Time and frequency transmissions over telecoms fibres

Josef Vojtech, CESNET josef.vojtech@cesnet.cz

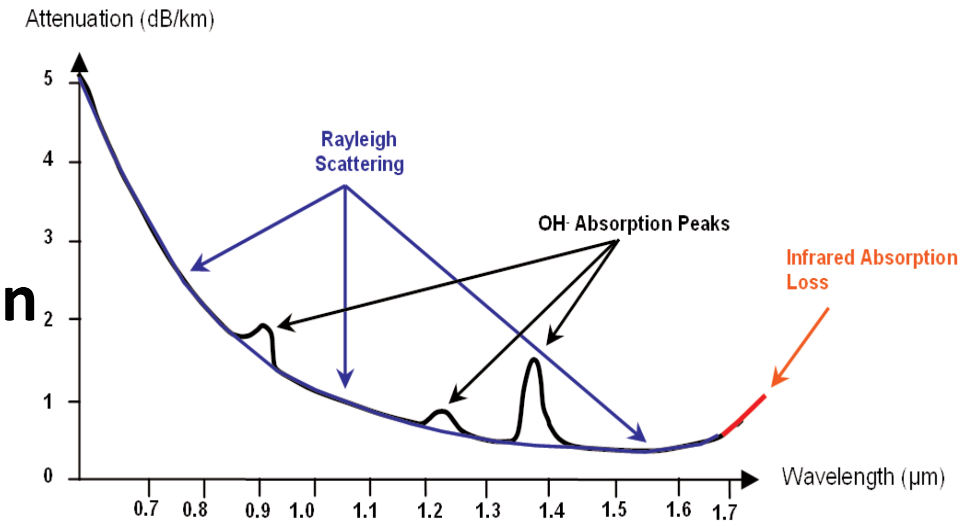
CLONETS
CLOCK NETWORK SERVICES

Outline

- **Evolution of Optical Fibre Communication Systems**
  - **1st, 2nd, 3rd, 4th, %th generations**
  - **Capacity of optical communication systems**
  - **Usual signals within optical communication systems**
  - **Wavelength processing nodes – traditional vs. contemporary colourless, directionless,**
- **Optical transport of T/F Signals over Telecom Fibres - Examples**
  - **Using telco transmission system – examples**
  - **Bypassing telco transmission system – examples**

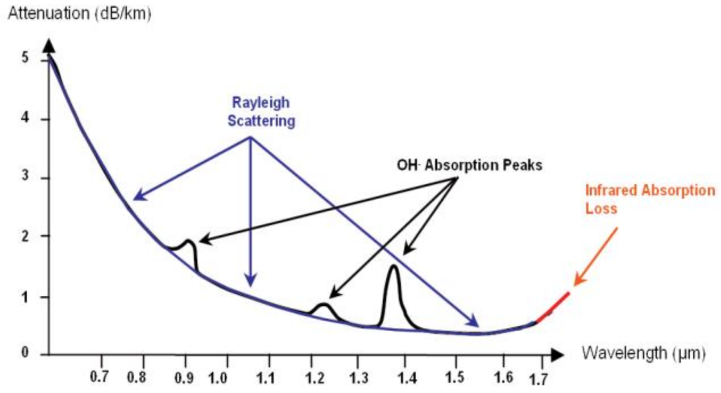
Evolution of Optical Communication Systems

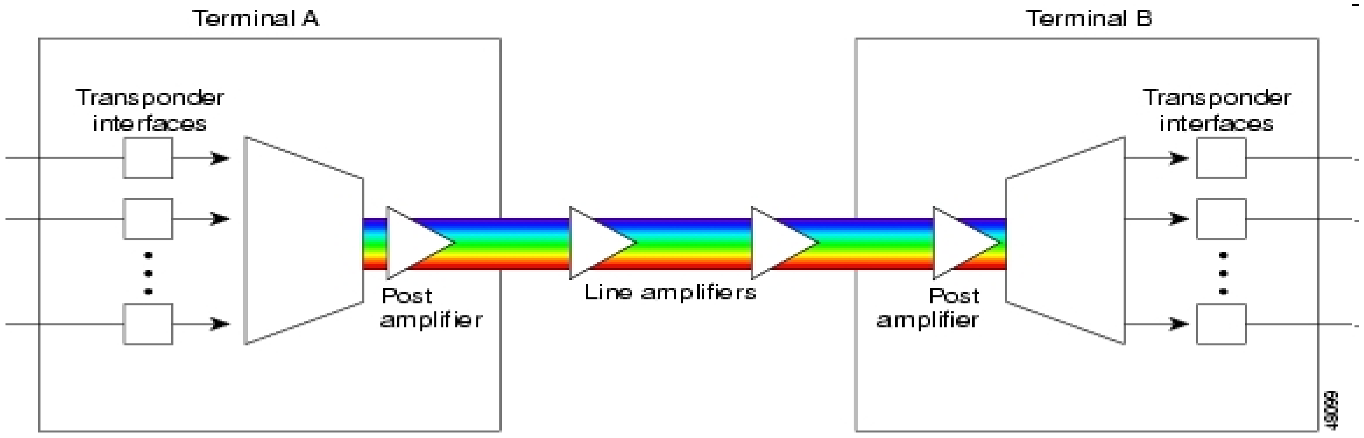
- 1960 – the invention of laser (suitable transmission medium?)
- 1962 – the invention of semiconductor laser
- 1966 – Charles K. Kao fiber 1000dB/km
- 1970 – 20dB/km at 1 um
- **1st generation GaAs lasers 850nm, 10km regeneration**
- 1980 – 45 Mb/s (**1st generation**) multi-mode fibres
- **2nd generation 1310 nm**
- 1980s – 1310 nm, 1 dB/km, 100 Mb/s, multi-mode fibres
- Late 1980s – 2 Gb/s, single mode fibres, repeater spacing 50 km (**2nd generation**)
- **3rd generation 1550 nm**
- 1990s – 1550 nm (problem with lasers, dispersion of fibres, typical repeater spacing 60 -70km), 2.5 Gb/s or 10 Gb/s (**3rd generation**)



Evolution of Optical Communication Systems

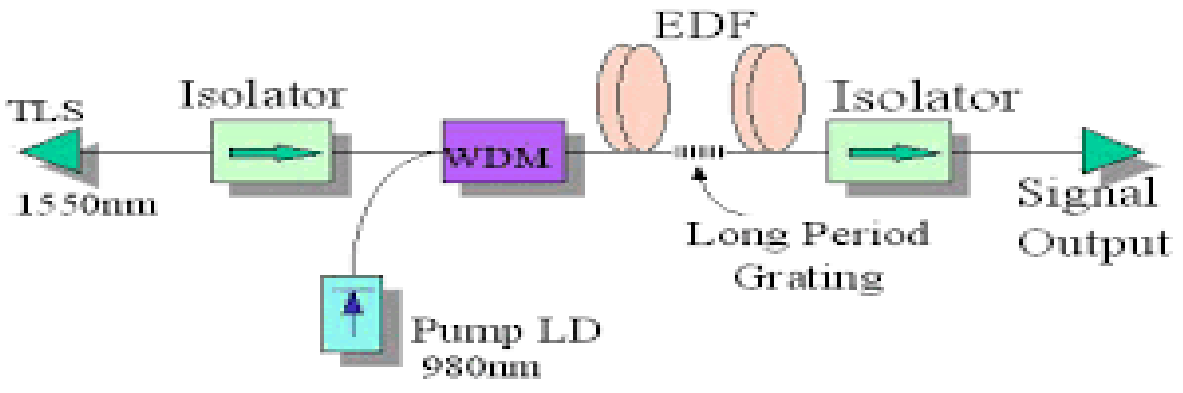
- **4th generation** – 1550 nm – WDM - **DWDM**, CWDM
- 1990s - DWDM, optical amplification by Erbium Doped Fibre Amplifiers, developed late 1980s, spans 80 km
- Typically amplified, long distances
- Thermally stabilized lasers and filters
- Grids:
  - 200 GHz, **100** GHz
  - **50** GHz standard ~ 0,4 nm (C band ~ 80/96 channels)
  - 33 GHz submarine
  - Flexible



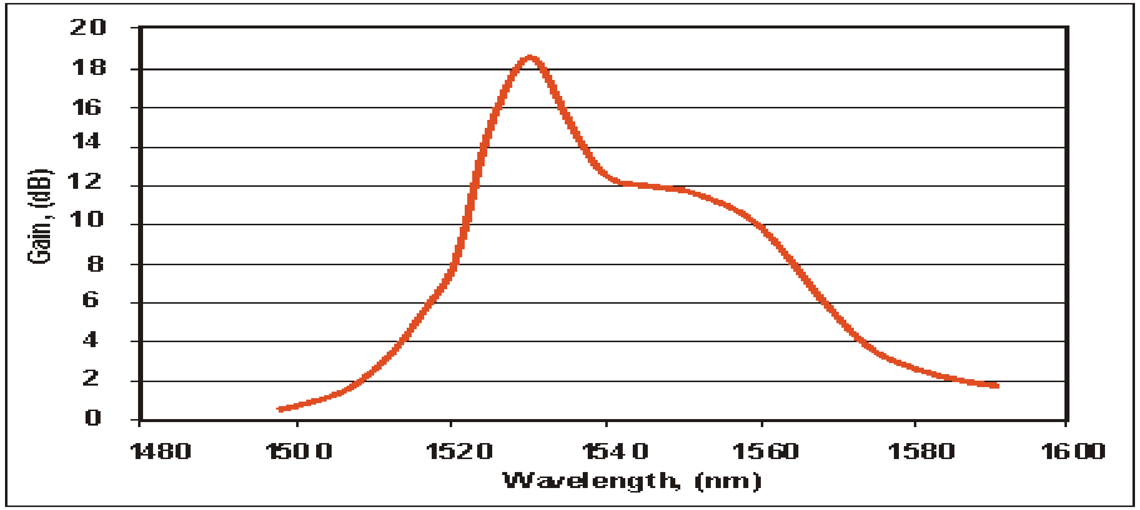


Evolution of Optical Communication Systems

- Erbium Doped Fibre Amplifier
- Gain (30 dB), not uniform across C (L) band
- Output powers (5 Watts or more)
- Input power (-35 dBm)
- Noise Figure (NF): 3.8, typ 5-7dB, teoretical minimum 3 dB. Noise from ASE



