Energy Efficient Resilient Optical Transport Networks

Achille Pattavina, Francesco Musumeci, Politecnico di Milano
Jorge Lopez Vizcaino, Yabin Ye, Huawei

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Outline
- Motivation
- Facing the network challenges
- Energy-efficiency in resilient networks
- Conclusions
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Traffic growth in core networks: challenges

Challenges for operators:
- Need for higher capacity
- Upgrade network capacity (1)
- More critical services
- Ensure network resilience (2)


Internet traffic forecast: +50% per year
Energy consumption increases with traffic

- Increase in OpEx
- Increase in CapEx
- Increase in GHG emissions

Internet Traffic Growth

Deployment of additional equipment

Increase in Energy Consumption

Goal: Increase Network Capacity and improve Energy Efficiency

Outline

- Motivation
- Facing the network challenges
  - Network capacity upgrade
  - Ensuring network resilience
- Energy-efficiency in resilient networks
- Conclusions
Challenge (1): Network capacity upgrade

- Current WDM networks:
  - Full wavelength capacity is assigned to a connection
  - Single Line Rate (SLR)
  - ITU-T Grid operation

- How to provide more capacity in WDM Networks?
  - Deploy more fibers and devices (simplest solution but less efficient)
  - Increase wavelengths spectral efficiency (higher-level modulation formats): 2.5 → 10 → 40 → 100 Gbit/s → ?

- Drawbacks:
  - Coarse wavelength granularity → inefficient resource utilization (lack of flexibility in allocating the actual required capacity)
  - Fixed channel spacing → Next generation transmission technologies (400G, 1T) would not fit into 50 GHz channels

Flexible Optical Transport Networks

- How to make optical transport networks more flexible?
  - Mixed Line Rate (MLR)
    - Maintain fixed ITU-T 50 GHz channel spacing
    - Enable different line rates within different wavelengths: 10 / 40 / 100 Gbit/s
  - Elastic Optical Networks (EONs)
    - Finer channel spacing (12.5 GHz wide frequency slots)
    - Flexible-grid operation
    - Enabler for higher capacity channels (superchannels)
    - OFDM-enabled
    - Finer capacity granularity thanks to:
      - Elastic bandwidth operation
      - Different modulation formats
Challenge (2): Ensure network resilience

- High resilience against devices failures is needed
  - New fundamental network services (telemedicine, teleconference, VoD, etc.)
  - Failures criticality: a single fiber cut might cause huge data losses

How to provide resilience in optical networks?

- Restoration: dynamic recovery performed after a failure has occurred
- Protection: pre-planned failure recovery → higher reliability

Protection in optical transport networks:

- Many possible solutions
  - dedicated vs shared protection
  - link vs path protection
  - …

Dedicated vs Shared Path Protection

- Each end-to-end path protected via an alternative route from source to dest.
- Dedicated Path Protection (DPP)
  - 1+1 DP: simultaneous transmission in both working and backup paths
  - 1:1 DP: transmission over backup path is activated after a failure occurs
  - resiliency is provided with fast recovery but…
  - more resources are needed → more CAPEX
- Shared Path Protection (SPP)
  - protection resources are shared but…
  - lower resiliency (single point of failure)
Every physical link connecting two nodes A and B is protected via an alternative route connecting A to B
- Link-disjoint protection
- Dedicated Link Protection (DLP)
  - Demands routed over the same link are protected independently
  - more resources are needed
- Shared Link Protection (SLP)
  - Protection resources are shared by different connections
  - Lower resilience: single point of failure

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  - Energy-efficiency in resilient networks
    - Sleep mode
    - Rate adaptation
- Conclusions
Energy-efficiency and network resilience: Sleep-mode

- Resources used for protection can be set into sleep-mode in order to save energy
- Traffic grooming is useful
  - Working paths are groomed together → more resources used only for protection

 longer routes might be preferred when exploiting traffic grooming in order to activate (power-ON) less links and set protection links in sleep-mode


Sleep-mode - Network scenario

- IP routers
  - Perform electronic traffic processing
- WDM transponders
  - Perform EO (resp., OE) signal conversion for signal transmission (reception)
  - Optical signals (wavelengths) are multiplexed into the same optical fiber
- WDM links
  - Optical amplifiers are used (1 in-line EDFA every 80 km + 2 additional EDFAs at the edges, as booster and pre-amplifier)
Sleep-mode - Power consumption model

- Considered power contributions
  - **Electronic processing (IP routers):**
    - traffic-independent contribution
    - traffic-dependent contribution
    - consumption in IDLE state is negligible
  - **WDM transponders:**
    - set in sleep-mode if used only for protection (only lasers and photodiodes are powered-on)
  - **WDM links (EDFAs):**
    - consumption in IDLE state is negligible

