Filter Optimization in SDN-based Flexgrid Networks

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Abstract: The novel super-filter technique for flexgrid optical networks is proposed to compact spectrum-contiguous lightpaths. The technique is applied in a specifically extended SDN architecture, showing significant gains in terms of spectral efficiency.

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1. Introduction

In flexgrid optical networks, spectrum efficiency is enabled by spectrum selective switches (SSSs), which are configured in order to minimize the spectrum reserved to each lightpath connection [1]. However, SSSs present non-ideal filter shapes [2]. Filter cascade effects may then strongly affect the overall lightpath optical reach or the maximum number of SSSs that can be traversed with adequate quality of transmission (QoT). To avoid detrimental filtering effects, a larger amount of spectrum could be reserved implying a waste of spectrum resources. Indeed, a large spectrum enables the transmitted signals to avoid the transition region of the filters and to safely operate on filter flat central region.

In this study, we propose a novel technique, called *super-filter*, aiming at reducing these detrimental effects and improve the overall network spectrum efficiency. A super-filter consists in the aggregation of multiple independent SSS filter configurations related to different lightpath connections that flow through common SSS output ports. Super-filters are suitable for Software Defined Networking (SDN) architecture thanks to its capability to directly perform independent SSS configurations [3]. On the other hand, super-filters could be more difficultly implemented in the context of PCE and GMPLS architectures where SSS resources are reserved according to head-end lightpath parameters. In this study, super-filters are introduced, evaluated and successfully implemented in a testbed controlled by a specifically enhanced SDN-based architecture.

2. Cascade of Spectrum Selective Switches

Fig. 1 shows three optical carriers traversing a cascade of filters. Each optical carrier consists of a 160Gb/s polarization multiplexing quadrature phase shift keying (PM-QPSK) signal transmitted at a baud rate of 40GBaud/s. Time-frequency-packing transmission technique employing low-density parity-check (LDPC) coding (with code-rate 8/9) and coherent detection is adopted as in [3]. The shapes of the filters are obtained from measurements on a commercially available LCoS-based SSS [2]. In particular, Fig. 1 shows the shape of three considered flexgrid-compliant filter configurations: S=25GHz (2 slices of 12.5GHz [4], Fig. 1a central carrier), 37.5GHz (3 slices, Fig. 1b) and 100GHz (8 slices, Fig. 1c) applied to the signal central frequency. In the last two cases, extremely flat performance is experienced in the central region of the filter. However, in all three cases, the transition bands are not negligible and the SSS presents non-ideal rectangular behavior, thus introducing distortions on the transmitted signal that need to be carefully evaluated. This is particularly evident in the case of S=25GHz, where the flat region is hardly visible (see Fig. 1a, central frequency).

Simulations have been conducted to investigate the propagation performance under these non-ideal filtering conditions. Cross-talk and cross-phase modulation during propagation among adjacent signals have also been considered. We focus on the performance of the central carrier, which traverses $N+1$ filters. The first filter is the one at the transmitter, which is always present and fixed to the narrow value of S=25GHz. The remaining N filters (emulating a cascade of N transit SSSs) are configured according to the specific scenario. With N=0 and back-to-back operation, post-FEC error free performance is achieved for OSNR as low as 14.5dB.

In Fig. 1a, a configuration of S=37.5GHz is applied to the left and right carriers. Instead, the central carrier traverses a filter cascade with only S=25GHz. Simulation results show severe transmission degradation. Post-FEC error free performance is experienced by the central carrier when up to $N=3$ filters are traversed (around 1,5dB penalty per traversed filter is introduced). That is, the propagation through $N=5$ filters with S=25GHz (as shown in Fig. 1a) results unacceptable. Indeed, excessive filtering distortions are experienced even with acceptable OSNR.

In Fig. 1b, the central carrier traverses a cascade of filters with S=37.5GHz (as for the other carriers). Propagation through $N=5$ filters results acceptable: the central carrier experiences post-FEC error-free performance, with an acceptable amount of around 2dB OSNR penalty with respect to the back-to-back operation. However, with respect to the previous case, the carrier requires larger resources, with a 50% increment of the spectrum reservation.