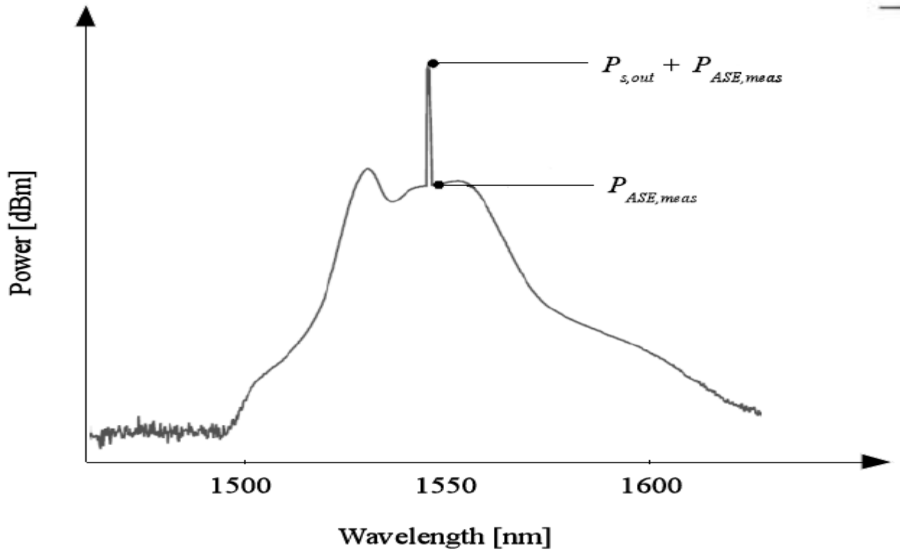
Schematic Diagram of EDFA

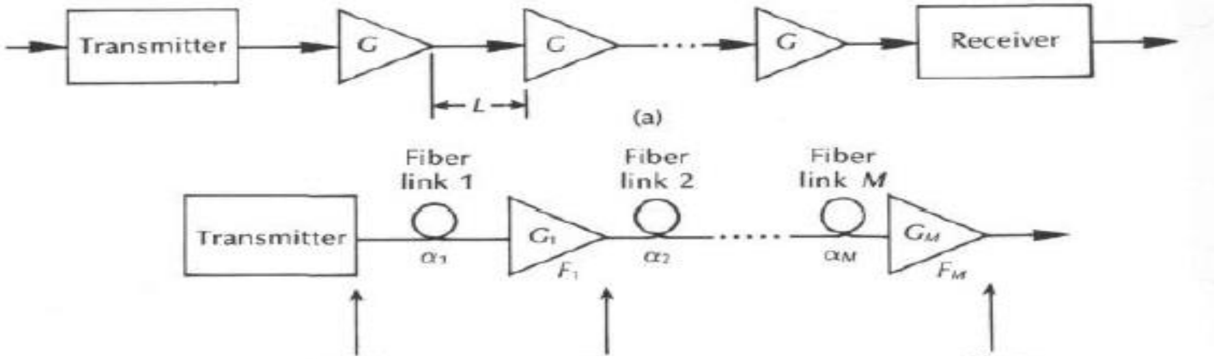


Evolution of Optical Communication Systems

- Noise Limited Reach

$$OSNR = \frac{signal\ power}{noise\ power} \qquad OSNR_{one} = \frac{P_{out}}{P_{ase}} = \frac{P_{in} \cdot G}{P_{ase}} = \frac{P_{in}}{F \cdot h\upsilon\,\partial f}$$

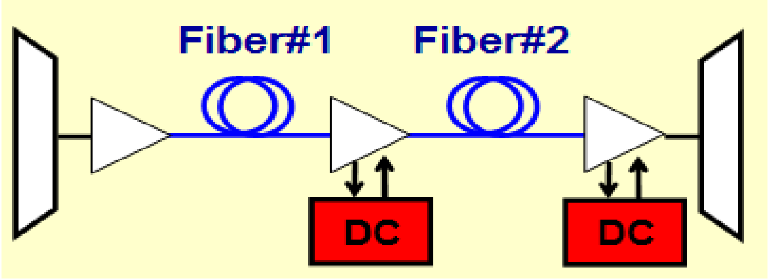


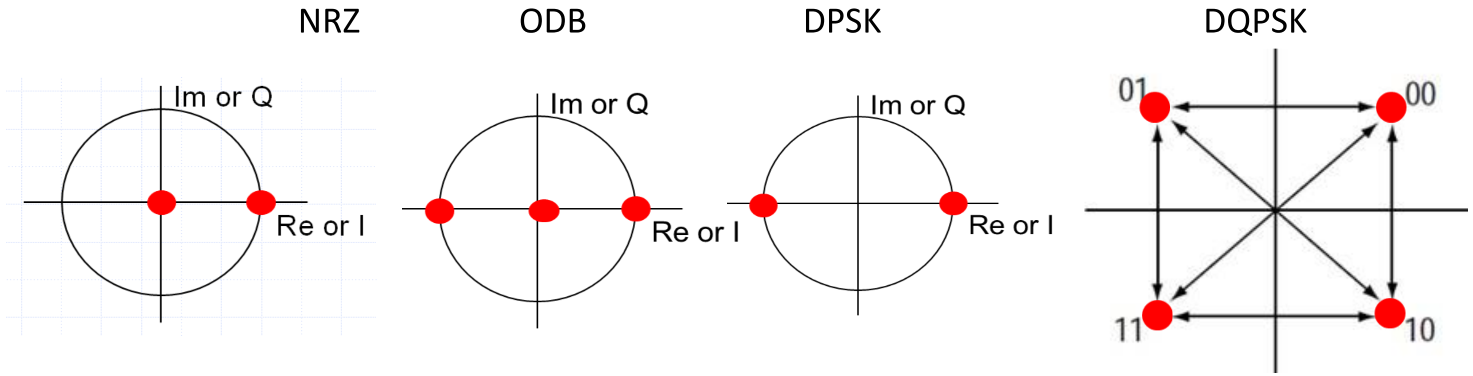


$$F_{total} = \frac{F_1}{\alpha_1} + \frac{F_2}{\alpha_1 G_1 \alpha_2} + \ldots\ldots \frac{F_m}{\alpha_m \prod_{k=1}^{m-1} G_k \alpha_k}$$

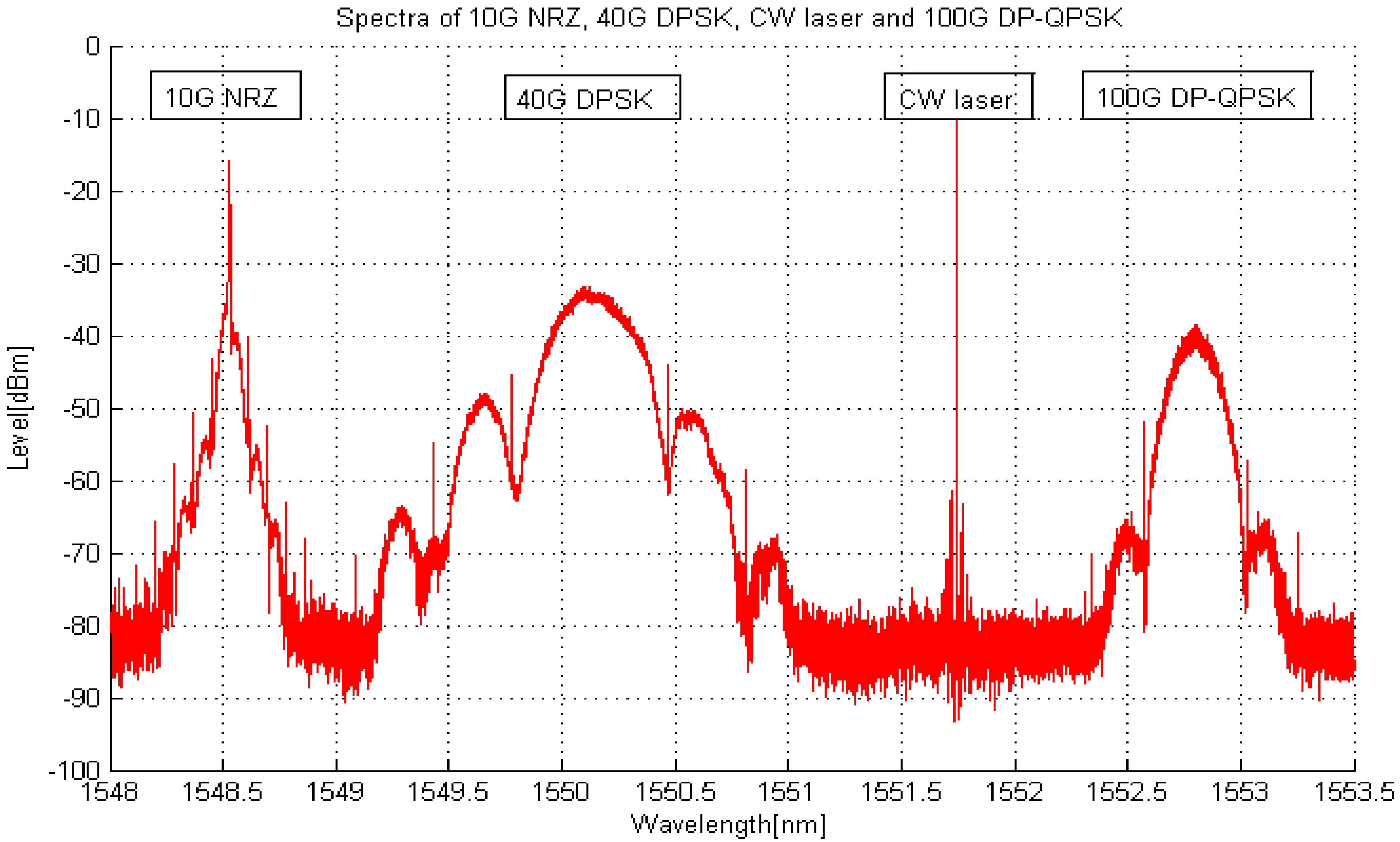
Evolution of Optical Communication Systems

- Bandwidth demand satisfied by serial speed of single channel growth
- 0.155-> 0.622->2.5->10->40 Gbps
- On-off keying, IM-DD - intensity modulation - direct detection
- 10->40G transition (bit interval 100 -> 25 ps)
  - 40G NRZ tolerance very weak CD 50ps/nm (equals to 3km of G.652 fibre), PMD 2.5 ps
  - ODB, DPSK proposed, but more strict design rules compared to 10G, DQPSK (20Gbaud)



