneration sites (MR-All), 3) MD routing with concentrated regeneration sites (MD-Conc), and 4) MR routing with concentrated regeneration sites (MR-Conc). We also simulated the case of dedicated $(1+1)$ protection as a baseline reference for comparison with SMR.

Simulations are performed over 100 runs of 2000 demands and averaged results are presented, where each demand set is generated randomly based on our population-weighted traffic matrix. The simulation counts the number of regenerators installed in the network, the number of those in service for working/backup, and the number of wavelengths assigned for working/backup in each link.

V. Simulation Results

A. Concentrated Regeneration Sites

In this subsection, we present the results of the heuristic algorithm for concentrated regeneration sites. When generating the paths in set A (Fig. 2) for MD routing, we found 167 s-d pairs (out of 2775) in the CONUS topology, where the shortest path could not be selected as the working path since it did not have a link and node diverse backup path. For these s-d pairs, the working path is selected to be the physically minimum distance working path that allowed a link and node diverse backup path.

Routing examples for MD and MR schemes are shown in Fig. 3. The blue line between nodes X and Y in Fig. 3 shows the shortest path, which is 4016 km, but it does not have a link and node diverse backup path. So for MD routing, the working path with a distance of 4075 km and its diverse backup path with a distance of 4947 km are selected. MD routing ensures the minimum latency in the working path with a diverse backup path. In MR routing, a routing path with 4116 km is chosen as a working path, which is longer than the working path found in MD routing. However, the backup path of MR routing is 4288 km, which is shorter than the backup path found in MD routing. If we compare the number of combined regenerators, five regenerators are required in MD routing, while only four regenerators are required in MR routing. The MR routing constraint forced a slightly longer working path but required fewer regenerators compared to MD routing. MR routing ensures minimum combined number of regenerators in working and backup path pairs with concentrated regeneration sites, R_{conc}. It is found that 424 s-d pairs have a longer working path with MR routing than MD routing.

Using the heuristic algorithm, we found 21 and 38 concentrated regeneration sites for MD and MR routing, respectively, as shown in the Fig. 4. The higher number of concentrated regeneration sites for MR, compared to MD, is due to the stronger constraint of minimal regenerator count applied to all working and backup path pairs.

B. Latency and Regenerator Statistics for Working/Backup Paths

We analyzed the statistics of latency and regenerator count associated with the working/backup paths for both routing schemes. Unlike the SV simulation results

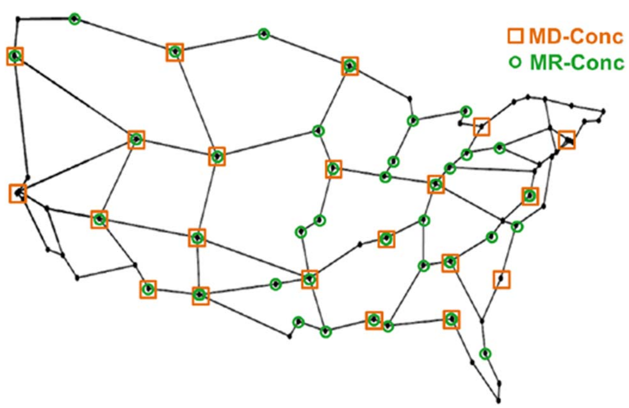

Fig. 4. Concentrated regeneration sites (squares, regeneration sites for MD-Conc; circles, regeneration sites for MR-Conc, and routing examples).

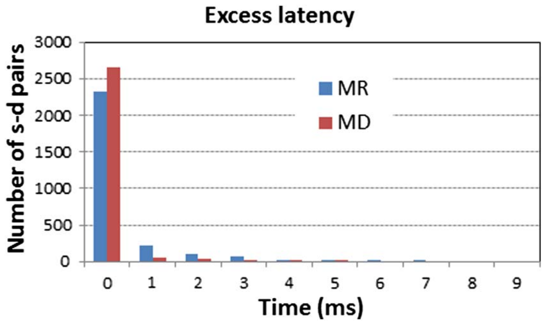

Fig. 5. Histogram of excess latency in working paths.

(presented in Subsection V.C), the statistics presented in this section consider just one datum for each s-d pair.

