Optical Protection with Pre-configured Backup Paths and Limited Backup Resource Sharing

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***Abstract*—In this paper, we consider provisioning protection in WDM optical networks with pre-configured backup paths. In the traditional protection approach, backup resources are not shared among pre-configured backup paths, and thus resources are not utilized efficiently. We propose a protection approach with the use of a switch architecture, which allows limited sharing of backup resources among pre-configured backup paths (referred to as *pre-configured backup protection with limited sharing (PBPLS)*). The architecture uses switching components with a flexible feature of splitting optical power on need basis in addition to directing the power towards one output port only. Further, configuration can be done which connects two (or more) input ports to the same output port at the same time. These features allow sharing backup resources while provisioning pre-configured backup paths. This approach can be adopted in networks in small geographical area such as metro networks since the power splitting feature is used. While sharing backup resources in this approach, we consider power loss particularly due to potential repeated power splitting. Amplifiers can be used, at additional cost, to compensate the power loss. Instead, we adopt an approach of limiting the number of power splitting to small values to reduce the power loss. Constraining the number of power splitting limits the degree of backup sharing. Through simulation experiments in a single class and multi-class traffic scenarios, we demonstrate that, even with the small number of power splitting such as one or two, significant improvement in blocking performance can be achieved.**

***Keywords*-optical networks; wavelength-division-multiplexing; survivability;**

I. INTRODUCTION

Survivability or fault tolerance is an important requirement in wavelength-division-multiplexing (WDM) optical networks. Among the several survivability approaches, provisioning optical layer protection with pre-configured backup paths such as optical dedicated protection (or 1:1 protection) is preferred for traffic which require short recovery time. In this approach, a backup path is configured at the time when the connection is established. In the event of a component failure on a primary path, this approach requires no further switch configuration to set up the backup path. This protection approach has been investigated in research works under several scenarios such as path, segment, and link based protection, protection with traffic grooming, differentiated survivability services, and protection with multi-line-rate consideration. In [1], two 1:1 path protection methods, static and dynamic have been investigated. The static method provides fixed primary and backup paths, and the dynamic method allows rearrangement of backup paths. The work in [2] investigates capacity utilization and protection switching time for a dedicated path protection scheme and protection approaches which share backup resources. Dedicated protection for traffic grooming of sub-lambda traffic using a generic grooming-node architecture has been investigated in [3]. In [4], a comparison of schemes which include path and segment based protection for differentiated availability-guaranteed services is given. The recent work in [5] investigates dedicated protection approaches considering various transmission rates of wavelength channels.

A major drawback in provisioning pre-configured backup paths using the traditional protection approach is its inefficient resource usage. Unlike the optical layer shared protection approach, in this approach backup resources are not shared among the pre-configured backup paths and thus resources are not utilized efficiently. The traditional optical shared protection has long recovery time, in which backup paths are not pre-configured and backup wavelength links can be shared by other backup paths. The work in [2] shows that, with 10ms switch configuration time, the recovery times of dedicated and shared protection approaches are 3ms and 56ms respectively under a distributed protocol (for a random demand of 30 connections on a representative network topology). The configuration time of switches widely used could be several 10's of ms and the difference in recovery time for the two approaches would, therefore, be even more significant. Several mission critical applications require short recovery time. Pre-configured backup protection is suitable for such applications. The shared protection approach may not satisfy their stringent recovery time needs.

We propose a protection approach which allows limited sharing of backup resources among pre-configured backup paths (referred to as *pre-configured backup protection with limited sharing (PBPLS)*). The proposed approach can be used under single component failure scenarios. To allow such resource sharing, we use the switch architecture proposed in [6]. The architecture has the following flexible features. In addition to directing the input power towards one output port only (like the traditional switches), the power can be split on a desired sub-set of output ports on need basis. When the switch is pre-configured to split power on two output ports, the traffic can be switched on one of the ports with the split power which requires no further configuration. Further, the switch can be configured to connect two (or more) input ports to the same output port at the same time. With this pre-configuration, the traffic can be switched from one of the input ports to the

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same output port which requires no further configuration. In the proposed approach, when backup paths are set up, similar pre-configurations can be done so that backup resources can be shared. The recovery time in this case is equivalent to the case of the traditional dedicated protection approach since no further configuration is needed at intermediate nodes. This protection approach can be adopted in networks in small geographical area such as metro networks since the power splitting feature is used when sharing backup resources.

