Design of low-margin optical networks

Yvan Pointurier
Bell Labs, Alcatel-Lucent, Nozay, France
yvan@ieee.org

Abstract: We review margins used in optical networks and show how they can be reduced through proper design to increase network capacity; flexible optoelectronic nodes coupled with optical monitoring are key to fully leverage network margins.
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1. Margins in optical transport networks

Significant margins are considered as mandatory to ensure that an optical network supports the planned demand capacity during network deployment or when deploying a new service (a lightpath) virtually error-free during operation over the full network life, which may span several decades. At the optical layer, the margin of a lightpath may be quantified as the difference between the actual quality of transmission (QoT) metric (e.g., electrical or optical signal to noise ratio (SNR/OSNR), Q^2-factor, reach, bit error rate) of the signal supporting the lightpath, and the threshold above which the signal is deemed recoverable error-free (i.e., the Forward Error Correction (FEC) limit). In [1], Augé proposed the following margins taxonomy: system margins (thereafter, S-margins), unallocated margins (U-margins), and design margins (D-margins).

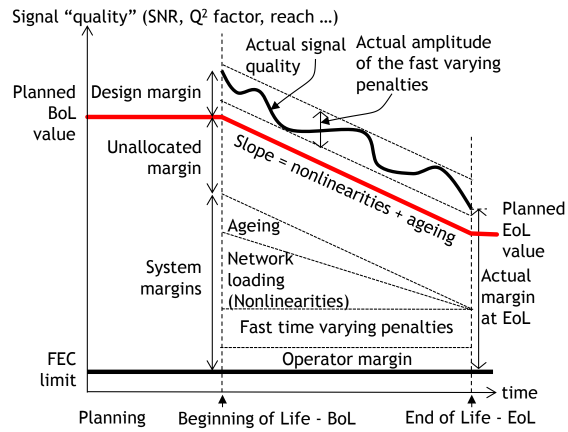

Figure 1: Margins and their evolution in a transport optical network.

In this paper, we first review margins types, their key characteristics and their typical values. We then explain how each type of margin can be reduced through careful network planning, using a combination of flexible equipment (transponders (TRX), optical and electronic switching fabrics) for the U- and S-margins, and monitoring for the D-margins. Last, we outline the upcoming challenges to design and operate a low-margin network.

S-margins account for time-varying network operating conditions. S-margins include fast varying impairments such as polarization effects, and slow varying impairments; the latter are due to either increasing channel loading during the network life, which translates into additional nonlinearities, or to network equipment ageing: increasing fiber losses due to splices to repair fiber cuts, degrading amplifier noise factor, and detuning of the lasers leading to misalignment with optical filters in the intermediate nodes. S-margins may include an additional operator margin [1]. S-margins define the minimum quality value of the signal to be met at network Beginning of Life (BoL).

U-margins encompass both the capacity and reach margins, i.e., the difference of capacity/reach between the demand and that of the equipment, in particular the TRX that are really deployed. U-margins result from the discrete datarate and reach granularity of commercial transmission equipment.

D-margins are the difference between the planned BoL value and the real value of the quality metric, and are due to the inaccuracy of the design tool used to evaluate the QoT of all signals during network planning, which stem from 2 main sources: the inaccuracy of the inputs of the QoT model, and the inaccuracy of the QoT model itself.

Margin evolution with time is illustrated in Fig. 1 and typical values can be found in Table 1. As an example, assuming a 600 km long lightpath carrying a 100G PDM-QPSK signal with soft decision FEC active for 10 years in a network with route-and-select optical crossconnects (i.e., 2 filters per intermediate node), 100 km fiber spans of

Table 1: Margin types and typical values

Margin type	SNR Margin	Margin type	SNR margin
Unallocated margins (U)	Several dB	Fiber ageing (cuts) (S)	1.6e-3 dB/km/year (OSNR) [4]
Design margin (D)	<2 dB [1]	Nodes ageing (filtering) (S)	0.05 dB / filter [5,6]
Nonlinearities (S)	1.5-3dB [2]	Transponder ageing (S)	0.5 dB [6]
Amplifier NF ageing (S)	0.7 dB [3]	Fast variations (S)	0.4 dB [7]

