Cross-layer and Dynamic Network Orchestration based on Optical Performance Monitoring

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ORCHESTRA

Outline

- Motivation
- ORCHESTRA solution
- Monitoring based QoT estimation
- QoT aware dynamic adaptation
- Planning with reduced margins

Motivation

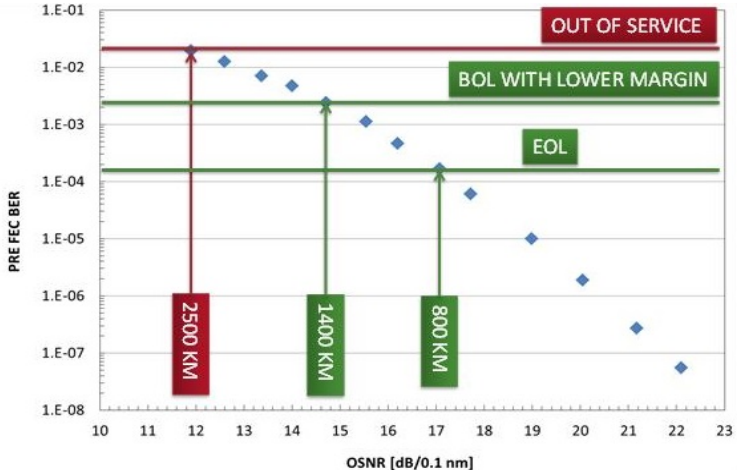
Provision lightpaths with acceptable quality of transmission (QoT)

☒ Uninterrupted operation until End-of-life (EOL)

→ QoT estimation with EOL margins

- Equipment (amps, transceivers) ageing
- Higher interference (traffic increase)
- Maintenance (e.g. splices for fiber cuts)
- Estimation model inaccuracy (design margin)

☒ EOL margins: low efficiency, overprovisioning

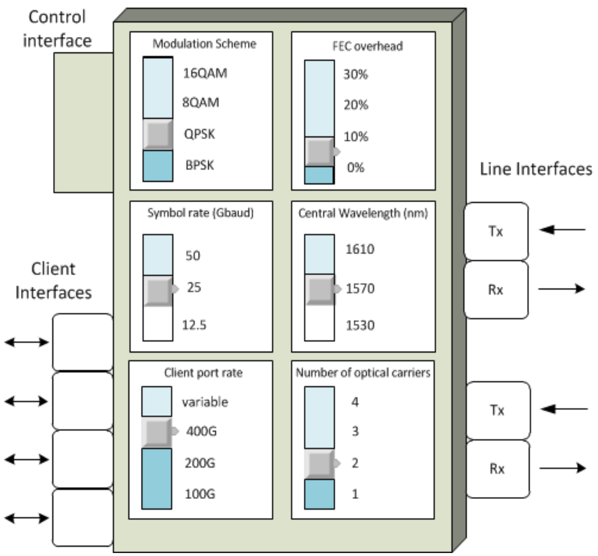


☑ Reduced margins improves efficiency & reduces or postpones investments

☒ BER issues (soft-failures) arise, no current mechanisms to solve them

Motivation

- ☒ Physical layer monitoring information is barely used in the network lifecycle
  - ☒ Provisioning inefficiencies are never corrected
  - ☒ Failures are treated as black or white
  - ☒ Tunable transceivers provide vast optimization options, but are not efficiently configured without physical layer feedback

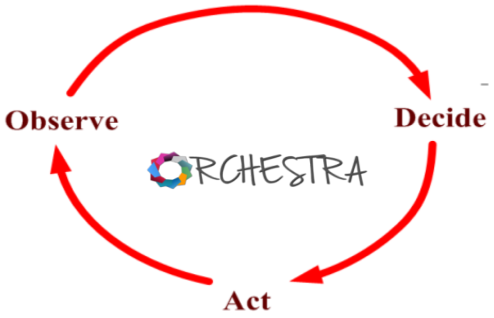


- ☑ ORCHESTRA proposes to close the loop between the physical layer and the control plane
  - ☑ Improve QoT estimation accuracy
  - ☑ Dynamically identify and solve soft-failures
  - ☑ Enable the reduction of provisioning margins