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Power consumption in ACTIVE state</th>
<th>Power consumption in IDLE state</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electronic processing (IP routers)</td>
<td>Traffic-independent $P_0 = 2401$ W (2240 Gbit/s rack)</td>
<td>$P_1 = 0$</td>
</tr>
<tr>
<td></td>
<td>Traffic-dependent $P_1 = 437$ W (40 Gbit/s card)</td>
<td></td>
</tr>
<tr>
<td>WDM transponders (transmitter-receiver)</td>
<td>$T_a = R_a = 79.4$ W (40 Gbit/s transp.)</td>
<td>$T_1 = R_1 = 9.84$ W</td>
</tr>
<tr>
<td>WDM links (EDFAs)</td>
<td>$L_0 = 55$ W (single EDFA)</td>
<td>$L_1 = 0$</td>
</tr>
</tbody>
</table>
Sleep-mode - Case study

- NSFNET topology (14 nodes, 22 bidirectional single-fiber links)
  - 20 wavelengths @ 40 Gbit/s per fiber
  - Non-uniform traffic matrix (180 Gbit/s overall traffic)
  - Results for different traffic-matrix scaling factor \( f \) (\( f = 1, 2, 5, 10, 20 \))

- Comparison between:
  - SLP vs SPP vs DLP vs DPP
  - Sleep-mode vs all-ON
  - Protected vs unprotected scenarios
  - Power-aware vs power-unaware (minimize nr of wavelengths)

![NSFNET topology diagram](image)

Sleep-mode - Power consumptions (kW)

<table>
<thead>
<tr>
<th>Scaling factor</th>
<th>SLP</th>
<th>SPP</th>
<th>DLP</th>
<th>DPP</th>
<th>Unprotected</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>sleep-mode</td>
<td>all-ON</td>
<td>sleep-mode</td>
<td>all-ON</td>
<td>sleep-mode</td>
</tr>
<tr>
<td>( f = 1 )</td>
<td>73.791</td>
<td>110.297</td>
<td>73.89</td>
<td>108.054</td>
<td>74.008</td>
</tr>
<tr>
<td>( f = 2 )</td>
<td>86.469</td>
<td>130.672</td>
<td>86.469</td>
<td>121.974</td>
<td>86.902</td>
</tr>
<tr>
<td>( f = 5 )</td>
<td>121.365</td>
<td>185.5</td>
<td>121.954</td>
<td>186.406</td>
<td>122.388</td>
</tr>
<tr>
<td>( f = 10 )</td>
<td>172.764</td>
<td>277.409</td>
<td>173.275</td>
<td>274.573</td>
<td>174.579</td>
</tr>
<tr>
<td>( f = 20 )</td>
<td>270.23</td>
<td>455.448</td>
<td>270.992</td>
<td>442.877</td>
<td>274.186</td>
</tr>
</tbody>
</table>

- Relevant power savings (up to 60%) wrt Always-ON scenarios
- Small (1-2%) additional power required to provide resilience with sleep mode for protection resources compared to an unprotected power-aware design
- Small difference (within 1%) between the various protection strategies
  - Main power contribution at the IP layer (> 65% of the total power), almost independent from the adopted protection strategy
Sleep-mode - Power reduction

- Power-Aware (PA) vs Power-Unaware design of protected network

Up to 18% of savings compared to power-unaware (cost-minimized) strategies

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  - Sleep mode
  - Rate adaptation
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Energy-efficiency and network resilience:

**Rate-adaptation**

- Devices activation can follow the traffic dynamics
  - Resource provisioning performed according to the *peak traffic*
  - In *low-peak* hours many devices can be powered-OFF (or set in sleep-mode) → save energy
- Working paths
  - Transmission remains fully active (dimensioned to peak demand)
- Backup paths
  - Spectral resources are reserved for peak demand value, but
  - *Transmission is adapted to hourly traffic conditions*

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Rate-adaptation - Traffic/power-aware design

- **Step 1:** Resource allocation for 1+1 protection (peak-rate)
  - Resources (transponders) are allocated according to the demands peak rate (for both working and backup paths)
  - Maximum power consumption corresponding to peak hours

- **Step 2:** Protection paths rate adaptation to hourly traffic variation
  - Protection paths remain reserved, but the transmission is adapted to the current traffic situation
  - Power reduction in backup paths given by:
    - Deactivation of transponders (WDM)
    - Subcarrier reduction or modulation format changing (EON)

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Rate-adaptation - Power contributions

- Transponders
  
  **WDM Transponders [3]**
  
<table>
<thead>
<tr>
<th>Wavelength (Gbps)</th>
<th>Power consumption (W)</th>
<th>Reach (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>34</td>
<td>3200</td>
</tr>
<tr>
<td>40</td>
<td>98</td>
<td>2200</td>
</tr>
<tr>
<td>100</td>
<td>351</td>
<td>1800</td>
</tr>
</tbody>
</table>

