Flexible Survivability in Next-Generation Multi-Band Optical Transport Networks

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Abstract: We evaluate survivable network design options in the scope of C+L long-haul systems with high baud-rate channels. The analysis shows how design margins required for different failure response levels significantly affect resource and cost efficiency.

1. Introduction

Optical survivability mechanisms provide backup resources directly at layer-0, by offering alternate routes to protect or restore lightpaths in case of failures in e.g. fiber links. These mechanisms allow fast recovery and are most attractive in scenarios with large capacity and high-density transponders orchestrated by SDN control, which can better exploit the available backup resources such as spectrum or regenerators for each failure case [1]. Typically, optical resiliency can be achieved via protection or restoration, with the usual trade-off revolving around design costs vs. recovery speed. With optical protection, all backup traffic is pre-provisioned allowing fast switching in case of failures. In the case of restoration, backup channels are activated in response to failures, which is slower but allows more flexibility in network design, as backup spectrum and/or regenerators can be shared between services not affected by a single failure [2].

An additional aspect related to network resiliency is that failures in fiber links not only affect the traffic going through those links, but further cause transient effects in the network due to the immediate change in the power profile of the links downstream from the failure, as depicted in Fig. 1a. These effects can be quite detrimental to surviving channels, as the sudden power loss from affected channels leads to both amplifier and fiber responses that change the normal operating power levels of still running channels. While amplifier gain/tilt compensation can be quite fast, the fiber effect due to stimulated Raman scattering (SRS) accumulates more systematically over long paths and needs a larger time scale to be properly compensated as it depends on the specific pre/post-failure power profile. The power transfer from higher to lower frequencies leads surviving channels to experience sub-optimal launch powers into each span and can also result in low receiver power levels that induce penalties in the generalized signal to noise ratio (GSNR). These effects are magnified when considering systems operating beyond the standard C-band, as the power transfer due to SRS grows with the frequency distance between signal bands. Thus, as the example in Fig. 1b shows, the scale of difference in pre/post-failure path GSNR of surviving channels for each possible link failure can in the worst case be very significant given enough fiber spans systematically accumulating detrimental SRS effects [3].

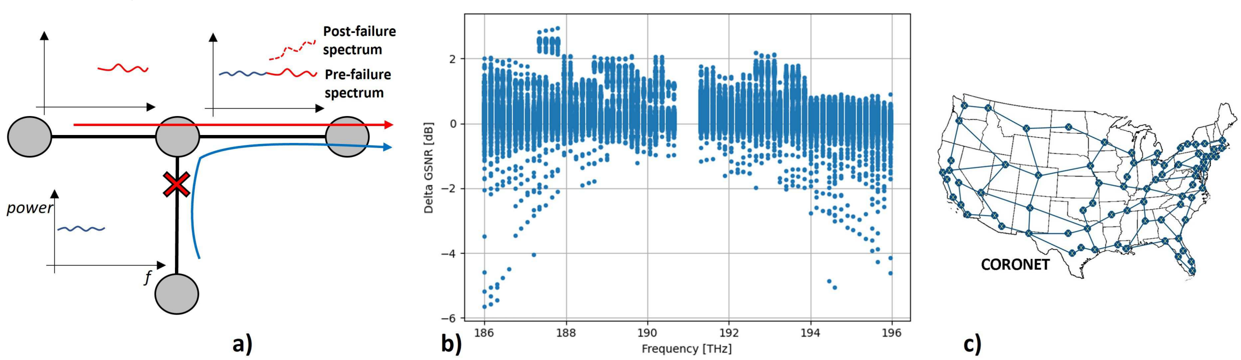

Fig. 1 – a) Link failure affecting power profile of surviving channels; b) Difference in pre/post-failure GSNR per frequency for each link failure; c) CORONET topology.

The system design consequence of these effects is that either they are acceptable, and as such surviving channels can experience a relatively short disruption until the line system can re-adjust (requiring active measurement and power level adjustment), or the surviving channels must have minimal or no interruption. The latter can be achieved by quickly stabilizing the power levels in the event of a failure, by means of replacing failed channels with an equivalent power source in each span/link. This requires a more complex line system capable of quickly phasing in noise to replace failed channels and involves operating the network continuously near full loading conditions.

The alternative is to ensure all channels are given enough margin that any SRS profile change due to a fiber break will not bring them below acceptable GSNR levels. This depends on analyzing the worst-case impact of a fiber break on all surviving channels, and results in having to provision less aggressive channel formats (or additional regenerators) due to the higher margins required.

