Resilience of optical networks based on Architecture on Demand nodes

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***Abstract*— Due to the high data rates, optical networks need to be highly resilient in order to minimize transmission interruptions and data losses resulting from failures. Optical nodes implemented by Architecture on Demand (AoD), which comprise an optical backplane hosting optical modules (e.g. optical splitters, amplifiers, bandwidth-variable wavelength-selective switches, etc.), represent a very promising technology for realizing highly flexible and reliable optical networks. AoD improves connection availability by enabling bypass of unneeded components and supporting self-healing of component failures at the node level. We analyze the impact of AoD to network resilience and propose further improvements through tailored survivable lightpath routing.**

Keywords—availability; failure survivability; dedicated path protection; fibre switching

I. INTRODUCTION

Immense growth of network traffic and the emerging network services with stringent bandwidth and Quality of Service requirements drive the need for high availability of backbone optical networks. In general, approaches for increasing network availability and reducing service disruption, along with the associated data and revenue losses, include *(i)* providing redundancy in the network to be used for failure recovery, and *(ii)* reducing the number of failure-prone components used by each lightpath thus lowering the associated risk of failure. Recovery from link and node failures most commonly takes place at the *network level* by rerouting lightpath to disjoint paths when components at links or nodes included in the working paths of connections fail. Redundant path can be precomputed and reserved at connection setup time (protection), or upon a failure (restoration). Several approaches for network-level failure recovery with connection rerouting can be found in [1], [2].

Recently introduced synthetic reconfigurable add-drop multiplexers (ROADMs) implemented by Architecture on Demand (AoD) [3] offer new prospects of improving network reliability performance by supporting *node-level recovery*, i.e. self-healing from failures of node components. Furthermore, AoD nodes can also improve network availability through reduction of the number of failure-prone components used by each lightpath. Interconnections between optical components in AoD nodes, e.g., optical splitters, bandwidth-variable wavelength-selective switches (BV-WSSs), (de)multiplexers or amplifiers, are realized in a highly flexible and reconfigurable manner via an optical backplane (e.g. high-port count 3-dimensional micro-electro-mechanical switch (3D MEMS) or piezoelectric optical switch), thus providing the network with an unparalleled adaptability to traffic diversity.

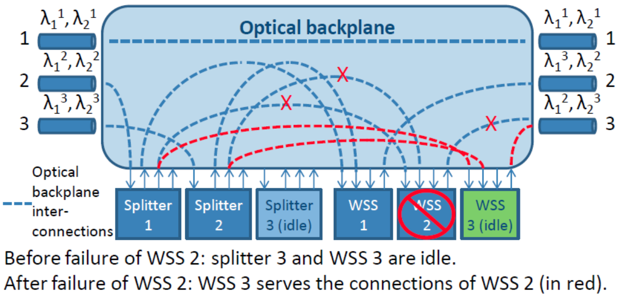

Figure 1. Self healing in an AoD node.

A major benefit of AoD is the flexibility to concurrently accommodate multiple bit-rates including existing 10 Gbit/s, 40 Gbit/s, 100 Gbit/s, as well as future higher bit-rates with arbitrary bandwidth requirements and bit-rate variable multicarrier channels with elastic bandwidth allocation. AoD also supports arbitrary switching granularities, such as fibre, waveband, wavelength and sub-wavelength switching. The modularity of AoD facilitates dimensioning, provisioning and upgrading the optical node with enhanced or new functionalities. The greatest advantage of AoD nodes from the availability perspective is the fact they are characterized with self-healing capabilities due to their architectural flexibility and the ability to employ components which are not used (i.e. idle components) in current switching or processing operations for redundancy and failure recovery [4]. Self-healing of an AoD ROADM in the event of a WSS failure is shown in Fig. 1. Dashed lines indicate cross-connections in the optical backplane. When a working WSS (here, WSS 2) fails, an idle, redundant WSS (i.e. WSS 3), takes over the failed connections.