In Fig. 1c, all three carriers are transmitted through *S*=100GHz filter cascade. The spacing among the carriers is the one of Fig. 1a, i.e. the central carrier is transported as if only 25GHz are available between the left and right carriers. That is, the spectrum utilization is as efficient as for the case of Fig 1a (which however experiences unacceptable QoT). Propagation of the central carrier through *N=5* filters results acceptable, showing only 0.5 dB of OSNR penalty with respect to the back-to-back operation. Indeed, the filter shape is entirely flat in the considered region and no detrimental filtering effects are practically experienced.

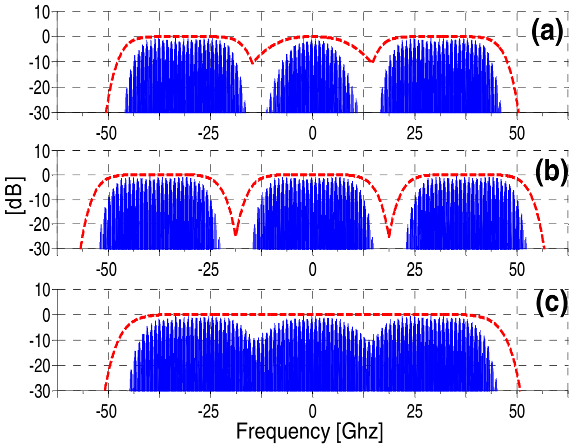


Fig. 1: PM-QPSK signals and actual LCoS filter shapes

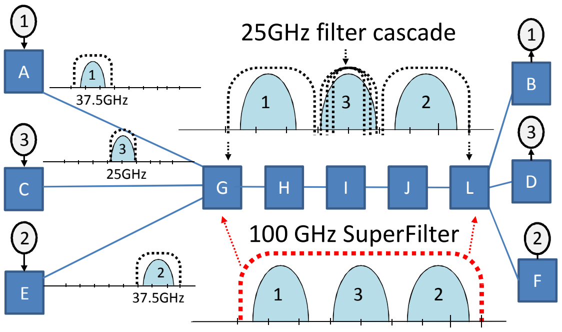


Fig. 2: Example of Super-filter application

3. Proposed super-filter technique

Fig. 2 shows two lightpaths *A-B* and *E-F* routed through transit nodes *G-L* (a broadcast-and-select architecture with one SSS per node is here assumed). Each lightpath occupies 37.5GHz of spectrum resources. An amount of spectrum of *S*=25GHz is available between the two lightpaths along transit nodes *G-L.*

A new lightpath request arrives from *C* to *D*. With traditional strategies, the path computation only accounts for the available *S*=25GHz along *G-L*. Given the aforementioned transmission performance through filter cascade, the *C-D* path computation fails along the considered resources and the request is rejected.

The proposed super-filter technique consists in a path computation strategy which specifically accounts for other existing lightpaths and in particular, for the actual configuration of SSS filters in the network nodes. That is, filter configuration is computed such that different lightpaths (e.g., with *different* source or destination nodes) can co-exist within the same flat region of a single filter configuration. With reference to the example above, when the new lightpath request arrives from *C* to *D*, the technique enables the path computation to also account for the whole SSS filter configuration in all candidate nodes. In particular, the path computation can also consider a unique filter configuration in nodes *G-L* among all three lightpaths. That is, the path computation can be successfully achieved with only *S*=25GHz of available spectrum resources. Indeed, a filter of value *S*=100GHz is computed and applied to all three lightpaths in transit *D-G* nodes, as shown in Fig 2 (bottom). Lightpath *C-D* then traverses a cascade of filters in their flat region, without experiencing significant transmission degradation along the *G-L* route.

Differently with respect to traditional networking solutions, also in case of tear down, the behavior is modified. If the *A-B* lightpath is torn-down, the SDN controller has to account for the presence of the considered *C-D* connection. Thus, all the *A-B* spectrum resources will not be completely released. In particular, a slice of 12.5GHz contiguous to *C-D* resources will be maintained reserved along *G-L*.