- Optical Cross Connects (OXC)
  
  - Depends on node degree (N) and add/drop degree (α) [3]

  \[ P_{\text{trans}}(W) = N \cdot 85 + \alpha \cdot 100 + 150 \]

- Optical amplifiers (EDFAs)
  
  - 30 W per direction [3]

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**CO-OFDM Transponders**

Frequency slot: 12.5 GHz

<table>
<thead>
<tr>
<th>Mod. Format</th>
<th>Subc. Capacity (Gb/s)</th>
<th>Power Consumption (W)</th>
<th>Reach (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPSK</td>
<td>12.5</td>
<td>112.374</td>
<td>4000</td>
</tr>
<tr>
<td>QPSK</td>
<td>25</td>
<td>133.416</td>
<td>2000</td>
</tr>
<tr>
<td>8QAM</td>
<td>37.5</td>
<td>154.457</td>
<td>1000</td>
</tr>
<tr>
<td>16QAM</td>
<td>50</td>
<td>175.498</td>
<td>500</td>
</tr>
<tr>
<td>32QAM</td>
<td>62.5</td>
<td>196.539</td>
<td>250</td>
</tr>
<tr>
<td>64QAM</td>
<td>75</td>
<td>217.581</td>
<td>125</td>
</tr>
</tbody>
</table>


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Rate-adaptation - An example of power reduction

- Single traffic demand on a point-to-point link
  
  - 350 km span
  - 135 Gbit/s at peak hour (12 AM)
  - 17.6 Gbit/s at off-peak hour (5 AM)

<table>
<thead>
<tr>
<th>Network scenario</th>
<th>Conventional protection scheme (135 Gbit/s)</th>
<th>Traffic-aware protection scheme (17.6 Gbit/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Backup resources (transponders/subcarriers)</td>
<td>Backup resources (transponders/subcarriers)</td>
</tr>
<tr>
<td></td>
<td>Power (W)</td>
<td>Power (W)</td>
</tr>
<tr>
<td>10G SLR</td>
<td>14 @ 10G</td>
<td>2 @ 10G</td>
</tr>
<tr>
<td></td>
<td>14 - 34 = 476W</td>
<td>2 - 34 = 68W</td>
</tr>
<tr>
<td>40G SLR</td>
<td>4 @ 100G</td>
<td>1 @ 100G</td>
</tr>
<tr>
<td></td>
<td>4 - 98 = 92W</td>
<td>1 @ 98</td>
</tr>
<tr>
<td>100G SLR</td>
<td>2 @ 100G</td>
<td>1 @ 100G</td>
</tr>
<tr>
<td></td>
<td>2 - 351 = 702W</td>
<td>1 @ 351</td>
</tr>
<tr>
<td>10-40-100 MLR</td>
<td>1 @ 100G + 1 @ 40G</td>
<td>1 @ 100G</td>
</tr>
<tr>
<td></td>
<td>251 + 498 = 749W</td>
<td>1 @ 25G</td>
</tr>
<tr>
<td>100G MLR</td>
<td>3 @ 50G (16-QAM)</td>
<td>1 @ 25G (QPSK)</td>
</tr>
<tr>
<td></td>
<td>3 - 175.498 + 526.495W</td>
<td>133.416W</td>
</tr>
</tbody>
</table>

A. Pattavina – Energy Efficient Resilient Optical Transport Networks
Rate-adaptation - Case study

- Telefonica’s Spanish Core Network
  - Country-sized network
  - 30 optical nodes & 96 bidirectional links (1 fiber pair per link)
  - Fully transparent network
    - No regenerators
- Traffic demand reference
  - Traffic Matrix 2012
    - total traffic: 3.22 Tbit/s
  - Scaled by a factor $f$ up to 10 (up to 32.2 Tbit/s)
- Hourly-traffic variations on weekdays and weekend days

Rate-adaptation - Peak traffic

- Total power consumption with conventional DP 1+1 protection (working days) obtained for peak traffic (12:00 AM)
- 10G and 40G SLR support only low traffic
- High savings already in 1+1 DP with fully active devices thanks to MLR and EON
**Rate-adaptation - Energy savings**

- Energy savings (%) with Traffic/Power-aware design with respect to DP 1+1 ($f = 3$ and $f = 10$) during the day

  ![Graph 1](image1.png)

  ![Graph 2](image2.png)

- Significant savings especially for EON thanks to its better adaptability
- Savings become more significant (up to 27% for EON) as traffic load increases

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Conclusions

- Power consumption reduction is a major issue in current telecommunication networks
- Need for network resiliency
- Use traffic- and power- aware design for resource provisioning and management
  - Set protection resources into OFF (or sleep-mode) state
  - Adapt transponders transmission rate to current traffic
- Sleep-mode capability of subsystems and Elastic Optical Networks let us accomplish good savings in power consumptions