Design of Low-Margin Optical Networks

OFC 2016 – Paper Tu3F.5 (invited)

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Agenda

1. **Margins**
2. Reduction of system margins
3. Reduction of unallocated margins
4. Reduction of design margins
5. Conclusions

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Margins and design of optical networks

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- Margins
  - Trade cost for reliability
    - "margin of safety" = $\frac{\textbf{failure load}}{\textbf{design load}} - 1$
    - buildings: 100%; cars: 200%; planes: 20-200%
  - (Limited) margins are wanted by customers
- Design of optical networks
  - Green-field: given nodes, links, traffic demand → allocate resources (equipment: optical transponders, types of transponders, regenerators, IP ports) to minimize some cost metric (CAPEX)
  - Brown-field: allocate new traffic demands to minimize cost metric

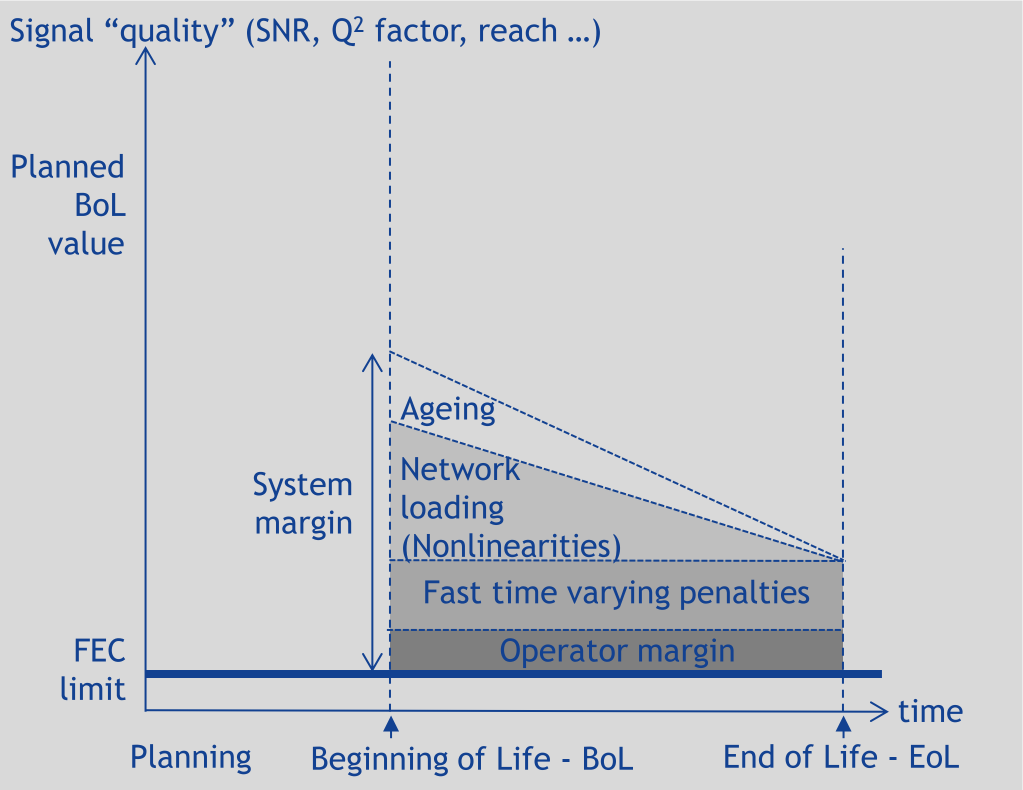
- How to decrease margins when designing a network?

Margins

System margin

Most data from:
Augé (Orange), OFC 2013, OTu2A.1
Pesic et al. (Bell Labs), OFC 2016, M3K.2

- [? dB] Operator margin
- [0.4 dB] Fast time-varying penalties
  - Typically: polarization effects
  - Use worst-case
- Slow time-varying penalties
  - [1.5-3 dB] Varying network load → varying nonlinear effects
  - [several dB] “Ageing”:
    - [0.7 dB] Amplifier noise figure (NF)
    - [1.6e-3 dB/km/year] Additional losses due to splices after fiber cuts
    - [0.05 dB/filter] Filter misalignment due to laser detuning
    - [0.5 dB] Transponder



