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Dedicated path protection for optical networks based on function programmable nodes

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ABSTRACT

Due to the constantly increasing volumes and tightening reliability requirements of network traffic, survivability is one of the key concerns in optical network design. Optical "white box" nodes based on the Architecture on Demand (AoD) paradigm allow for self-healing of nodal component failures due to their architectural flexibility and the ability to employ idle components for failure recovery. By incorporating node-level survivability with network-level protection from link failures, resiliency of optical networks can be significantly improved. To this end, we propose a survivable routing algorithm for AoD-based networks called Dedicated Path Protection with Enforced Fiber Switching (DPP-EFS), which combines self-healing at the node level with dedicated path protection at the network level. The algorithm aims at improving the self-healing capabilities of the nodes by increasing the percentage of fiber switching (FS). Namely, fiber-switched lightpaths require a minimal amount of processing within the node (i.e. only signal switching), while other aspects of processing (e.g. demultiplexing, bandwidth virtualization) and the related components (i.e. demultiplexers, splitters, wavelength selective switches) remain unused and may be used as redundancy. On the other hand, lightpaths that are not eligible for FS have to be re-routed to alternative, longer paths in order to allow for FS between certain ports within the node. Therefore, the proposed algorithm pursues an advantageous trade-off between the increase of the number of idle components which can be used as redundancy at the node level and the unwanted length increase of lightpaths re-routed to render components redundant. For particular cases when DPP-EFS is not able to reduce the mean down time (MDT) in the network merely by increasing the percentage of fiber switching, we propose an algorithm for Dedicated Path Protection with Fixed Shortest Path routing and added Redundancy (DPP-FSP-RED) which adds additional spare components at strategic nodes to ensure that all connections have at least one redundant node component along their path. Simulation results show a significant reduction in MDT with minimal extra capital expenses.

1. Introduction

The emergence of new bandwidth-intensive services and applications requires spectrum-efficient, performance-adaptive and highly scalable optical network infrastructure. Elastic optical networks (EONs) [1,2] has proven to be a worthwhile scalable solution enabling efficient and flexible resource allocation. In EONs, the frequency spectrum is divided into a number of spectrum slots whose allocation to user demands closely matches the bandwidth requirements. The tunable nature of spectrum allocation in EONs is supported by bandwidth-variable transponders (BVTs) [3] and reconfigurable optical add/drop multiplexers (ROADMs) based on bandwidth variable wavelength selective switches (BV-WSSs) or spectrum selective switches (SSSs) [4]. The BVTs adjust the transmission bit rate and bandwidth by adapting the modulation format or the number of spectrum slots (subcarriers), while ROADMs represent key elements in the core networks as they route signals directly in the optical domain, without O-E-O conversions [5]. Crucial aspects of ROADM design include minimizing cost and facilitating maintenance and manual interventions caused by faults, failures and node upgrades. Moreover, it is important to enable a high level of reconfigurability, adaptability and architectural flexibility in order to cope with the variations in network traffic requirements [6]. In the majority of conventional ROADMs, whose technological overview can be found in [7], the individual switching modules at the input and output ports are physically interconnected in a hard-wired manner. Such hard-wired ROADMs can be conceived as an *optical black box*. Even though optical black box ROADM architecture enables elastic spectrum allocation, its hard-wired nature limits upgradeability

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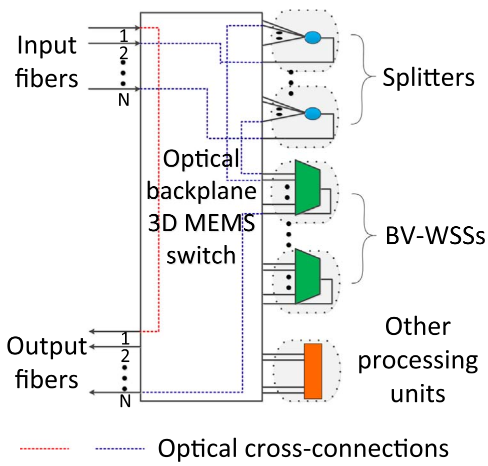

Fig. 1. A schematic view of AoD node architecture.

and restricts support of new functionalities, e.g. time space division multiplexing [8]. Moreover, the black box approach introduces several drawbacks and limitations, including inefficient component usage which can inherently degrade lightpath availability and increase power consumption [9].