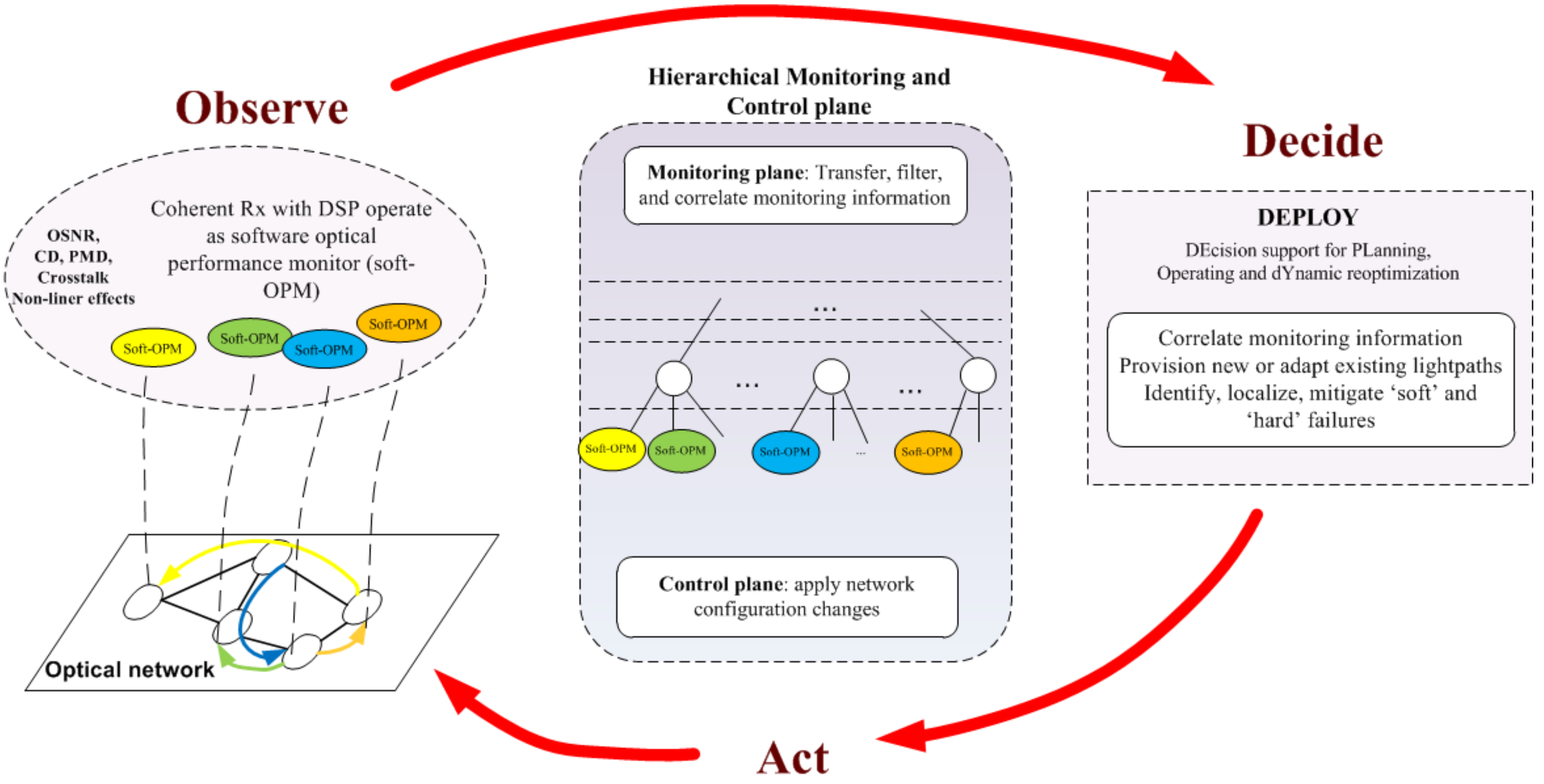
Closing the control loop

An optical network has to be observable before it can become controllable and be subject to optimization

- 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 optical performance monitors (soft-OPM)
- Physical layer information of single or correlated from multiple OPMs is used to take better optimization **decisions**
- Re-**acting** dynamically on the network to increase its efficiency