Margins

Unallocated margin

Unallocated margin

=

theoretical perf. of equipment

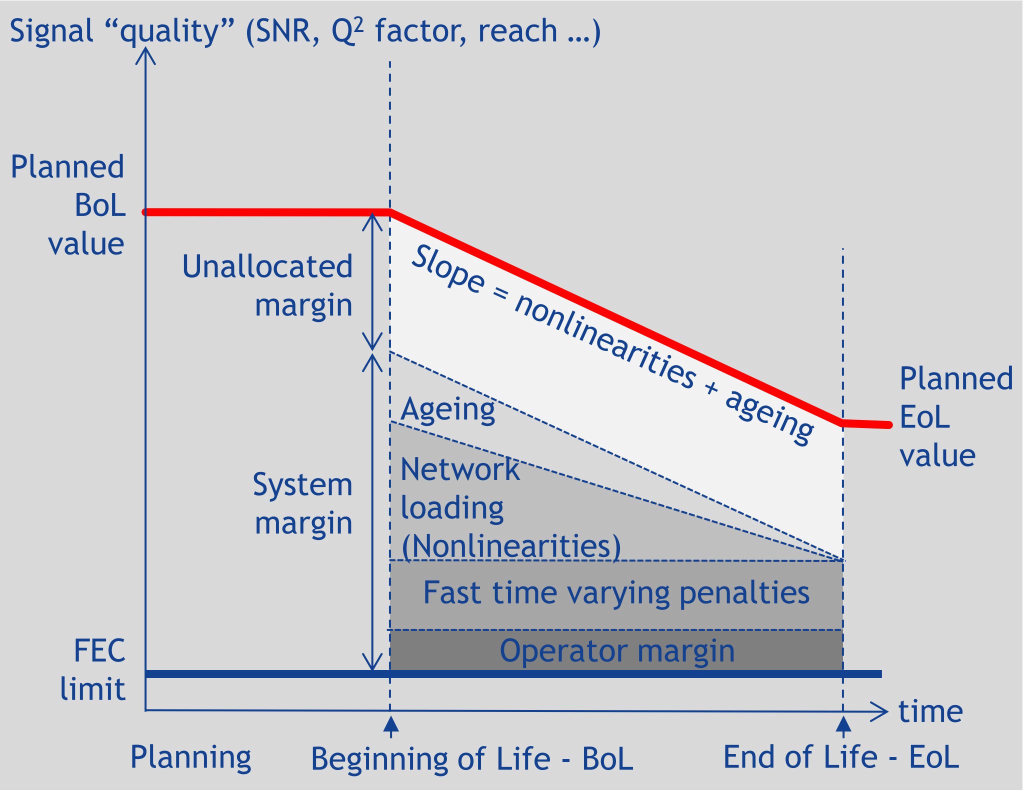
-

perf. really needed to satisfy demand

- Need reach (SNR) = x km (y dB) for demand of z Gb/s but equipment can provide x'>x km (y'>y dB) SNR

  → Unallocated margin (dB) = y'-y

- Driven by discrete granularity of equipment performance



Margins
Design margin

Design margin

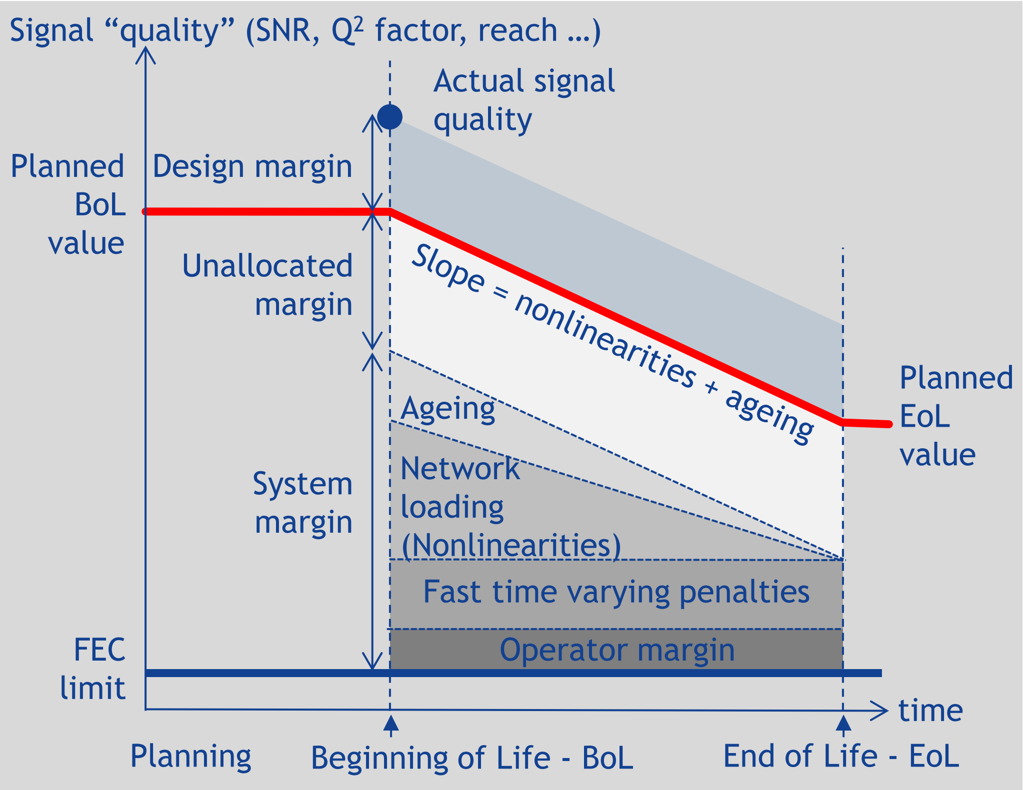
=

real performance on the field

-

planned performance

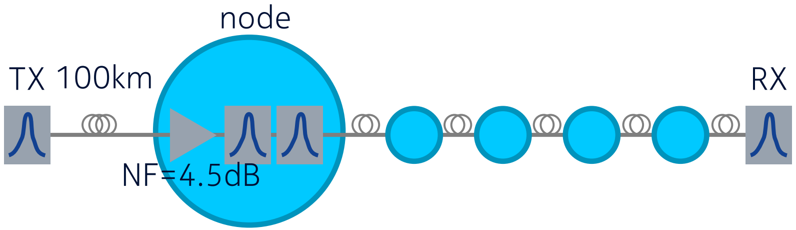
- Sources:
  - Inaccuracy of the **physical layer models** underlying the Quality of Transmission (QoT) tool
  - Inaccuracy of the **inputs** of the Quality of Transmission (QoT) tool
  - Estimation: <2 dB

