

Modulation Format-Aware Restoration and Re-Optimization in Flexgrid Optical Networks

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ABSTRACT

Sliceable Bandwidth-variable Transponders (SBVTs) enhance the configurability and flexibility of Flexgrid optical networks. A single SBVT can be used to transmit and receive several optical signals each modulated with a specific format. A SBVT can be seen as a set of sub-transponders that can be specifically configured to end a specific *lightpath*, by defining, among other parameters, the modulation format and the central frequency to be used. Modulation formats are characterized by its spectrum efficiency and reachability. In this paper, we propose modulation format-aware algorithms to restore connections affected by a link failure, as well as to re-optimize resource utilization after a link repair.

Keywords: flexgrid optical networks, in-operation planning.

1. INTRODUCTION

When a new lightpath needs to be set up, not only the route and spectrum allocation (RSA) [1] needs to be computed, but also a modulation format must be chosen for the requested bitrate and the distance between source and destination nodes, thus defining the RSMA problem [2]. When a failure occurs, a restoration algorithm computes a global solution for all the affected LSPs. However, as a result of the combined effect of longer routes and lack of resources, the bitrate of the restored LSPs could become squeezed. Consequently, when the failure is repaired, an in-operation planning algorithm [3] can be run to compute shortest routes that allow, not only to save resources as proposed in [4], but also increase the bitrate of those LSPs which bitrate was squeezed.

Modulation format-aware recovery and re-optimization algorithms must select the appropriate modulation format, among those available in the installed SBVTs, for the LSPs being restored or re-optimized, respectively. An example of such modulation format awareness is illustrated in Fig. 1a for the depicted 14-node Spanish topology. Table 1 shows the spectral efficiency and reachability of the considered modulation formats. Three LSPs are established in Fig. 1b; the route over the network is shown and the main characteristics are given in Table 2. In the event of a failure in link 4-8, LSPs are restored; Table 2 shows the resulting restored LSPs characteristics, where main changes are highlighted.

Three different cases can be identified as a result of longer restoration routes (in km) and/or resources availability: *i*) the lower spectral efficiency of the new modulation format entailed using more slices to serve all the requested bitrate (*lsp1*); *ii*) although the number of slices was kept invariant the restored bitrate was squeezed (*lsp2*); and *iii*) the number of slices was reduced and the bitrate squeezed (*lsp3*).

It is clear that when link 4-8 is repaired, re-optimization in the network can be performed not only to improve resource utilization by using shorter routes (in terms of hops), but also changes in the used modulation format can be performed for every LSP to serve the bitrate originally requested.

An additional problem is the availability of transponders in the end nodes of each demand. In that regard, let us assume that SBVTs are used in the network. Although many parameters can be used to model SBVTs, in this paper we use just two: total SBVT capacity, e.g., 400 Gb/s, and number of sub-carrier modules in the transponder, e.g., 4. We assume that any other parameter is fixed, e.g., the list of modulation formats, the baud rate of each sub-carrier module, e.g., 25 Gbaud/s, central frequency granularity, e.g. 6.25 GHz, etc.

Furthermore, we assume that each sub-carrier module can be configured independently of the rest of the modules in terms of modulation format, slot width, and central frequency. Because the different sub-carriers