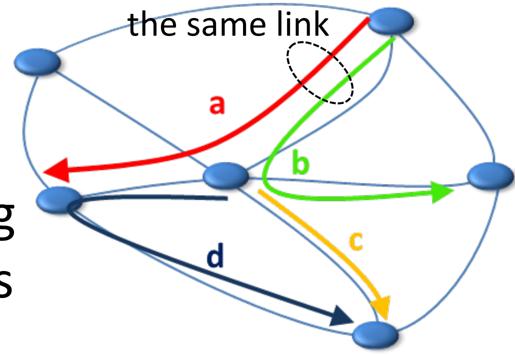


The big picture



Monitoring based QoT estimation

- Use monitoring information (feedback) from the Rx (OPM)
- Correlate information of multiple Rx taking into account their paths
  - Lightpaths cross several links and the Rx report "aggregated" measurements
  - Lightpaths crossing the same link give information about it
- Estimate the QoT of new or upgraded lightpaths with high accuracy
  - Actual ageing state of the network
  - Actual interference – more on this in the following
  - Low design margin (estimation model inaccuracy)
- Previous work [1][2] estimated QoT but only considering linear effects and previous generation 10 Gbps networks



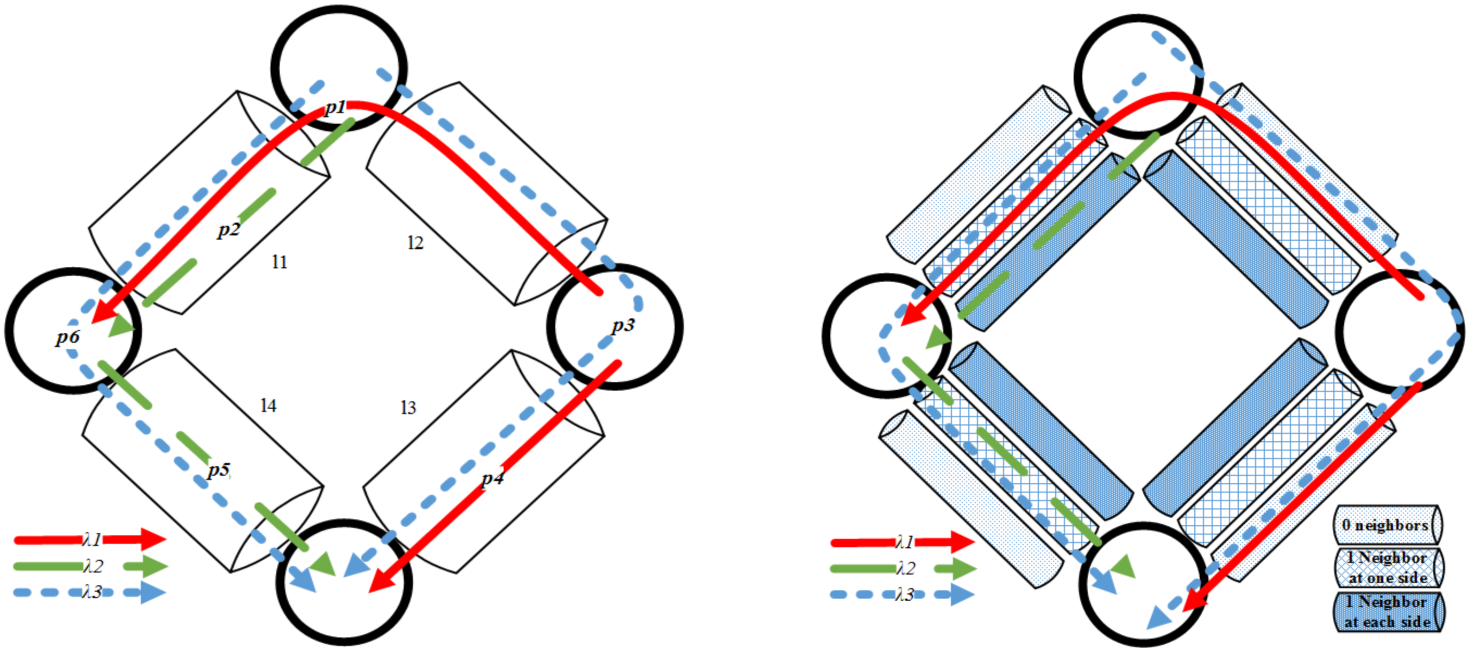
[1] N. Sambo, et al, "Lightpath Establishment Assisted by Offline QoT Estimation in Transparent Optical Networks," J. Opt. Com. Netw., 2010.
[2] Y. Pointurier, M. Coates, M. Rabbat, "Cross-layer Monitoring in Transparent Optical Networks," J. Opt. Commun. Netw., 2011.

