Coherent Systems and Wavelength Switching technologies in next generation Photonic Backbones

Marco Schiano

Transport Innovation

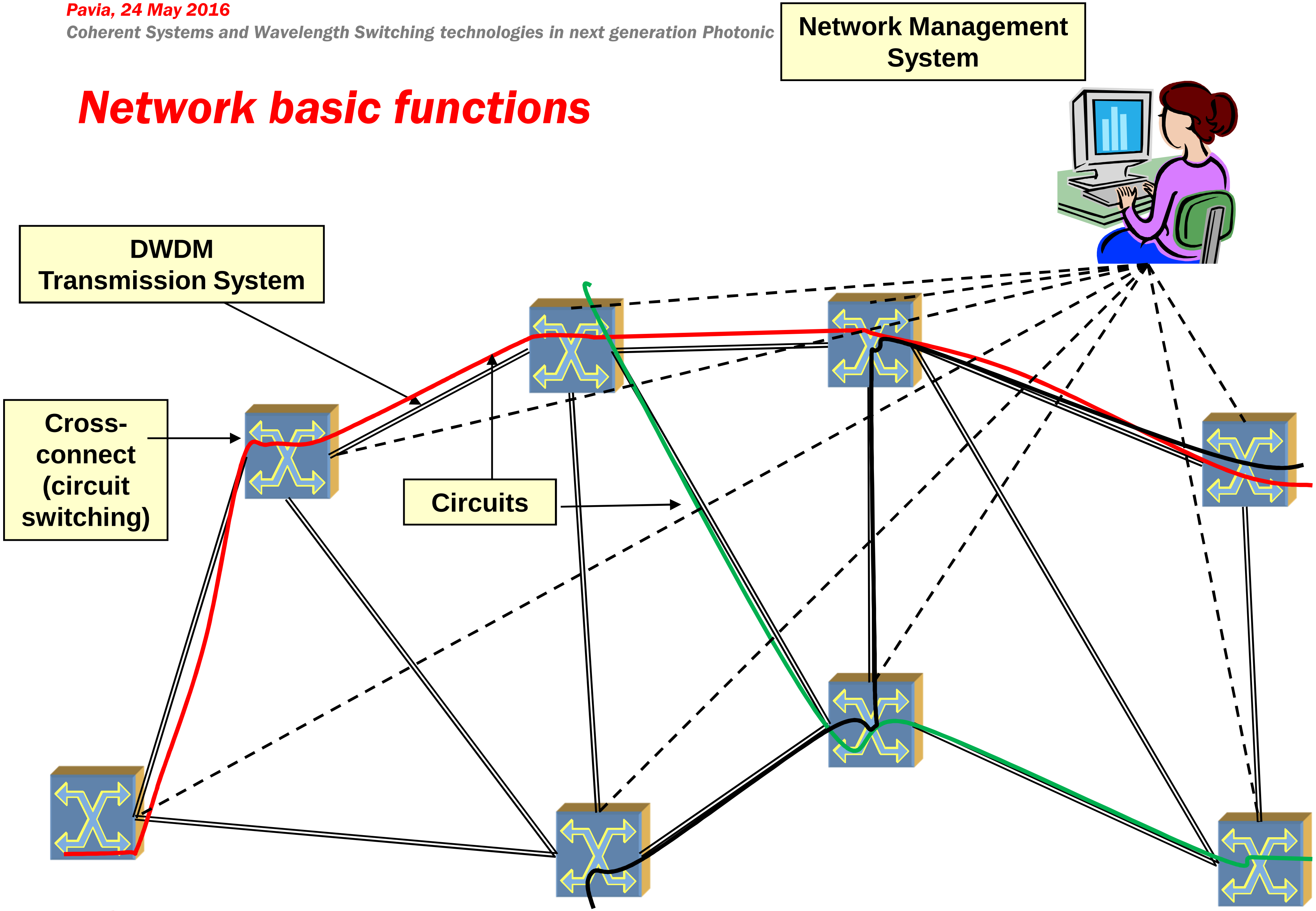
Summary

- ***Photonic Networks technologies***
- ***Transport Networks basic functions***
- ***The Kaleidon photonic backbone***

Transport network scope

- Networks designed for high capacity transport (Tbit/s) on very long distances (~ 10^3 km)
- Circuit-switched networks (they may represent the "server" layer of packet networks, e.g. IP)
- Sorted into 2 segments:
    - Backbone (national or continental)
    - Metro-Regional

Network basic functions



Network Management System

DWDM Transmission System

Cross-connect (circuit switching)

Circuits

Backbone networks examples

Telecom Italia Sparkle
Pan-European Backbone

- 31 nodes
- 9000 km total link length

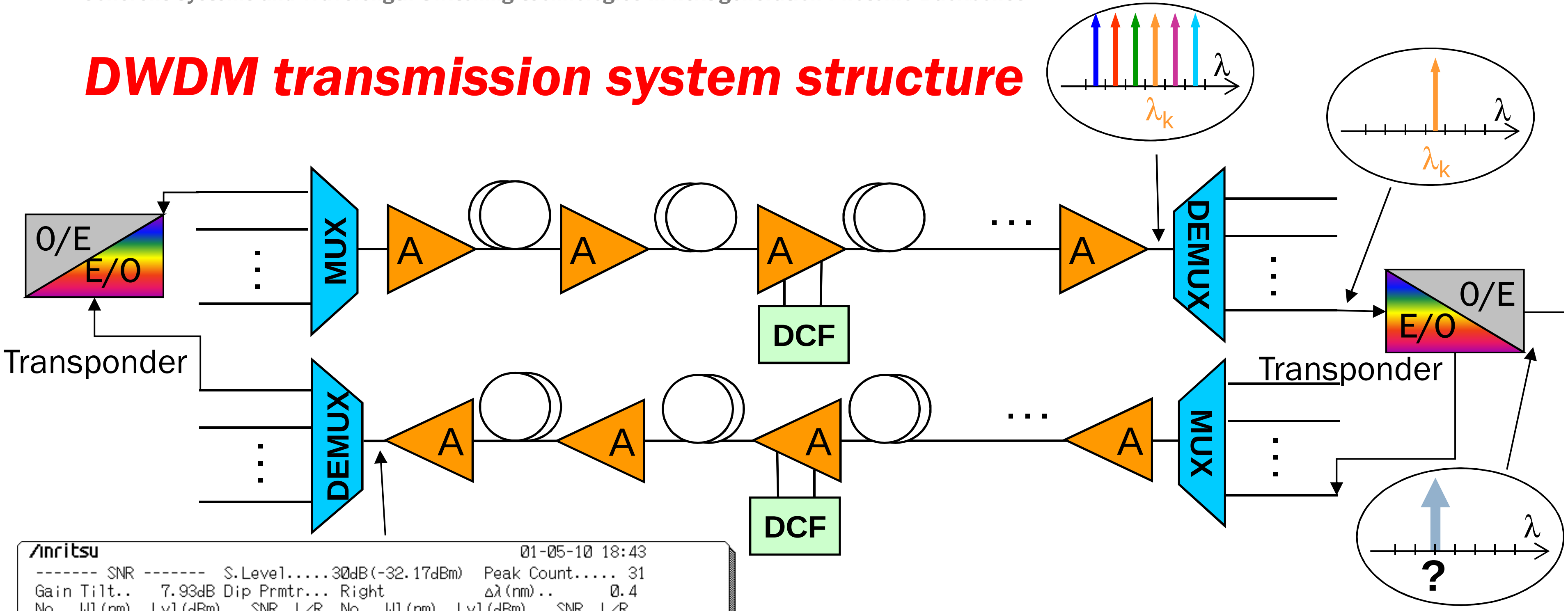
Telecom Italia
Kaleidon Backbone

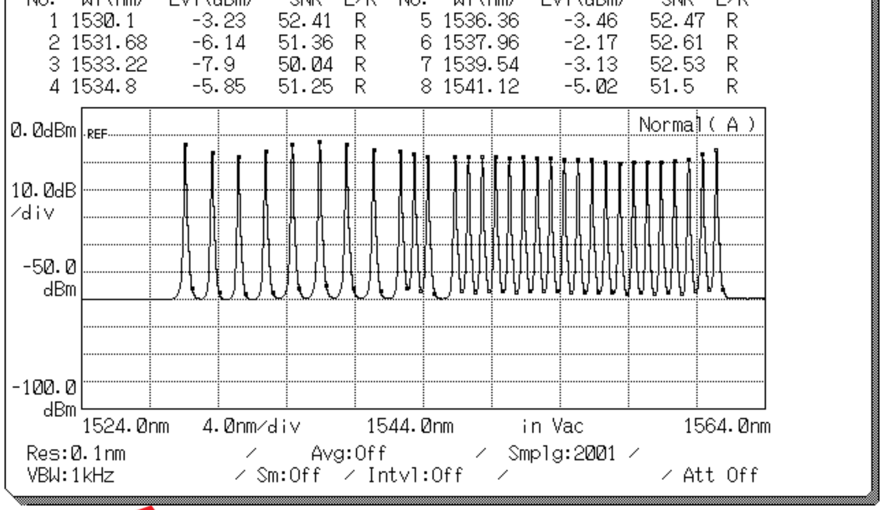
- 44 nodes
- 71 links
- 12000 km total link length

Summary

- **Photonic Networks technologies**
- **Transport Networks basic functions**
- **The Kaleidon photonic backbone**

DWDM transmission system structure




```
/inritsu                                                01-05-10 18:43
 ------- SNR -------   S.Level.....30dB(-32.17dBm)   Peak Count..... 31
 Gain Tilt..   7.93dB Dip Prmtr... Right              Δλ(nm)..       0.4
 No.   Wl(nm)   Lvl(dBm)    SNR  L/R No.   Wl(nm)   Lvl(dBm)    SNR  L/R
   1 1530.1      -3.23    52.41   R    5 1536.36     -3.46    52.47  R
   2 1531.68     -6.14    51.36   R    6 1537.96     -2.17    52.61  R
   3 1533.22     -7.9     50.04   R    7 1539.54     -3.13    52.53  R
   4 1534.8      -5.85    51.25   R    8 1541.12     -5.02    51.5   R
0.0dBm REF                                                Normal( A )
10.0dB
/div
 -50.0
   dBm
-100.0
   dBm 1524.0nm   4.0nm/div      1544.0nm     in Vac          1564.0nm
 Res:0.1nm            /      Avg:Off       /   Smplg:2001 /
 VBW:1kHz            / Sm:Off  / Intvl:Off   /                / Att Off
```

- ***40÷96 channels***
- ***100 or 50 GHz channel spacing***
- ***1530÷1565 nm (C band)***
- ***10, 40 and 100 Gbit/s per channel today***
- ***200 – 400 Gbit/s in the near future***

ITU-T fixed frequency grid

- ***Standard DWDM frequency grid defined in ITU-T Recommendation G.694.1***
- ***ITU channel spacing are 0.4 nm, 0.8 nm and 1.6 nm (50, 100 and 200 GHz)***
- ***This is the so called "fixed grid" with uniform channel spacing***

