Cross-layer optimization: network cost vs. physical layer margins

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Overview

- Motivation
- Reducing NLIs margins
  - Physical layer model
  - Network performance evaluation
- Recent study: aging effect
- Conclusions

Motivation

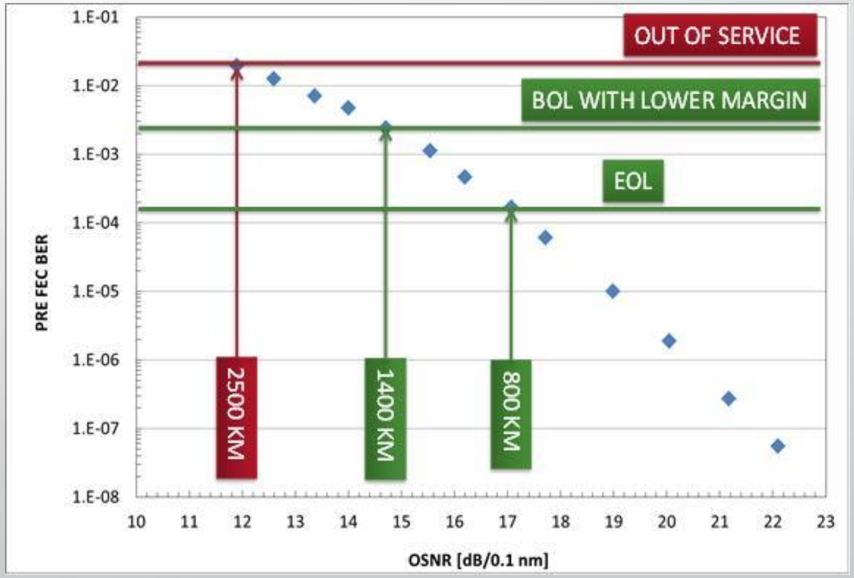
- The physical layer plays a major role in current and future optical systems
- An optical connection is affected by:
  - the traversed optical path
  - the existence and the characteristics of neighboring connections
- These parameters vary as time passes because of
  - component aging
  - the establishment of new connections
  - the modification of existing connections
- Worst-case assumptions for physical layer (in particular for interference impairments and aging effects) reduce the transmission reach
- Reducing the margins improves the efficiency and leads to CAPEX & OPEX savings
  - But in a static network BER (soft-failure) problems will arise

ORCHESTRA

- Horizon 2020 project (ICT-06-2014, Smart optical and wireless network technologies)
- Orchestra proposes to close the control loop by enabling physical layer observability
  - **Observability** relies on the coherent receivers that are extended, almost for free, to operate as software defined impairment optical performance monitors (soft-OPM)
  - Physical layer information of single or multiple soft-OPMs is used to take better optimization **decisions**
  - Re-**acting** dynamically on the network to increase its efficiency
- Margin reduction can be predicted or mitigated with the advanced monitoring and dynamic network capabilities of ORCHESTRA

Design margins

- **Begin of life (BOL)** refers to the performance of the equipment at the time of installation
- **End Of Life (EOL)** refers to the condition where the characteristics of the equipment have degraded and are out of the intended specifications (e.g. result in $BER>10^{-12}$)
- **System margins** are defined as the sum of several EOL values
  - EOL for: NLI, components aging and PDL
  - *Sum* no *sharing* among the margins
- NLIs
  - BOL: no adjacent lightpath (SPM)
  - EOL: worst case interference/all active channels (XPM, FWM, SPM)
- TRx and fiber aging
  - BOL=0, EOL is taken ~3 dB per span

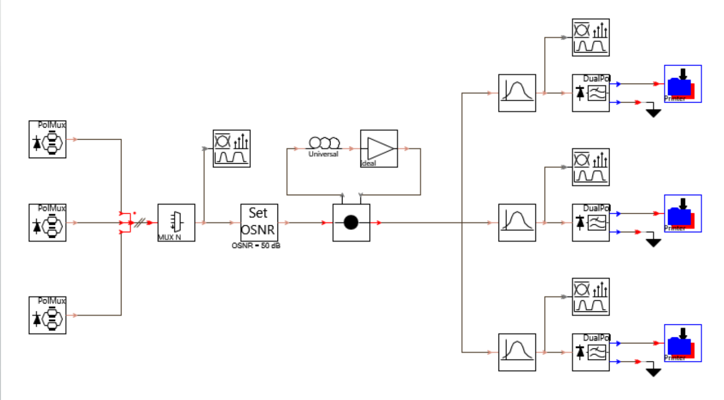


Reducing NLIs margins

- Optical networks are currently designed under worst-case NLI margins → all adjacent connections are assumed to be active
- The network can operate with the actual margins required to make feasible the transmission of each connection
- Spectrum guardbands can be used to
  - increases the number of available transmission options
  - Trade-off spectrum for reach to increase the reach of certain connections
- To harvest the use of spectrum as a guardband, appropriate Impairment Aware Routing and Spectrum Allocation (IA-RSA) algorithms have to be used