In the proposed approach, we consider limited sharing of backup resources. This is because of power loss when power splitting is used for backup sharing. Particularly, when repeated or cascading of power splitting occurs, power will be reduced significantly. One solution is to compensate power using amplifiers at additional cost. In this paper, we adopt the approach of limiting the number of power splitting on a backup path to reduce the power loss. Constraining the number of power splitting limits the degree of backup sharing. We investigate for small values for the maximum number of power splitting (one to three).

As explained above, the proposed protection approach utilizes the flexible features of the switch architecture used in this paper. The widely used traditional optical switches such as MEMS switches [7] do not support these features because of architectural limitations, and therefore similar protection approach cannot be adopted. The proposed approach can be employed in broadcast-and-select based architectures which are widely considered in optical burst/packet switching networks [8] [9]. These architectures generally consist splitters and semiconductor optical amplifiers (SOAs). Since SOAs are used, power loss due to power splitting would be compensated and the need for limiting the number of power splitting may not arise (or reduced). However, we do not use these architectures in this paper because of their high power loss and high cost. Splitters used in these architectures always split power towards all the output ports and thus significantly a large amount of power is wasted. Further, these architectures are expensive since a large number of SOAs are required. The switch architecture used in this paper uses components with the flexibility of controlled power directing and splitting as explained above. Therefore, it reduces power wastage significantly. In addition to this, we do not use amplifiers in the architecture in order to reduce the cost.

In [10], an approach has been proposed to improve resource usage in which a pre-configured backup path can share resources of non pre-configured backup paths. Unlike this approach, this paper investigates sharing backup resources among pre-configured backup paths. Power splitting has been considered in [11] [12] when provisioning protection. In [11], a 1+1 dedicated protection approach (traffic is simultaneously sent via the two alternate paths) has been investigated in which splitters are used in broadcast-and-select OADMs for a ring topology network. This work does not consider backup sharing. In [12], splitters are used in tree-based protection for multicast traffic. In this work, backup sharing is considered and nodes may require reconfigurations in the event of a failure. In our work, we consider unicast only and the proposed approach avoids reconfigurations when failure occurs. In the following sections, we illustrate the switch architecture first, and then illustrate our proposed protection approach.

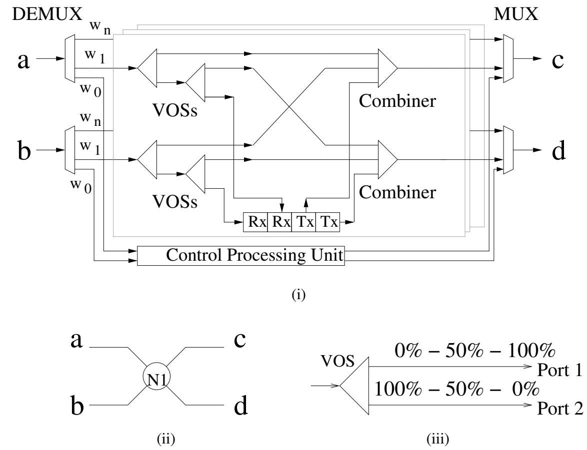

Fig. 1. Switch architecture with two input and two output links

II. Optical switch architecture

The proposed switch architecture [6] is shown in Fig. 1(i). In [6], we have investigated the transmission of bursty traffic. The switch can be used for the transmission of circuit level traffic also (transmission through lightpaths). We consider the switch for a node with two input and two output links as shown in Fig. 1(ii). Each link carries a control wavelength w_0 and n data wavelengths $(w_1, w_2, .., w_n)$. The basic architectural component is a 1x2 variable optical splitter (VOS). Other components are combiners, multiplexers (MUX), demultiplexers (DEMUX), receivers (Rx), transmitters (Tx), and a control processing unit. In Fig. 1(i), the components VOSs, combiners, receivers, and transmitters are shown for the data wavelength w_1. VOSs are cascaded and linked to combiners and receivers as shown in the figure. Additional VOSs and combiners can be cascaded and linked in the similar manner to accommodate more links. For F number of fiber links and N data wavelengths, a total of NF^2 VOSs and NF combiners (each is of type $(F+1)X1$) are required.