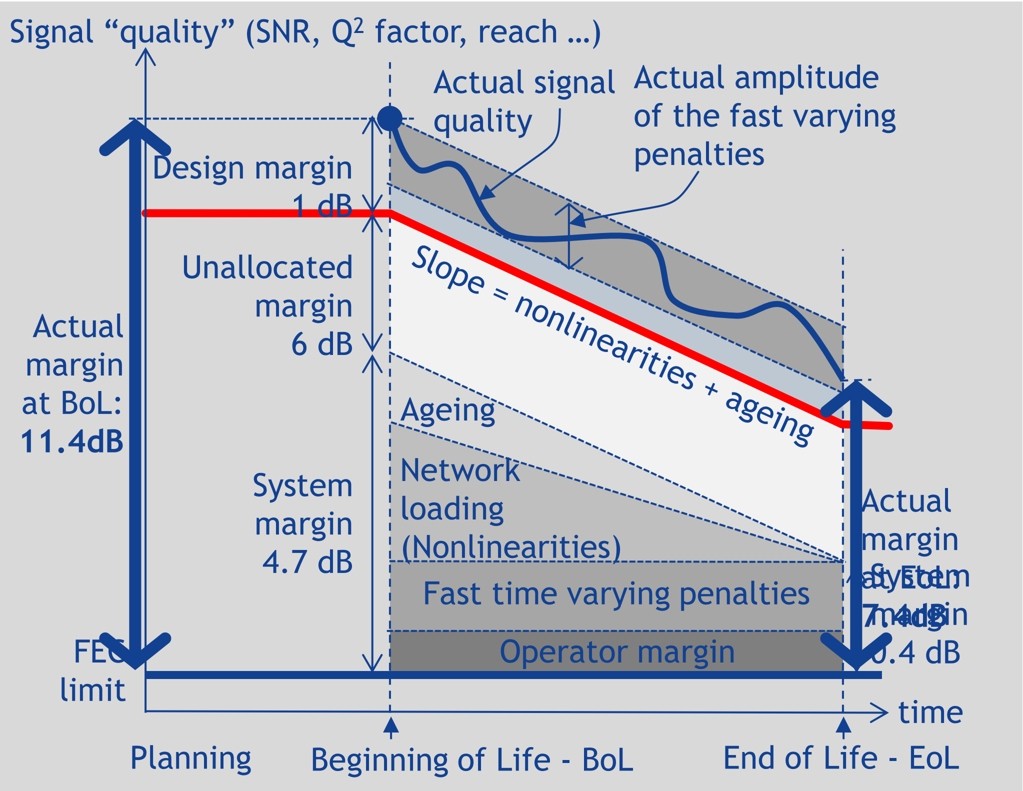


Margins

An example

- Consider the 600 km path below with a 100G PDM-QPSK lightpath
  - System:
    - BoL: 4.7 dB (0.4 dB fast varying penalties, 2.3 dB slow ageing, 2dB nonlinearities)
    - EoL: 0.4 dB (fast varying penalties)
  - Unallocated: 6dB (unloaded reach=7100 km)
  - Design: 1 dB (assumed)
  - **Total: 11.7 dB @ BoL, 7.4 dB @ EoL**





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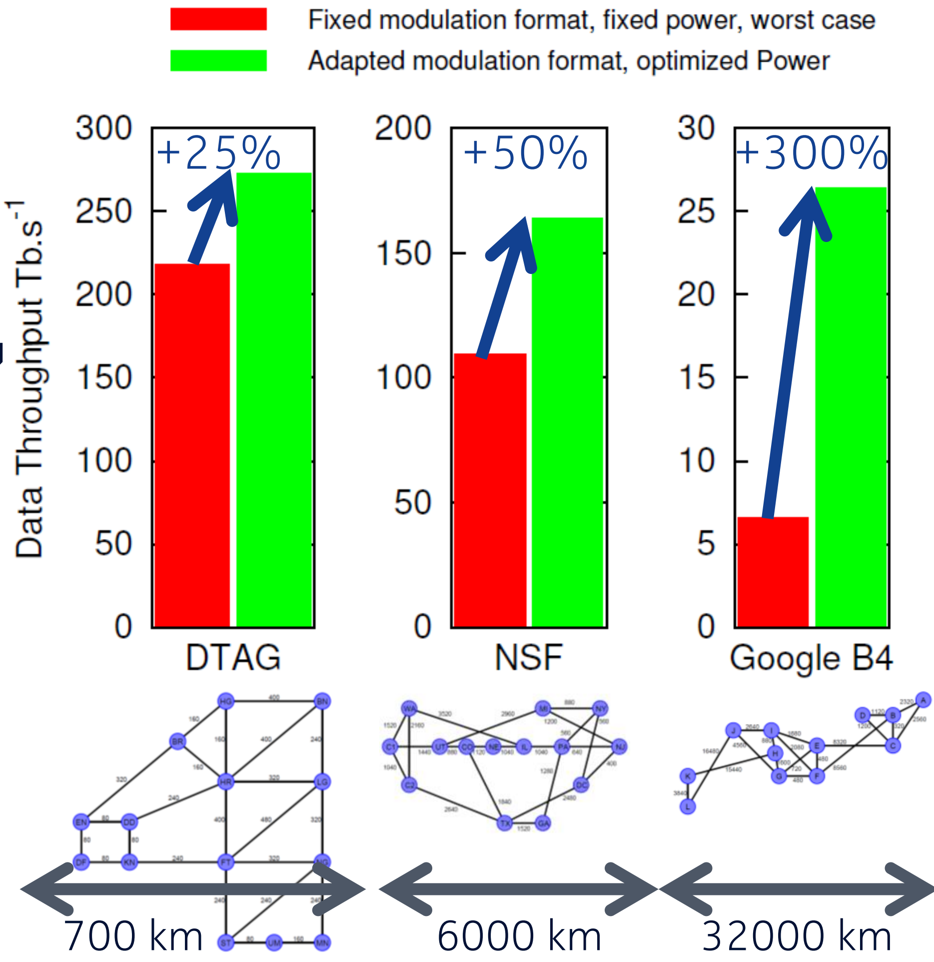
System margin
Load