This paper provides an analysis of the impact of AoD to network availability, combined with tailored routing approaches. Compared to hard-wired (HW) ROADM architecture based on splitters and BV-WSSs in a broadcast&select configuration, AoD nodes can significantly

Input: 1. Physical topology G = (E,V);
2. Lightpath demands $\tau = (s_i, d_i)$;
3. TFS = targeted portion of fibre-switched lightpaths;

Route lightpaths on their shortest paths and apply possible FS;
Calculate fs_temp = percentage of FS lightpaths in the network;
while $fs\_temp < TFS$ **do**
    1. Find the node n and its input-output node pair (i,j) with the maximum $fs\_ratio(n,i,j)$;
    if $fs\_ratio(n,i,j) = 0$ for all (n,i,j) **then**
        break;
    end if
    2. Apply FS between ports i and j and reroute extra lightpaths;
    if applying FS or re-routing of extra lightpaths not possible **then**
        break;
    end if
    3. update fs_temp;
end while

Figure 2. Enforced Fiber Switching (EFS) routing algorithm.

improve network availability. The paper is organized as follows. Section 2 describes a routing approach for working paths in AoD-based network, while section 3 presents an approach for routing with dedicated path protection. Section 4 gives the details of the availability model and simulation assumptions. Section 5 analyzes the results of the simulation and Section 6 concludes the paper.

II. ENFORCED FIBER SWITCHING (EFS) ROUTING ALGORITHM

The AoD functionality of switching at the fibre level is particularly beneficial from the availability aspect, as it decreases the number of optical components traversed by a lightpath and, thus, minimises the related risk of failure. Fiber switching (FS) also releases unused components which can then be used for the redundancy function. In order to utilize the adaptive nature of AoD nodes requesting minimization of number of used components, we developed the Enforced Fibre Switching (EFS) routing algorithm [4]. Given a set of lightpath demands and the physical topology of the network modeled as a graph G(V,E), where V is a set of nodes interconnected by a set of optical links E, the EFS algorithm aims at routing the lightpaths in a way which increases the percentage of fibre-switched lightpaths on the network level. The pseudocode of the EFS algorithm is shown in Fig. 2.

In the beginning, EFS finds the shortest path (SP) in the physical topology for each lightpath using Dijkstra's algorithm, and calculates the portion of lightpaths which undergo fibre switching (denoted as *fs_temp*). In highly-connected lightpath topologies, this value is typically very small (zero in most cases). In order for FS to be possible between an input port *i* and an output port *j* in node *n*, all lightpaths present at port *i* have to also be present at port *j*. If this condition is not satisfied, lightpaths which are present on either port *i* or port *j* (extra lightpaths) have to be rerouted along an alternative path through the network in order to allow for FS between ports *i* and *j*. The ratio between the number of lightpaths which are present on both port *i* and port *j* of node n (and can, therefore, be switched at the fibre level) and the number of lightpaths present only at port *i* or port *j* (and have to, therefore, be rerouted), is denoted as *fs_ratio(n,i,j)*. In each step of the algorithm, we choose node *n* and its input-output port pair *(i,j)* with the highest value of *fs_ratio(n,i,j)* to perform FS. After re-routing of extra lightpaths, the procedure of finding the next node candidate is repeated until reaching the specified or the highest possible percentage of fibre-switched lightpaths.

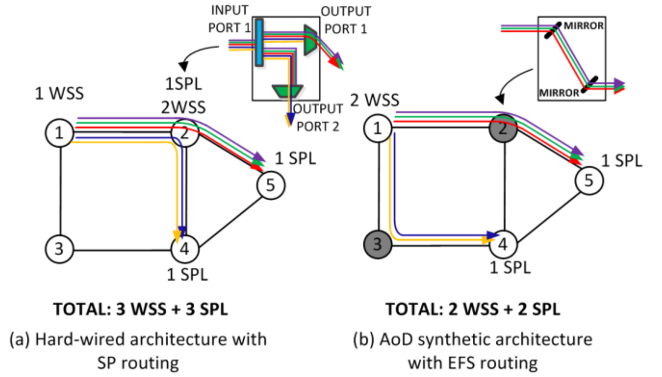

Figure 3. An example network deploying (a) hard-wired nodes with SP routing and (b) AoD nodes with EFS routing.