QoT evaluation

- We used VPI TransmissionMaker to evaluate the performance
- The Quality-of-Transmission (QoT) is based on the calculation of the BER considering
  - Multi-format (M-QAM) signal
  - multi-rate (28 and 32 GBaud) signal
  - single and multi-channel transmission
  - maximum reach and optimum launch power estimation
- The BER model accounted for all the major linear and non-linear impairments :
  - Chromatic Dispersion
  - Polarization Mode Dispersion
  - Self-phase Modulation
  - Cross-phase Modulation



QoT simulation assumptions

Calculated the maximum transmission reach assuming

- Neighboring channels have the same symbol rate and modulation format
- Span length = 80 km
- FEC
  - hard-FEC (BER ~ $1 \cdot 10^{-3}$, overhead 7%)
  - soft-FEC (BER ~ $1.9 \cdot 10^{-2}$, overhead 20%)

DP–QPSK 100 Gbps	**FEC=7%, Symbol rate: 28 Gbaud**		**FEC=20%, Symbol rate: 32 Gbaud**	
# neighboring channels	Launch power: 0 dBm	Launch power: 1.5 dBm	Launch power: 0 dBm	Launch power: 1.5 dBm
0 (single channel)	19x80 = 1520km	16x80 = 1280km	21x80 = 1680km	20x80 = 1600km
1	17x80 = 1360km	14x80 = 1120km	17x80 = 1360km	16x80 = 1280km
2	17x80 = 1360km	14x80 = 1120km	16x80 = 1280km	13x80 = 1040km

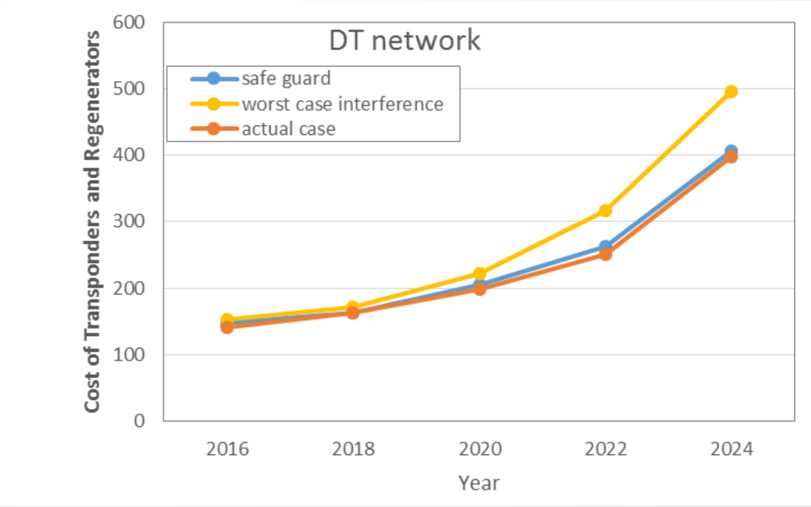
DP–16QAM 200 Gbps	**FEC=7%, Symbol rate: 28 Gbaud**		**FEC=20%, Symbol rate: 32 Gbaud**	
# neighboring channels	Launch power: 0 dBm	Launch power: 1.5 dBm	Launch power: 0 dBm	Launch power: 1.5 dBm
0 (single channel)	6x80 = 480km	5x80 = 400km	8x80 = 640km	8x80 = 640km
1	5x80 = 400km	3x80 = 240km	7x80 = 560km	6x80 = 480km
2	4x80 = 320km	3x80 = 240km	5x80 = 400km	6x80 = 480km