An alternative solution for ROADM design is the concept of the Architecture on Demand (AoD) [10], also referred to as synthetic, or programmable nodes. The aim of AoD is to address the limitations of hard-wired node architectures by providing flexible processing and switching of optical signals through programmable architecture. An AoD node comprises a set of individual modules interconnected via an optical backplane, as illustrated in Fig. 1. The building modules can be either distinctive components for optical processing such as multiplexers (MUX), demultiplexers (DEMUX), BV-WSS, SSS, or subsystems composed of several components. The backplane is implemented by a high port-count optical switch, which can be based on beam-steering or 3D-MEMS technology. The modules can be interconnected through the optical backplane in a completely arbitrary manner and can be dynamically added, removed, or relocated anywhere within the architecture to form new arrangements. Architectures that support the processing and switching requirements of a set of communication requests can be computed and implemented by a user-driven or automated mechanism. As architectures utilize only the modules needed to provide the required functionality, the requested processing complexity is reflected on the complexity of the implemented architecture. For instance, in the example architecture in Fig. 1 only one cross-connection is needed to switch the traffic from input port #1 to output port #1. Here, all signals from one input are switched together to the same output without any processing within the node, which is referred to as fiber switching. On the other hand, signals directed from input ports #2 and #*N* to output port #*N* require more complex switching and processing (i.e. elastic (de)multiplexing) that is realized by splitters and a BV-WSS. Therefore, each AoD port can implement different levels of switching granularity, ranging from fiber switching to sub-wavelength switching. Contrary to hard-wired ROADMs, AoD nodes can be considered as *optical white boxes*, since their architecture and the switching and processing capabilities can be adjusted to the needs of the supported traffic.

In comparison to the planning of optical networks that use conventional ROADMs, AoD-based networks require different network planning approaches, motivated by the fact that AoD can optimize individual component usage at the node level. Network planning in that case needs to address the nodal architecture design as well as the lightpath routing sub-problem, which are closely intertwined and need to be solved simultaneously. The most common objective of AoD network planning is to minimize the number of used components inside each node, which can have a positive effect on cost efficiency and network performance. Firstly, minimization of active modules with higher failure probability within the nodes reduces the related risk of connection failures, thus achieving more reliable communication, as well as lowering the power consumption. Secondly, due to architectural reconfigurability, AoD can re-use idle modules to recover from failures of modules of the same type. This phenomenon is referred to as *self-healing* at the node level and has been studied in our previous work [11]. Module usage minimization combined with self-healing can lead to lower operational expenses (OpEx) through the reduction of total revenue losses due to lower network unavailability [12].

Notwithstanding the possibility of node-level recovery through self-healing in AoD, protection mechanisms are needed at the network level as well to protect from link failures. Therefore, efficient survivable AoD network planning approaches should combine protection at the node with the protection at the network level. Various network protection schemes have been developed to ensure reliable optical transmission in the presence of single or multiple node and link failures [13]. Most common network protection schemes are based on dedicated approaches with path or link protection. Dedicated Path Protection (DPP) schemes [14,15] reserve dedicated protection paths and transmit simultaneously on both the working and the backup path (in 1 + 1 protection) or only on the working path while keeping a backup path in cold standby until a failure occurs (in 1:1 protection). 1 + 1 dedicated path protection is the most widely deployed network survivability scheme as it offers instantaneous recovery from node and link failures. Existing DPP approaches that protect from node failures consider only scenarios where one or more entire nodes are disabled by a failure, without discerning among individual nodal components and or supporting node-level recovery. To the best of the authors' knowledge, no existing approach combines node-level and network-level protection enabled by AoD based networks. Thus, in this paper, a dedicated path protection scheme for networks based on AoD ROADMs is proposed and evaluated through simulation on the German and Europe-wide optical network topologies. The proposed heuristic algorithm seeks an availability-enhancing trade-off between the number of idle components in AoD nodes which can be used as redundancy, and the increased length of some lightpaths that need to be re-routed in order to release redundancy within the nodes. Moreover, the algorithm is extended to sparsely add dedicted redundant modules when the node redundancy released through re-routing is insufficient to support a desired level of availability.

The remainder of the paper is organized as follows. A brief overview of the related work in AoD-based network planning is presented in Section 2. Section 3 presents the proposed dedicated path protection algorithms. Availability and simulation assumptions are presented in Section 4. Simulation results are analyzed in Section 5, and concluding remarks are given in Section 6.

2. Related work

The concept of optical white box (AoD) was initially proposed in [10] with the objective of overcoming issues concerning cost-effectiveness, architectural flexibility, and scalability of hard-wired node architectures. As shown in [16], AoD has the ability to simultaneously accommodate multiple bit rates including legacy 10, 40, and 100 Gbit/s connections, as well as future high speed super-channels with arbitrary bandwidth requirements and elastic bandwidth allocation. Furthermore, according to a method for flexibility evaluation of optical node components and architectures proposed in [17], AoD exhibits significantly higher functional and architectural flexibility compared to different hard-wired elastic node architectures. A synthesis algorithm for computing the architecture of a programmable node necessary to support a given traffic matrix was proposed in [18]. The results of the associated study indicate that efficient usage of cross-connections in the optical backplane can reduce the number of necessary hardware modules at least by half, compared to conventional hard-wired optical