50 GHz (0.4 nm) grid (wavelengths in nm)

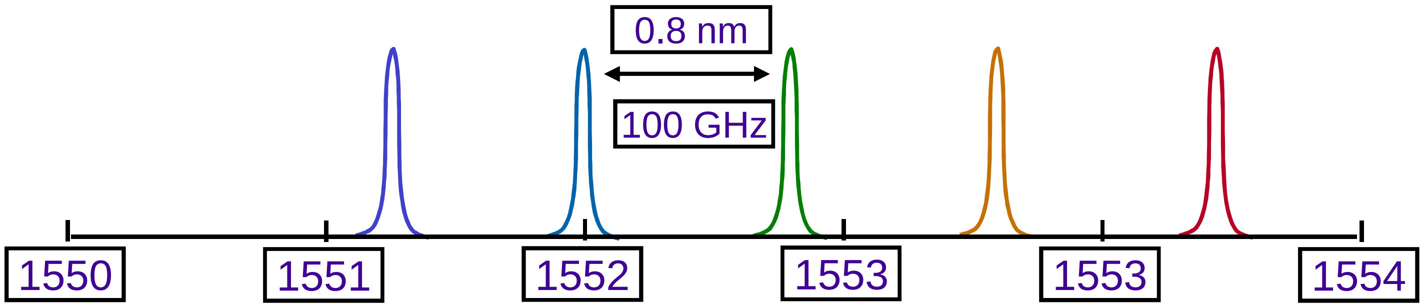
1528.77
1529.16
1529.55
1529.94
1530.33
1530.72
1531.12
1531.51
1531.90
1532.29
1532.68
1533.07
1533.47
1533.86
1534.25

1534.64
1535.04
1535.43
1535.82
1536.22
1536.61
1537.00
1537.40
1537.79
1538.19
1538.58
1538.98
1539.37
1539.77
1540.16

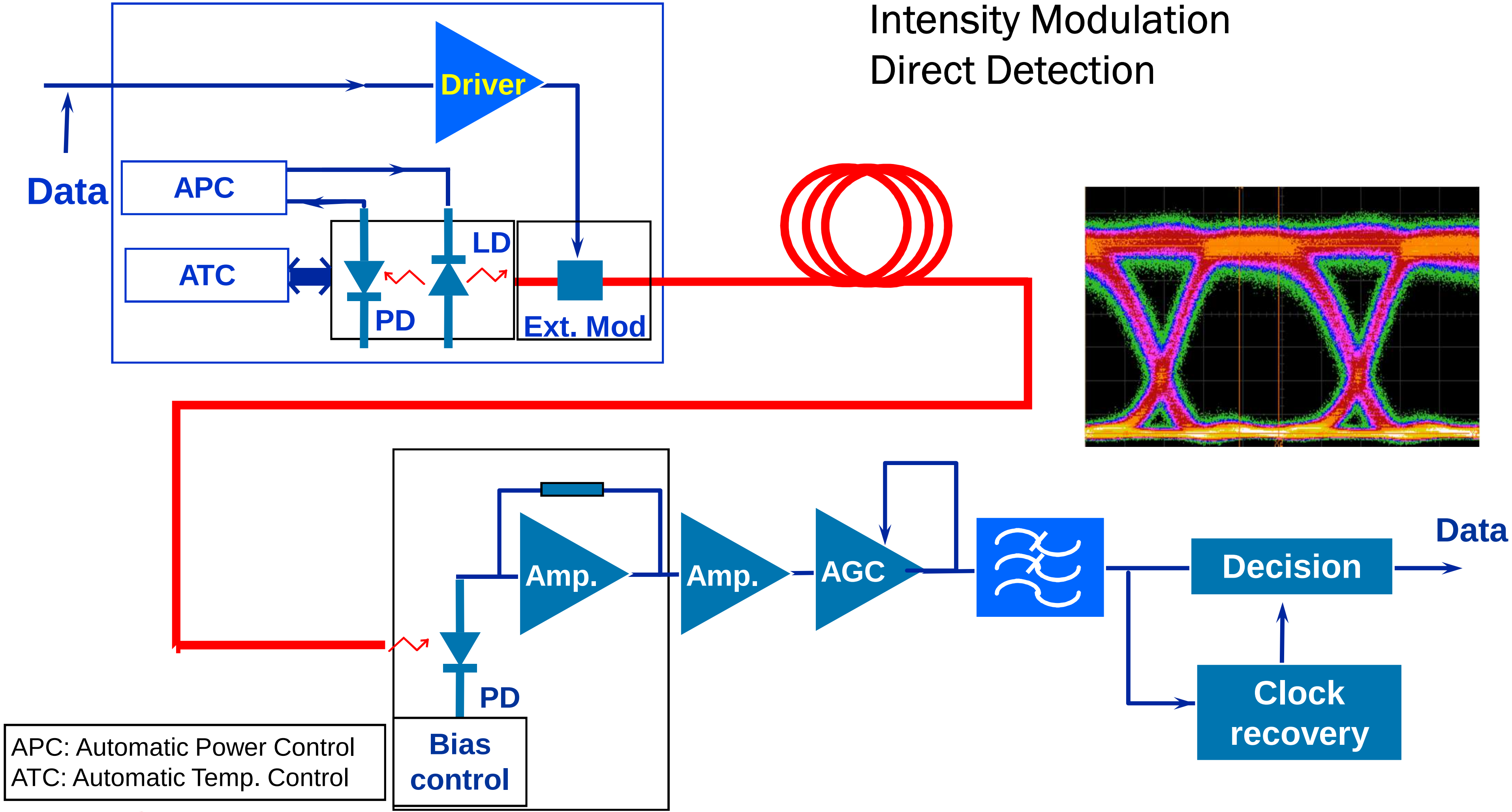
1540.56
1540.95
1541.35
1541.75
1542.14
1542.54
1542.94
1543.33
1543.73
1544.13
1544.53
1544.92
1545.32
1545.72
1546.12

1546.52
1546.92
1547.32
1547.72
1548.11
1548.51
1548.91
1549.32
1549.72
1550.12
1550.52
1550.92
1551.32
1551.72
1552.12

1552.52
1552.93
1553.33
1553.73
1554.13
1554.54
1554.94
1555.34
1555.75
1556.15
1556.55
1556.96
1557.36
1557.77
1558.17
1558.58
1558.98
1559.39
1559.79
1560.20
1560.61



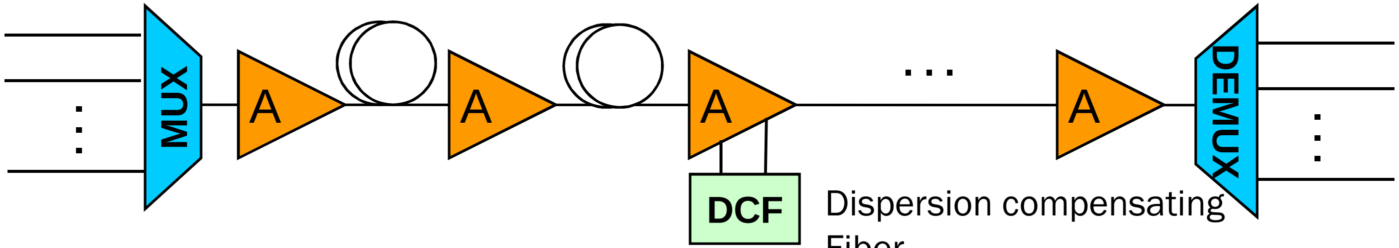
IM-DD transmission systems



Intensity Modulation
Direct Detection

APC: Automatic Power Control
ATC: Automatic Temp. Control

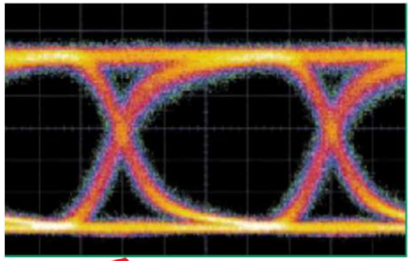
Transmission degradation effects



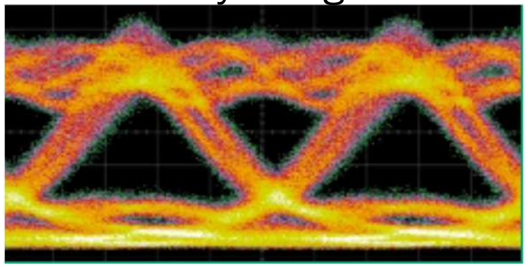
Dispersion compensating Fiber

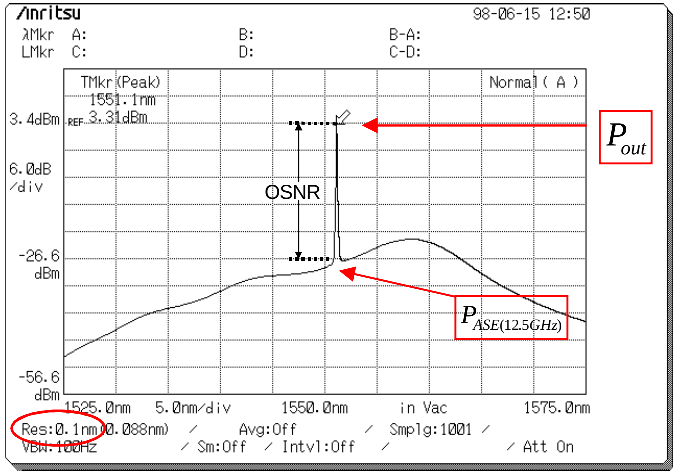
- ***Amplified Spontaneous Emission (ASE) noise accumulation***
- ***Chromatic dispersion (Group velocity dispersion)***
- ***Polarization Dependent Loss/Gain (EDFA, comp.)***
- ***Polarization Mode Dispersion (fiber random birefringence)***
- ***Non-linear channel crosstalk (Kerr effect)***
- ***Non-linear channel depletion (Raman effect)***

Tx eye diagram



Rx eye diagram





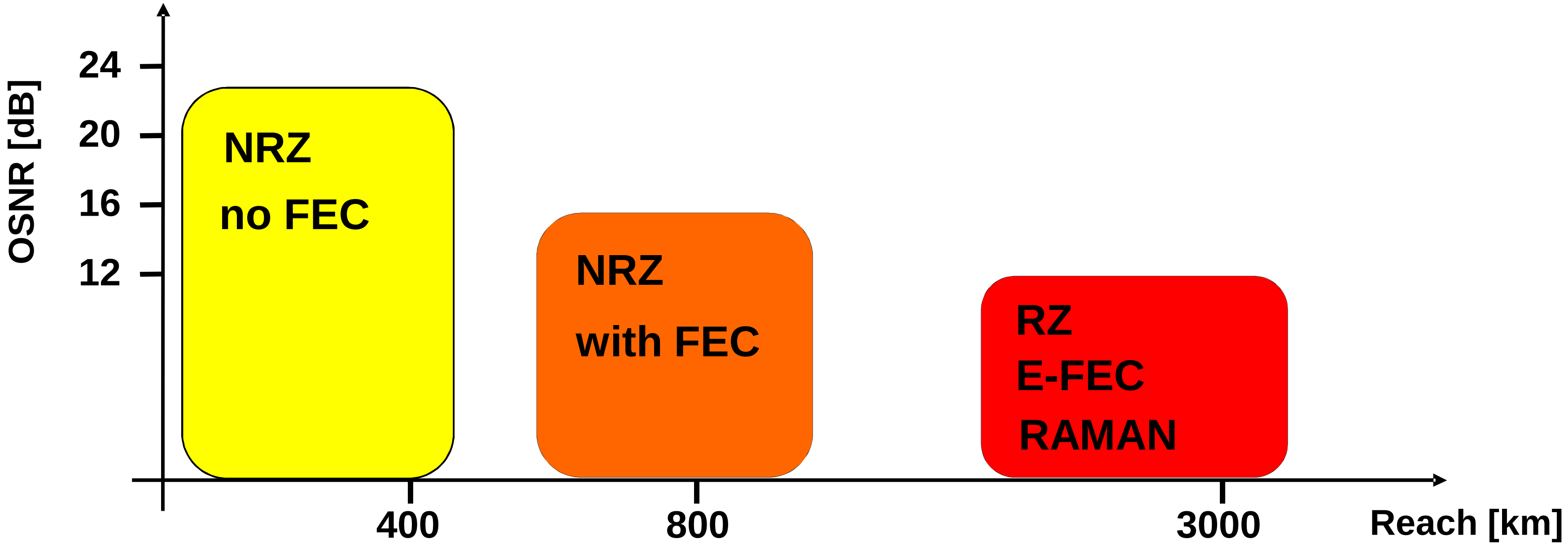
Typical reach of terrestrial DWDM systems (10G IM-DD)