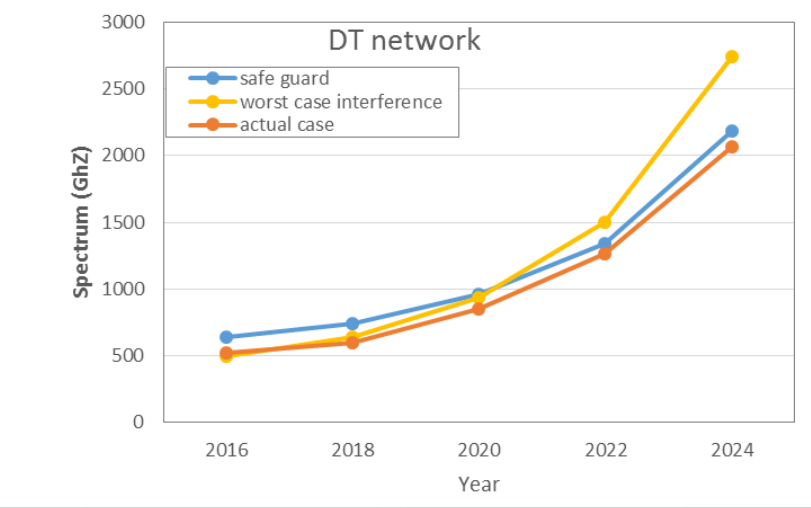
Network performance evaluation

- We examined three network scenarios:
  1. **worst case interference**: lightpaths are provisioned under EOL NLIs (lowest reach)
  2. **safe-guard**: always put guardband between lightapths
  3. **actual case**: algorithm decided to put or not guardband
- Flex TRx (40, 100, 200 and 400 Gbps)
  - Regenerator cost 0.8 times the cost of transponder
- DT and the GEANT network topologies
- Traffic: starting from realistic traffic matrices, we scaled them up assuming a uniform increase of 34% per year
- Each year we planned the network from scratch

DT network results

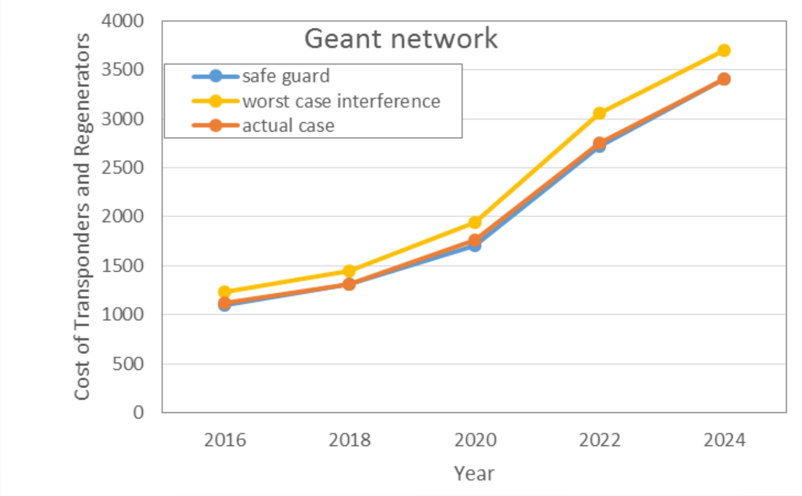
- Actual case scenario exhibits the best performance in both cost & spectrum
- Spectrum safe-guard scenario comes closely second in terms of cost but wastes spectrum
- Worst-case interference scenario has good performance in both cost and spectrum at light load, but as the load increases it becomes the worst in both
  - Heavy demands require more than one 400 G TRx and long lightpaths require regens. The lowest reach results in a considerable higher number of TRx and regens

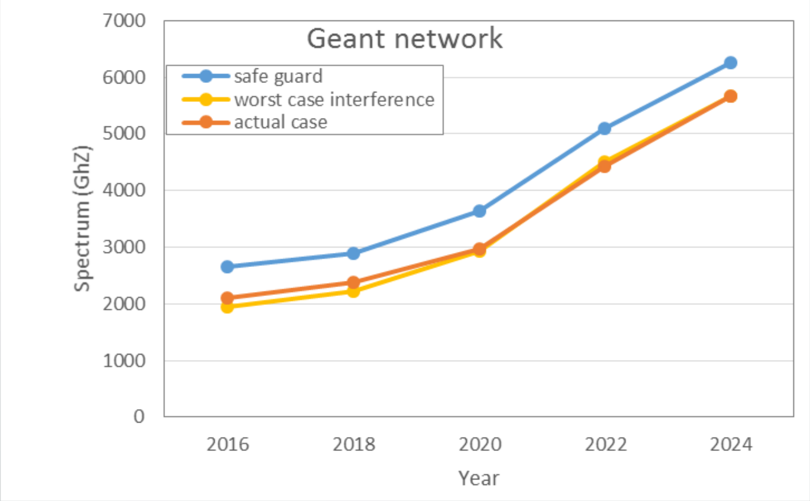




GEANT network results

- The findings for GEANT are similar
- Actual case performs better in terms of cost and spectrum
- Worst case has the highest cost, and safe-guard the highest spectrum utilization
  - Actually assuming a single fiber we would run out of spectrum …
- No crossing this time