The principle of the EFS routing algorithm is illustrated in Fig. 3 using a simple example with five lightpaths in the network comprising five nodes. Three lightpaths are established between nodes 1 and 5, while two lightpahts are established between nodes 1 and 4. The example scenario with hard-wired node architecture and deployed SP routing algorithm is shown in Fig. 3 (a). This scenario occupies the total of 3 splitters and 3 BV-WSSs. In the second scenario, shown in Fig. 3 (b), a hard-wired node architecture and SP routing algorithm are replaced by AoD and EFS routing algorithm, respectively. In the first step, the EFS routing algorithm selects node 2 as the candidate with the highest *fs_ratio*. Namely, there are three lightpaths (red, green and purple) that undergo FS at node 2 between input port 1 and output port 1, and two lightpaths (blue and yellow) that need to be re-routed on the network level to allow for this FS. Thus, the *fs_ratio* for node 2 (ports 1,1) is equal to 1.5. After re-routing two extra lightpaths (blue and yellow), FS is possible and applied at nodes 2 and 3 (grey nodes). Due to this modification, network uses only 2 splitters and 2 BV-WSSs for supporting the same set of lightpath demands, showing significant improvement in terms of resource allocation.

III. DEDICATED PATH PROTECTION WITH ENFORCED FIBER SWITCHING (DPP-EFS)

In order to enforce FS, some lightpaths must be re-routed to alternative, longer paths. When the probability of failures of physical links is taken into account, added fiber length and node components traversed by re-routed lightpaths might result in an undesired decrease of connection availability (we refer to connection as a combination of a working and a backup path). Therefore, approaches for protection of AoD-based networks from failures of node components and links must pursue an advantageous trade-off between increasing the number of idle components which can be used as redundancy for failure recovery at the node level (thus increasing availability of certain connections while reducing the complexity of network-wide recovery management), and increasing the length of re-routed lightpaths to release this redundancy (leading to a decrease in availability). To this end, we proposed 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 1+1 protection at the network level [5].

Given a set of connection requests and a physical topology of an optical network based on AoD, the DPP-EFS algorithm establishes a pair of physically disjoint working and backup paths for each request, while trying to maximize the portion of lightpaths undergoing FS along their routes. The routing of the working paths is done using the EFS algorithm. Therefore, DPP-EFS begins by routing all working paths on the shortest paths, followed by an attempt to increase FS by rerouting certain paths to alternative routes. When no further increase in FS of the working paths is possible, the algorithm proceeds with establishing a shortest possible link-disjoint backup path for each connection request without violating the established FS. In order to reflect the fact that establishing FS restricts port connectivity, physical network G(V, E) is transformed into network G'(V', E') such that V' is the set of nodes corresponding to ports of nodes from V, and E' is the set of links modeling the connectivity of the set V'. If we denote nodes and edges from V and E as v_i and e_i, while v_i' and e_i' denote nodes and edges from V' and E', the steps for the network transformation can be summarized as follows:

1. Create a node v_i' corresponding to each input and output port of each node v_i.
2. Create edges e_i' between appropriate nodes v_i' and v_j' for each edge e_i. This maps the connectivity *between* nodes v_i in the original network topology.
3. To map connectivity *inside* individual nodes v_i, i.e. between nodes v_i' and v_j' corresponding respectively to an input and an output port of the *same* node v_i, do the following: if fiber switching is established between v_i' and v_j', connect v_i' only to v_j' by adding a new edge e_i'. If there is no FS between v_i' and any v_j', add edges e_i' to connect v_i' to all nodes v_j' which correspond to output ports of v_i that are not fiber-switched to any input port corresponding to a node v_k'.

An illustrative example of transforming a simple 5-node network is shown in Fig. 4. After routing the four lightpaths on the routes shown in the left part of the figure, FS is established in nodes B and D. The right part of the figure shows the network after transformation. Vertices 1 to 24 correspond to the input and the output ports of nodes A to E. The red lines denote FS between a pair of input/output ports inside the same network node. For example, vertices 5 and 9 of node B correspond to FS ports and are connected only to each other, because routing any connection from port 5 to any output port but 9 would violate the established FS. The same