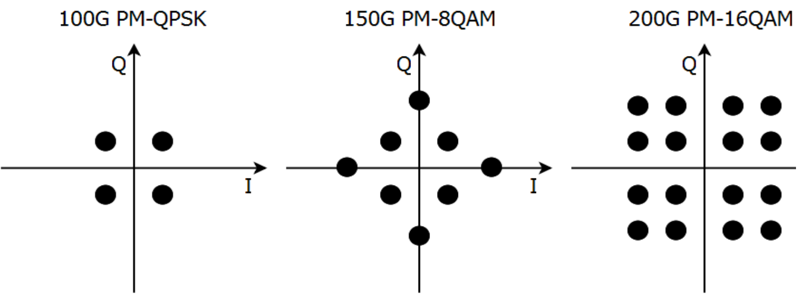


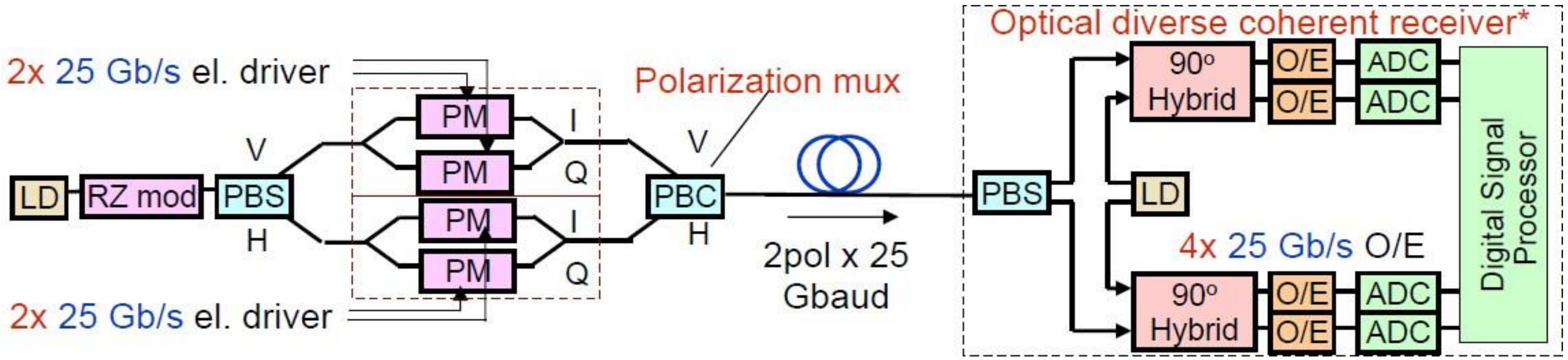
Evolution of Optical Communication Systems



Evolution of Optical Communication Systems

- Bandwidth demand satisfied with more complex modulation format and polarisation multiplexing
- 0.155-> 0.622->2.5->10->40->100G->200G->400G
- 100G coherent Dual Polarisation - DQPSK (28GBaud) solves some issues, 5th generation
  - + Works over 50 GHz grid,+ Design rules almost 10G; CD, PMD electronic compensation
  - - Sensitive to non-linearities, FWM->DCFs removal->coexistence with legacy 10G channels
  - - Cost of complicated modulation format (TX+RX) + necessity of powerful DSPs and ADCs

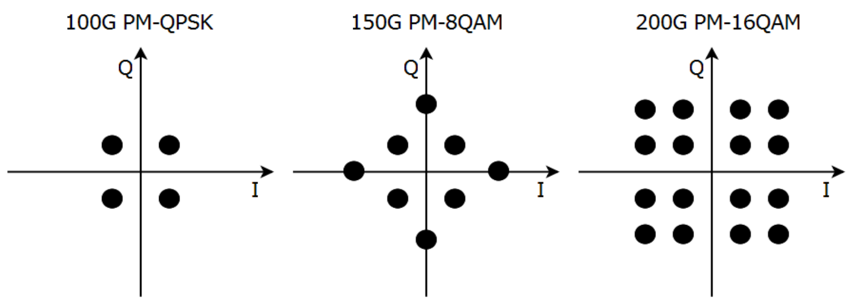




C.R.S. Fludger *et. al*, OFC'2007, PDP22.

Evolution of Optical Communication Systems

- Bandwidth demand satisfied with more complex modulation format and polarisation multiplexing
- 0.155-> 0.622->2.5->10->40->100G->200G->400G



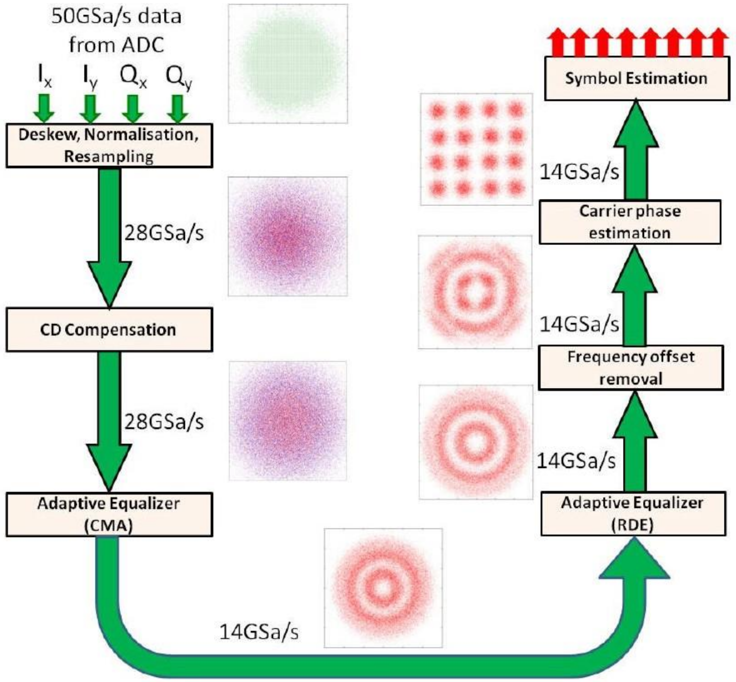
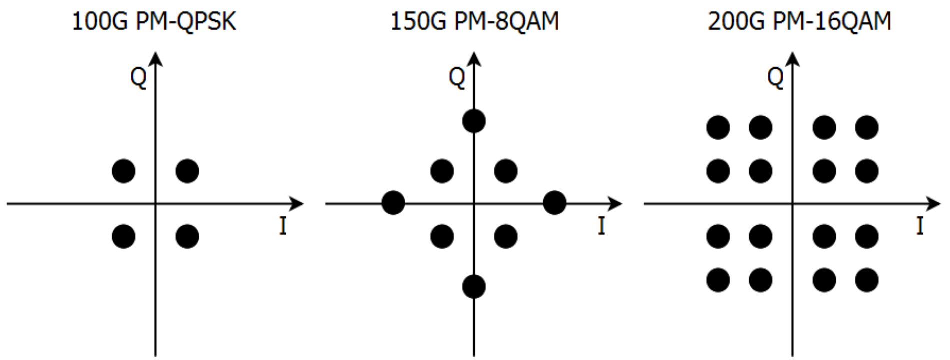


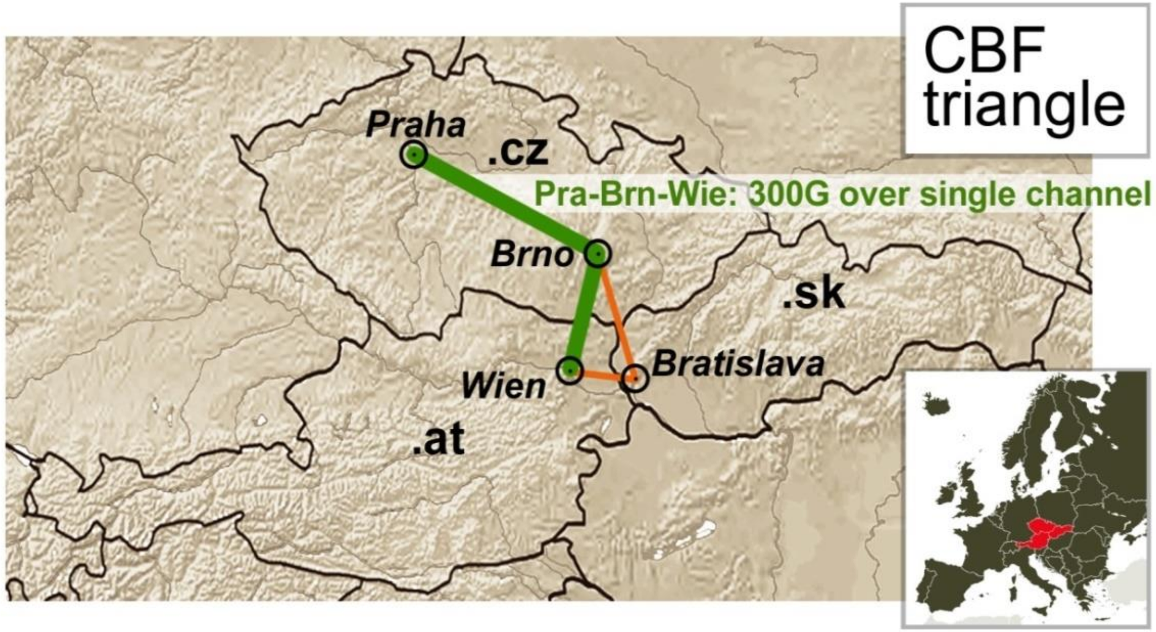
Figure 32: DSP flow for received 112Gbit/s PDM-QAM16 signal after transmission