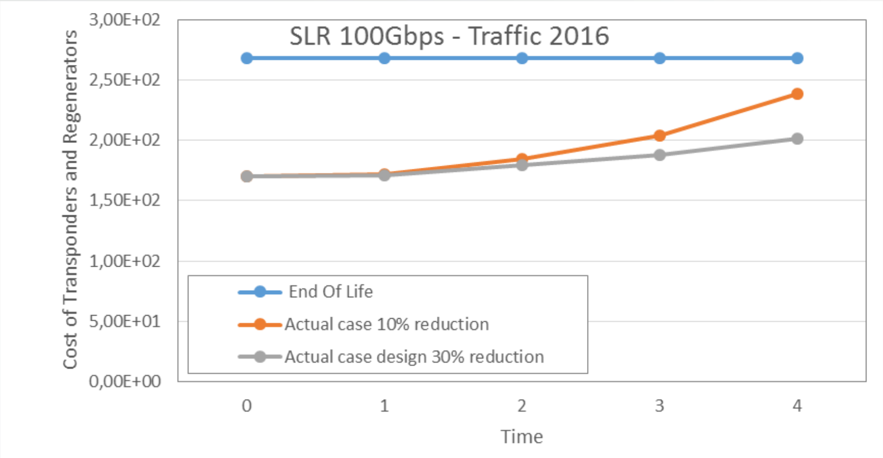


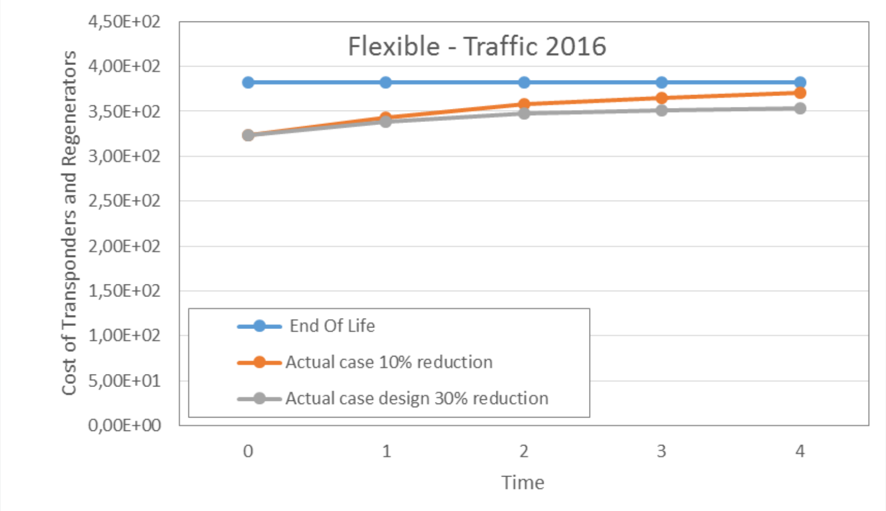
Recent study: aging effect

Transponder (Gbps)	BOL reach (Km)	EOL reach (Km)
40 (BPSK)	3200	2500
100 (QPSK)	1500	800
200 (QAM)	450	320
400 (QAM)	400	310

- Transponders assumed:
  - Single-line-rate (SLR) 100Gbps
  - Flex with 40,100,200 & 400 Gbps
  - Flex cost assumed 1.7 times the cost of SLR 100Gbps cost
- Network: DT network for traffic 2016
- Comparison scenarios
  - EOL: all the expenditure is paid upfront
  - BOL
    - Network planned with BOL and left without new traffic for 4 time intervals
    - Linear model for aging: in each time interval (out of the 4) the reach is linearly decreased by (EOL-BOL)/4
    - Cost model
      - Cost of TRx and regens falls by 10% or 30% in each time interval
      - Expenditure is summed over the 4 time intervals

DT Traffic 2016





- At the end of the 4th time intervals, the number of TRx and regens are the same
- But, cost savings are obtained by the delayed purchase of equipment, than when purchases is cheaper
- In the end (end of the 4^{th} time interval): reductions range from 8% to 40% depending on the TRx types and % of cost reduction

Conclusions

- Optical networks are designed under worst-case assumptions and gross margins for the physical layer
- Reducing the margins improves the efficiency and leads to CAPEX & OPEX savings
- Non-linear impairments interference:
  - Interference from adjacent lightpaths reduces the reach
  - Spectrum guardband between lightpaths can tradeoff spectrum for reach

  → Obtain savings by using an algorithm that leaves guardband space when needed
- TRx and fiber aging: reach is reduced over the network lifecycle

  → Obtain savings by postponing investment (e.g. regenerators) for when it is needed
- Reducing the margins can cause BER/QoT problems during network operation
- ORCHESTRA control and monitoring plane creates the ecosystem for margins reduction: QoT issues are predicted or mitigated using advanced monitoring and dynamic network capabilities