- **Target:**
  - network capacity ↗ (green field)
  - decreased or delayed investment; network life ↗
- **Method:** power, spectrum, rate allocation
- **Gain:** +25-300% capacity (depending on network diameter)
- **Requirement:** flex-grid and rate TRX/ROADMs; control plane.
- **Possible improvement:** flex-grid, multi-layer
- **Challenges:** very fine (per-lightpath) power management; requires network re-optimization during operation

D.J. Ives et al., PNC, 29 (3), 2015; Bononi et al., NOC 2014.



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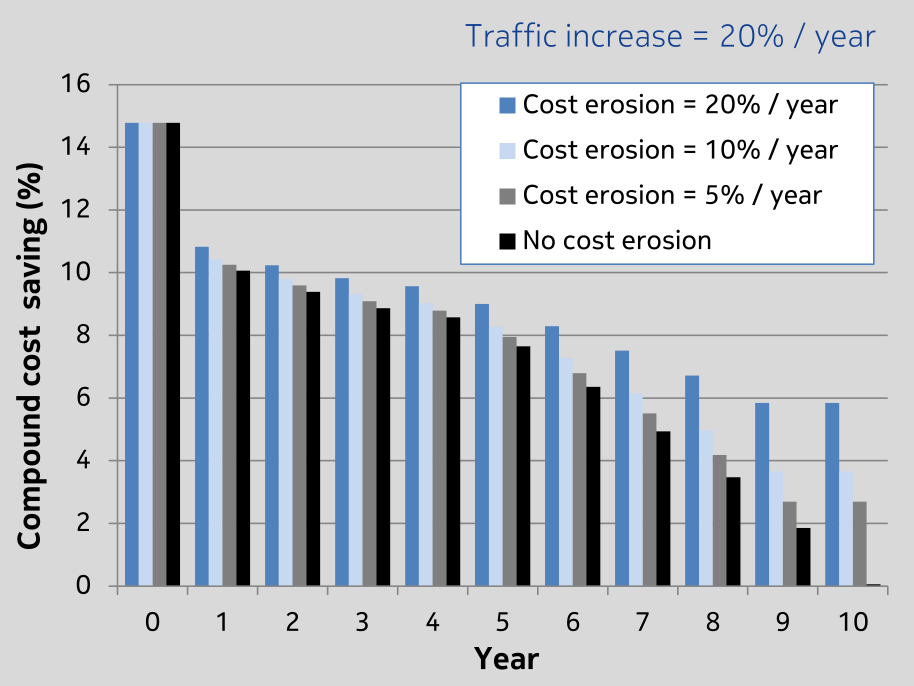
Pesic et al, OFC 2016, M3K.2

System & unallocated margins
Ageing & unallocated

- **Target:**
  - decreased or delayed investment
  - increase network capacity during first years of operation
- **Method:** routing, spectrum, mod. *multi-period* allocation
  - change modulation + deploy new equipment as network ages and traffic increases
  - lightpath datarate may change → leverage unallocated margin
- **Sample study:**
  - System margins around 2 dB (ageing)
  - Nonlinear effects: worst case – fully loaded links
- **Gain:** -10% TRX cost during first few years – few % at EoL
- **Requirement:** control plane, flex-grid and rate TRX/ROADMs
- **Possible improvement:** flex-grid, multi-layer, account for network load (nonlinear effects)
- **Challenges:** change signal rate during network operation



See also Dupas et al., OFC 2016, Th3I.1 – Hitless 100 Gbit/s OTN Bandwidth Variable Transmitter for SDN