We use the 1x2 VOS component presented in [14] [15] [13] in our switch. The self-latching VOS is based on magneto-optical technology. The VOS is designed using mainly a variable faraday rotator and a walk-off crystal. In the VOS, input optical power can be distributed (or split) on the two output ports with various ratios (states) such as $(0\% - 100\%)$, $(50\% - 50\%)$, and $(100\% - 0\%)$ as shown in Fig. 1(iii). The component requires an electric pulse to switch states (i.e. increase/decrease the power on a port). By applying the electric pulse appropriately the various states can be achieved. It takes 0.25ms time to switch between $(0\% - 100\%)$ and $(50\% - 50\%)$ states. We assume the same time period to switch between $(50\% - 50\%)$, and $(100\% - 0\%)$ because of near symmetrical power splitting pattern seen in [15]. We denote the 0.5ms configuration time required to change the split power

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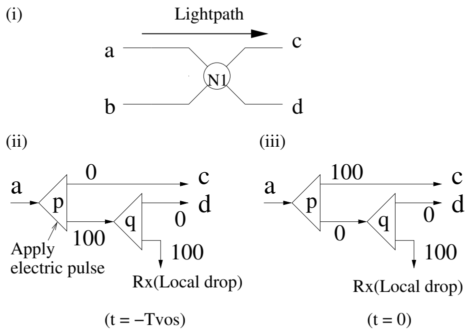

Fig. 2. Switch configuration

on an output port from 0% to 100% (i.e., from $(0\% - 100\%)$ to $(100\% - 0\%)$) as $Tvos$. The states $(0\% - 100\%)$ and $(100\% - 0\%)$ can be used to direct the full power towards one output port only (like the traditional optical switches). Further, the state $(50\% - 50\%)$ can be used to split power. Particularly, unlike the traditional switches, the power can be split on a desired sub-set of output ports on need basis by appropriately changing the state of VOSs in the switch. We use this feature in our protection approach, which is illustrated in Section III. The low-cost magneto-optic component available in [16] can also be used in our architecture.

Average insertion loss (IL) of the VOS is 0.6dB (for $(0\% - 100\%)$ and $(100\% - 0\%)$) and 4dB (for $(50\% - 50\%)$) and polarization-dependent loss (PDL) is less than 0.1dB. The VOS energy consumption is very low ($\sim 120\mu J$) [14]. For a typical nodal degree such as two and three, the insertion loss at core components (VOSs and combiners) is in the range of 6.6dB to 7.2dB and 6.6dB to 7.8dB respectively (VOSs: 1.2dB and 1.8dB when traversing up to 2 and 3 VOSs with $(0\% - 100\%)$ and $(100\% - 0\%)$ states, and combiners: 6dB when two cascaded combiners (each of 3dB type) are traversed with these nodal degrees in a 4X1 type). When the VOS is used with $(50\% - 50\%)$ state (used when failure recovery only), slightly more power loss occurs. Therefore, the architecture is suitable for networks in small geographical areas because of the power-loss. Otherwise, amplifiers are required to compensate the power-loss.

A. Switch configuration

An optical connection/lightpath can be set up by configuring intermediate nodes along the lightpath. Generally, control messages are sent (on the control wavelength w_0) using a two-way reservation approach for establishing the lightpath (on a data wavelength, say w_1). The control message is processed electronically at the control processing unit at intermediate nodes. The control message carries the details about the connection which are used to configure VOSs at intermediate nodes. Below, we illustrate how VOSs are configured at a node which connects an input port to an output port for establishing the lightpath. We consider a node with two input and two output links as shown in Fig. 1(ii) for illustration.