In this paper, we analyze the optical interface requirements for optical protection/restoration when considering regular and transient-proof design margins for both C and C+L systems. The typical recovery speed vs. cost trade-off has a further layer added due to the different margins and interfaces that can be deployed. This is especially important considering new generation channel formats which are highly granular in channel rate/width, since operating at the most efficient format tends to result in lowering the average margins per channel [4].

2. Network Scenarios and Survivability Options

This analysis is focused on long-haul DWDM systems featuring a 4.8 THz C-band, or a 9.6 THz C+L band. We assume that the network is planned using either layer-0 line-side protection or shared optical restoration. In the former case, each lightpath signal is split via Y-cable towards the working and protection A/D ports, which means the format and wavelength must be common on both the working and protection paths. In the shared restoration case, a backup path is provisioned through the reconfigurable optical add/drop multiplexer (ROADM) network, and the source signal is switched to the backup path. Since this operation involves a temporary service disruption anyway, it also enables the transceiver itself to reconfigure the central frequency, baud-rate and/or modulation format (assuming the same payload). The ROADMs may also adapt the signal passband, thereby enabling different line formats to be used between working/protection paths. In the restoration case, the on-demand provisioning also allows both the spectrum and any regenerators used by backup paths to be shared by different channels, as long as they do not contend for the same resources in the event of a single fiber cut. We assume CDC ROADMs are employed, enabling dynamic switching between working/restoration paths. Channel formats employed can vary between 400/600/800 Gb/s with ~126Gbd in a 150 GHz window.

3. Design Margins and Planning Framework

The baseline performance modeling employs the generalized Gaussian noise model (GGN) to estimate the per frequency performance in each fiber link and the accumulated non-linear impairments in the link in the presence of SRS. The baseline case optimizes the channel launch powers assuming an end-of-life fully loaded system. The signal-to-noise-ratio (SNR) of each path is obtained by adding to the fiber contribution, the equivalent SNR of the add/drop amplifier and express nodes, assumed to be 38dB each. A system margin of 1dB is required to validate a lightpath. The baseline analysis yields the deployable path/format combinations in an instance where resiliency to fault-induced transients is not necessary, either because surviving channels may be temporarily affected, or it is assumed that fast noise loading is in place to mitigate the SRS effect. In order to estimate the required margins to ensure valid lightpaths can withstand any fault-induced transient, we simulated the post transient network state after each failure and assume the per frequency link GSNRs are the worst recorded case over all simulated failure scenarios. The new link GSNRs are used to produce a new set of valid lightpaths which are utilized to do the transient-proof planning.

Figure 2 shows an example of this process, depicting the difference in GSNR for each network link between the baseline and worst-case failure states (the biggest difference over all frequencies is shown). The average delta per link is 0.5dB for C-band only and 1.4dB for C+L, but can be quite significant for some of the links (where failures cause larger profile changes), up to 3dB in C-band and 8 dB in C+L.

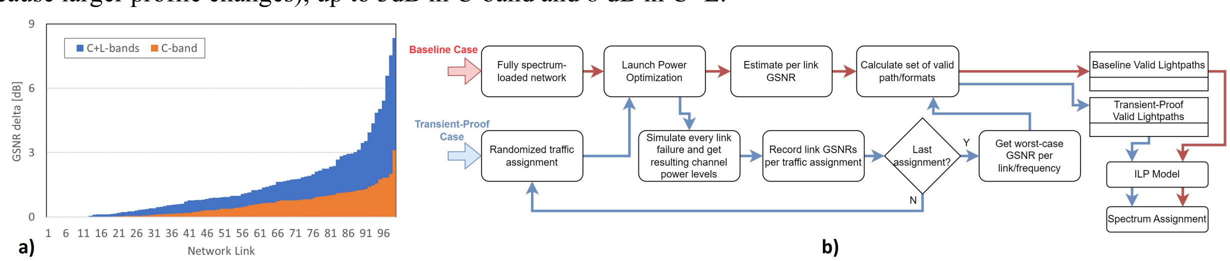

Fig. 2 – a) Link GSNR deltas between baseline and post-failure cases for C-band and C+L band; b) Lightpath validation and planning framework