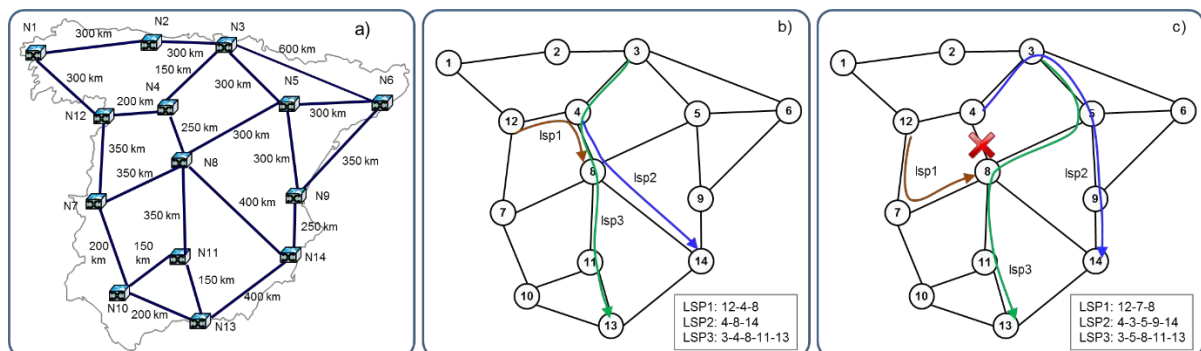


Figure 1. Network topology considered (a). Example network before failure (b) and after restoration (c).

Table 1. Modulation formats.

Mod. Format	Spectral Efficiency (bit/symbol)	Reach (km)
DP-QPSK	4	3000
DP-QAM8	6	1000
DP-QAM16	8	650

Table 2. LSP configuration.

Before Failure					
LSP	Bit Rate (Gb/s)	Len. (km)	Hops	Mod. Format	# Slices
lsp1	200	450	2	DP-QAM16	2
lsp2	400	650	2	DP-QAM16	4
lsp3	400	900	4	DP-QAM8	6
After Restoration					
lsp1	200	700	2	DP-QAM8	4
lsp2	300	1000	4	DP-QAM8	4
lsp3	200	1100	4	DP-QPSK	4

modules in the same SBVT are combined optically, frequency slices can be used by one single sub-carrier as much. Therefore, to avoid frequency slice overlapping RMSA algorithms must consider SBVTs as being connected by an optical link to an optical node. Note that the optical link should exist irrespective of whether SBVTs are installed in L2/L3 nodes (routers/switches) or inside optical nodes (L0).

It is worth noting that the number of alternative routes between any pair of nodes increases exponentially with the number of installed SBVTs per node and hence, RMSA algorithms must be carefully design to limit its complexity, while ensuring that optimal solutions are found. The next section focuses on devising algorithms to solve the proposed modulation format -aware recovery and re-optimization problems under the above assumptions.

2. MODULATION FORMAT -AWARE ROUTING AND SPECTRUM ALLOCATION

As introduced in the previous section, one optical link needs to be considered connecting each SBVT to an optical. We assume that SBVTs are installed in L3 routers so L0 demands start/end in those routers, thus enabling demands to use any of the available SBVT modules. As a result of the large number of links to be added, the size of the resulting graph might entail long computation times. For this very reason, we create a per-demand simplified auxiliary graph removing every node representing an adaptation or SBVT module not in the source and destination of that demand. We also remove every SBVT without available sub-carrier modules and every optical link without a slot available of at least the minimum spectral width allowed (e.g. $3 \times 12.5 = 37.5$ GHz). Note that only those SBVTs connected to the end nodes with available sub-carrier modules and those links with enough spectrum availability remain in the auxiliary graph.

Table 3 presents the pseudocode of the proposed algorithm to solve the RMSA problem. Once the auxiliary graph is created for the given demand d (line 2 in Table 3), a set of shortest paths are computed (line 3); each path includes its physical route k (sequence of hops), and the width of the largest continuous slot in that route, n_k . Each path is afterwards checked to verify the width of the largest slot available (line 5) and that it does not exceed the maximum width specified (line 6). Next, the best modulation format is selected from a set F , ordered by its spectral efficiency, provided that the reach works for the length of the route (lines 8-12). Finally, the path

Table 3. Compute RMSA algorithm.