We consider that a lightpath is set up which traverse from link a to link c on the wavelength w_1 as shown in Fig. 2(i). It is considered that, at $t = -Tvos$, the control message has been processed and the switch configuration is initiated. The default status of VOSs in our switch (at $t = -Tvos$) is shown in Fig. 2(ii). VOS-p and VOS-q shown are the two VOSs connected with link a in our switch architecture shown in Fig. 1(i). We do not show the other VOSs connected with link b as no configuration is done in these VOSs. At $t = -Tvos$, the default power splitting status of both VOS-p and VOS-q is $(0\% - 100\%)$ with 0% power directed towards links c and d. That is, paths within the switch from a to c and a to d are shut initially. Once the control message has been processed, the node identifies the output port of the connection and selects the VOS which is connected to that port (i.e. VOS-p). An electrical pulse is applied to the selected VOS, i.e. VOS-p, at $t = -Tvos$ as shown in Fig. 2(ii). It changes the power splitting state of VOS-p to $(100\% - 0\%)$ at $t = 0$ (i.e. it requires $Tvos$ time to change the state) with 100% power directed towards links c. This is shown in Fig. 2(iii). That is, power directed towards link c increases from 0% (at $t = -Tvos$) to 100% (at $t = 0$). Therefore, at $t = 0$, the path $a - c$ is connected/opened. When optical signals arrive on the lightpath they are switched with full input power directed towards link c. Paths $a - d$ remains shut. Note that, at the receiver node (egress), the optical signals can be received at the default state as full power is directed towards the local receiver (Rx).

III. PRE-CONFIGURED BACKUP PROTECTION WITH LIMITED SHARING (*PBPLS*)

The traditional optical layer dedicated protection has short recovery time because of pre-configured backup paths. Achieving short recovery time by pre-configured backup paths and at the same time employing backup sharing are not done. This is because of the limitations in the traditional OXCs. Consider that a switch configuration is done to connect an input port to an output port within a widely used OXC such as a MEMS optical switch. While maintaining this connection, another configuration to connect (1) the same input port to a different output port, or (2) a different input port to the same output port is not done. This is because, this later configuration disrupts the existing connection. The configuration is, therefore, done only after the existing connection is over or released. This constraint does not allow setting up two backup lightpaths which are pre-configured and at the same time they share one or more wavelength links.

As explained in Section II, the switch architecture considered in this paper has increased flexibility of how optical power received on an input port can be directed or split on need basis. This flexibility can be used to overcome the above constraint. Power splitting allows connecting an input port to two (or more) output ports within the switch. In addition to this, the components are cascaded in the architecture such that they allow configurations which connect two (or more) input ports to the same output port. We illustrate how these features are used in our protection approach below.

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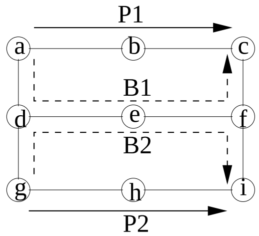