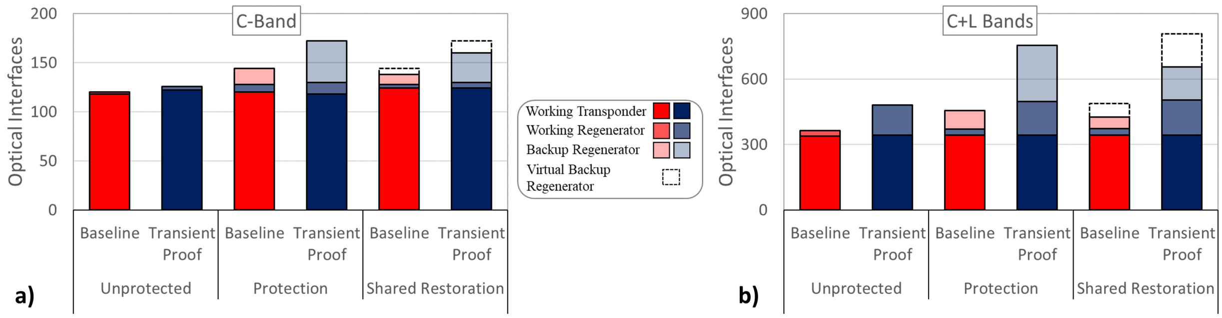

Fig. 3 – Optical interface counts per protection scheme and design margin for: a) C-band only; b) C+L-bands

Figure 2b shows the overall planning framework. The different sets of lightpaths for the baseline and transient-proof cases are given as input to an integer linear programming (ILP) model [5], which optimizes the interface count (transponders and regenerators) when serving a given traffic matrix with either optical protection or shared restoration. In the case of shared restoration, the model exploits sharing the backup regenerators to reduce the interface count. The output of the model is passed to a spectrum assignment routine which assigns channels to valid frequencies and solves wavelength continuity bottlenecks by adding regenerators sequentially [5].

4. Results and Discussion

The simulation work used the CORONET topology shown in Fig. 1c. Baseline and transient-proof valid lightpath sets were generated for C and C+L cases. For each of these cases, the optimization workflow was executed for protection and shared restoration, as well as a non-protected case only with working lightpaths for reference. A total of 45 Tb/s and 90 Tb/s of traffic are planned for C and C+L cases, respectively, divided over demand rates between 0.1 and 1.6 Tb/s uniformly distributed over all node pairs.

Figure 3 shows the interface counts divided over working transponders+regenerators, and backup regenerators. In the shared restoration case, the number of "virtual" regenerators is further shown, in order to highlight how many interfaces would be required if no regenerator sharing was in place. In Fig. 3a, the results for the C-band system are shown. In the baseline case, optical protection adds around 20% extra interface count, while shared restoration brings the extra resources down to 15%. When the transient-proof requirements are enacted, there is an additional 5%, 19% and 16% extra transponders needed in unprotected, protection and restoration cases, respectively. The C+L case depicted in Fig. 3b exhibits more pronounced differences. The added interface count between baseline/transient-proof scenarios is 32% for unprotected, 65% for protection and 54% for restoration use-cases. The worst-case magnitude of the SRS effect in the C+L case significantly curtails the set of deployable lightpaths, leading to an increased use of lower capacity formats and/or regenerators. The relative savings of restoration vs. protection are higher in the C+L case vs. C-only, mostly due to a more effective sharing of backup regenerators, which are much more plentiful in the former.

5. Conclusion

We studied how design margins are affected when considering resiliency to fault-induced transient events in C- and C+L-band long-haul networks. Considering worst-case SRS effects leads to much more stringent margin requirements in C+L deployments, which result in between 32-64% extra interfaces between unprotected and protected scenarios. These results suggest that as we move towards multi-band long-haul environments, high levels of resiliency against transient events become progressively more cost effective through enhancements to the line system (such as fast noise loading) than through stricter design margins.

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References

[1] Gangopadhyay et al., "5G-ready multi-failure resilient and cost-effective transport networks", JLT, vol.37, no.16, Aug 2019
[2] Kim et al, "Regenerator predeployment in CN-ROADM networks with shared mesh restoration", JOCN, vol.5, no.10, Oct 2013
[3] Semrau et al, "The gaussian noise model in the presence of inter-channel stimulated Raman scattering", JLT, vol.36, no.14, Jul 2018
[4] Eira et al, "On the effect of in-band crosstalk margins for optimized format selection in meshed optical networks", ECOC, Sep 2019
[5] Eira et al, "On the comparative efficiency of next-generation coherent interfaces for survivable network design", DRCN, Apr 2021