QoT estimation - Background

- Rx (OPM) provides information for the SNR of the lightpath
  - SNR accounts for all impairments: amplifiers noise (ASE), residual (Chromatic, Polarization mode) dispersion, Non Linearities (NLI)
    - Or we use the estimation framework for each of these parameters
  - The BER is calculated from the SNR value (for known modulation format and FEC)
- Assumption: the inverse of SNR is additive per link
- For validation we used the GN model [1] as the ground truth
  - Monitored values from OPMs would be used in a real network
  - Ongoing: testbed/field trials to obtain real network monitoring data and re-evaluate the accuracy

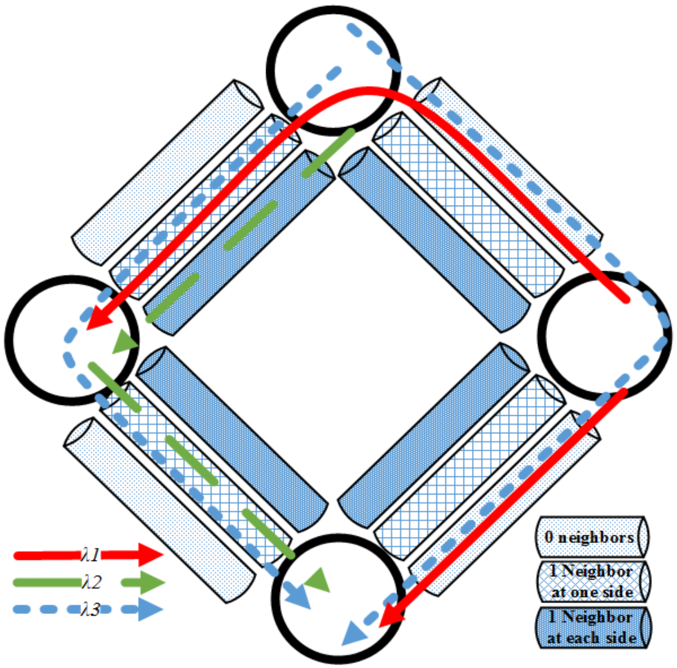
[1] P. Poggiolini, "The GN Model of Non-Linear Propagation in Uncompensated Coherent Optical Systems", IEEE/OSA JLT 2012

Accounting for interference



- Assumption: lightpaths with same position of neighbors experience equal interference
- Interference aware (IA)-graph
  - Replace a link by a set of *IA-links* representing the number & position of neighbors
  - Route lightpaths on the IA-graph according to their neighbors

QoT estimation formulation



Input:

- ***m*** set of monitored lightpaths, ***n*** set of lightpaths to-be-estimated
- $\boldsymbol{y}_m$ vector of end-to-end (monitored) parameter of known lightpaths ***m***
- $G\ \{0,1\}^{PxL}$: routing matrix, $G_{p,l}$=1 when lightpath *p* uses link *l*, G= [G_m G_n]

Unknown:

- $\boldsymbol{y}_n$: vector of end-to-end parameters of lightpaths ***n*** (to be estimated)
- ***x***: vector of *link-level* parameters

Estimation problem: $[\boldsymbol{y}_m\ \boldsymbol{y}_n]=[G_m\ G_n]\cdot\boldsymbol{x}$, Parameter ***y***=1/SNR

Estimate $\boldsymbol{y}_n$ with Network Kriging (NK) or Norm Minimization (NM) technique [1]

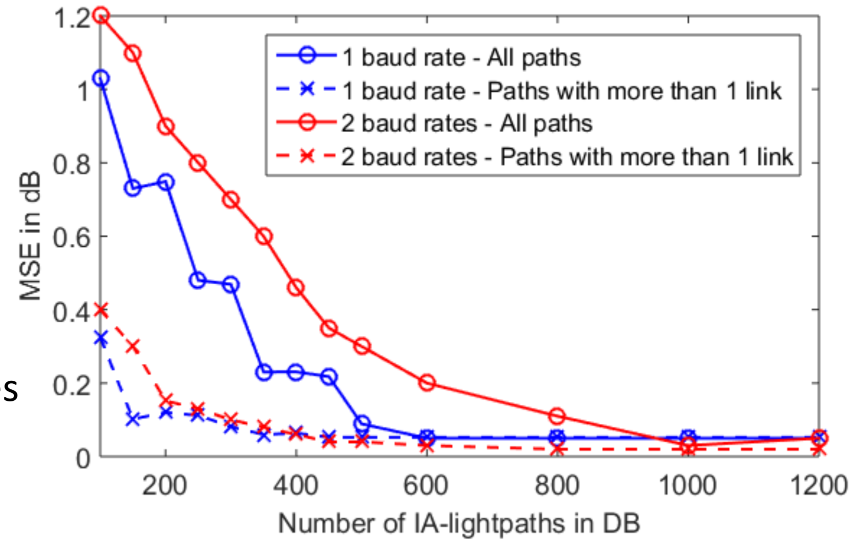
- Run NK on IA-graph: calculated SNR (and BER afterwards) takes into account interference
- Database (DB) to store past measurement data