In this study, we only considered the transmission delay along the fiber links as the latency of the working/backup path. The typical contribution to latency from regenerators (~μs) is negligible compared to transmission delay (~ms) [13]. We assumed the use of digital coherent receivers with uncompensated links, so no latency is contributed by dispersion compensating fiber (DCF) [14,15]. The excess latency for each s-d pair is calculated as the difference in latency between the selected working path and the shortest path without protection. Figure 5 shows the histogram of excess latency of the working path for MD/MR routing schemes. As expected, the excess latency in the working path of MR routing can be larger than that of MD routing, as illustrated in Fig. 3. Indeed, the average excess latency is about 0.32 ms in MR routing, but it is only 0.08 ms in MD routing. The percentage of s-d pairs with excess latency <1 ms is about 97% in MD routing, while it is about 89% in MR routing. For some s-d pairs, the constraint of a diverse backup path can cause a significant increase in the latency of the working path. The maximum excess latency in the working path is about 7.1 ms in MR routing and about 5 ms in MD routing.

We also calculated the latency imbalance, which is the difference in latency between the working and the backup paths for a given s-d pair. Figure 6 shows the histogram of latency imbalance for MD/MR routing schemes. The average latency imbalance is 5.65 and 6.8 ms for MR and MD routing, respectively. The constraint of MR routing to minimize the number of *combined* regenerators results in

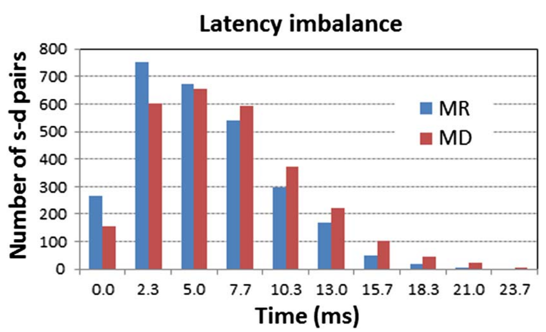

Fig. 6. Histogram of latency imbalance.

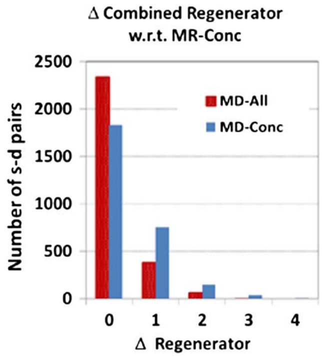

Fig. 7. Histogram of the additional number of combined regenerators in MD-All/MD-Conc routing with respect to MR-Conc routing.

smaller latency imbalance than that of the MD routing scheme. In both routing schemes, the latency imbalance can go above 20 ms due to the constraint of the link-and-node diverse backup path.

Figure 7 shows the histogram of the extra regenerators for working/backup path pairs in MD-All and MD-Conc routing compared to MR-Conc routing. MR-All is not shown in the figure since there is no difference between MR-Conc and MR-All in terms of regenerators required for given s-d working/backup paths. Out of 2775 total s-d pairs, there are 942 pairs that have higher combined regenerators for MD-Conc routing than for MR-Conc routing, and 440 pairs that have higher combined regenerators for MD-All routing. On average, 0.18 and 0.42 extra regenerators per s-d pair are used in MD-All and MD-Conc, respectively, compared to MR-Conc. The maximum number of extra regenerators is 3 for MD-All and 4 for MD-Conc. This shows that with site concentration, MD-Conc requires extra regenerators to guarantee optical reachability.

Whereas Fig. 7 shows the extra regenerators for the combined working + backup path pair, Fig. 8 shows the histogram of the extra regenerators in working and backup paths separately. Figure 8(a) tabulates MD-All routing, while Fig. 8(b) shows MD-Conc routing compared to MR-Conc routing. In general, the backup paths have higher contributions of extra regenerators. As shown in the routing examples of Fig. 3, MD routing may select a much