- ***Typical characteristics of a 10 Gbit/s IM-DD transponder***

  Max. Chromatic Dispersion: ~800 ps/nm (~60 km G.652)

  Max. PMD: 10 ps

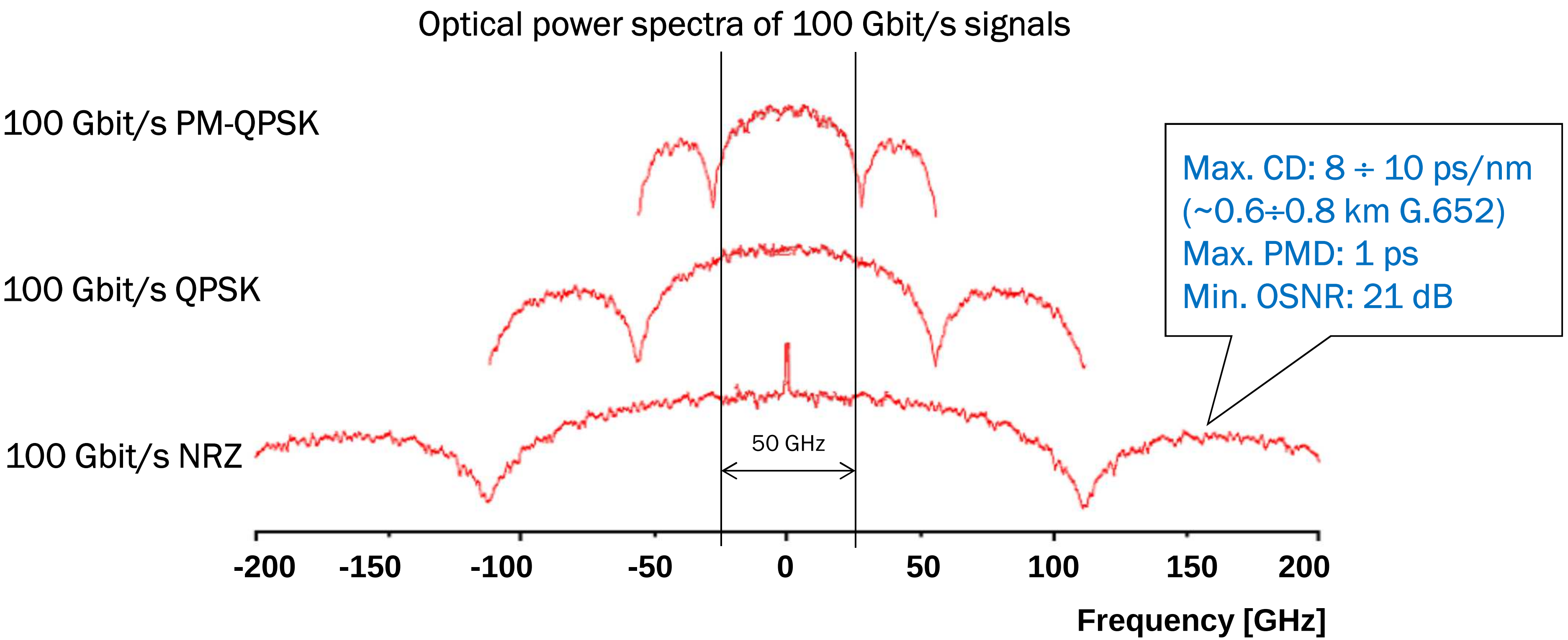
  Min. OSNR: 24 ÷ 11 dB (depending on FEC code and modulation format NRZ/RZ)



Transport network evolution

- Remarkable traffic growth rate: 30÷50% per year
- Strategies to increase network capacity:
  - To increase the bit rate of individual channels
  - To increase the number of DWDM channels
  - To exploit polarization multiplexing
  - To exploit multilevel modulation formats(>1 bit/symbol)

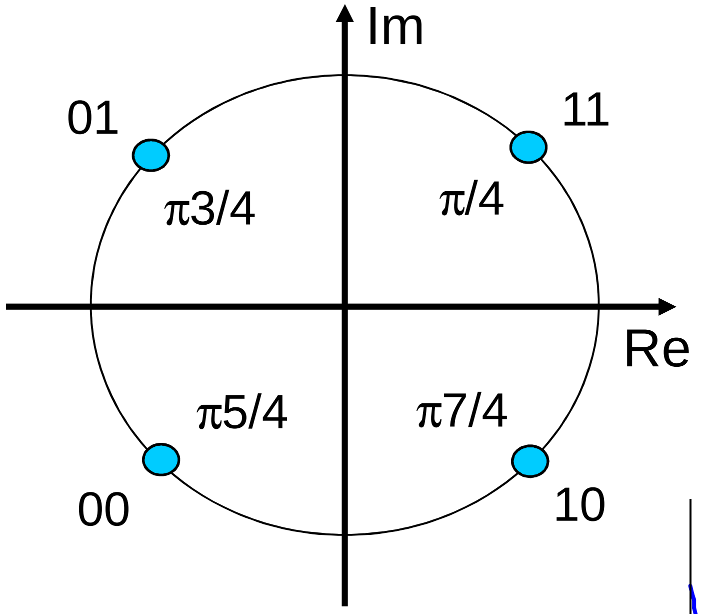
The spectral efficency issue



Max. CD: 8 ÷ 10 ps/nm
(~0.6÷0.8 km G.652)
Max. PMD: 1 ps
Min. OSNR: 21 dB

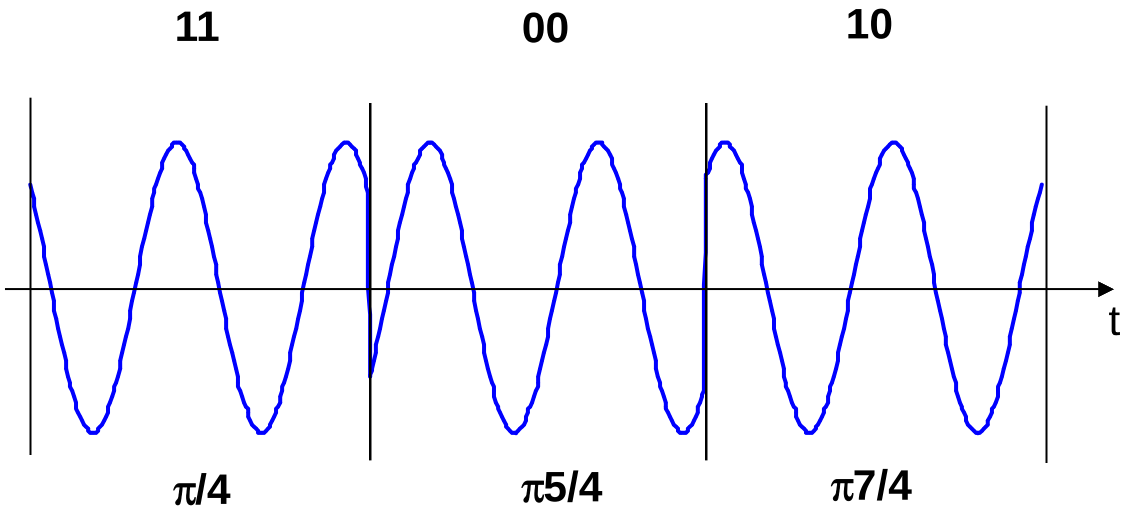
- ***Multilevel modulation formats and polarization multiplexing is mandatory to preserve compatibility with 50 GHz ITU-T grid***
- ***Transmission performance of NRZ format at 100 Gbit/s are too poor***

QPSK modulation format



- ***Phase modulated sine wave signal***
- ***4 phase values***
- ***2 bit/symbol***

$$\cos(\omega t + \phi(t))$$



Amplitude and phase modulated signals

- ***Any amplitude and phase modulated signal can be written as:***

$$s(t) = A(t)\cos[\omega_c t + \phi(t)]$$
$$= A(t)\cos\phi(t)\cos\omega_c t - A(t)\sin\phi(t)\sin\omega_c t$$

- ***The signal is a linear combination of the two orthogonal signals $\cos(\omega_c t)$ e $-\sin(\omega_c t)$***

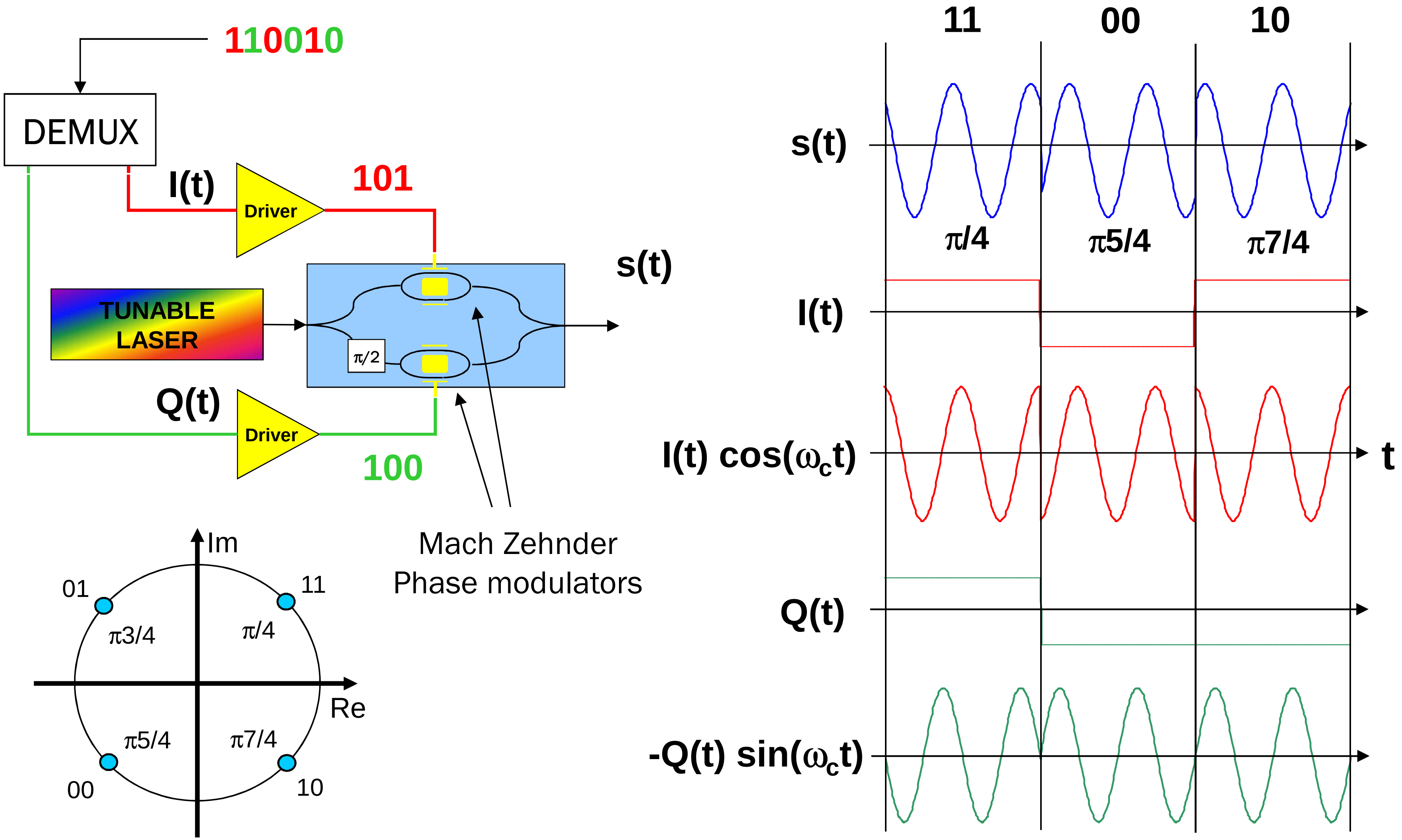
- ***The components are:***

$I(t)=A(t)\cos\phi(t)$	In-phase component
$Q(t)=A(t)\sin\phi(t)$	Quadrature component