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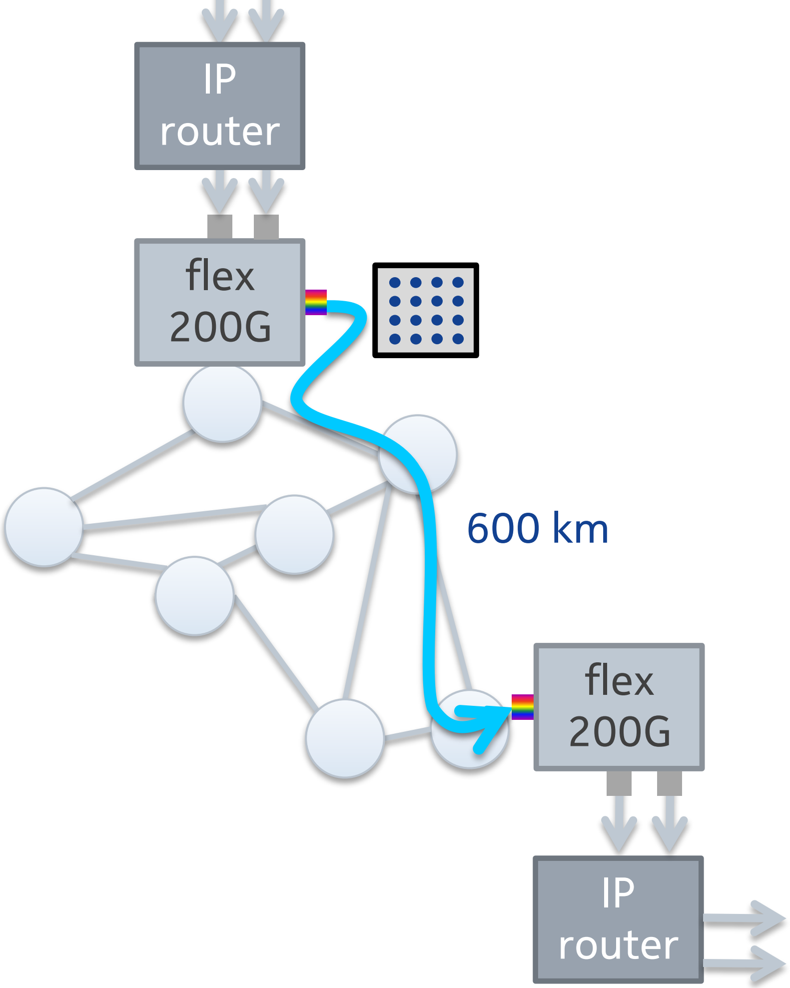
Unallocated margin
Traffic growth

- **Target:** network capacity ↗, network cost ↘
- **Method:** (multilayer) rate allocation
- **Gain:** TBD
  - Note: previous multi-year study also leveraged unallocated margins
- **Requirement:** multilayer control plane, flex-rate TRX
- **Challenges:** optical TRX at high rate deployed at commissioning; online re-allocation



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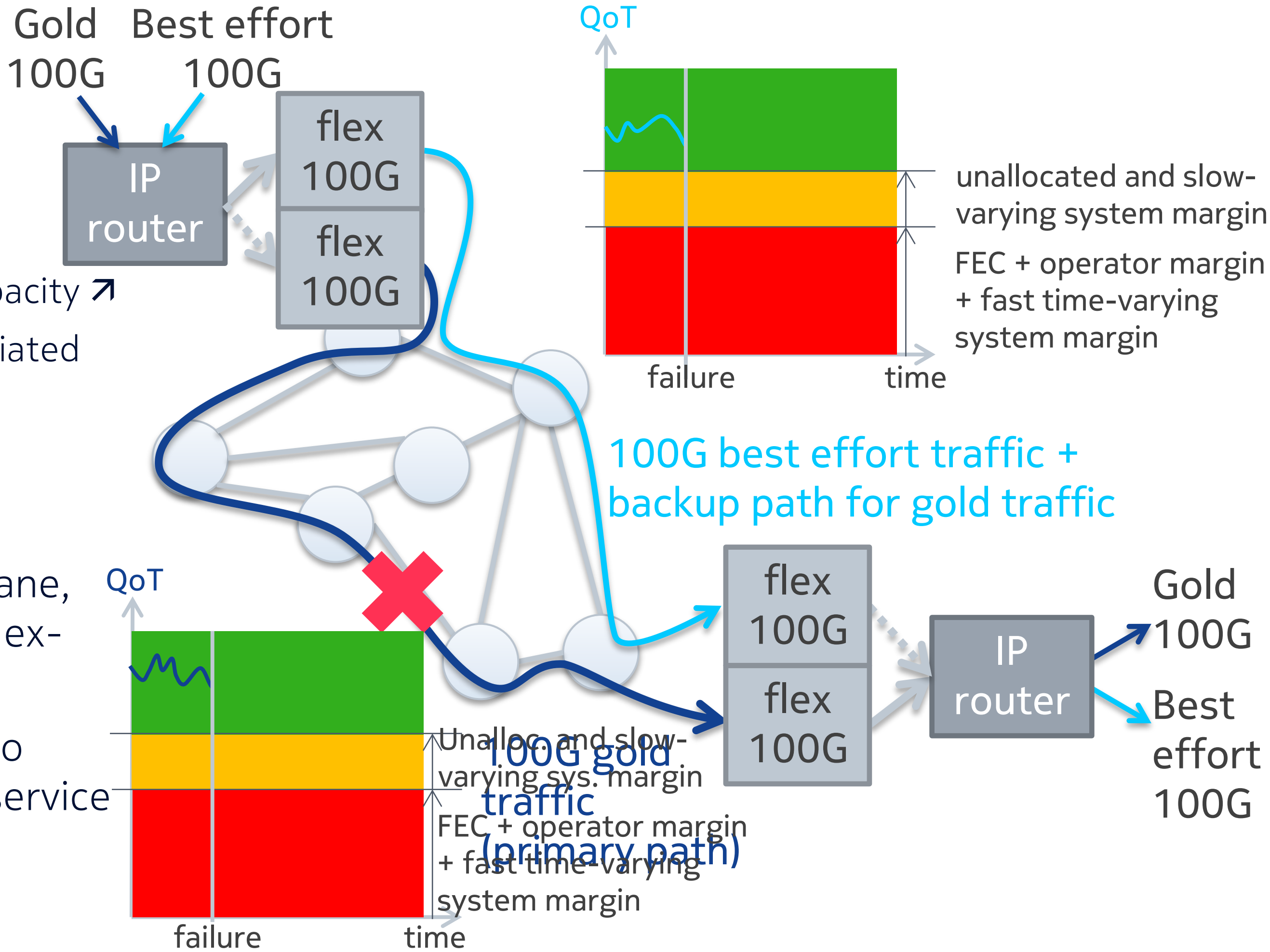
Unallocated margin
Protection