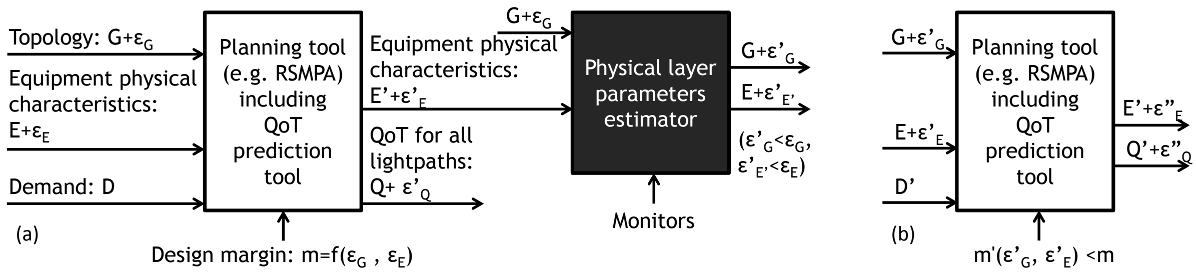

Figure 2: Design margin reduction with monitoring. (a) Training phase; (b) Estimation phase.

standard single mode fiber with no in-line dispersion compensation, 1 node every 100 km, and amplifier noise factor of 4.5 dB. Assuming 2 dB (SNR) margins for the nonlinearities, the S-margin is 4.7 dB. At BoL, assuming a completely unloaded system and using the model in [8] and accounting for penalties of 1 dB for TRX and 0.03 dB per filter, the reach of such a system is ~7100 km resulting in a combined U- and S-margin of 10.7 dB, i.e. a U-margin of 6 dB. We assume a D-margin of 1 dB, resulting in an 11.7 dB SNR margin at BoL. Assuming that components have aged as planned (typically a worst case) and that the network is fully loaded, the S-margins ideally amount to 0.4 dB (i.e., fast varying effects) at network End of Life (EoL), for a total EoL margin of 7.4 dB.

2. Flexible equipment for unallocated and system margin reduction

As explained in [1], U-margins are not known until the network is deployed, and thus can only be leveraged after deployment or on network upgrades. U-margins may be partially or even completely used through the utilization of a rate-flexible transponder (flex-TRX), which adjusts its datarate to the targeted reach. Coarse granularity flex-TRX (e.g., 100/200/400G) will use only part of the U-margin, while fine granularity flex-TRX (leveraging for instance time hybrid QAM or 4-D modulation formats) [9,10,11] may use all of it.

S-margins are also known after network deployment, and may vary with time. Fast time varying effects that are not directly mitigated through TRX digital signal processing may be translated into capacity only at the expense of reduced network resilience, or to time-varying transported capacity which may temporarily be below the demand.

Slow varying effects such as nonlinear effects, which increase as new channels are lit, and component ageing, are more predictable, and may be leveraged when upgrading the network. To fully leverage S-margins stemming from network loading (i.e., from nonlinear impairments), careful power allocation is required; in fact, each lightpath may have its own modulation and power, leading to a RMSPA (routing, modulation, spectrum, power allocation) network design problem. At the lightpath level, [12] shows that, when accounting for the exact link load, the reach for a standard PDM-QPSK signal is almost double at BoL compared with EoL; the highest reach gains are achieved in lightly loaded networks when nonlinearities are smaller, i.e., in the early stages of the life of the network. At the network level, the supported traffic capacity increase through leveraging the (nonlinear) S-margin yields a capacity gain of ~30% for a continental network, while the joint exploitation of the U- and S-margins (nonlinear effects only) reaches 60% [2]. Authors in [13] find similar results for continental networks.

Furthermore, margin reduction through equipment data rate variation enables to use costly equipment at maximum capacity upon network deployment, and to delay investments to later stages of the network life to benefit from equipment cost erosion [14]. The impact of such multi-year network planning is further studied in [6], where slow variations only account for ageing (typically 2 dB in a national network).