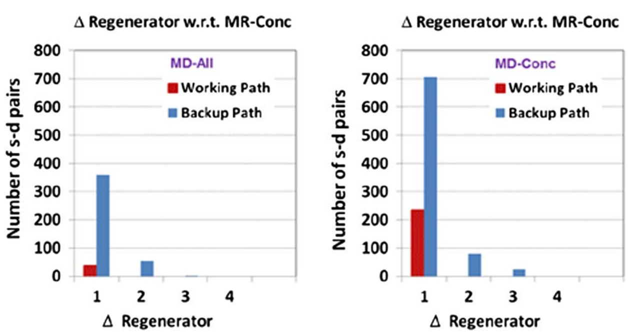

Fig. 8. Histogram of the additional number of regenerators in working/backup paths for (a) MD-All routing and (b) MD-Conc routing with respect to MR-Conc routing.

longer backup path than MR. (This is also observed as latency imbalance in Fig. 6.) More than 400 backup paths in MD-All require extra regenerators with respect to MR-Conc, as shown in Fig. 8(a), while only about 40 working paths require extra regenerators. However, with MD-Conc, these numbers increase to 235 and 810 in working and backup paths, respectively. This is because there is a higher chance of excess regenerators due to longer routing distances in MD-Conc.

C. Service Velocity Simulation Results

We performed SV simulations to estimate the timing and allocation of regenerators to be predeployed at each regeneration site with traffic growth. Figure 9 shows the counts of total and idle regenerators for the four scenarios as a function of demand growth before any blocking. We also plotted the total regenerators for dedicated protection with MD routing. As can be seen, SMR supports 650/700 demands, for MD/MR routings, respectively, before network blocking (due to wavelength exhaust) occurs, while dedicated protection is limited to 500 demands. Thus, SMR achieves 30%/40% higher network capacity. MR routing supports more demands than MD routing because the routes are spread across the network with better load balancing among the links. For example, MR routing takes longer working paths for 424 s-d pairs with respect to MD routing, which helps to avoid busy links for some traffic. We also note that the total number of regenerators is consistently lower when regenerator site concentration is used. This is due to the improved sharing of regenerators as well as fewer numbers of idle regenerators at the concentrated regeneration sites. The numbers of idle regenerators for MD-Conc, MR Conc, and MR-All (or MD-All) are 21, 38, and ~75, respectively. The plots of total regenerators for MR-Conc and MD-Conc cross over around 300 demands. For below ~300 demands, MR-Conc has a larger total number of regenerators because of its higher number of idle regenerators. However, for beyond ~300 demands, MD-Conc has a larger total number of regenerators because MD-Conc uses more regenerators per demand than MR-Conc.

To quantify the sharing of backup resources, we plotted the number of backup regenerators per demand for all scenarios in Fig. 10. In the case of dedicated protection

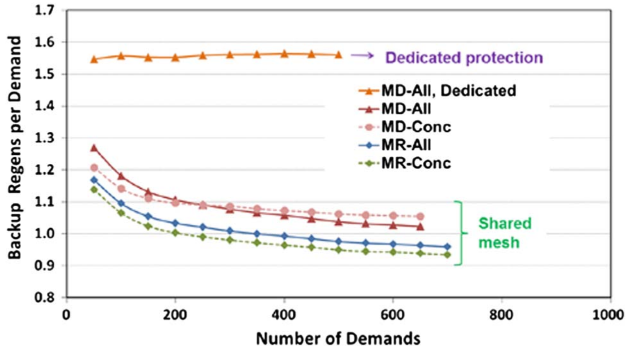

Fig. 10. Backup regenerators per demand versus traffic demand.

(no sharing of regenerators), the plot is almost flat at ~1.55 backup regenerators for each demand. On the other hand, the number of backup regenerators per demand for SMR decreases with number of demands, falling below 1 for the best options.

Figure 11 shows the wavelength-km of working paths and the total (= working + reserved) wavelength-km versus traffic demand. Wavelength-km is a useful way to estimate the allocated cost of resources, such as line amplifiers and optical fiber, which are shared among multiple demands. Dedicated protection consumes the largest total wavelength-km since the wavelengths are not shared among the backup paths. Remarkably, the MR-Conc case shows lower total wavelength-km than MD-Conc, despite the choice of the shortest possible working path for the latter. This occurs because some of the diverse backup paths take longer routes with MD routing as explained in Figs. 3 and 6.