IN: $G(N, E), d, \text{maxSlotWidth}, bw$
OUT: $\langle d, k, c_k, f_k, b_k \rangle$
1: $Q' \leftarrow \emptyset$
2: $G' \leftarrow \text{createAuxGraph}(G, d)$
3: $Q = \{ \langle k, n_k \rangle \} \leftarrow \text{kSP}(G', d.\text{src}, d.\text{dst})$
4: for each q in Q do
5: if $q.n_k < \text{minSlotWidth}$ then continue
6: $q.n_k \leftarrow \min(q.n_k, \text{maxSlotWidth})$
7: $q.f_k \leftarrow 0$
8: for each f in F do
9: if $\text{len}(q.k) \leq \text{len}(f)$ then
10: $q.f_k \leftarrow f$
11: $q.b_k \leftarrow \min(\Delta_s * f.m * q.n_k, bw)$
12: break
13: if $q.f_k = 0$ then continue
14: if $\text{TPFeasible}(\text{TP}(q.k, A), q.b_k)$ AND $\text{TPFeasible}(\text{TP}(q.k, Z), q.b_k)$ then $Q' \leftarrow Q' \cup \{q\}$
15: if $Q' = \emptyset$ then return \emptyset
16: $\text{sort}(Q', \langle q.b_k, \text{DESC} \rangle, \langle q.k, \text{ASC} \rangle)$
17: $q' = \langle k, n_k, f_k, b_k \rangle \leftarrow \text{first}(Q')$
18: return $\text{selectSlot}(d, q')$

is accepted as long as the included SBVTs have enough resources available (sub-carrier modules and capacity) (line 14). The set of paths satisfying the previous constraints, if any, is sorted first by its bitrate and second by the length of its route (line 16) and the best path is selected (line 17). A slot of the proper width is selected and the computed lightpath is eventually returned (line 18).

3. MODULATION FORMAT -AWARE RESTORATION AND RE-OPTIMIZATION ALGORITHMS

Once the proposed algorithm for the RMSA problem has been introduced, we focus on the modulation format-aware recovery (MF-RESTORATION) and re-optimization (MF-AFRO) problems. The MF-RESTORATION problem can be stated as follows:

Given:

- a graph $G(N, E)$ representing the network topology. The set N includes the set of optical nodes, the set of adaptation nodes, and the set of SBVT nodes. The set of optical links E includes all the optical links connecting nodes in N , where each link e is of a given length. Links connecting an adaptation node and a SBVT node have a null distance.
- the availability of every frequency slice in the optical spectrum of every link in E . The availability of frequency slices in links connecting an adaptation node and a SBVT node is the same than that of the link connecting the same SBVT to the optical node;
- the characteristics of the installed SBVTs, including available capacity and sub-carrier modules;
- a sorted set F of modulation formats supported by the SBVTs;
- a set E_F of failed links;
- a set D of demands affected by the failure to be restored.

Output: the SBVTs and the RSMA for each demand in D .

Objective: minimize the optical resources while minimizing the total unserved bitrate.

To solve the MF-RESTORATION problem, we propose the heuristic algorithm presented in Table 4. The algorithm first de-allocates the demands in D (line 2 in Table4) and removes the failed links from G (line 3). Next, *maxIter* solutions are generated, each allocating the demands in D in a random order (lines 4-16). At each iteration, a new solution S is created, where failed demands are in a first step restored using the minimum slot width (lines 7-11) and then, the allocated slot is expanded to increment the restored bitrate (lines 12-14).

The fitness of the generated solution S is computed and it is stored if it improves the best solution found so far (*bestS*) (lines 15-16). The best solution is eventually returned. Note that since D contains failed demands, they are discarded, i.e., they are not reallocated at the end of the algorithm.

When failed links are repaired, re-optimization of the network can be triggered targeting at improving resource utilization by using shortest routes that include the repaired links and increasing the bitrate of those demands whose bitrate was squeezed during the restoration. The MF-AFRO problem can be formally stated as follows:

Given:

- a graph $G(N, E)$ representing the network topology and the availability of frequency slices in every link in E ;
- the characteristics of the installed SBVTs and the set F of modulation formats available;
- a set D of demands candidate for re-optimization, each with the requested bitrate.

Output: the SBVTs and the RSMA for each demand in D .