S. Makovejs: High-speed optical fibre transmission using advanced modulation formats, PhD thesis, UCL, 2011.

Evolution of Optical Communication Systems

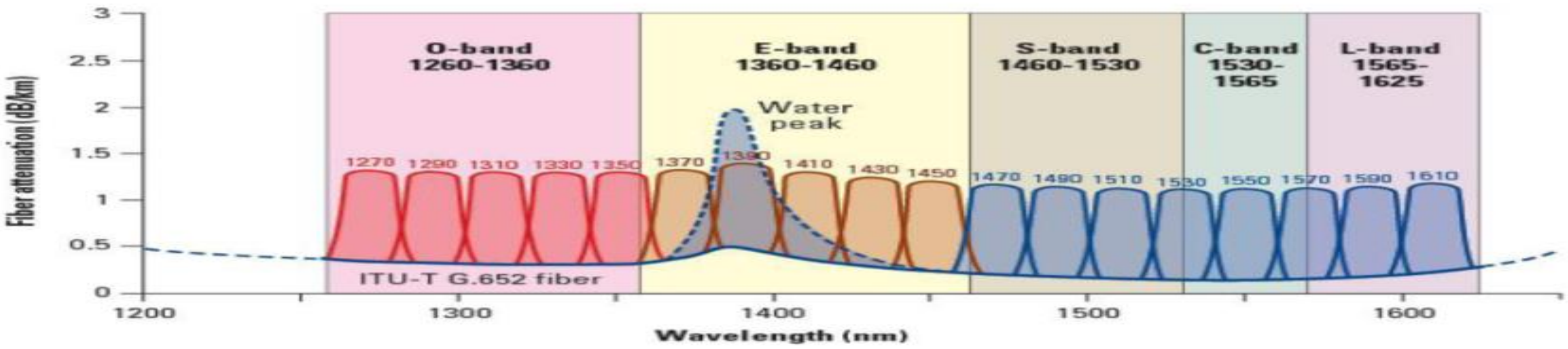
- Bandwidth demand satisfied by serial speed growth
- 0.155-> 0.622->2.5->10->40->100G->200G->400G
- 400 G (56 Gbaud - 16 QAM)
  - CESNET + GEANT trial over Open Line System Czech Light® (fibers : 519 km and 134 dB)
  - 300G single wave all optical transmission over 513 km, five spans where four are 30 dB





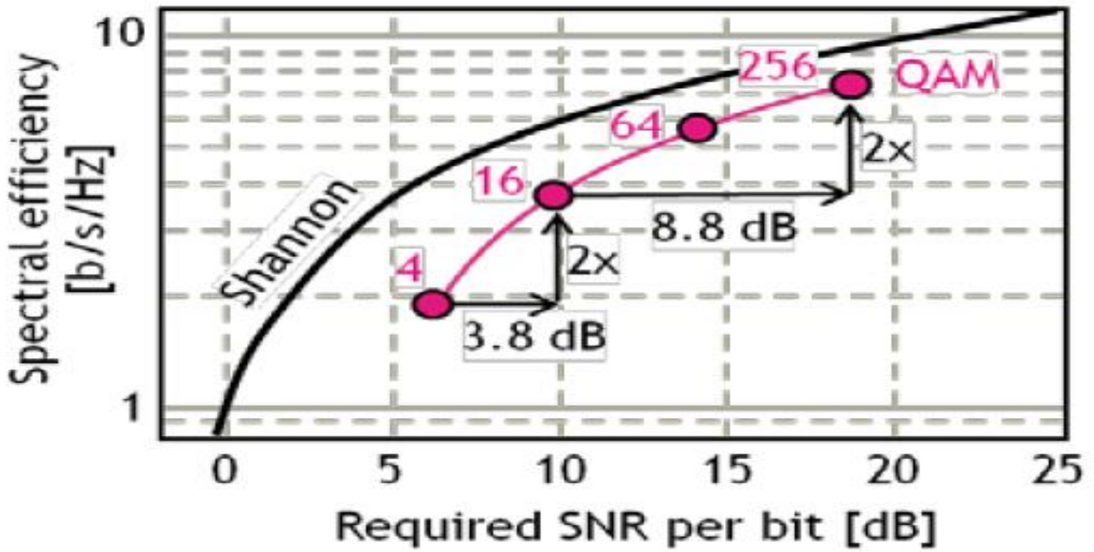
Evolution of Optical Communication Systems

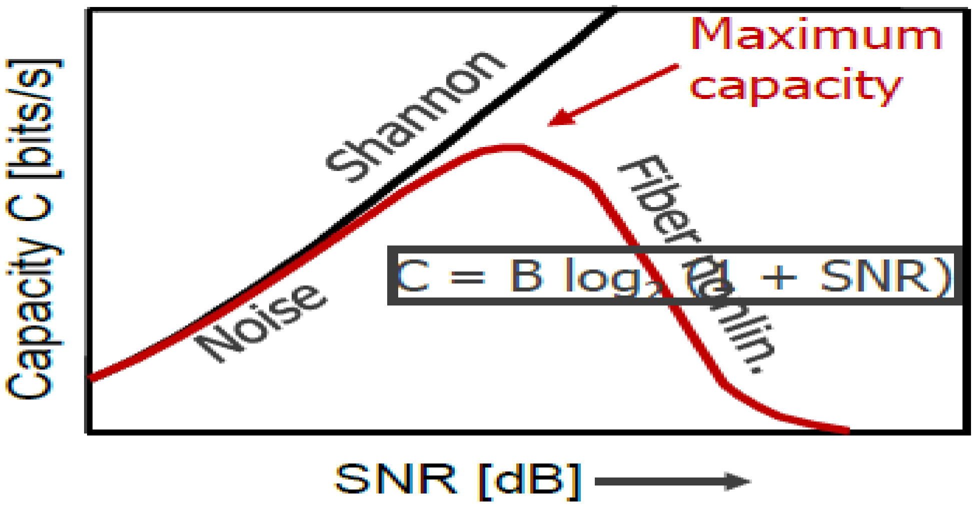
- Capacities – 4+5th generations
  - Obsolete – 96 ch. per 10 Gbit/s – 0,96 Tbit/s (OOK
  - Mature – 96 ch. per 200 Gbit/s – 19,2 Tbit/s (DP16QAM)
  - Present – 80 ch. per 400 Gbit/s – 32 Tbit/s (**60 GHz**, DP16QAM)
  - L band technology available since late 1990 – 90nm
  - Low loss window in SSMF ~ 400nm



Evolution of Optical Communication Systems

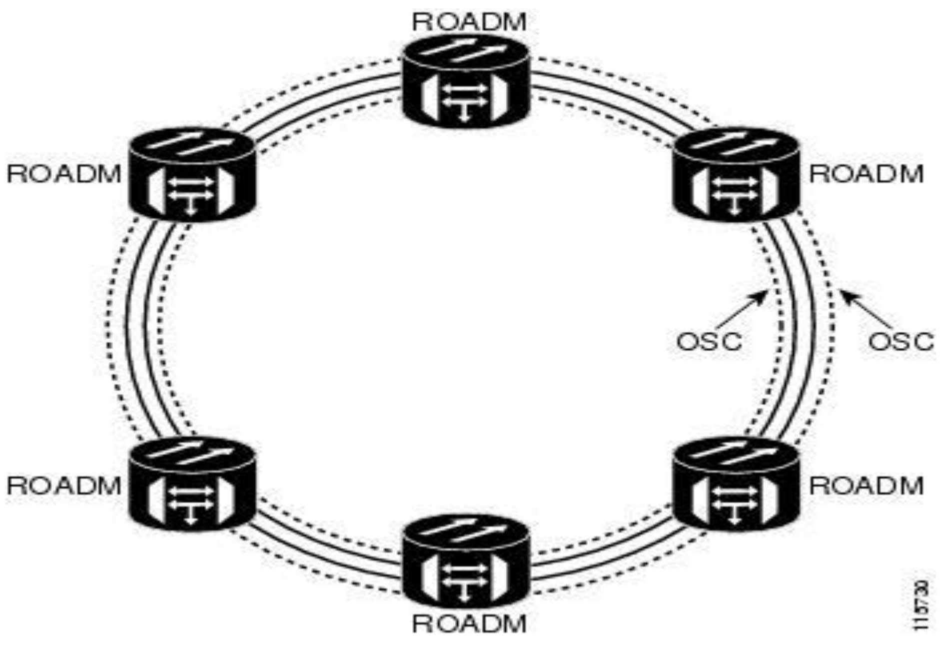
- Shannon's law $C = B \cdot \log_2(1+SNR)$
- C/B (capacity per unit bandwidth) is limited by noise