Fig. 3. Shared protection

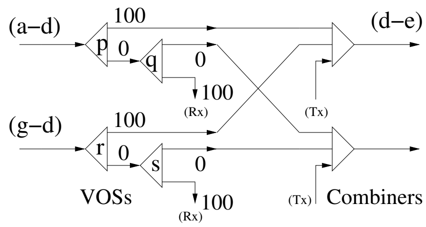

Fig. 4. Switch configuration at node-d

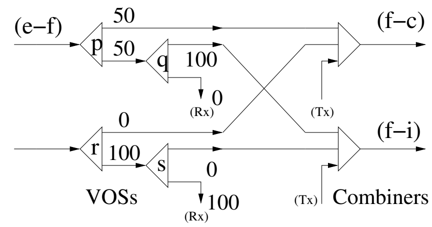

Fig. 5. Switch configuration at node-f

The protection approach allows provisioning pre-configured backup paths with limited backup resource sharing. Such backup sharing is possible in single component failure scenarios. We assume single link failures which are the predominant type of component failures. The proposed approach is illustrated in Fig. 3. It shows two primary lightpaths (P1 and P2) and their backup lightpaths (B1 and B2). Each of the backup lightpaths is link-disjoint with its primary lightpath. Further, primary lightpaths P1 and P2 are also link-disjoint as shown. Links $d{-}e$ and $e{-}f$ are shared among the backup paths. When using the proposed switch, configurations can be done at node *d* such that the link $d{-}e$ can be opened for both the links $a{-}d$ and $g - d$ for transmission at the same time. This is shown in Fig. 4 (The same switch shown in Fig. 1(i) is used for this illustration. Only the VOSs and combiners for wavelength w_1 are shown in Fig. 4. The additional output link which is not labeled in the figure is not used). In this configuration, VOS-p and VOS-r are configured such that their power splitting state becomes $(100\%{-}0\%)$ with 100% power directed towards link $d{-}e$. The configurations are done by applying electric pulses as explained in Section II-A. Further, at node *f*, power from $e - f$ can be split on $f - c$ and $f - i$. This configuration is shown in Fig. 5. In this configuration, VOS-p is configured to the splitting state $(50\% - 50\%)$ and VOS-q is configured to the splitting state $(100\% - 0\%)$ $(100\%$ directed towards link $f - i)$. As a result of these configurations, the power from $e - f$ is split on $f - c$ and $f - i$. While sharing backup links $d{-}e$ and $e{-}f$, these configurations allow transmission over a backup path without needing further configuration. No power splitting occurs at VOSs at nodes *d* and *e* (at node *e*, similar configuration illustrated in Section II-A is done). Note that, the above configurations are done at the time when the primary connections are established.

In case of failure on P1, traffic can be immediately rerouted through B1 since it is pre-configured. The traffic will be switched from $a{-}d$ to $d{-}e$ because of the switch configuration illustrated above. Further, the traffic will be switched from $e - f$ to $f - c$ because of the power splitting configuration. Hence, it provides short recovery time which is equivalent to the case of dedicated protection. When rerouting the traffic, a copy of traffic is routed on the link $f - i$ also due to power splitting. Similar rerouting can be done when failure occurs on P2. Note that, in Fig. 5, power from $e - f$ is split towards the desired output links $f - c$ and $f - i$ only, and power wastage can be reduced by not splitting on unwanted ports (if any).

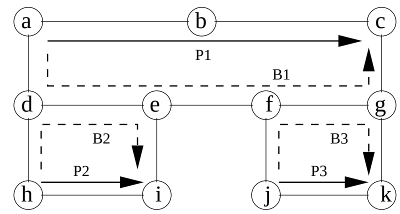

Fig. 6. A backup sharing scenario

A. Limited backup sharing

Backup sharing while provisioning pre-configured backup paths is limited because of power loss due to power splitting. We mainly consider splitting loss at VOSs. Repeated or cascading of power splitting may occur when backup links are shared by many backup lightpaths. This is illustrated in Fig 6. Three primary lightpaths (P1, P2, and P3) are protected by their pre-configured backup paths (B1, B2, and B3). Links $d - e$ and $f - g$ are shared by backup lightpaths B1 & B2, and B1 & B3 respectively. In case of failure on P1, traffic is rerouted via B1. In this case, power splitting occurs at nodes e and g (at VOSs). To reduce the power loss due to such repeated power splitting, we adopt the approach of limiting the number of power splitting at intermediated nodes (at VOSs) on a backup lightpath. Limiting the number of power splitting limits the degree of backup sharing. We denote the maximum number of power splitting at intermediate nodes on a backup lightpath as *K*. For instance, the three backup lightpaths can be provisioned in Fig 6 when $K = 2$. However, if $K = 1$, only primary lightpaths P1 & P2 can be set up with backup paths B1 & B2 respectively. Lightpath P3 has to be rejected since B3 would, otherwise, cause additional power splitting at node *g*. Similarly, once P1 and P2 have been admitted with their backup lightpaths, consider admitting a future request with its primary and its backup lightpaths (say, P4 and B4 (not shown)). Assume that B4 shares the same backup link $d - e$ and additional power splitting occurs at node e to a link (say $e - l$) in addition to the links $e - f$ and $e - i$ (the link $e - l$ is not shown). In this scenario, with $K = 1$, this new request is rejected since additional power splitting occurs.