Objective: minimize the total unserved bitrate whilst minimizing the optical resources.

To solve the MF-AFRO, we propose a similar approach as that proposed for the MF-RESTORATION problem; the heuristic algorithm is presented in Table 5. In this algorithm we assume that graph G is updated with the current link availability. The algorithm finds a feasible lightpath for each of the demands that can convey, at least, the currently served bitrate (line 7 in Table 5). Once a feasible (hopefully shorter) lightpath is found, the selected slot is tried to be expanded to serve as much bitrate as possible targeting at serving the originally requested bitrate.

Table 4. MF_RESTORATION heuristic algorithm.

IN: $G(N, E), E_F, D$
OUT: $bestS$
1: $bestS \leftarrow \emptyset$
2: for each d in D do deallocate(G, d)
3: $E \leftarrow E \setminus E_F$
4: for $i = 1..maxIter$ do
5: $S \leftarrow \emptyset; G' \leftarrow G$
6: sort($D, random$)
7: for each d in D do
8: $p = \langle d, k, c_k, f_k, b_k \rangle \leftarrow \text{computeRMSA}(G', d, \text{minSlotWidth}, d.b_{req})$
9: if $p = \emptyset$ then continue
10: allocate(G', p)
11: $S \leftarrow S \cup \{p\}$
12: for each p in S do
13: if $p.b_k < p.d.b_{req}$ then
14: $p \leftarrow \text{expandSlot}(G', p, p.d.b_{req})$
15: Compute $\Phi(S)$
16: if $\Phi(S) < \Phi(bestS)$ then $bestS \leftarrow S$
17: return $bestS$

Table 5. MF-AFRO heuristic algorithm.

IN: $G(N, E), D$	OUT: $bestS$
1: $bestS \leftarrow D$	
2: for each d in D do deallocate(G, d)	
3: for $i = 1..maxIter$ do	
4: $S \leftarrow \emptyset; G' \leftarrow G; feasible \leftarrow true$	
5: sort($D, random$)	
6: for each d in D do	
7: $p = \langle d, k, c_k, f_k, b_k \rangle \leftarrow \text{computeRMSA}(G', d, \infty, d.b_{cur})$	
8: if $p = \emptyset$ OR $p.b_k < d.b_{cur}$ then	
9: $feasible \leftarrow false$	
10: break	
11: allocate(G', p)	
12: $S \leftarrow S \cup \{p\}$	
13: if NOT $feasible$ then continue	
14: for each p in S do	
15: if $p.b_k < p.d.b_{req}$ then	
16: $p \leftarrow \text{expandSlot}(G', p, p.d.b_{req})$	
17: Compute $\Phi(S)$	
18: if $\Phi(S) < \Phi(bestS)$ then $bestS \leftarrow S$	
19: for each d in D do allocate(G, d)	
20: return $bestS$	

4. CONCLUDING DISCUSSION

The IETF has recently standardized the Applications-based Network Operations (ABNO)-based [6] architecture, which supports in-operation planning. ABNO is based on several components, among which: *i*) the PCE is responsible serving incoming requests in thus, it must be in charge of for solving the RSMA problem for each of them individually; *ii*) the ABNO controller, implements workflows for each type of request from applications or the Network Management System. Specifically for in-operation planning problems that might require high computational effort, the PCE can be split into a front-end PCE and an in-operation planning tool, running as a back-end PCE, able to solve complex optimization problems, such as the MF-AFRO problem; and *iii*) the Operations, Administration, and Maintenance (OAM) handler is responsible for detecting faults and taking actions to react to problems in the network.

In such architecture, the MF-RESTORATION workflow should be triggered by the OAM Handler; after it receives failure notifications from the data plane and correlates them to locate the failure element(s). In contrast, the MF-AFRO workflow should be triggered by the NMS (manually or automatically) that issues a request to run the MF-AFRO workflow after a link has been repaired. In the request, the NMS must include the set of candidate demands subject to re-optimization with their originally requested bitrate.

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