[1] N. Sambo, et al, “Lightpath Establishment Assisted by Offline QoT Estimation in Transparent Optical Networks,” J. Opt. Com. Netw., 2010.

Accuracy Results

- NSFNET topology, 100G PM-QPSK with (i) 28 Gbaud, (ii) 28 and 32Gbaud
- Dynamic provisioning of lightpaths

  For a lightpath:
  - use database (DB) with stored values
  - estimate its BER with proposed algorithm
  - establish and use GN model to "measure" BER
  - Insert measurement in DB, find estimation error



- Establishing a lightpath creates multiple DB entries
- High MSE for single link lightpaths (unimportant)
- More baudrates, more IA-links, higher MSE

- Maximum underestimation (**design margin**): 0.1dB (1000 IA-lightpaths in DB)

Papers:

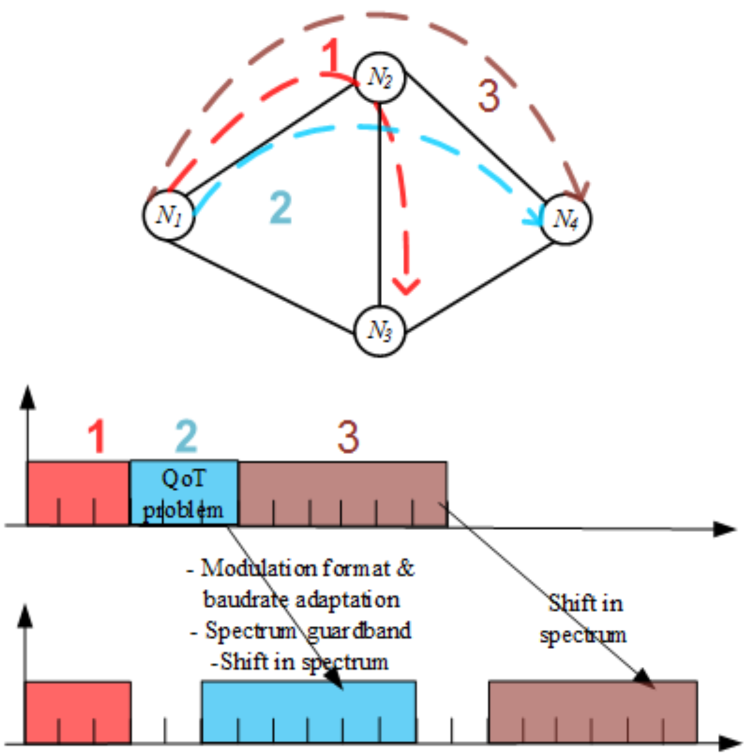
I. Sartzetakis, K. Christodoulopoulos, C.Tsekrekos, D. Syvridis, E. Varvarigos, "Quality of Transmission Estimation Accounting for Space–Spectrum Dependencies," JOCN, 2016

I. Sartzetakis, K. Christodoulopoulos, C. P. Tsekrekos, D. Syvridis, E. Varvarigos, "Estimating QoT of Unestablished Lightpaths," OFC, 2016.

QoT aware reconfiguration

- Lightpaths operated close to their capabilities, are susceptible to *soft-failures*
  - Soft-failure: progressive (ageing, increased interference by new connections) or sudden (malfunctioning) QoT degradation
  - hard-failure: total loss of the signal (fiber cut, equipment break-down)
- Propose: a Toolkit to decide on reconfiguration actions to restore QoT
  - Triggered by alarms from Rx – OPM (thresholds and alarm types are configurable)
  - Considers the combination of three reconfiguration actions
    - Increase the FEC overhead
    - Create spectrum guard-band to decrease interference
    - Change the modulation format
  - Examines the actions taking into account their control plane overhead
  - Use the QoT estimation module previously described to estimate if problem is solved