4. Super-filter implementation, OpenFlow extensions and experimental demonstration

A flexgrid network testbed with SDN control is utilized, derived from [5]. In particular, the testbed includes a specifically extended OpenFlow (OF) controller and OF-enabled node controllers operating on LCoS-based SSSs [2]. At the data plane, some nodes are emulated (the agreement between simulative and experimental studies on transmission performance was proved in previous studies, e.g. [6]). The testbed, which reproduces the topology shown in Fig. 2, aims at proposing and validating the control plane implementation of the proposed technique.

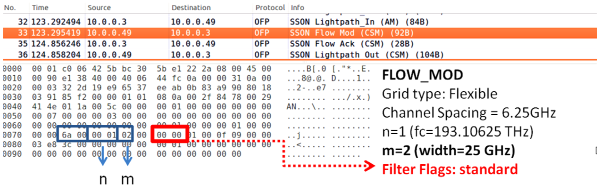
Once the request from source *C* to destination *D* arrives, the node controller at *C* sends a modified version of PACKET_IN message suitably designed for optical connections (now called LIGHTPATH_IN) to the OF-controller to request both path computation and lightpath set up. The message is extended for flex-grid optical networks [5, 7]. Upon message reception, the OF-controller computes the path *C* and *D*. The OF-controller exploits a physical path database (PPD) to have knowledge of the QoT experienced by the lightpath along the network for the considered modulation format (PM-QPSK in this paper). The stateful OF-controller also exploits a label switch path database (LSP-DB) storing the attributes of existing active lightpaths, including their routes and related SSS filtering configurations. This way, the OF-controller is able to account for filtering cascade effects as well as QoT parameters (e.g., OSNR) during path computation.

As described above, when super-filters are not considered, the OF-controller relies only on available network resources (i.e., 25GHz along *G-L*). Thus, the *C-D* request can not be computed along *G-L* due to unacceptable QoT.

On the other hand, by accounting for super-filters, the OF-controller successfully computes the path through those spectrum resources along *G-L*. In particular, the OF-controller accounts for the presence of contiguous spectrum resources reserved along the path and it computes their expansions to incorporate the new request. The OF-controller then communicates to the node controllers at *C*, *D* and to all the intermediate nodes along *G-L* to perform the lightpath setup. In particular, the OF-Controller sends FLOW_MOD messages extended for flexgrid networks to configure the optical switches, the transmitter and the receiver. The FLOW_MOD messages directed to the transit nodes change the filter configuration identified by the nominal central frequency (n) and the channel width in terms of frequency slices (m) [4]. In this study, the nominal central frequency has no more the meaning of actual central frequency of a specific signal, but is referred to the central value of the frequency filter to be enforced at the SSS-equipped nodes.

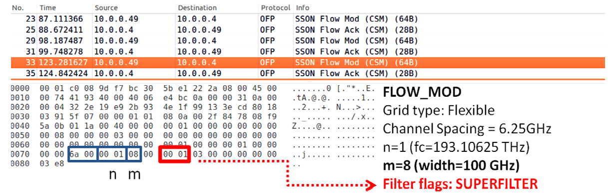
As shown in the Wireshark captures of Fig. 3 and 4, a spectrum reservation of 25GHz is sent by the OF-Controller (IP: 10.0.0.49) to node *C* and *D*, while 100GHz is configured in nodes *G* to *L*. In the latter case (Fig. 4), the novel flag SUPERFILTER is enclosed within the FLOW_MOD to bypass local filter contention and admission control and allow the filter overlap on the existing filters of *A-B* and *E-F* lightpaths. This way, the path is successfully activated. Note that no detrimental effects are induced on the adjacent *A-B* and *E-F* lightpaths during filter adaptations since the LCoS configuration is not modified at that frequencies.