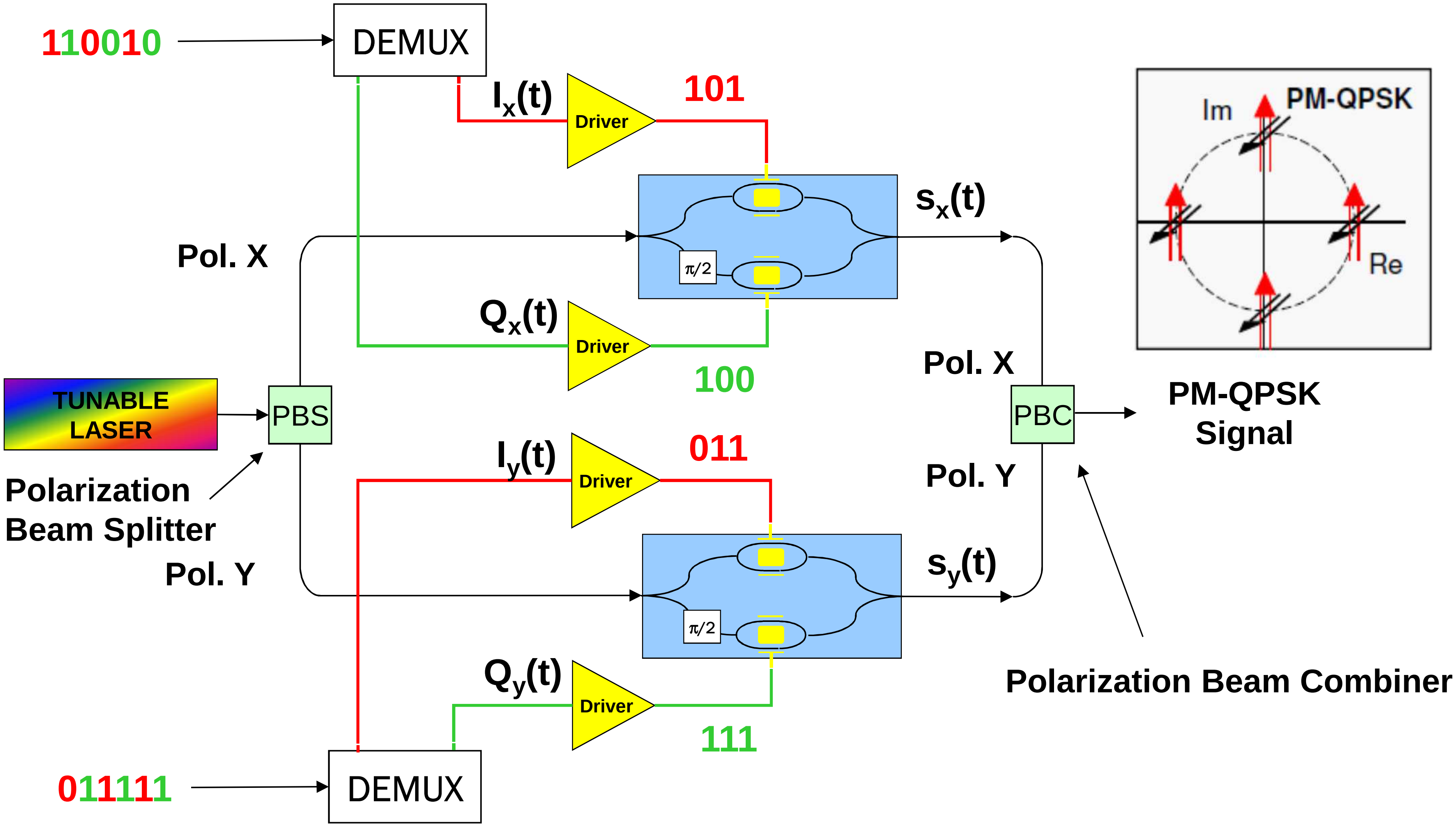
- ***I(t) and Q(t) are the real and Immaginary part of the COMPLEX ENVELOPE:***

$$c(t) = I(t) + jQ(t)$$
$$s(t) = \mathrm{Re}[c(t)\, e^{j\omega_c t}]$$

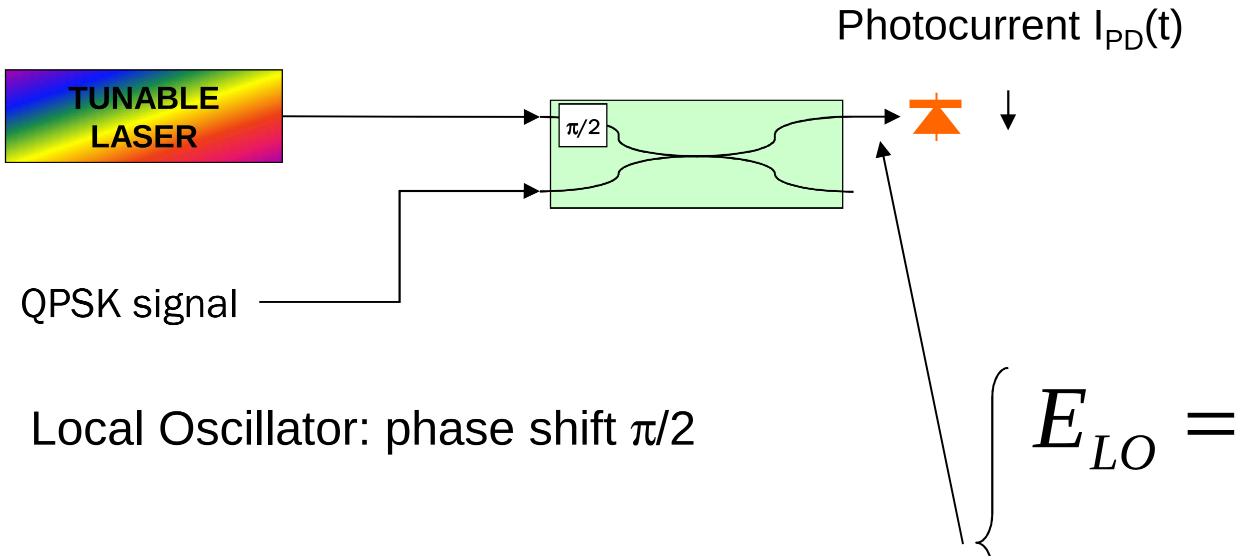
QPSK signal generation



Polarization multiplexing



QPSK signal coherent detection (I)



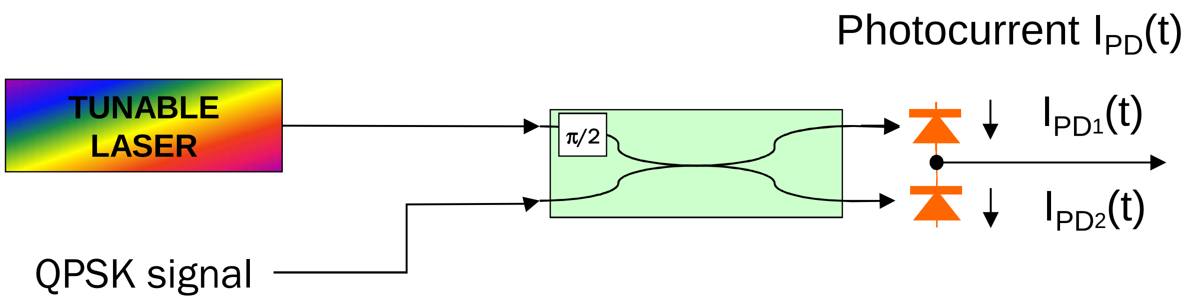
Local Oscillator: phase shift π/2

QPSK signal: coupling → π/2

$$\begin{cases} E_{LO} = A_{LO} e^{j\omega_{LO} t} e^{j\pi/2} \\ E_S = A_S e^{j(\varphi(t)+\pi/2)} e^{j\omega_S t} \end{cases}$$

$$I_{PD} \propto \left|E_{LO} + E_S\right|^2 \propto \left|A_S\right|^2 + \left|A_{LO}\right|^2 + 2 A_S A_{LO} \underset{\overset{\uparrow}{\boxed{\sim I(t)}}}{\cos}\left[(\omega_S - \omega_{OL})t + \varphi(t)\right]$$

QPSK coherent detection (II)



$$I_{PD}(t)=I_{PD1}(t)-I_{PD2}(t)$$

Local Oscillator: phase shift π/2 + coupling → π

QPSK signal: no phase shift

Photodiode 2

$$E_{LO} = A_{LO} e^{j\omega_{LO}t} e^{j\pi}$$

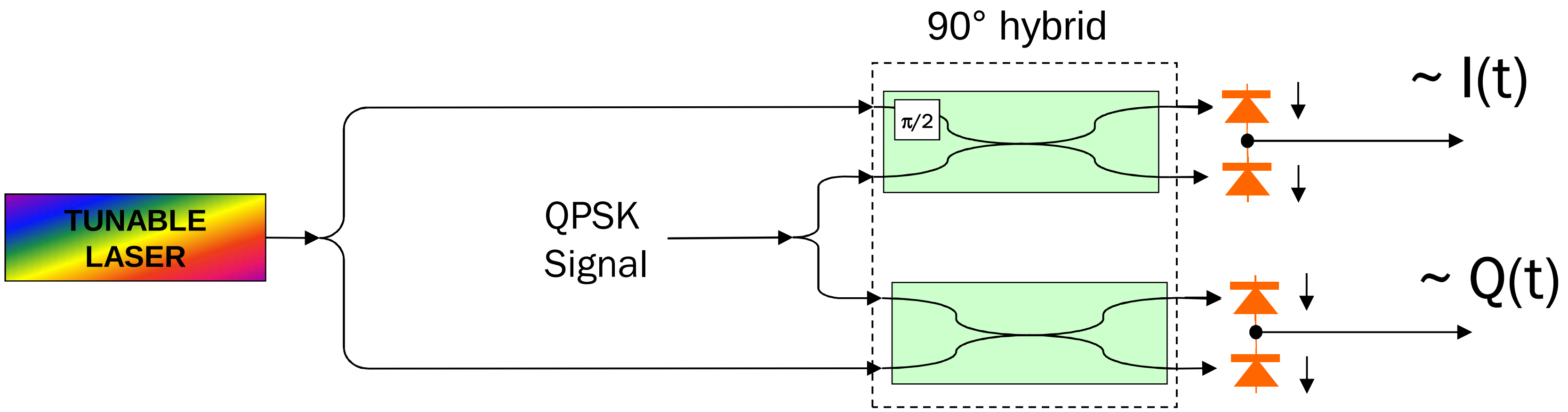
$$E_S = A_S e^{j\varphi(t)} e^{j\omega_S t}$$

$$I_{PD2} \propto \left|E_{LO} + E_S\right|^2 \propto \left|A_S\right|^2 + \left|A_{LO}\right|^2 - 2A_S A_{LO} \cos\left[(\omega_S - \omega_{OL})t + \varphi(t)\right]$$

$$I_{PD} = I_{PD1} - I_{PD2} \propto 4A_S A_{LO} \cos\left[(\omega_S - \omega_{OL})t + \varphi(t)\right]$$