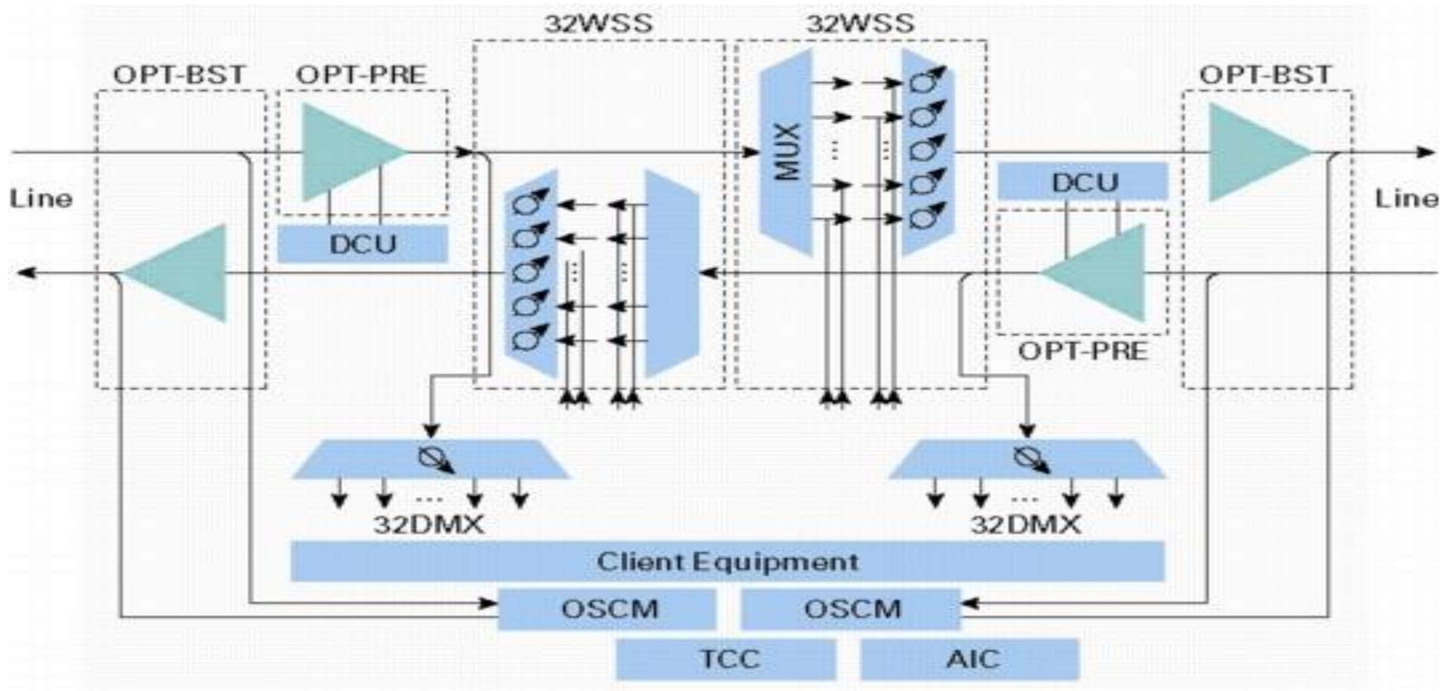




Evolution of Optical Communication Systems

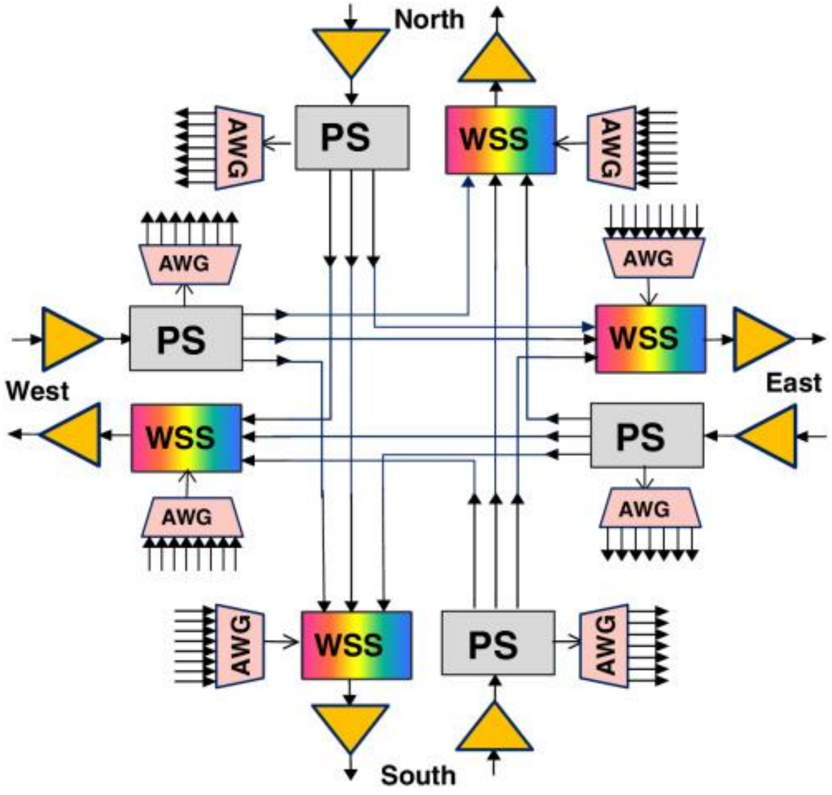
- Linear and ring topologies - ROADMs

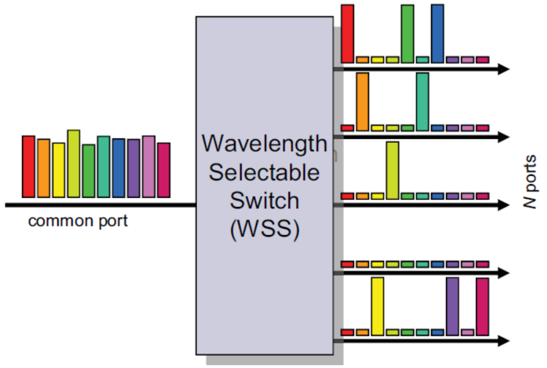


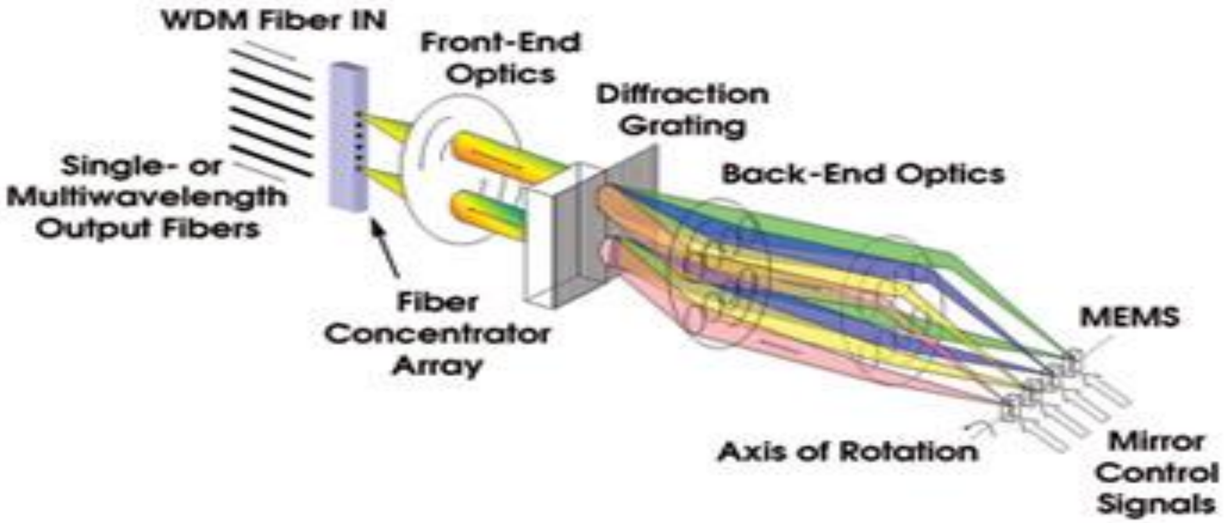


Evolution of Optical Communication Systems

- Meshed topologies - WSSs



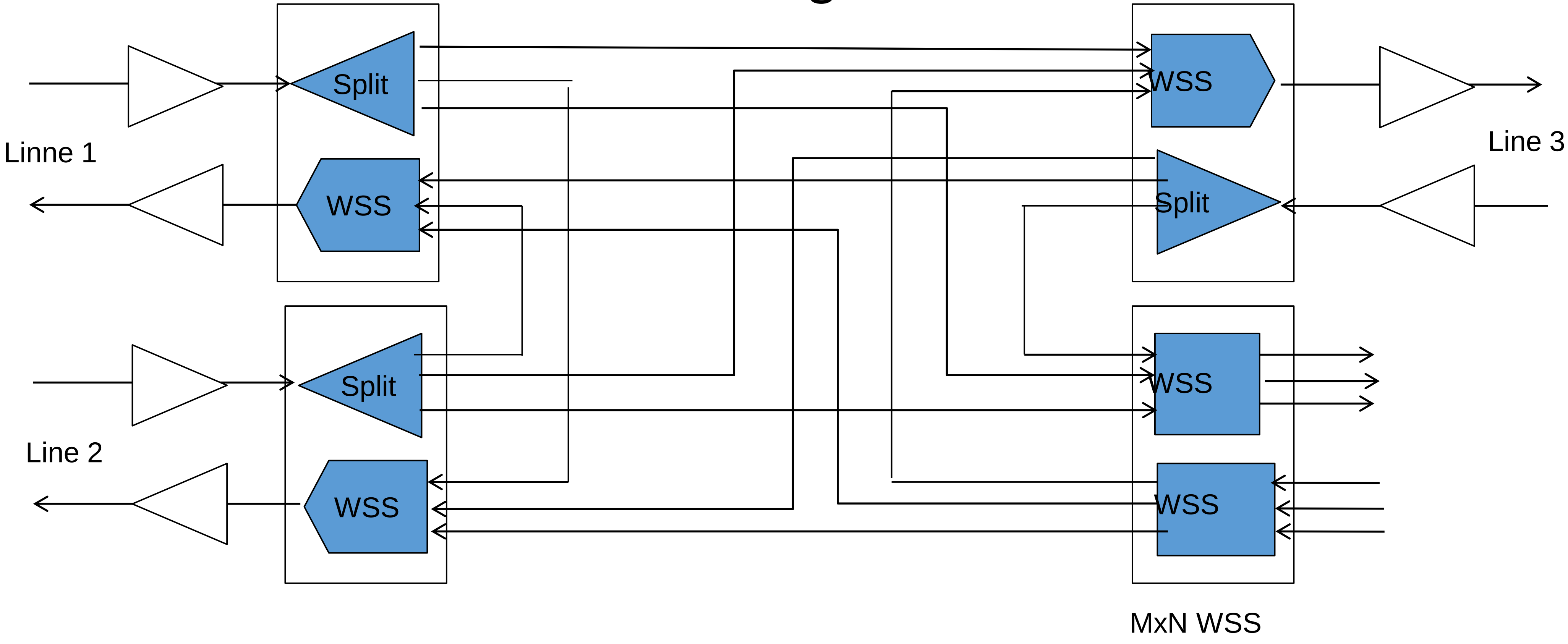




Evolution of Optical Communication Systems

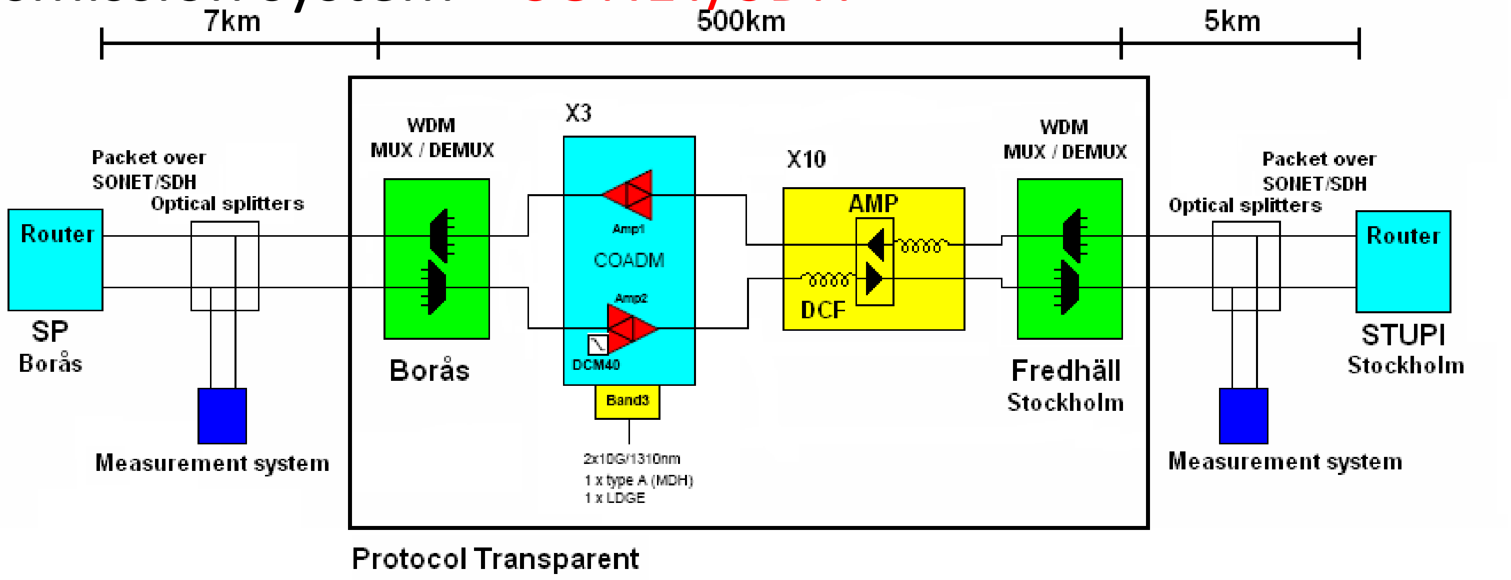
- Colorless, directionless node, degree 3