- **Target:**
  - (brown field) network capacity ↗
  - protection with differentiated classes of service
- **Method:** rate allocation
- **Gain:** TBD
- **Requirement:** control plane, IP/optical cooperation, flex-rate TRX
- **Challenges:** willingness to differentiate classes of service



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Unallocated margin

Protection

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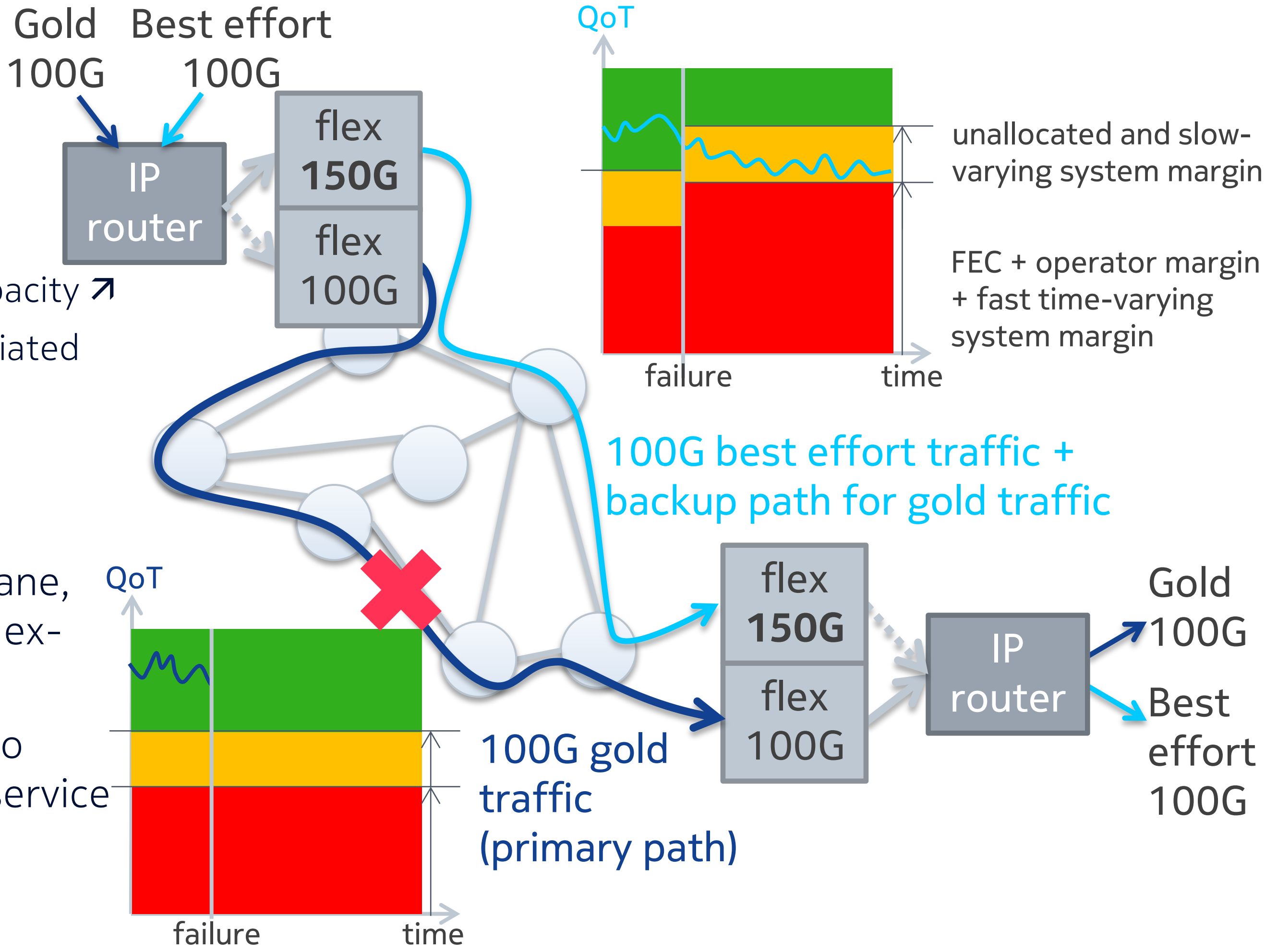