3. Monitoring for design margin reduction

D-margins come from the uncertainty of both the QoT estimation tool, and of the inputs of the tool, which include topological information (link attenuation, chromatic dispersion map …) and network equipment characteristics (amplifier noise factor, filter alignment …). Those 2 effects are fundamentally difficult to separate and their compounded impact is only known at deployment time. It is, however, possible to reduce the QoT tool inputs uncertainty through monitoring techniques, in order to make more accurate QoT prediction for new lightpaths during network upgrades. Consider the 2-step process illustrated in Fig. 2. A resource allocation tool (e.g., RMSPA) is used at network planning time, with imperfect knowledge of the topology $G+\varepsilon_G$ (where G abstracts the actual physical topology e.g. link lengths, dispersion map,… and ε_G quantifies the uncertainty on G) and imperfect knowledge of the deployed equipment characteristics $E+\varepsilon_E$ subject to traffic demand D. Uncertainties are accounted for a resource allocation algorithm via D-margin $m=f(\varepsilon_G,\varepsilon_E)$; these margins can be pre-defined or dependent on each lightpath, e.g. longer lightpaths may be associated with higher margin as in [15]. After the network is deployed, D-margins are known and may be mitigated with flexible equipment as with the U- and S-margins, however, any new lightpath will still be subject to the original D-margin. To avoid this, it is possible to leverage the wealth of path-level monitoring information made available by coherent receivers almost for free, including received power, residual chromatic dispersion, noise level, and polarization [16]. This additional information can be used to feed a "physical layer parameters estimator", which goal is to refine the knowledge of the underlying physical layer (Fig. 2a) and thus decrease (ε_G, ε_E) to (ε'_G,ε'_E). The network planner will then be able to use a lower D-margin $m'(\varepsilon'_G,\varepsilon'_E)$ when establishing a new lightpath upon a network upgrade (Fig. 2b). Observe that QoT estimators typically require link-level characteristics while coherent receivers yield path-level measurements; link-level metrics may be obtained via correlation techniques such as network kriging [17] when the characteristics are linearly additive (i.e. addition of link-level metrics yields path-level metric), or more advanced techniques such as machine learning, which are better adapted to nonlinear network characteristics [18].

4. Challenges

Although designing low-margin networks can result in a clear network capacity increase (60%, not accounting for the D-margin [2]), translation into CAPEX gains will prove challenging for the following reasons. First, margins are highly fragmented, despite the total margin reaching an appealing 10 dB or even more, as mentioned in the example above. The U-margins (several dB) are easier to leverage, essentially requiring flexible transponders. Within the S-margins, the fast variable component (a fraction of a dB) will be difficult to leverage, as either a fast variable transponder, or a fast reconfigurable network infrastructure, would be needed. Ageing excluding nonlinearities may reach 3-4 dB, which can only be exploited with proper monitoring. Network loading (nonlinearities) may amount to another 3 dB, but exploiting them requires fine, difficult per-wavelength power tuning. Mitigating D-margins, which account for less than 2 dB, requires advanced monitoring and control plane support for information correlation [19].

Hence, a flexible network infrastructure is required to fully exploit most margins. Deploying flexible interfaces and varying their capacity with time, however, means that the interfaces' client and WDM sides should be independent. Indeed, demands (on the client side) should be met even when the interface WDM rate changes to adjust to a varying margin. Multilayer nodes that are able to dynamically map electronic resources to optical resources are thus needed. Electronic switching, in addition to the optical transmission equipment, should therefore be provisioned appropriately. This calls for multilayer (electronic and optical), multi-year (accounting for foreseeable ageing such as nonlinearities) routing, spectrum, modulation format, power allocation algorithms relying on monitoring information to constantly adjust network capacity and capacity prediction to the true network state.

5. Conclusions

Network margins, although plentiful, require a variety of technologies to be fully exploited and translated into additional capacity: flexible reconfigurable equipment, multilayer electrical/optical nodes and transponders, monitoring, multi-year dimensioning algorithms that can adjust the power of each lightpath and (scalable) support from the control plane. Although many of those blocks already exist at least at the research level, using them in real networks is still considered as a tremendous operational challenge.

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