non-blocking



Optical transport of T/F Signals over Telecom Fibres

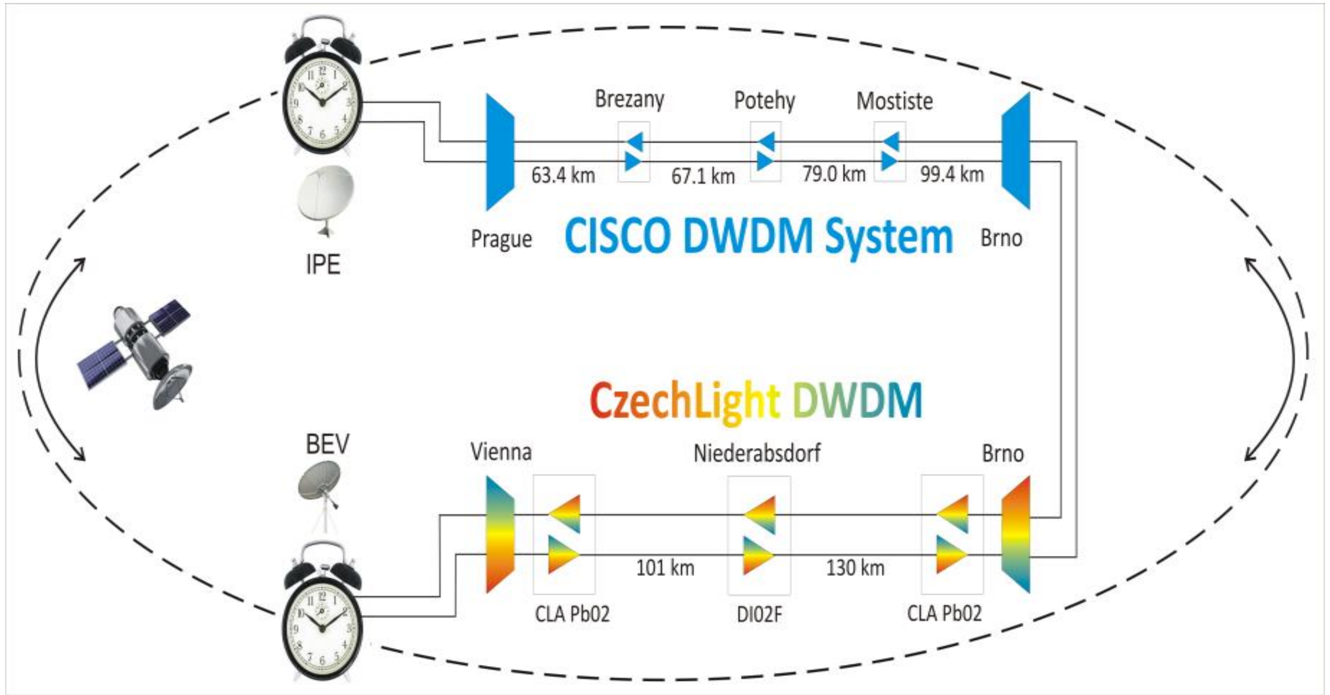
- Using telco transmission system – SONET/SDH

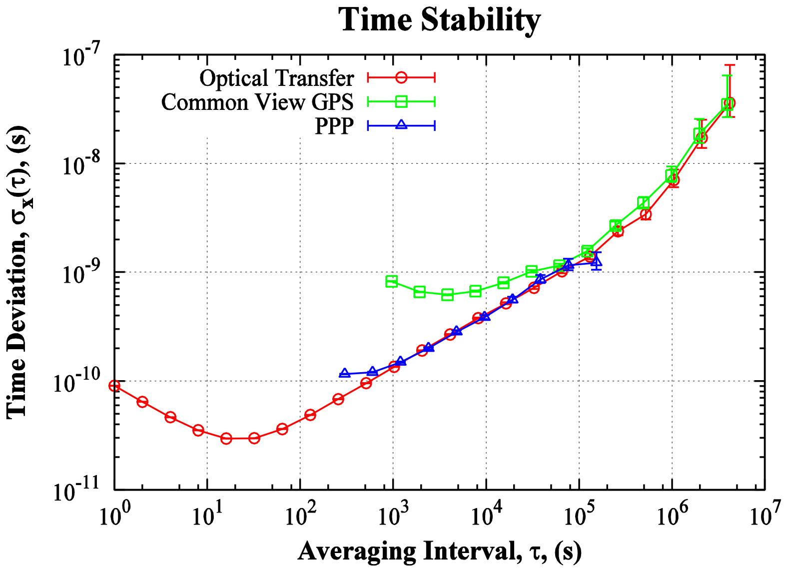


- Ebenhag S. et al. ”Time Transfer Using an Asynchronous Computer Network: Results from a 500-km Baseline Experiment”, PTTI 2007
- “A precision relative to GPS carrier phase of < 1 ns was obtained, which is similar to previous experiments”.
- “More studies are needed especially on differential path delays in the optical fiber links (DCF) due to asymmetry and temperature dependence of the equipment”.
- Extended to 1130 km in 2011

Optical transport of T/F Signals over Telecom Fibres

- Using telecom transmission system – lambdas
- Comparison of time scales between IPE-BEV 550 km, since Aug 2011
- Smotlacha et al. “Optical Link Time Transfer between IPE and BEV” PTTI 2011



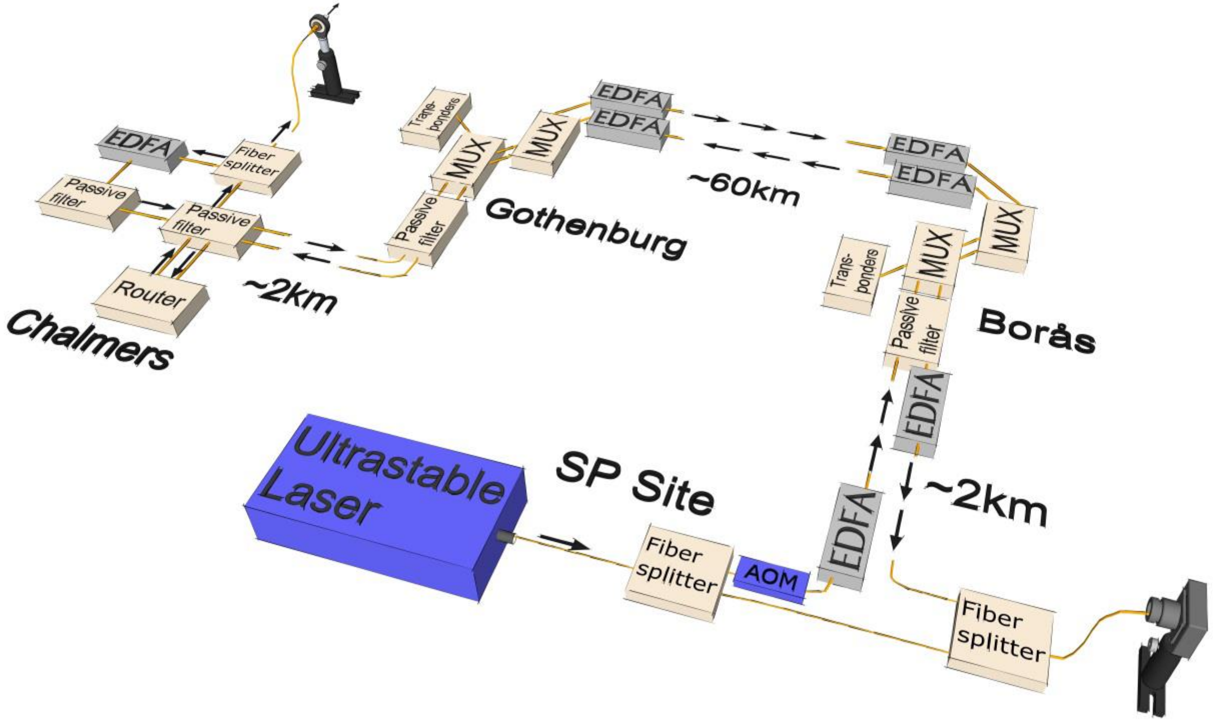


Optical transport of T/F Signals over Telecom Fibres

- Using telecom transmission system - lambdas
  - White Rabbit time-transfer experiment between Espoo and Kajaani in Finland
  - 2013 Collaboration: MIKES/CSC/FUNET ~ 900 km
  - https://www.ohwr.org/projects/white-rabbit/wiki/mikes

Optical transport of T/F Signals over Telecom Fibres

- Using telecom transmission system – lambdas
- Ebenhag S. et al "Coherent Optical Two-Way Frequency Transfer in a Commercial DWDM Network" PTTI 2016



Optical transport of T/F Signals over Telecom Fibres

- Bypassing telco transmission system – within C band
- Univ. Paris 13, LNE-SYRTE, RENATER, 150 km
- Lopez et al., Opt. Express 18, 16849 (2010)