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Design margin
Monitoring

- Uncertainty on Quality of Transmission models (assuming perfect inputs)
  - Ongoing work in many teams
  - Always include more effects, more inputs: per-channel power, interactions of channels with different modulation formats, etc.
  - More inputs → more knowledge of physical layer is needed
  - Some inputs can be set or measured and considered as known ("perfect") at network deployment; for the other inputs…
- Uncertainty on Quality of Transmission inputs
  - Some inputs are not or cannot be known prior to network deployment
    - Sometimes even seemingly straightforward inputs (fiber type or length, dispersion map …) are not known!
    - Exact characteristics of network equipment cannot be known prior to deployment
  - On-the-field measurements (monitoring) only helps in brown-field scenarios

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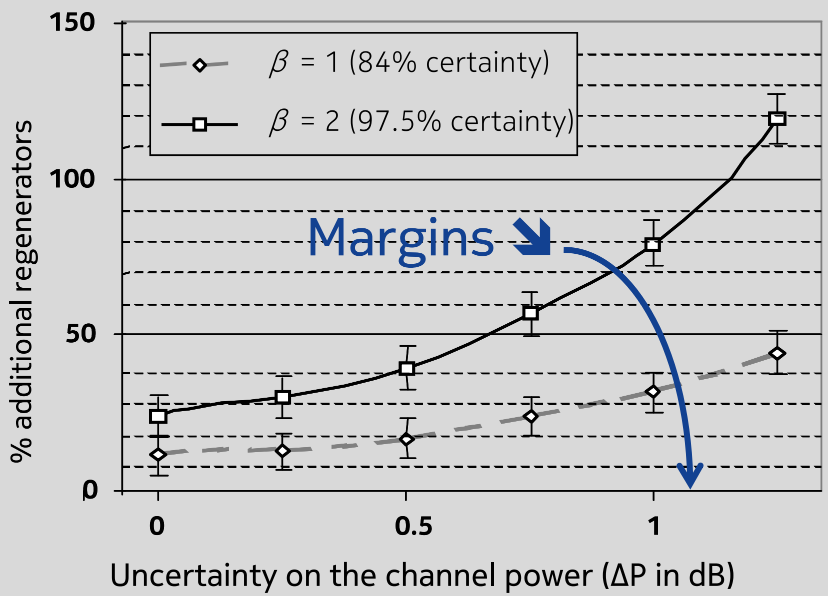
Zami et al., BLTJ
***14** (4), 2010*

Design margin
QoT inputs

- **Target:**
  - (brown field) network capacity ↗, network cost ↘
  - lightpath establishment, network re-optimization
- **Method:** spectrum allocation
- **Gain:** +10-120% regenerators (10G OOK network)
- **Possible improvement:** flex-grid, multi-layer, multi-rate
- **Requirement:** knowledge of the network
- **Challenges:** margin estimation, probabilistic design

Reference: QoT > $QoT_{FEC} + m_0$ (no uncertainty)
Proposed: QoT > $QoT_{FEC} + \beta.m(\Delta P$, lightpath)



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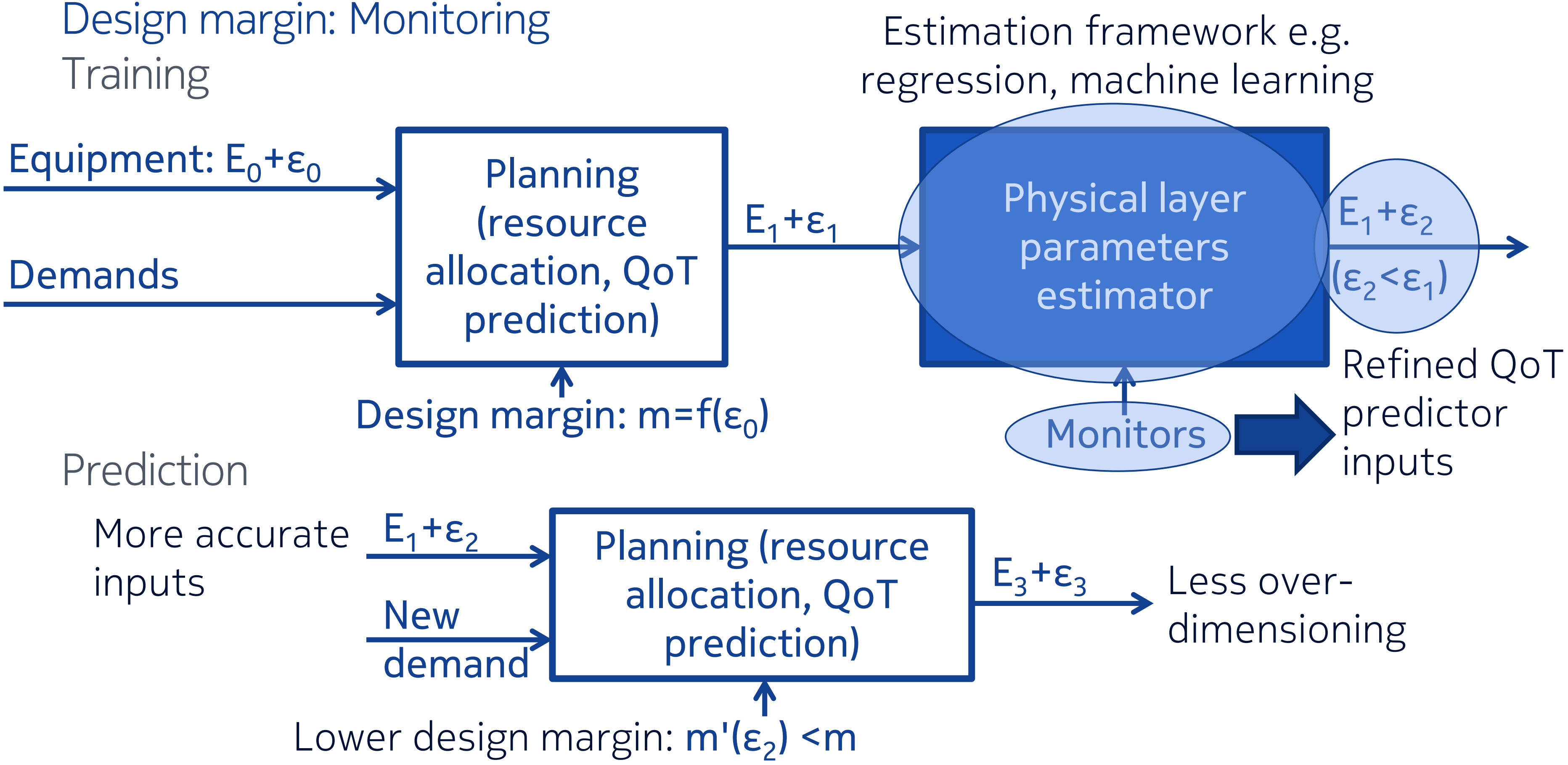
Design margin: Monitoring