Adaptation Actions



- Actions to increase QoT of a problematic lightpath
  - i. FEC adaptation
  - ii. Spectrum guard-band creation
  - iii. Modulation format adaptation
- All actions require extra spectrum
  - In cases i and iii we increase the baud-rate to compensate for the lost net rate
  - Case ii, by definition, requires extra spectrum
- Providing extra spectrum relies on the hitless frequency push-pull technique[1]
- Although push-pull is hitless we prefer to avoid using it on many lightpaths

[1] F. Cugini, et. al. "Push-Pull Defragmentation Without Traffic Disruption in Flexible Grid Optical Networks," JLT 2012

Actions & control plane overhead

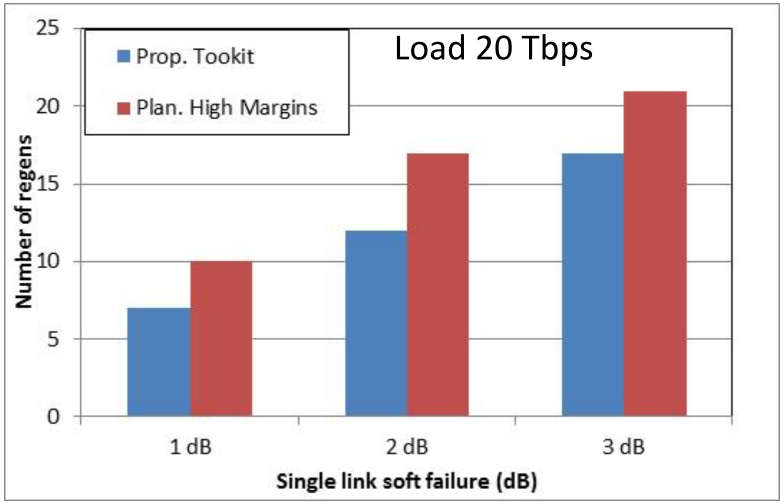
- Investigated adaptation actions in increasing control overhead order:
  - The FEC adaptation requires one extra spectrum slot
  - The spectrum guard-band requires several slots
  - The modulation format adaptation also requires several slots and is considered the most expensive (hitless transition would require IP rerouting)
- Algorithmic toolkit
  - Examines actions of the same class
  - Leverages the QoT estimation tool to check if the problem is solved
  - Calculates the control overhead (number of lightpaths to push-pull) to free the required slots
  - Selects the action that solves the problem and has the lowest control overhead
  - If the problem is not solved it moves to higher control overhead actions

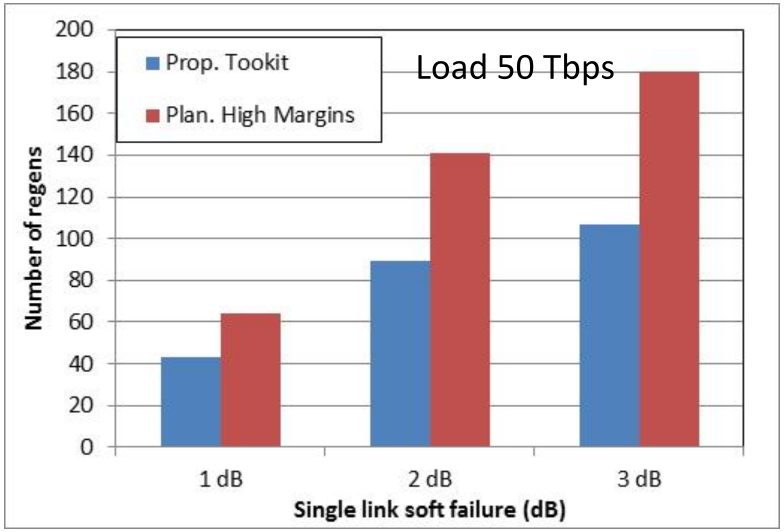
Performance results

- Simulate single link soft failures (e.g. equipment malfunctioning)
- Topology inspired by Telecom Italia European backbone
- Net rates: 100G, 200G
- Mod. Formats: PM-QPSK, PM-16QAM
- Baud-Rates: 28, 32, 56, 64 Gbaud
- FEC: 12%, 28% with BER thresholds -2.2dB and -1.88dB, respectively