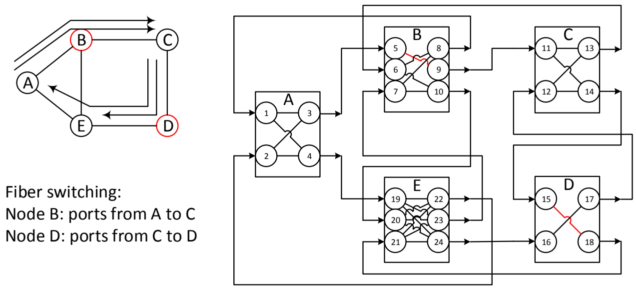

Figure 4. Transforming the network to reflect the impact of established FS to port connectivity.

applies to ports 15 and 18 of node D. On the other hand, connectivity of ports not connected via FS to any other port is much greater, as can be seen , e.g., inside node E in the figure.

After the network is transformed to incorporate the changes in connectivity introduced by FS, the backup path for each connection is found by deleting the nodes and links used by the working path and running Dijkstra's algorithm. We then evaluate the impact of the proposed approaches to network availability via simulation.

IV. Availability Model for AoD

Steady state availability A_c of a component c is a measure of the probability that the considered component works correctly. The variability of the type and the number of traversed components and the existence of redundant components inside each node introduce variations in the availability model of each lightpaths, as shown in Fig. 5. Lightpaths which undergo fiber switching in a node traverse only a pair of mirrors, one at the input and one at the output port. The availability a_i of such lightpaths can be calculated as the probability that both mirrors are working correctly. Availability of lightpaths which are added, dropped, or traverse a node without redundant WSSs or splitters is calculated as a product of availabilities of the traversed components. In general, each lightpaths traverses a pair of mirrors in the optical backplane between any two components or input/output ports. The existence of redundant components in the node changes the availability model as shown in the bottom part of Fig. 5. Here, the serial model turns into the general *r of n* availability model, where at least *r* out of *n* total components work correctly. If we consider only one lightpath in our example, *r* is equal to 1 and *n* to the total number of components of the same type. If there are *P* redundant WSSs and *Q* redundant splitters, then at least 1 out of *P+1* WSSs and 1 out of *Q+1* splitters must be operational to support the considered lightpath.

To gain insight into availability performance of networks based on AoD nodes, we implemented a Monte Carlo simulator of failures and reparations of node components and links. The values of the failure rates λ of each component used in the simulation, expressed in FIT (1 FIT = 1 failure in 10^9 hours) are shown in Table 1. The repair rate μ was assumed to be equal to 1/6 h^{-1}, corresponding to the mean time to repair (MTTR) equal to 6 h. The assumptions of the simulation are the following:

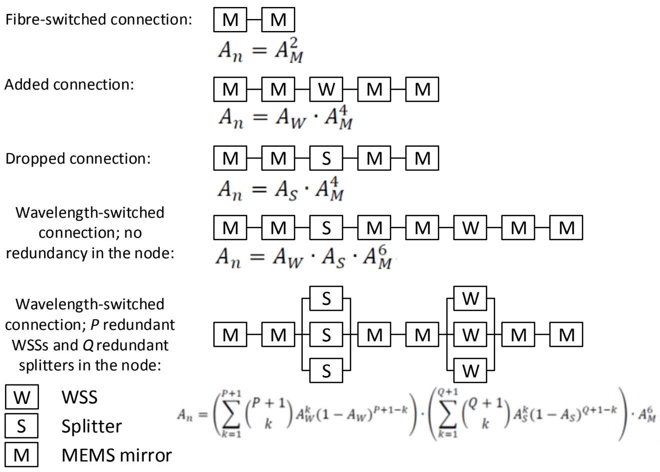

Figure 5. Availability models of lightpaths in AoD nodes.

1. In time zero, all optical components are set to *UP* state.
2. For each component, uniformly distributed random number *x* from the interval [0,1) is generated.
3. Using generated random numbers, exponentially distributed times to failure (TTFs) and times to repair (TTRs) for all components on the network level are calculated according to:

$$TTR = -\ln(1-x)/\lambda$$
$$TTR = -\ln(1-x)/\mu$$

4. Each lightpath is affected by the failures and reparations of traversed components, causing the lightpath timeline to alternate between *UP* and *DOWN* states. A connection, consisting of two lightpaths, i.e. a working and a backup path, is considered to be in the *DOWN* state when both the working and the backup paths are *DOWN*.
5. For each lightpath and each connection the cumulative *UPtime* and *DOWNtime* are recorded. In scenarios when protection at the network level is not applied (i.e., for EFS algorithm), the availability a_i of lightpath i is calculated at the end of simulation by:

$$a_i = UPtime/(UPtime+DOWNtime)$$

In scenarios when protection at the network level is implemented, the availability a_c of connection c is calculated at the end of simulation using the same formula as for a_i.