To summarize the economic benefits of SMR with regeneration site concentration, we show the breakdown of the number of regenerators (idle, working, backup) at 500 demands for MD and MR routing schemes in Fig. 12. The savings in total regenerators for SMR compared to dedicated protection is in the range of ~18%–27%. Within the SMR cases, the savings due to regeneration site concentration are around ~18%–9%, principally from savings in idle regenerators. Comparing MD cases, the numbers of working and backup regenerators increase slightly (by ~2%–5%) when site concentration is used, because some paths need more regenerators. In the case of MR routing, all scenarios use the same number of working regenerators. There is a

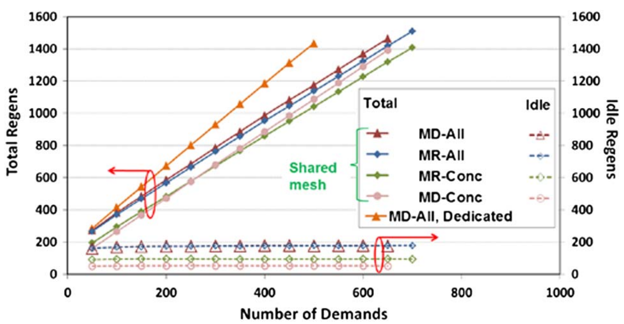

Fig. 9. Counts of total and idle regenerators versus traffic demand.

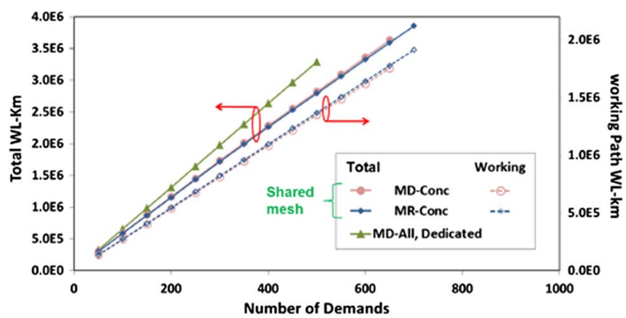

Fig. 11. Wavelength-km versus traffic demand.

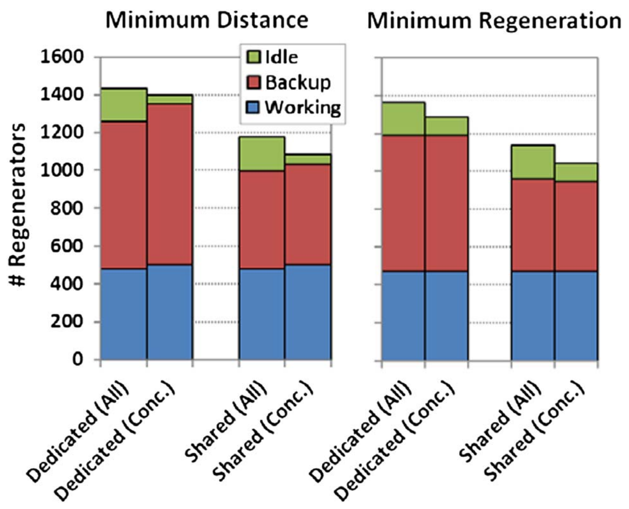

Fig. 12. Number of regenerators at 500 demands.

slight decrease of ~3% in the number of backup regenerators for MR-Conc compared to MR-All due to improved sharing. The total regenerator count at 500 demands is minimized by MR-Conc with SMR.

VI. Conclusion

Through simulation of quasi-static traffic growth, we have studied the capacity and resource requirements of a continental-scale backbone network of CN-ROADMs supporting SMR and SV. Our results show that shared restoration yields significantly better network capacity than dedicated protection, while requiring fewer regenerators and consuming fewer wavelength-kms.

We have further compared several options for lightpath routing and for concentration of regeneration sites. We presented a heuristic algorithm for regenerator site selection including protection paths and applied it to both MD and MR routing schemes. We find that MD routing has larger latency imbalance. Furthermore, it requires extra regenerators with concentrated regeneration sites.

We find that MR routing with site concentration offers the lowest total regenerator count and wavelength-km usage, as well as the highest network capacity. We conclude that MR routing with site concentration, implemented in a CN-ROADM network, offers an attractive solution for future services requiring restoration.

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