Equipment Savings

- Scenario
  - Plan the network to survive from any single-link degradation (e.g. equipment malfunctioning) of 1, 2 or 3 dB in SNR
  - Survive: lightpaths with acceptable QoT
- Compare
  - Toolkit (restoration)
    - Calculate actions to restore the QoT
    - If solution is not found, place regens
    - Regens are reused for different failures
  - Planning with high margins (protection)
    - Provision lightpaths with a margin to protect against any single-link failure
- At least 22%, at most 40% regens savings





I. Sartzetakis,K. Christodoulopoulos, E. Varvarigos, “QoT Aware Adaptive Elastic Optical Networks” OfC 2017

Provisioning with reduced margins

- Multi-period/incremental network evolution
- Each period new lightpaths are provisioned
  1. Traditional: with high margins to reach end-of-life with acceptable QoT
     - System margins: equipment ageing, interference increases, maintenance operations
     - Design margin: QoT estimation model inaccuracy
  2. With reduced margins
     - Requires accurate QoT estimation (actual system and low design margins)

     → Discussed in the first part of this presentation
     - Each period check the QoT of previously established lightpaths and restore the QoT of those that are about to become unacceptable (solve soft-failures)

     → Discussed in the second part of this presentation

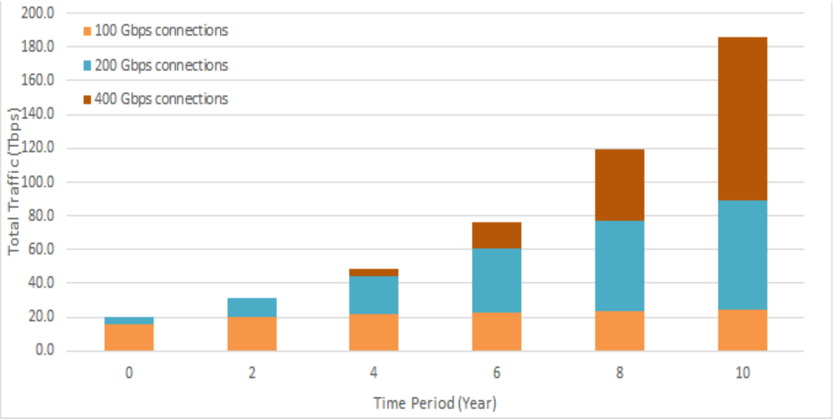
RSA algorithm

- Generic RSA algorithm, applicable in both fixed- and flex-grid networks
- Input for time τ_i
  - Traffic matrix $\Lambda(\tau_i)$ at time τ_i
  - Tunable (or not) TRx, described by a single or a set of transmission configuration
    t={*modulation format*$_t$, *baud rate*$_t$, *FEC*$_t$}
  - Equipment installed at previous time periods (up to τ_{i-1})
- 2 phases
  - Pre-processing phase
    - Calculate best (no interference) and worst (full load interference) reaches
    - For each demand (s,d) find the candidate (path, transmission configuration, regeneration points) options $Q_{s,d}$
    - Each option uses $S_{p,t,r}$ spectrum and has $C_{p,t,r}$ cost
  - Serve demands one-by-one
    - For each transceiver, (path, transmission configuration, regeneration points) option,
    - Find free spectrum
    - Re-evaluate QoT taking into account the actual interference
    - Select the one that minimizes $\underset{(p,t,r)\in Q_{s,d}}{\text{Min}} \left(w \cdot S_{p,r,t}(\tau) + (1\text{-}w) \cdot C_{p,r,t}(\tau) \right)$

Case study - Topology and traffic

Topology based on Telecom Italia's Pan-European backbone

72 uncompensated G.652 links
49 Flexgrid ROADMs
100 km uniform span length



- Multi-period planning for 10 years
  - Re-plan every 2 years
- 100, 200, 400 Gbps client rates matched with equal line rate TRx
  - 400 Gbps demands appear at 4th year

Case study - Cost and ageing models

Network equipment	Relative Price at τ_0 (C.U.)
Flexible TRx/ regen.	1.75
EDFA	0.15
WSS (1x20)	0.30
WSS (1x9)	0.20

Prices fall by 10% per year

Margins	BOL	EOL
System margin: Fiber attenuation coefficient (dB/km)	0.22	0.25
System margin: Noise Figure EDFA (dB)	4.5	5.5
System margin: Transponders sensitivity margin (dB)	1	1.5
System margin: Interference	Low load	full
Design margin (dB)	2	1