V. Simulation Results

The EFS and DPP-EFS algorithms were implemented in C++ and tested on the reference backbone networks shown in Fig. 6. For generating traffic demands for each network topology,

TABLE I
Failure Rates of the Components Used in Simulations

Component	Failure rate in FIT
WSS	2000
Splitter 1:N	25·N
MEMS mirror	21
Optical fiber	100/km

we used a method from [6] that generates traffic intensity based on node populations and distances (taken from [7] and [8], respectively). The generated traffic is bi-directional, directly proportional to the node populations and inversely proportional to their distances, with a randomness factor set to 25% to create random fluctuations around the deterministic value. Generated traffic matrices were normalized to different values of the total traffic to obtain different traffic densities within each traffic profile. The logical topology, i.e. the set of lightpath demands corresponding to each traffic matrix is determined by establishing as many 10 Gbit/s lightpaths as necessary between each pair of nodes to accommodate the offered traffic. Applying the described procedure, we create 10 different traffic matrices and corresponding lightpath topologies.

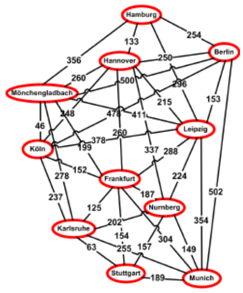

Figure 6. GER network with 11 nodes and 34 links used in the simulations.

Using the described simulation assumptions, we analyse availability of the network deploying AoD and HW ROADMs nodes *(i)* without any protection at the network level (the results are shown in Fig. 7 a)-c)) and *(ii)* using dedicated path protection at the network level (the results are shown in Fig. 7 d)-f)). In each case, we record the minimal (s,t) availability, average lightpath availability and the associated revenue losses, and the network mean down time (MDT), defined as the average number of minutes per year when at least one connection is in *DOWN* state due to failures.

Fig. 7 a) shows s,t availability of all lightpaths in the network obtained by the SP and EFS routing algorithm with different values of targeted FS. Although each lightpath in the AoD nodes traverses additional mirrors that decrease lightpath availability, redundancy that appears in certain nodes due to component idleness results in an increase of both s,t and average availability. This is due to the fact that the gain in lightpath availability due to redundancy within the nodes is greater than the decrease of lightpath availability due to extra traversed mirrors inside AoD. In general, s,t and average unavailabilities are lower up to 51% and 30% than in hard-wired architecture, respectively (for the AoD nodes FS 15% case). The MDT is shown in Fig. 7 b). Under low traffic load, AoD achieves lower MDT because some components will remain idle and can be used as redundancy when used components fail. For higher traffic demands (number of lightpaths higher than 110), when lightpath topology becomes fully connected, all components in AoD become used and MDT of AoD slightly surpasses that of the hard-wired architecture. This trend arises from the fact that, aside from the BV-WSSs and splitters in hard-wired nodes, lightpaths in AoD nodes additionally traverse mirrors used for component interconnections, whose failures contribute to the overall lightpath unavailability.