If the *A-B* lightpath is torn-down, the OF-controller will not completely release the *A-B* resources. In particular, a slice of 12.5GHz contiguous to C-D resources will be maintained along *G-L*. To this extent, the FLOW_MOD of type "delete" will include the SUPERFILTER flag and will enclose the (n) and (m) values (different from those installed within the flow entry) corresponding to the portion of the filter to be released.


```
No.  Time        Source      Destination  Protocol  Info
  32 123.292494  10.0.0.3    10.0.0.49    OFP       SSON Lightpath_In (AM) (84B)
  33 123.295419  10.0.0.49   10.0.0.3     OFP       SSON Flow Mod (CSM) (92B)
  35 124.856246  10.0.0.3    10.0.0.49    OFP       SSON Flow Ack (CSM) (28B)
  36 124.858204  10.0.0.49   10.0.0.3     OFP       SSON Lightpath Out (CSM) (104B)

0000  00 01 c0 06 42 5b bc 30  5b e1 22 2a 08 00 45 00   ....B[.0 [."*..E.
0010  00 90 e1 38 40 00 40 06  44 fc 0a 00 00 31 0a 00   ...8@.@. D....1..
0020  00 03 32 2d 19 e9 65 37  ee ab 0b 83 a9 90 80 18   ..2-..e7 ........
0030  03 91 85 f2 00 00 01 01  08 0a 00 2f 84 78 00 29   ........ .../.x.)
0040  41 4e 01 1a 00 5c 00 00  00 01 00 00 00 00 00 00   AN...\.. ........
0050  00 07 00 00 00 03 00 00  00 00 00 00 00 00 00 00   ........ ........
0060  00 00 00 00 00 00 00 00  00 01 00 00 00 01 00 00   ........ ........
0070  00 00 6a 00 00 01 02 00  00 00 01 00 0f 09 00 00   ..j..... ........
0080  03 e8 3c 00 00 00 00 00  00 01 00 00 00 00 00 00   ..<..... ........
0090  00 00 00 00 00 00 00 00  00 00 00 00 00 00         ........ ......
```

FLOW_MOD
Grid type: Flexible
Channel Spacing = 6.25GHz
n=1 (fc=193.10625 THz)
m=2 (width=25 GHz)
Filter Flags: standard


```
No.  Time        Source      Destination  Protocol  Info
  23 87.111366   10.0.0.49   10.0.0.4     OFP       SSON Flow Mod (CSM) (64B)
  25 88.672411   10.0.0.4    10.0.0.49    OFP       SSON Flow Ack (CSM) (28B)
  29 98.187487   10.0.0.49   10.0.0.4     OFP       SSON Flow Mod (CSM) (64B)
  31 99.748278   10.0.0.4    10.0.0.49    OFP       SSON Flow Ack (CSM) (28B)
  33 123.281627  10.0.0.49   10.0.0.4     OFP       SSON Flow Mod (CSM) (64B)
  35 124.842424  10.0.0.4    10.0.0.49    OFP       SSON Flow Ack (CSM) (28B)

0000  00 01 c0 08 9d f7 bc 30  5b e1 22 2a 08 00 45 00   .......0 [."*..E.
0010  00 74 41 93 40 00 40 06  e4 bc 0a 00 00 31 0a 00   .tA.@.@. .....1..
0020  00 04 32 2e 19 e9 2b 93  4e 1f 99 13 3e cd 80 18   ..2...+. N...>...
0030  03 91 5f 07 00 00 01 01  08 0a 00 2f 84 78 08 f9   .._..... .../.x..
0040  5a 0b 01 1a 00 40 00 00  00 01 00 00 00 00 00 00   Z....@.. ........
0050  00 08 00 00 00 03 00 00  00 00 00 00 00 00 00 00   ........ ........
0060  00 00 00 00 00 00 00 00  00 01 00 00 00 01 00 00   ........ ........
0070  00 00 6a 00 00 01 08 00  00 01 03 00 00 00 00 00   ..j..... ........
0080  03 e8                                              ..
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FLOW_MOD
Grid type: Flexible
Channel Spacing = 6.25GHz
n=1 (fc=193.10625 THz)
m=8 (width=100 GHz)
Filter flags: SUPERFILTER

Fig. 3: Message capture at node-controller C (IP: 10.0.0.3)

Fig. 4: Message capture at node-controller G (IP:10.0.0.4)

Conclusions

The novel super-filter technique for flexgrid optical networks was introduced to reduce lightpath blocking or avoid over-reservation of spectrum resources during path computation. Results showed relevant spectrum efficiency improvements. OpenFlow extensions for flexgrid optical networks were proposed and successfully demonstrated.

The proposed super-filter technique opens the way for a new family of efficient routing and spectrum assignment solutions and re-optimization procedures, where lightpaths are routed trying to maximize the spectrum contiguity along common network segments.

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4. References

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