B. Protection with fixed splitters vs. VOS

Our proposed protection approach can also be implemented with traditional (fixed) splitters and shutters instead of using VOSs. (Similar splitter-shutter type switches are broadcast and

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select based switches [8] considered for optical burst/packet switching networks) A major drawback with fixed splitters based switches is their high power loss. This is because power is always split towards all the output ports. Therefore, only a small portion of power is used to transmit data and the remaining power is wasted. This small power may not be enough for transmission over long distance. In addition to this, additional shutters are required. With VOSs, even with a large number of ports, optical signals are switched with 100% power directed at VOSs towards the output link during normal working conditions. In case of failure-recovery using shared backup lightpaths, optical power is split towards necessary output ports only. Therefore, power-wastage is significantly reduced. In addition to this, additional shutters are not required when VOSs are used. Because of these reasons, we use VOSs instead of traditional splitters.

IV. PERFORMANCE STUDY

We evaluate the performance of the proposed protection approach (PBPLS) on the 14 node and 21 bi-directional link NSFNET topology. We consider 16 wavelengths per fiber. We consider sub-lambda connection requests (or LSPs) which require optical layer protection. A sub-lambda connection can traverse a number of lambda connections or lightpaths. In the optical layer protection, each of the lightpaths traversed is protected by a backup lightpath. Traffic requests arrive dynamically. Request arrivals follow Poisson distribution and holding time of a request follows exponential distribution with unit mean. We assume wavelength capacity to be 10 units. Bandwidth requests for traffic are uniformly distributed in the range of (4-10). Each request's source node and destination node are selected based on uniform distribution. We use a shortest path selection algorithm (Dijkstra's algorithm) with the objective of minimizing the total number of physical hops to route the requests. Each experiment is carried out with a large number of request arrivals on the order of 10^5.

We investigate whether significant performance improvement is seen when limiting the number of power splitting at intermediate nodes (K) to small values ($K = 1$, $K = 2$, and $K = 3$). First, we consider that all the traffic requests require short recovery time and they are protected with pre-configured backup paths using our proposed protection approach, PBPLS. We compare the performance with the traditional dedicated protection since it also provides pre-configured backup paths (recovery time in PBPLS is equivalent to the case of the traditional dedicated protection). In addition to this, we also study the performance with two classes of traffic when only a portion of requests require short recovery time (class-1) while the rest can tolerate slightly longer recovery time (class-2). For class-1, pre-configured backup paths are provided using PBPLS (and compared with the traditional dedicated protection). For class-2, non pre-configured backup paths are given using the traditional optical layer shared protection approach. In this study, two traffic arrival distributions are considered. The traffic arrival follows the distribution, class-1 : class-2 = (1) 50% : 50%, and (2) 25% : 75%. In this study, we

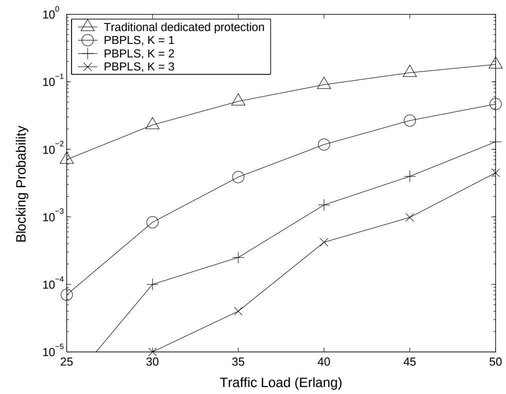

Fig. 7. Performance for the traditional and proposed protection approaches

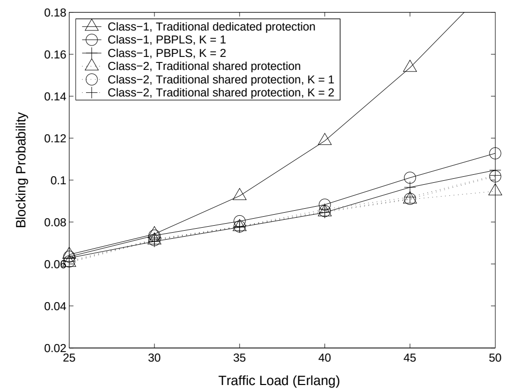

Fig. 8. Performance of class-1 (50%) and class-2 (50%) requests

also observe whether the performance improvement for class-1 traffic due to limited backup sharing penalizes class-2 traffic. When both the PBPLS and the traditional optical layer shared protection are provided, we consider that backup resources associated to these two protections are separated (i.e., pre-configured backup paths and traditionally shared backup paths (not pre-configured) do not share the same resources) in order to reduce the complexity.