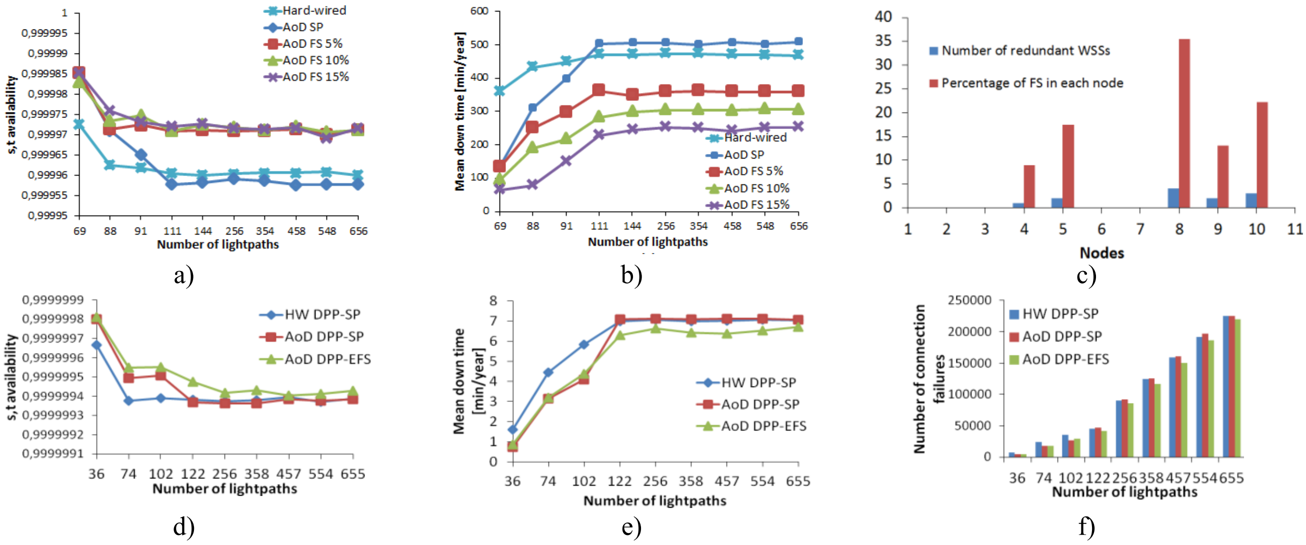

Figure 7. (a) s,t availability, (b) mean down time and (c) number of idle components obtained by EFS and SP. (d) s,t availability, (e) mean down time and (f) number of connection failures obtained by DPP-EFS and DPP-SP.

The correspondence between the percentage of lightpaths that undergo FS at particular node and the number of released components at that node is shown in Fig. 9 for the case when network deploys AoD architecture with 656 lightpaths and 15% FS. By increasing the percentage of lightpaths that undergo FS within the node, the number of released components increases, as well. For example, with 35% of FS lightpaths within node 8 (Leipzig), it is possible to release up to 4 BV-WSSs and 4 splitters which equals to 50% of all node components, since the degree of this node is 8.

The results obtained by DPP-EFS are compared to the network deploying *(i)* AoD and *(ii)* HW ROADMs and fixed shortest path routing with dedicated path protection (denoted as DPP-SP), as shown in Fig. 7 d)-f). Under lower traffic load, the *s,t* availability in network deploying AoD is greater than for HW ROADMs even when SP routing is used, due to the fact that enough components remain idle and can be used for self-healing. When the logical topology becomes fully connected (≥122 lightpaths), all components in AoD nodes become utilized. In such cases, AoD combined with DPP-SP routing has slightly lower availability than HW ROADMs due to the additionally traversed optical backplane elements. DPP-EFS releases additional redundancy in AoD nodes by establishing on average 11% longer paths than DPP-SP. Consequently, DPP-EFS can heal more failures at the node level then SP applied to AoD or HW ROADMs, as shown in Fig. 7 f)), which results in higher *s,t* availability (Fig. 7 d)) and 12.2% lower MDT (Fig. 7 e)) than for HW ROADMs.

VI. Conclusion

The paper studies the impact of synthetic AoD ROADM deployment to network availability. To exploit the benefits of different traffic switching granularities supported by AoD, we proposed a routing approach aimed at increasing the portion of lightpaths switched at the fiber level. We investigate the impact of self-healing at the node level supported by AoD via a routing algorithm which considers only node component failures. To further investigate the influence of fiber failures and to find a beneficial combination of failure recover at the node and at the network level, we extend the propose routing to a survivability scheme with dedicated path protection. Using Monte Carlo simulation of node element failures and reparations, we analyze the availability performances of both approaches. The results indicate that combining AoD deployment with tailored routing significantly improves availability performance of the network, compared to shortest path routing schemes and deployment of ROADMs with hard-wired implementation.

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