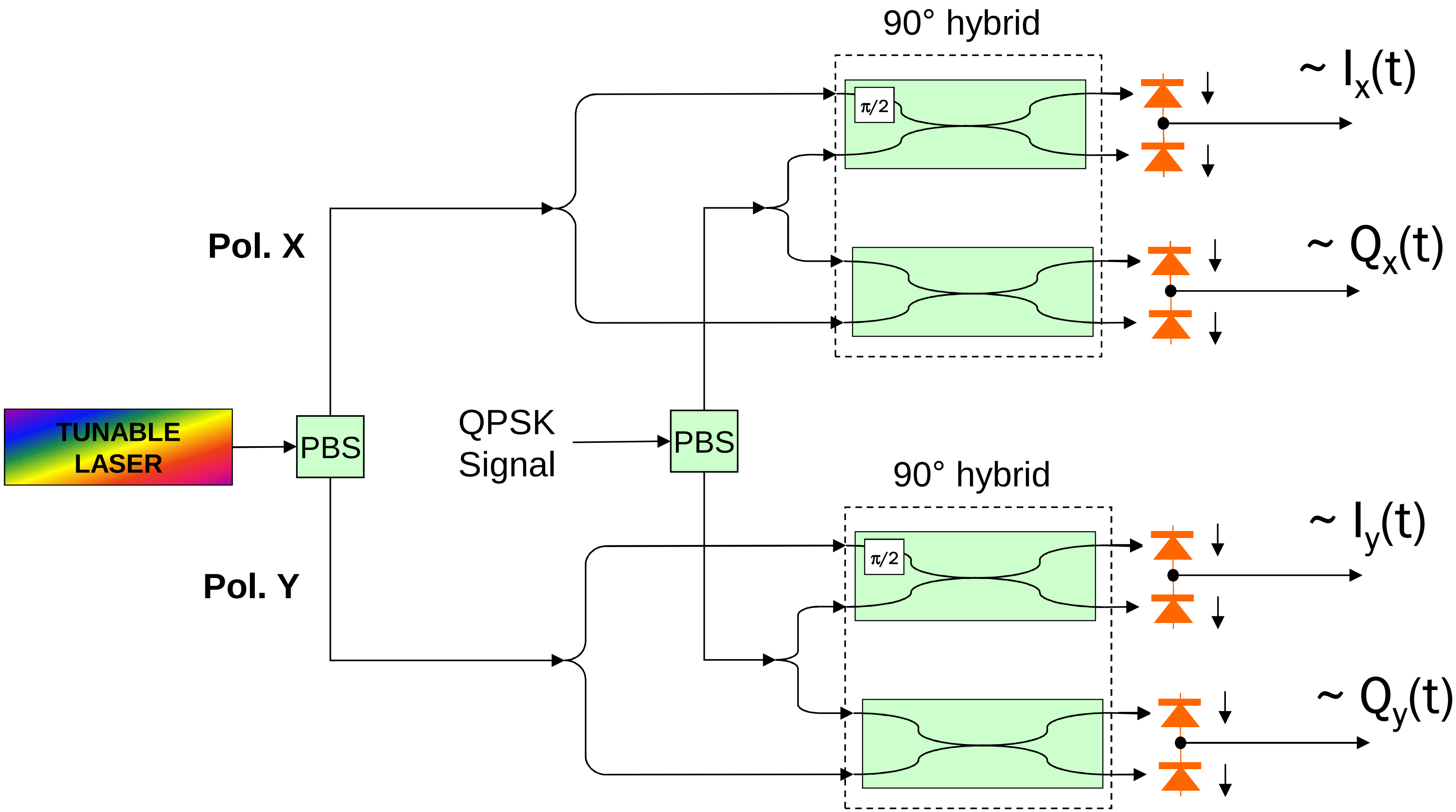
~ I(t)

QPSK coherent detection (III)

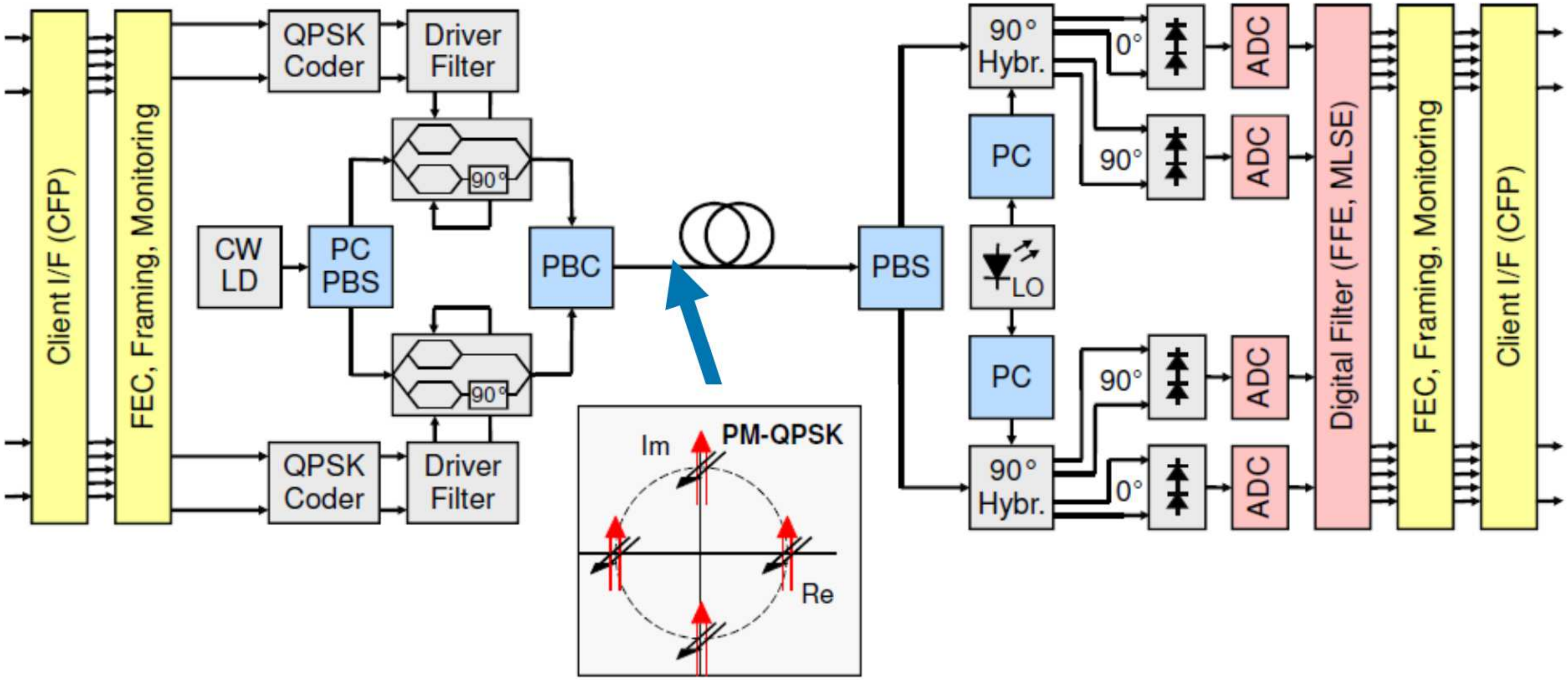


- ***If $\omega_S = \omega_{LO}$ the two photo detected signals are proportional to transmission impaired versions of I(t) and Q(t)***
- ***I(t) and Q(t) are then recovered by digital signal processing techniques***