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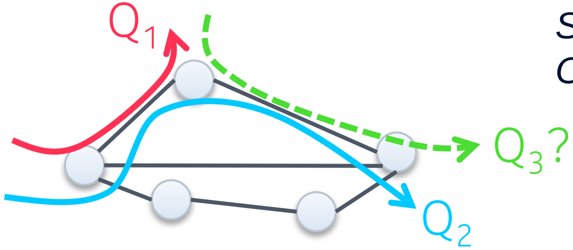
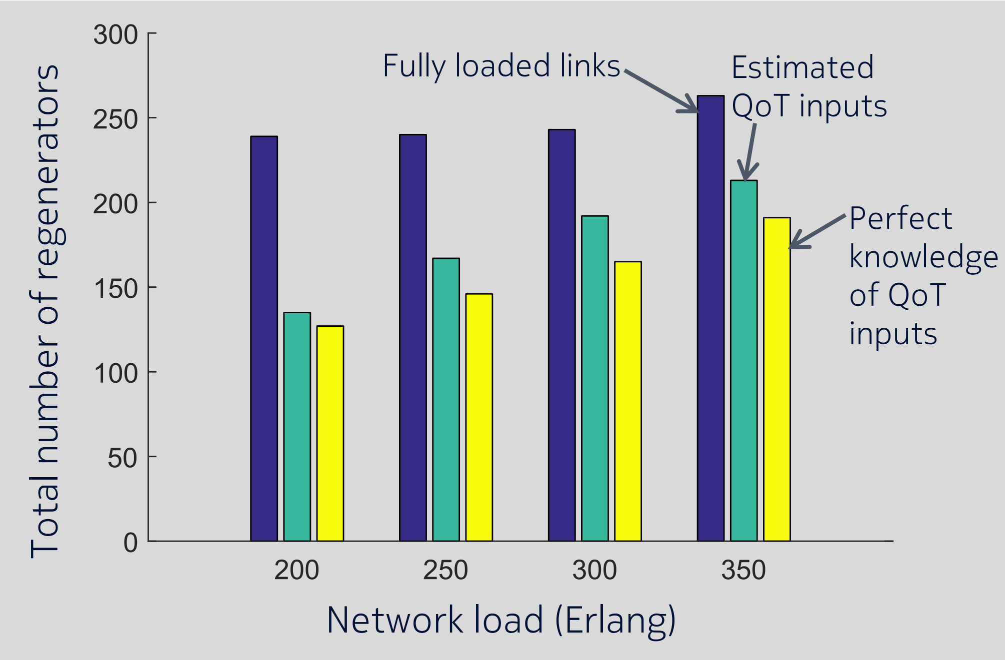
Design margin

QoT inputs

Sartzetakis et al, OFC 2016, Tu3F.2



- **Target:** (brown field)
  - network capacity ↗, network cost ↘
- **Method:** monitoring, estimation framework, spectrum allocation on lightpath establishment and network re-optimization
- **Gain:** up to #regenerators / 2
- **Possible improvement:** flex-grid, multi-layer, multi-rate
- **Requirement:** monitoring, control plane
- **Challenges:** margin estimation (accurate monitoring), probabilistic design, online re-allocation



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Conclusions

- Different types of margins → different impacts
  - Commissioning (green-field) network cost
  - Upgrade (brown-field) network cost
  - Longer network life

  } → Total cost of ownership
- Addition of small gains to lead to substantial overall gains
- Most key building blocks are available (or close)
  - Flex-everything, (most) monitors, control plane
- Not a free lunch
  - per lightpath power settings
  - dynamics / online re-optimization
  - (more) monitors
  - (more) complex control plane

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Bell Labs recruits!

Researcher positions available.

Contact: yvan@bell-labs.com

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