The blocking performance for the proposed PBPLS approach with different values of the number of power splitting ($K = 1$, $K = 2$, and $K = 3$) and the traditional dedicated protection approach are shown in Fig. 7. In this study, a single class of traffic is considered and all the requests are admitted using the same protection method. It can be seen that, significant reduction in blocking is achieved in PBPLS with $K = 1$ (more than 74% reduction in blocking when compared to the traditional approach). This is because, significantly a large number of requests can find backup resources as resources can be shared though it is limited in our approach. Further reduction in blocking is observed with increasing number of power splitting (with $K = 2$ and $K = 3$, additional 18% and 23% blocking reduction is seen at high loads).

Figure 8 shows the blocking performance when 50% of requests (class-1) are protected by pre-configured backup paths (PBPLS is used. The traditional dedicated protection is used

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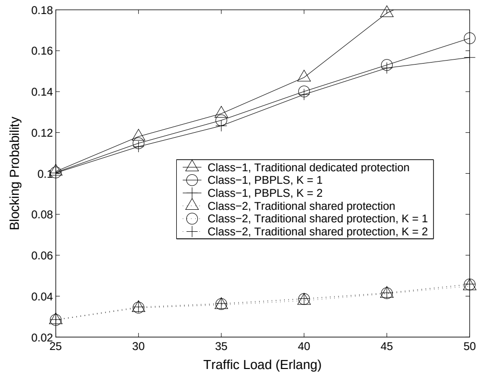

Fig. 9. Performance of class-1 (25%) and class-2 (75%) requests

for comparison), and 50% of requests (class-2) are protected by non pre-configured backup paths (the traditional optical layer shared protection approach is used). Two values for the number of power splitting ($K = 1$, and $K = 2$) are investigated. In the figure, we denote the performance of class-2 traffic when class-1 traffic is admitted using PBPLS with $K = p$ as 'Class-2, Traditional shared protection, $K = p$'. We denote the performance of class-2 traffic when class-1 traffic is admitted using the traditional dedicated protection as 'Class-2, Traditional shared protection'. For class-1 requests, up to about 42% reduction in blocking is seen for PBPLS with $K = 1$, when compared to the traditional dedicated protection approach. With $K = 2$, additional blocking reduction of up to 4% only is seen. The performance of class-2 requests is shown in dotted lines. The impact on the performance of class-2 requests as a result of using our proposed protection for class-1 requests is seen at very high loads only (above 45 Erlang). For class-2 requests, about 7% additional blocking is seen at 50 Erlang when $K = 1$ in our protection approach.

Figure 9 shows the blocking performance when 25% of requests (class-1) are protected by pre-configured backup paths and 75% of requests (class-2) are protected by non pre-configured backup paths. Overall, more blocking is seen for class-1 requests. This is because, more resources are occupied by frequently arriving class-2 requests. Class-1 requests do not arrive frequently with the given small percentage of traffic arrival. Therefore, they may not find enough available resources and they are blocked. Even with the small percentage of traffic arrival, considerable blocking reduction of up to 15% is seen for class-1 requests with the proposed protection with $K = 1$. The impact on the performance of class-2 requests as a result of improved performance for class-1 requests is not significant (only about 2% additional blocking is seen for class-2 requests)

V. Conclusions

In this paper, we proposed an optical protection approach with pre-configured backup paths, which allows limited backup resource sharing. We investigated the performance in a single class (all the requests were provisioned with pre-configured backup paths) and two-class (class-1 and class-2 requests were provisioned using pre-configured and non pre-configured backup paths respectively) traffic scenarios. We demonstrated that even with the small number of power splitting (K), significant performance improvement is seen. In the single class scenario, our proposed approach with *K=1* showed more than 74% reduction in blocking when compared to the traditional dedication protection approach. In the two-class scenario, it showed up to 42% and 15% reduction in blocking for class-1 traffic with 50% and 25% traffic distributions respectively.

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