DP-QPSK coherent detection

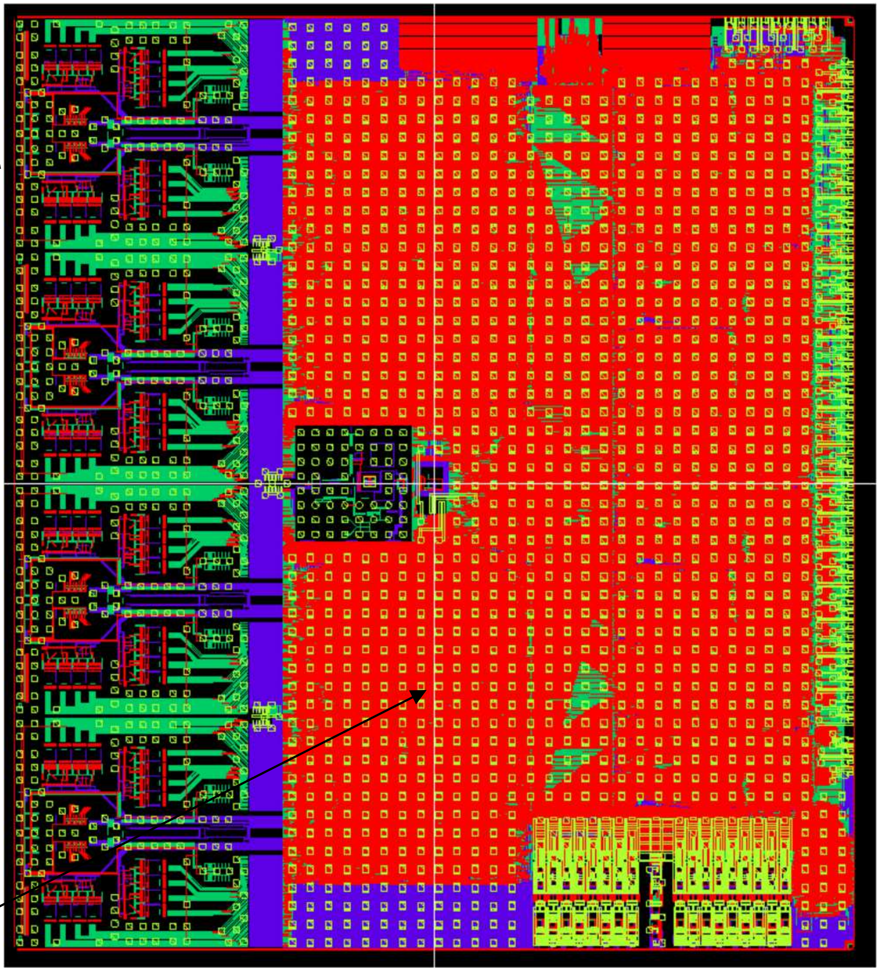


DP-QPSK 100G transmission systems



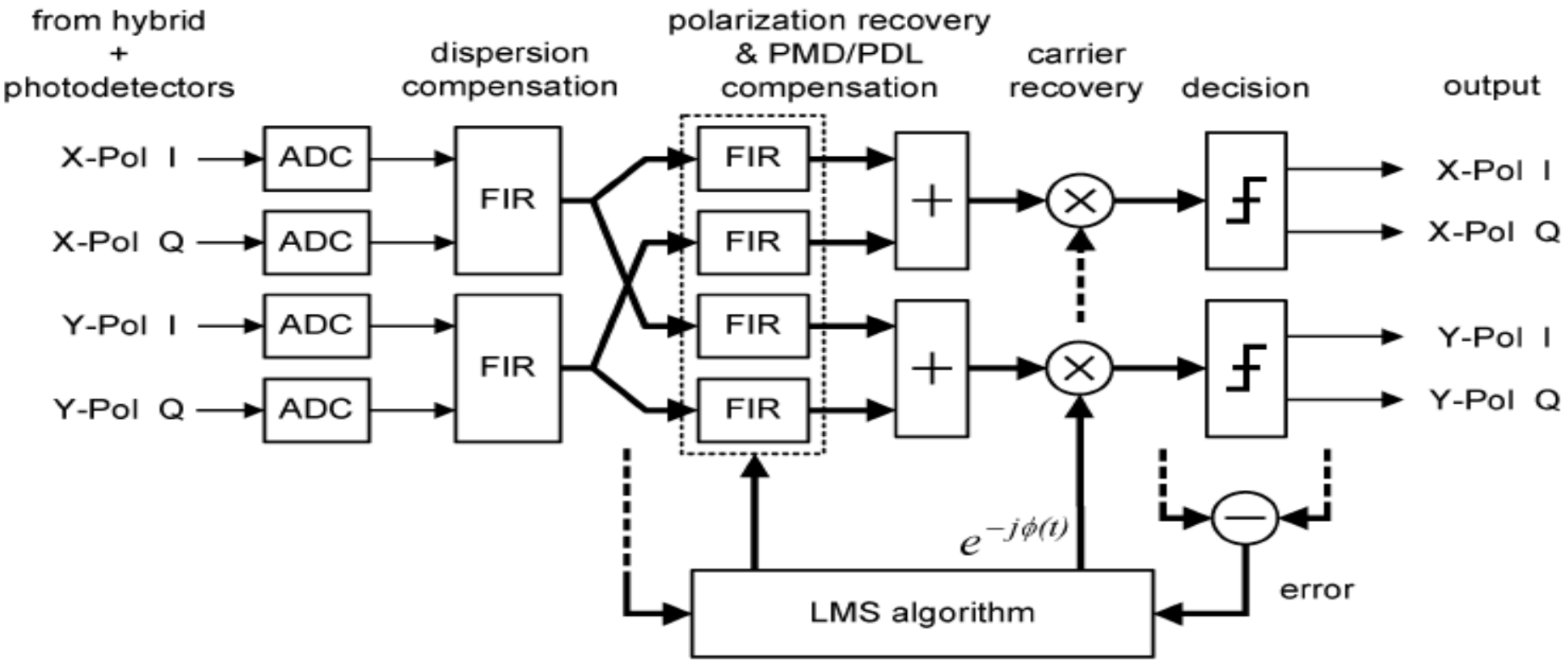
Digital Signal Processing in coherent receivers

- ***Photodetected signals are digitalized (2 samples/symbol, 5-6 bit ADC)***
- ***Digital processing includes:***
    - ***Chromatic dispersion compensation***
    - ***Polarization demultiplexing***
    - ***PMD compensation***
    - ***Phase recovery***
    - ***FEC processing***



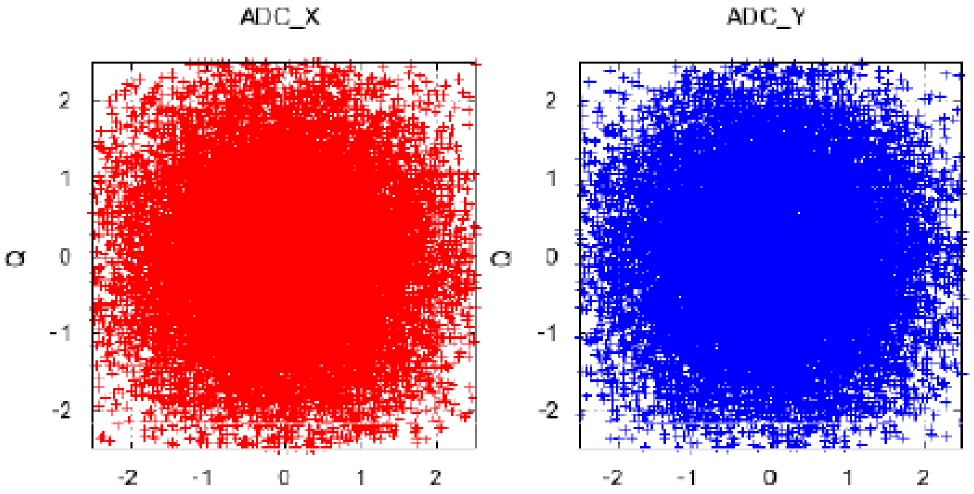
CMOS ASIC for coherent receivers (20 million logic gates, Nortel [1])

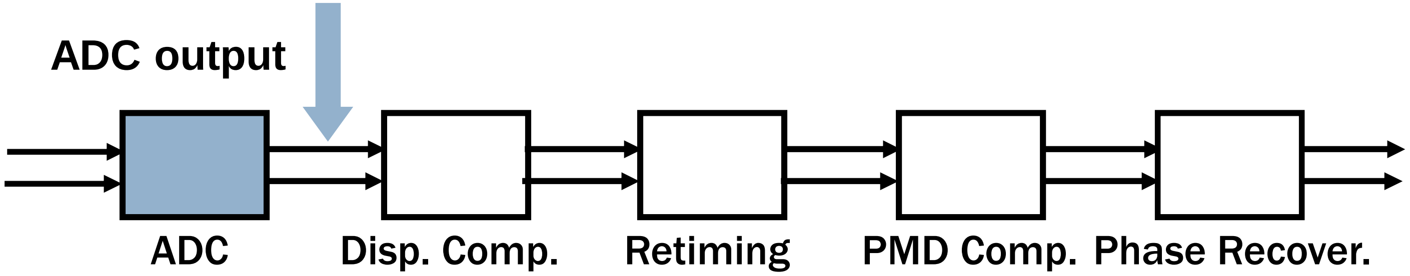
Digital Signal Processing



From [1]: "Performance of Dual-Polarization QPSK for Optical Transport Systems"

Digital Signal Processing step by step (I)





ADC output

ADC

Disp. Comp.

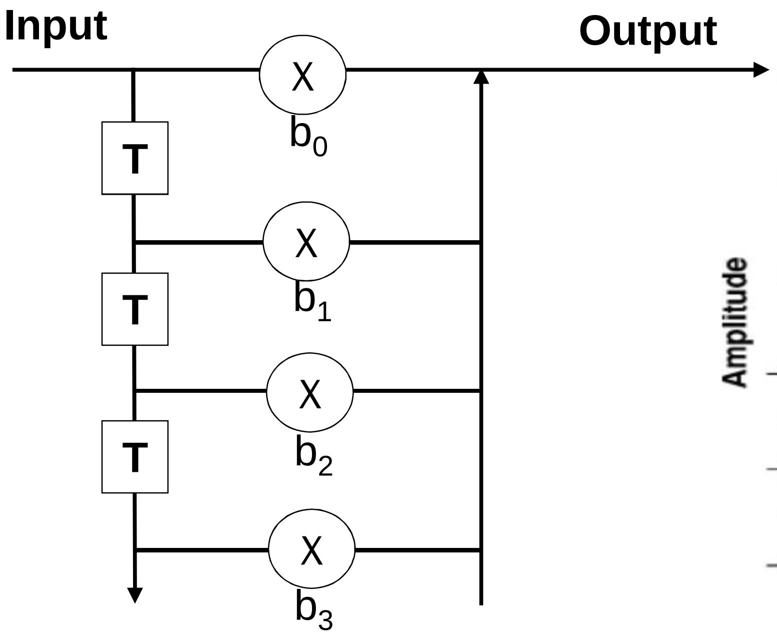
Retiming

PMD Comp.

Phase Recover.

- ***PMD and chromatic dispersion distorted signal***
- ***Asinchronous sampling***
- ***Phase noise***

Chromatic dispersion compensation



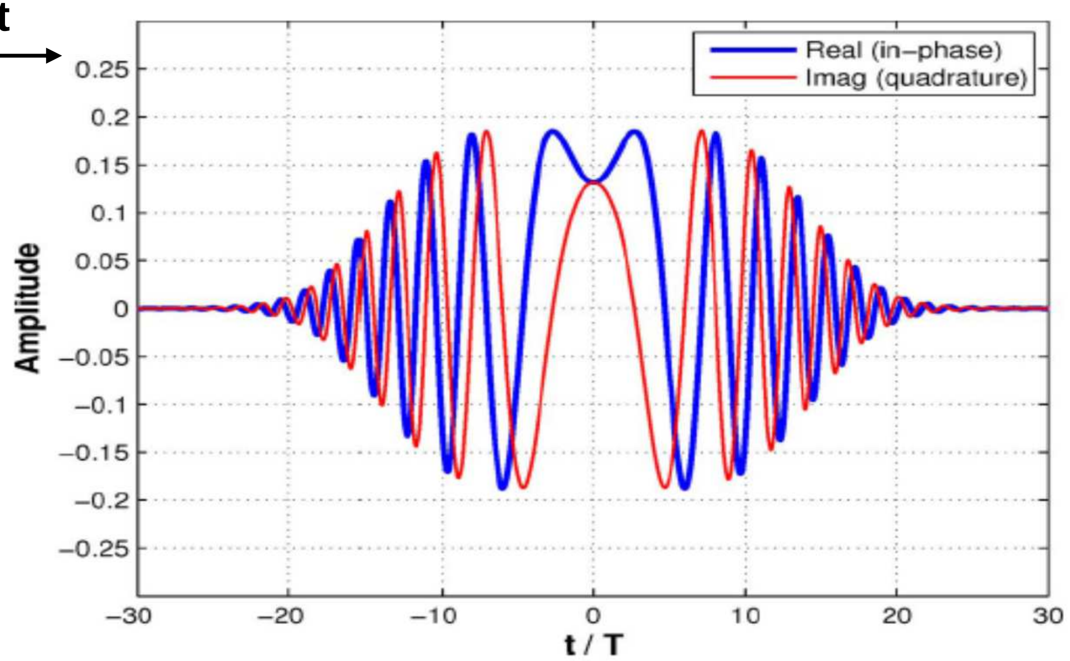


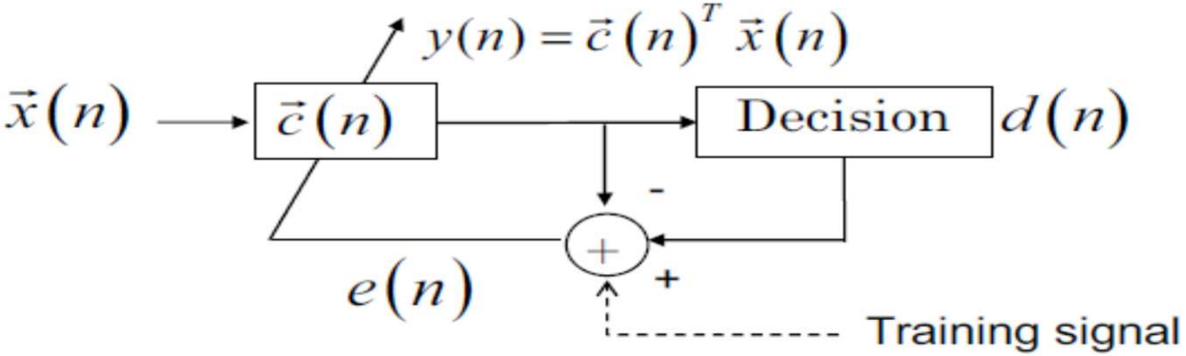
Fig. 10. Example of impulse response for dispersion $= 27\,200$ ps/nm with an ideal raised-cosine filter (roll-off factor $= 0.5$).