Assumption: linear evolution of margins between their Begin-of-life (BOL) and End-of-life (EOL) values

BOL – EOL= 10 years

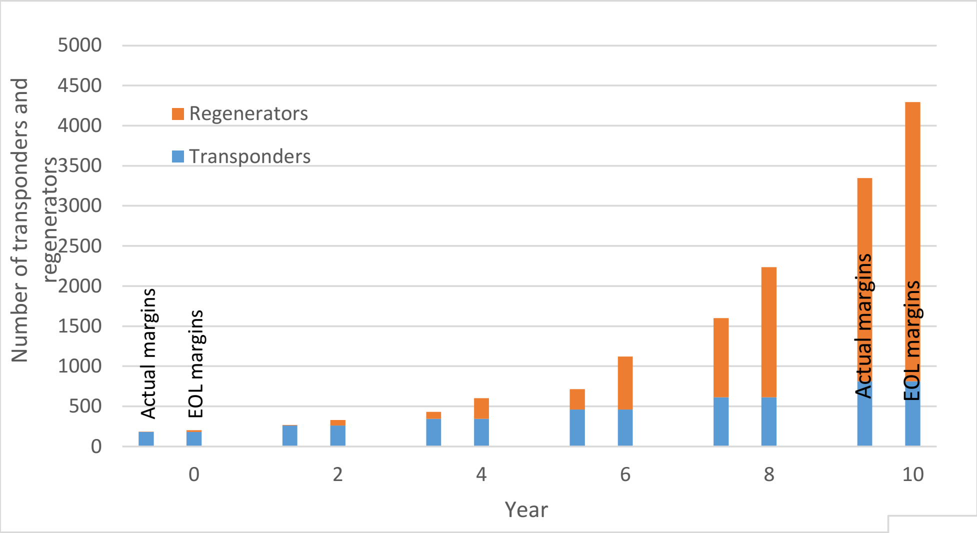
System margins increase

Design margin decreases (learn the network)

Compare provisioning with

- Actual margins: follow the system and design margins evolution
- Traditional – high margins: EOL system and BOL design margin

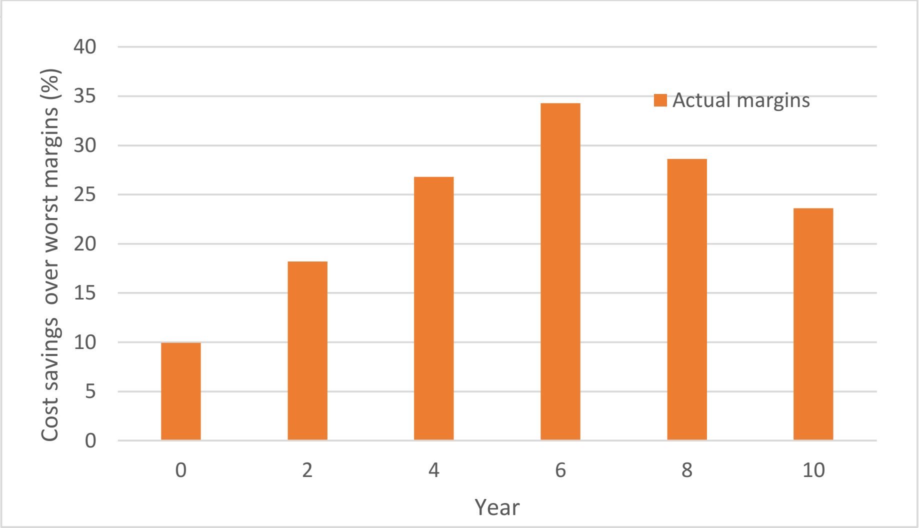
Performance results - number



- Regenerators mainly added at the later periods when 400G lightpaths appear (short reach)
- Reducing the system margins postpones the purchase of equipment
- Reducing the design margin avoids the purchase

10% price depreciation per period

~24% savings for provisioning with *actual margins* as opposed to provisioning with high margins



P. Soumplis, K. Christodoulopoulos, M. Quaglioti, A. Paggano, E. Varvarigos, "Actual Margins Algorithm for Multi-Period Planning" OFC 2017

Conclusions

- ORCHESTRA proposes to close the control loop
- Use OPM information in cross-layer optimization decisions so as to control and operate the network close to its capabilities
- Accurate QoT estimation
- Reconfiguration actions to solve QoT problems
- Reduce provisioning margins

Thank you

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