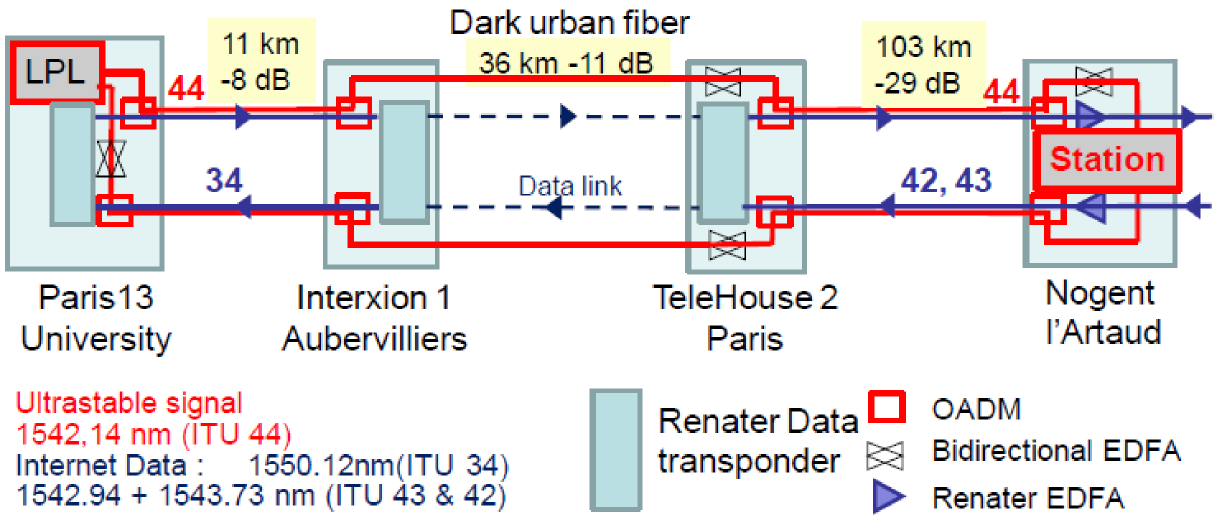
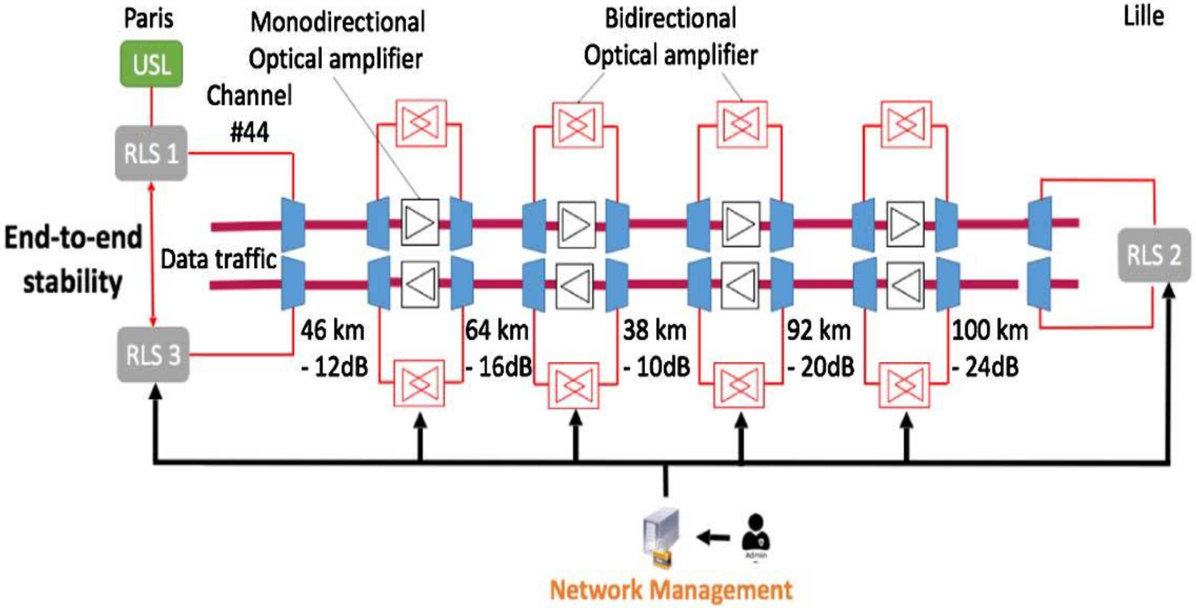
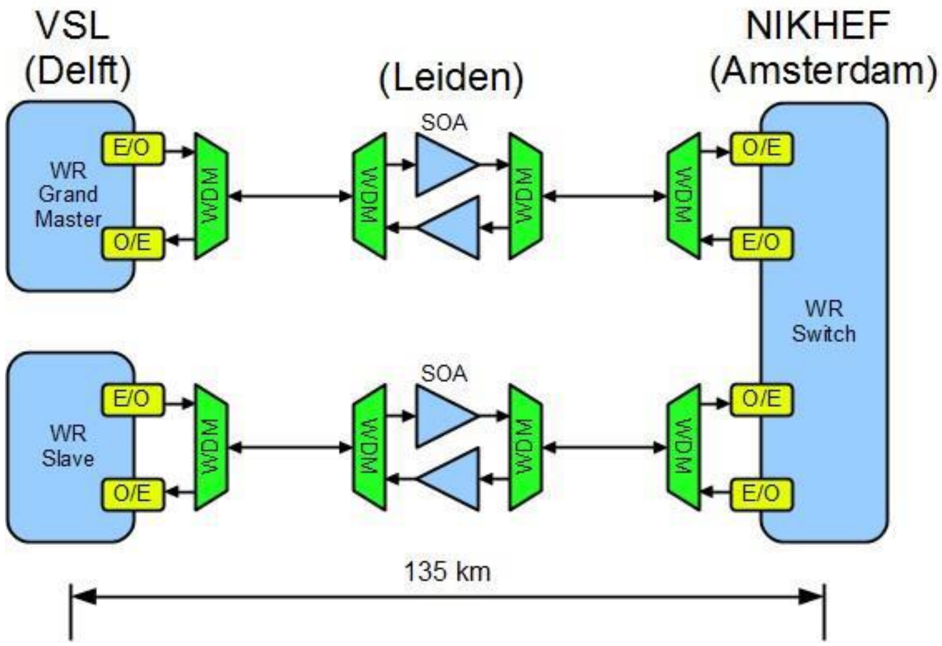


Fig. 3. Scheme of the 2 x 150 km cascaded optical link.



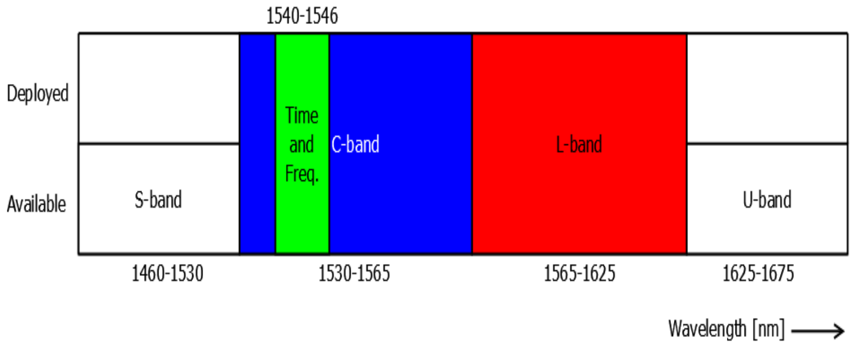
Optical transport of T/F Signals over Telecom Fibres

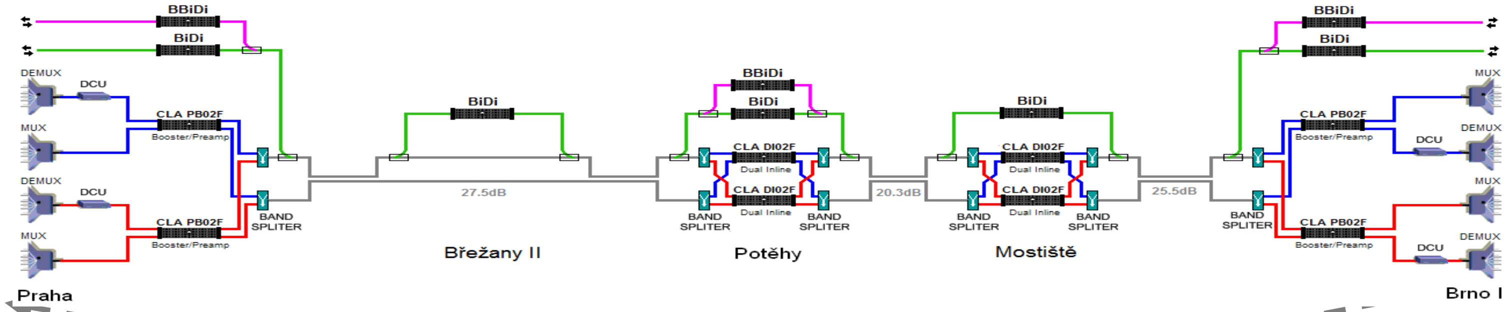
- Bypassing telco transmission system – within S band
- NIKHEF – VSL 2014, 137 km
- Koelemeij J. et al “Methods for data, time and ultrastable frequency transfer through long-haul fiber-optic links”

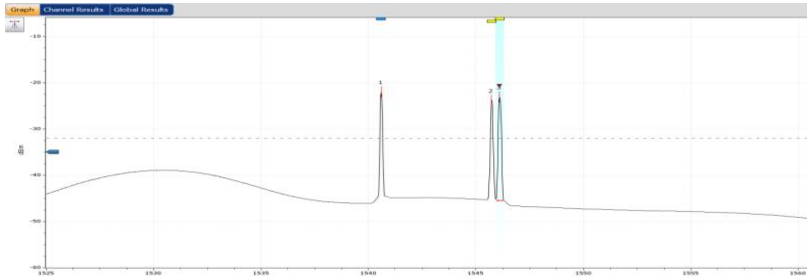


Optical transport of T/F Signals over Telecom Fibres

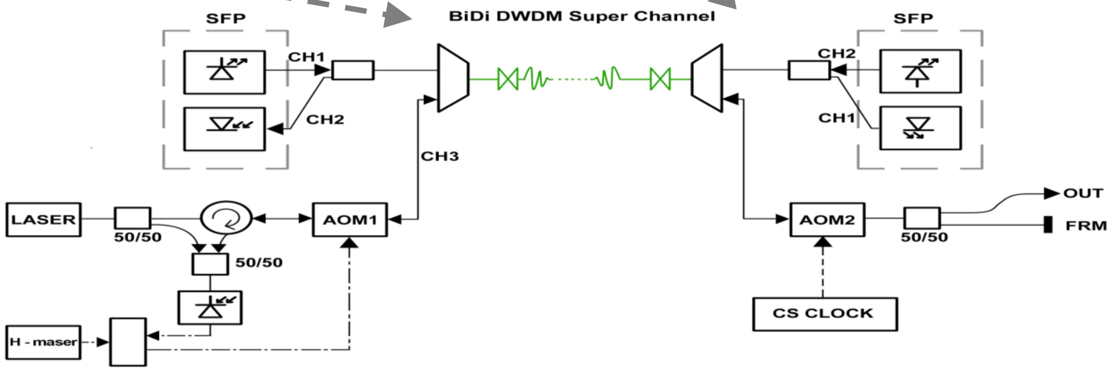
- Bypassing telco transmission system – C, L band
- 800 GHz, T+F, since 2014
- Vojtech J. et al. “Simultaneous transmission of accurate time and stable frequency through bidirectional channel over telecommunication infrastructure with excessive spans”.