- ***FIR filter with a frequency response that compensates the fiber one***
- ***N. of coefficients proportional to the maximum chromatic dispersion to be compensated***

From [1]:
“Performance of Dual-Polarization QPSK for Optical Transport Systems”

$$N = 2\left[\frac{|D|L\lambda^2}{2cT^2}\right] + 1$$

LMS algorithm



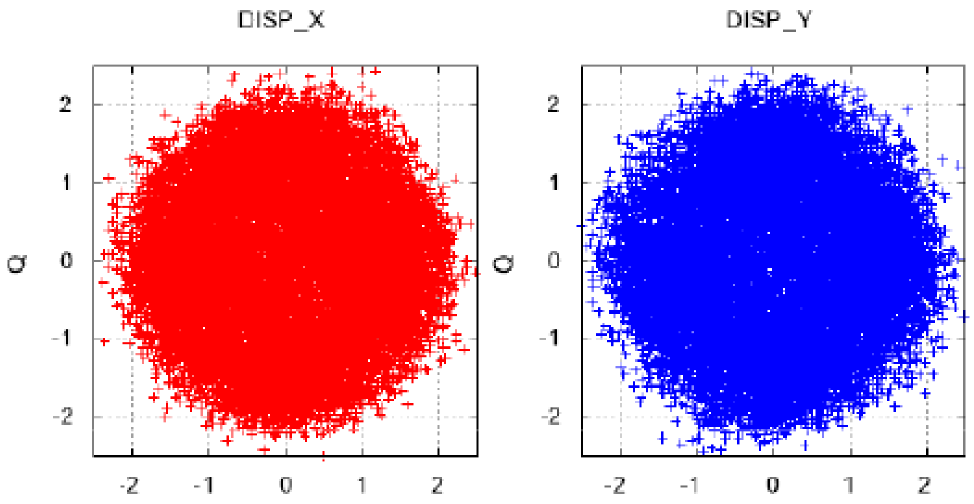
$$\vec{x}(n) = \begin{bmatrix} x(n) \\ x(n-1) \\ \vdots \\ x(n-k+1) \\ x(n-k) \end{bmatrix} \qquad \vec{c}(n) = \begin{bmatrix} c_0(n) \\ c_1(n) \\ \vdots \\ c_{k-1}(n) \\ c_k(n) \end{bmatrix}$$

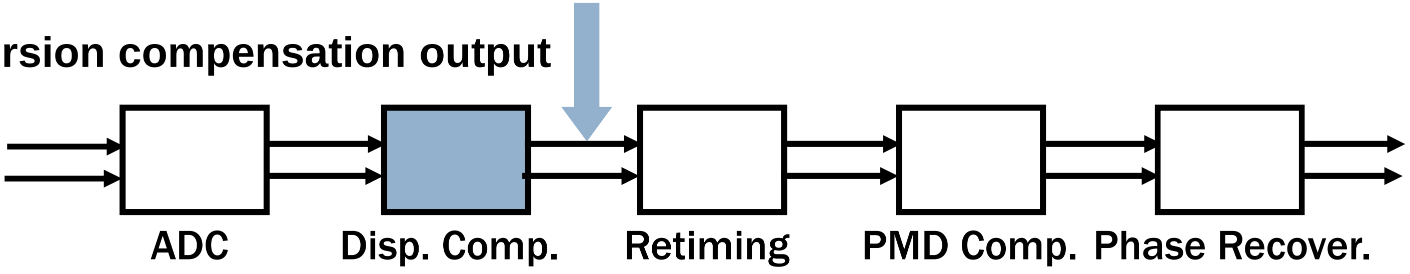
FIR filter

$$y(n) = \sum_{i=0}^{k} c_i(n) x(n-i)$$

LMS algorism $\begin{cases} \vec{c}(n+1) = \vec{c}(n) + \mu e(n) \vec{x}(n)^* \\ e(n) = d(n) - \vec{c}(n)^T \vec{x}(n) \end{cases}$

Digital Signal Processing step by step (II)

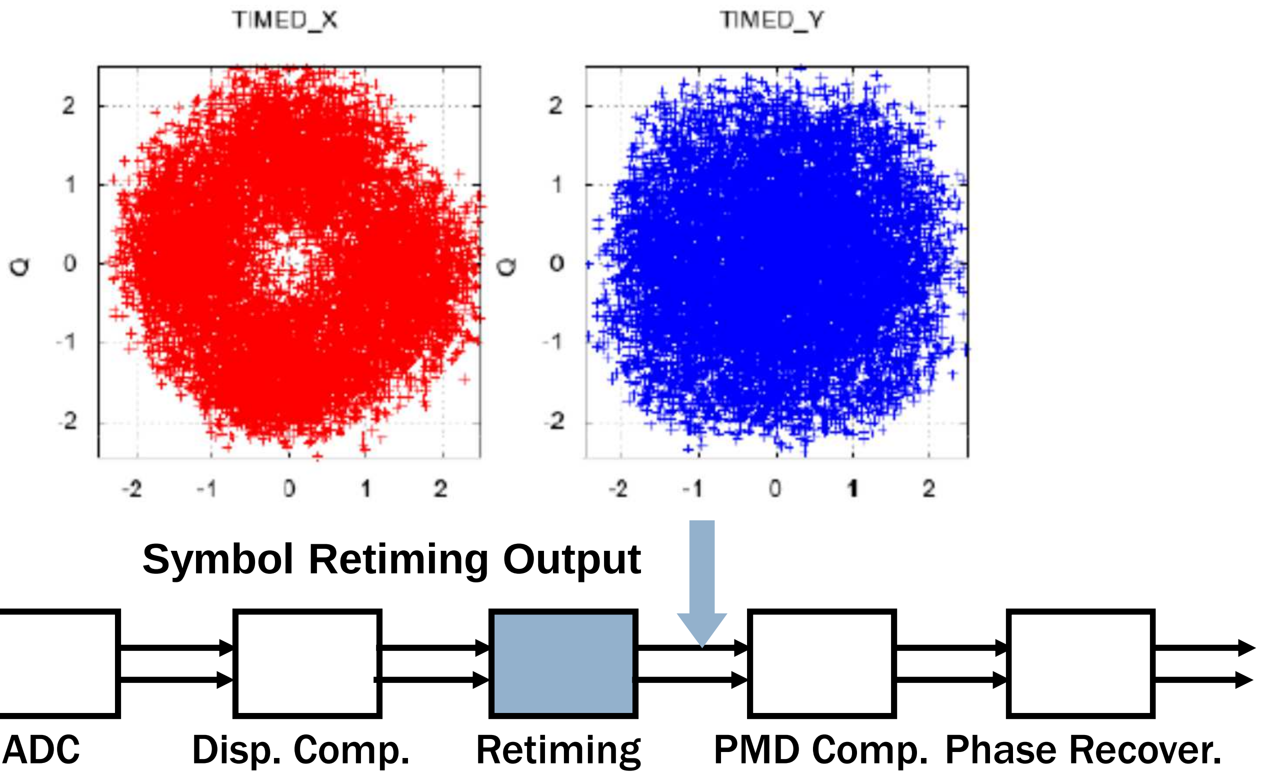




Dispersion compensation output

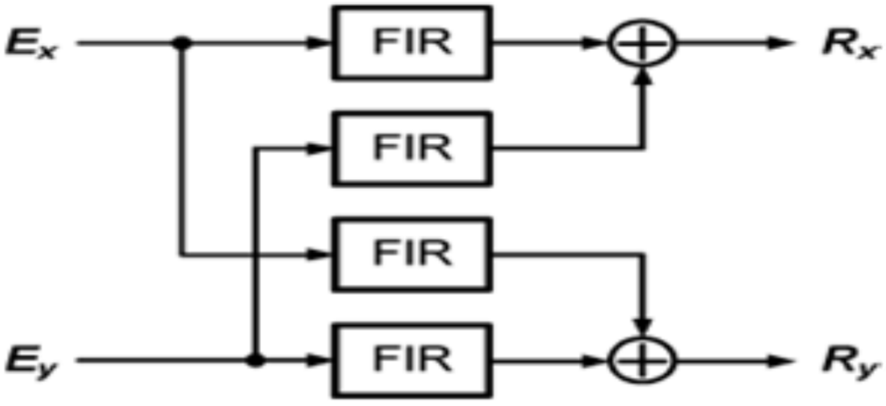
- ***Chromatic dispersion is compensated (typically 40-50000 ps/nm, >2000 km G.652)***
- ***The signal is still distorted by PMD and not yet polarization demultiplexed***

Digital Signal Processing step by step (III)



- ***Retiming***
- ***The signals are still distorted by PMD and phase noise and polarizations are not demultiplexed***

PMD compensation and polarization demultiplexing



From [1]:
“Performance of Dual-Polarization QPSK for Optical Transport Systems”

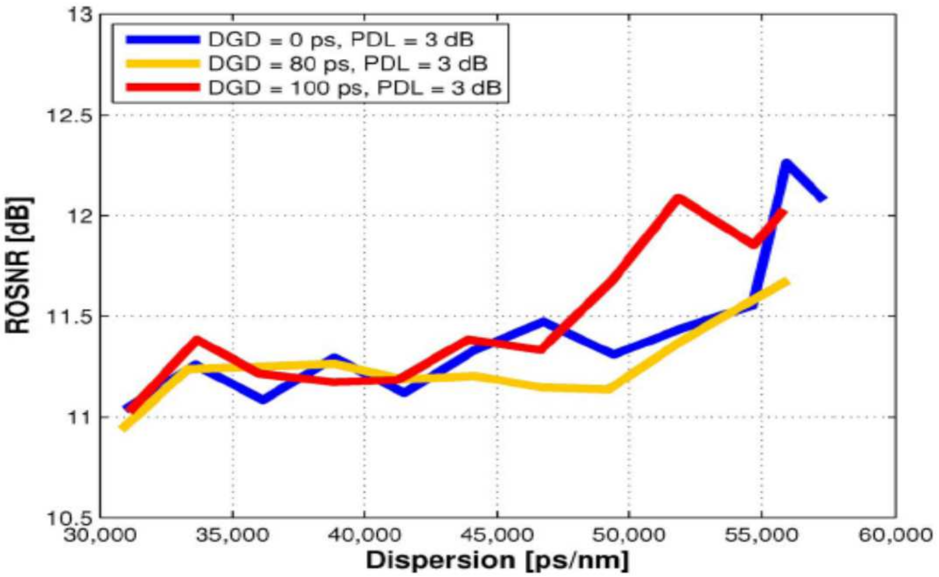
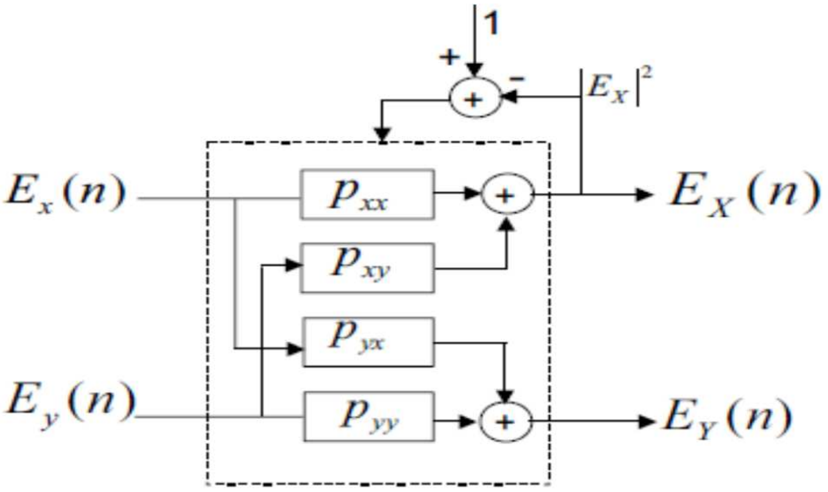


Fig. 11. Required OSNR as a function of link dispersion and PMD for single-channel propagation on G.652 fiber. Wavelength is set to 1546.92 nm. Launch power is set to -4 dBm. Resolution bandwidth $= 0.1$ nm.