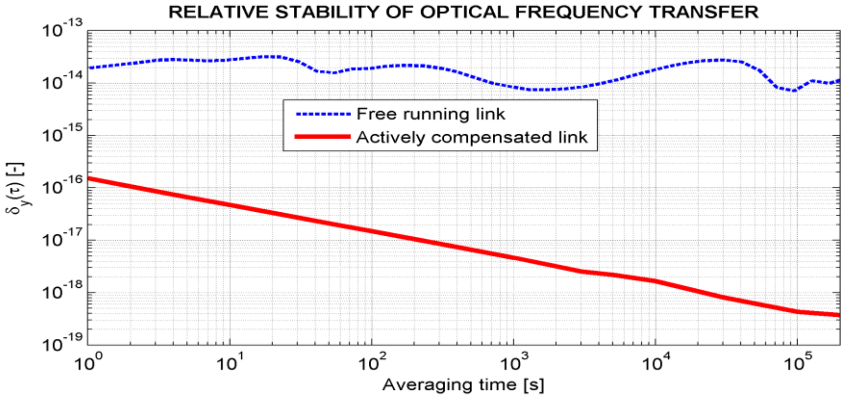






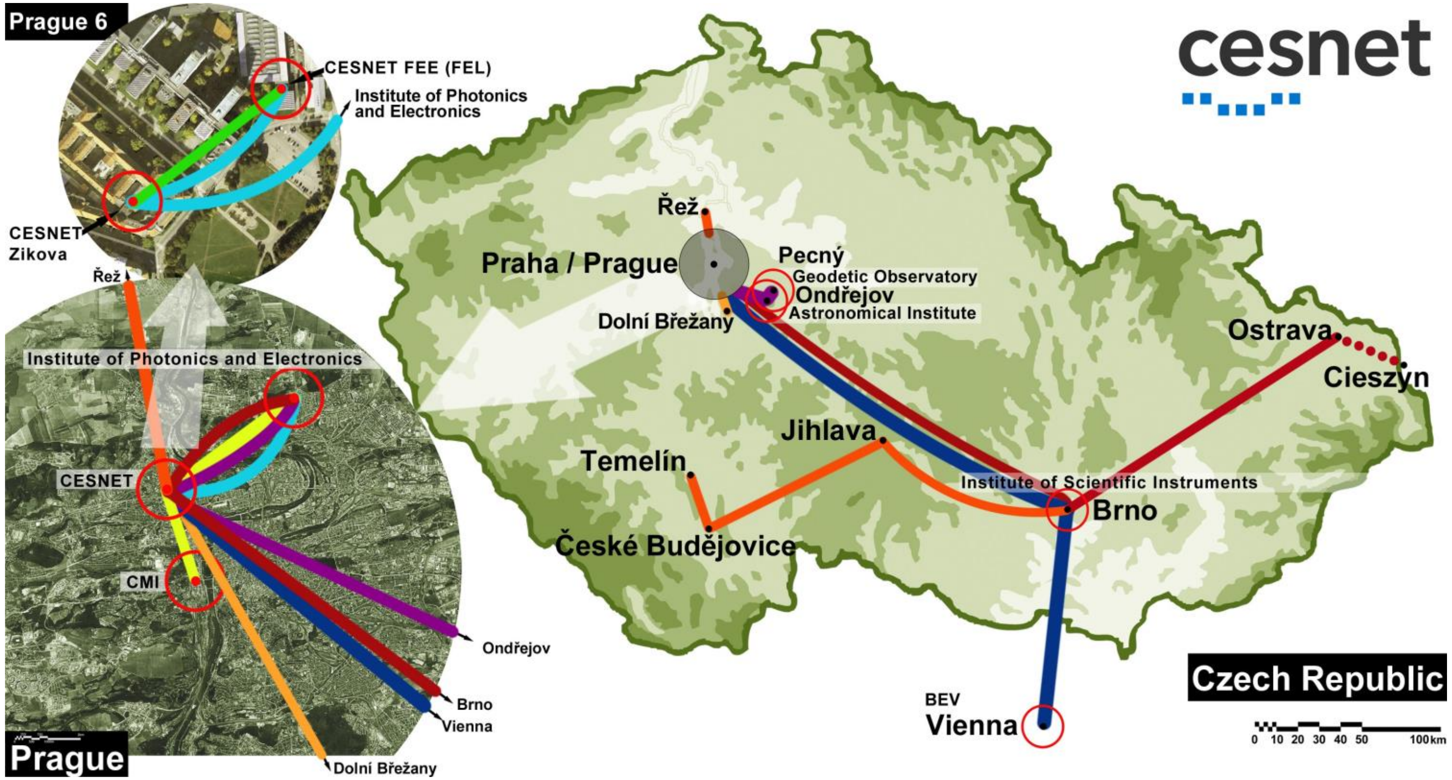
CESNET (Prague) – ISI (Brno) 306km





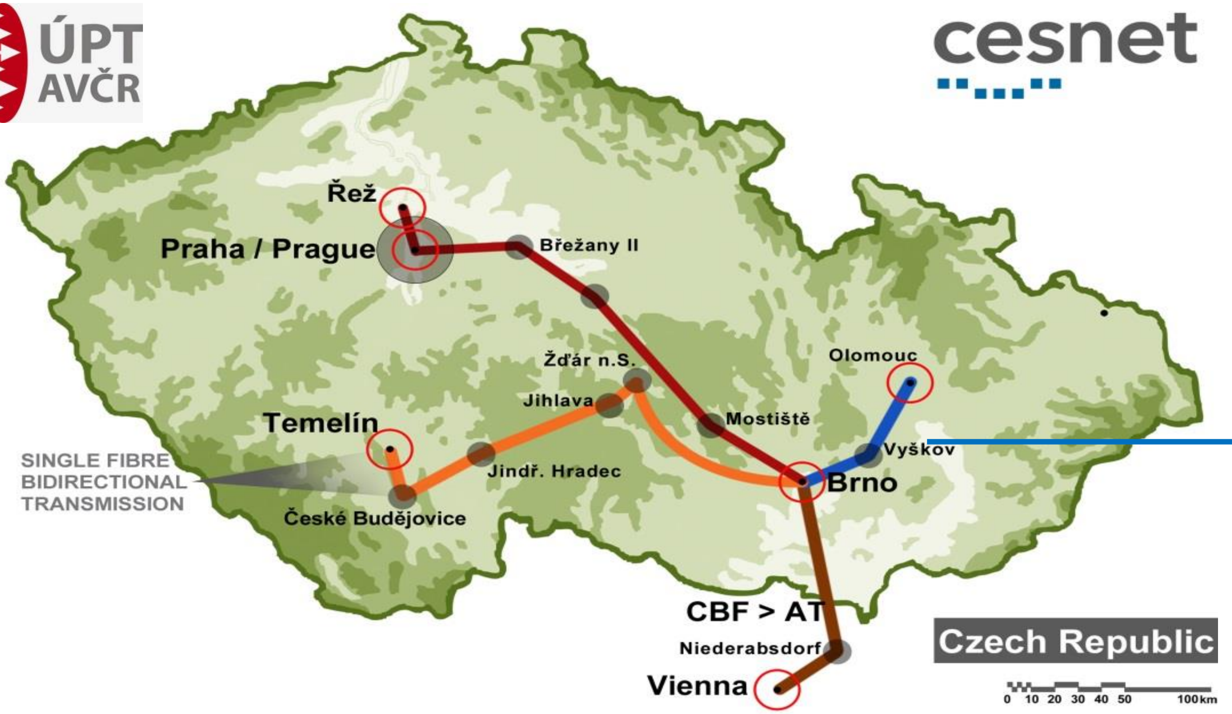
Optical transport of T/F Signals over Telecom Fibres

- CESNET T/F INFRASTRUCTURE almost 1300 km lines with bidirectional transmission with 26 bidi amplifiers, + 550 km unidirectional line



Optical transport of T/F Signals over Telecom Fibres

- Coherent frequency transfer almost on 1000 km of lines
- All (excluding last miles in Vienna, Brno) shared with data



- TBF 2020 within NCS 2000 by Cisco
- C band ch 46-43
- S band

Acknowledgement

Čáp O., Čížek M., Hucl V., Hrabina J., Pravdová L., Řeřucha Š.
Department of Coherence Optics, Institute of Scientific Instruments, Brno, Czech Republic

Altmannová L., Havliš O., Hažlinský M., Horváth T ., Kundrát J., Münster P., Radil J., Smotlacha* V., Škoda P., Šlapák M., Velc R., Vohnout R.
Department of Optical Networks/*Technology for network applications, CESNET, Prague, Czech Republic

Thank you very much for your kind attention

josef.vojtech@cesnet.cz

This project receives funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement no. 731107

CLONETS – CLock NETwork Services

Strategy and innovation for clock services over optical-fibre networks

Proposal ID: **731107**
Topic: **INFRAINNOV-2016**
Duration: **30 months**
Start date: **1st January 2017**
Web page: **http://www.clonets.eu**

Coordinator

Participants

Third Parties