- ***4 FIR in butterly configuration provide the folowing functions:***
  - ***Polarization demultiplexing***
  - ***PMD and PDL compensation***
  - ***Compensation of receiver’s components defects***

Polarization demultiplexing



$$\begin{pmatrix} E_X \\ E_Y \end{pmatrix} = \begin{pmatrix} p_{xx} & p_{xy} \\ p_{yx} & p_{yy} \end{pmatrix} \begin{pmatrix} E_x \\ E_y \end{pmatrix} \to J^{-1} \begin{pmatrix} E_x \\ E_y \end{pmatrix}$$

Constant modulus algorithm (CMA)

$$p_{xx}(n+1) = p_{xx}(n) + \mu(1 - |E_X(n)|^2) E_X(n) E_x^*(n) \ ,$$

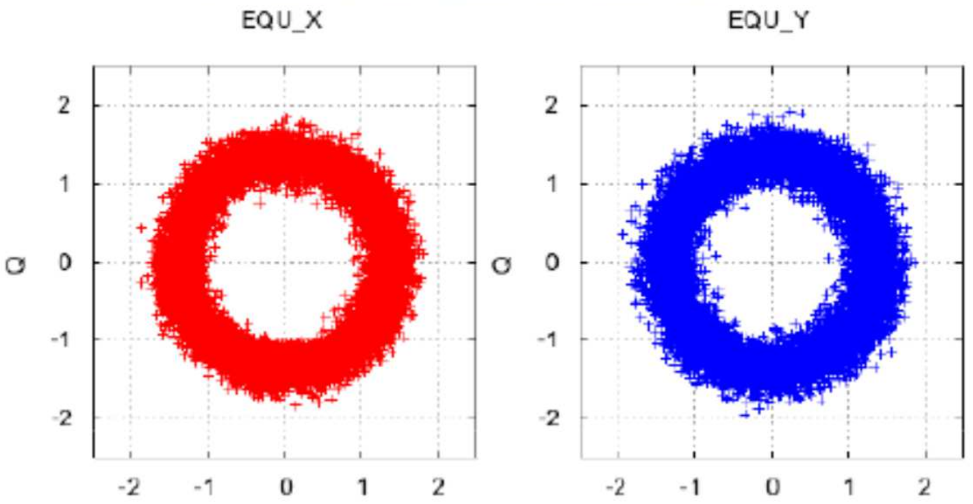
$$p_{xy}(n+1) = p_{xy}(n) + \mu(1 - |E_X(n)|^2) E_X(n) E_y^*(n) \ ,$$

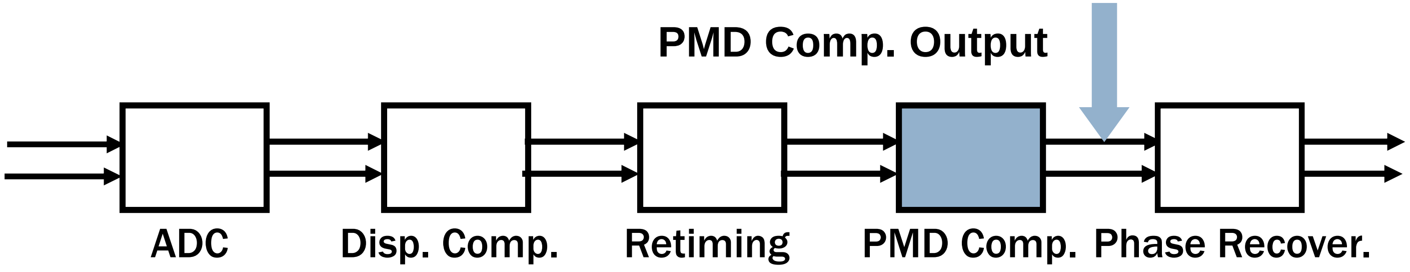
$$p_{xy} = -p_{yx}^* \ ,$$

$$p_{yy} = p_{xx}^* \ .$$

From [5]: Kazuro Kikuchi, "Coherent transmission systems"

Digital Signal Processing step by step (IV)

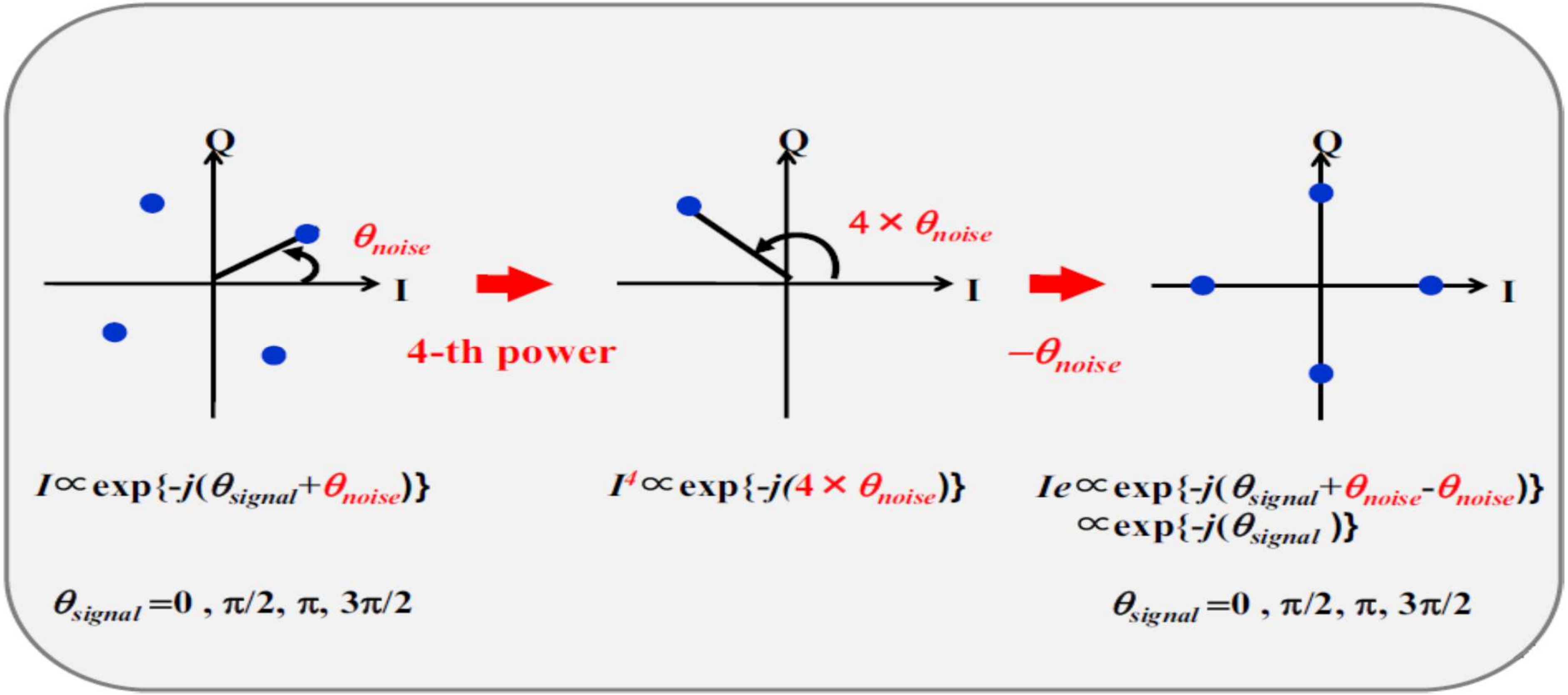




PMD Comp. Output

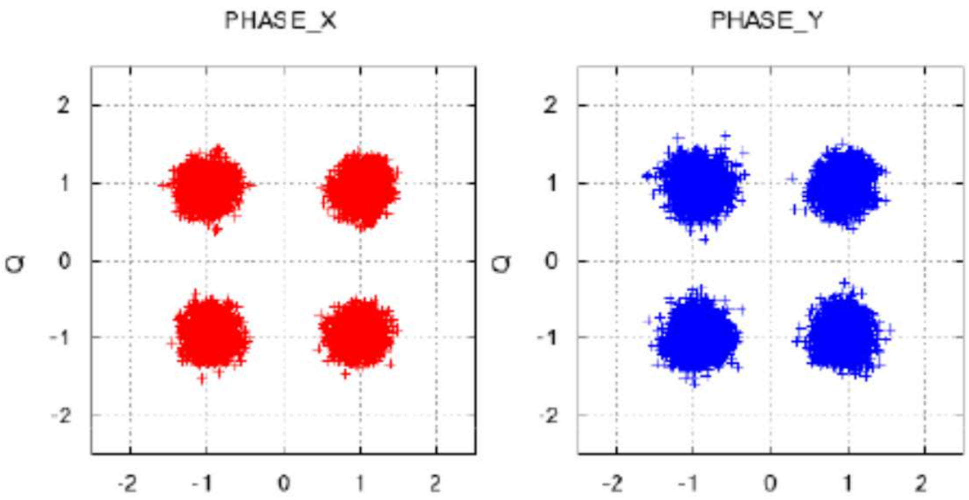
- ***Polarization is correctly demultiplexed and PMD is compensated***
- ***Constellation points rotate due to the difference of frequencies ω_S ω_{LO}***

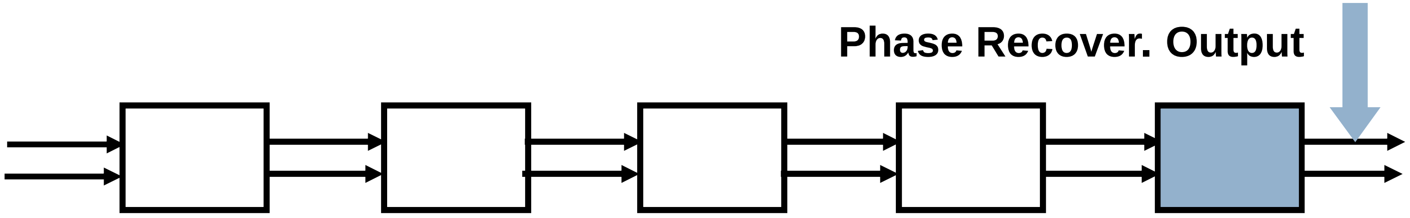
Carrier phase estimation



From [5]: Kazuro Kikuchi, “Coherent transmission systems”

Digital Signal Processing step by step (V)





Phase Recover. Output

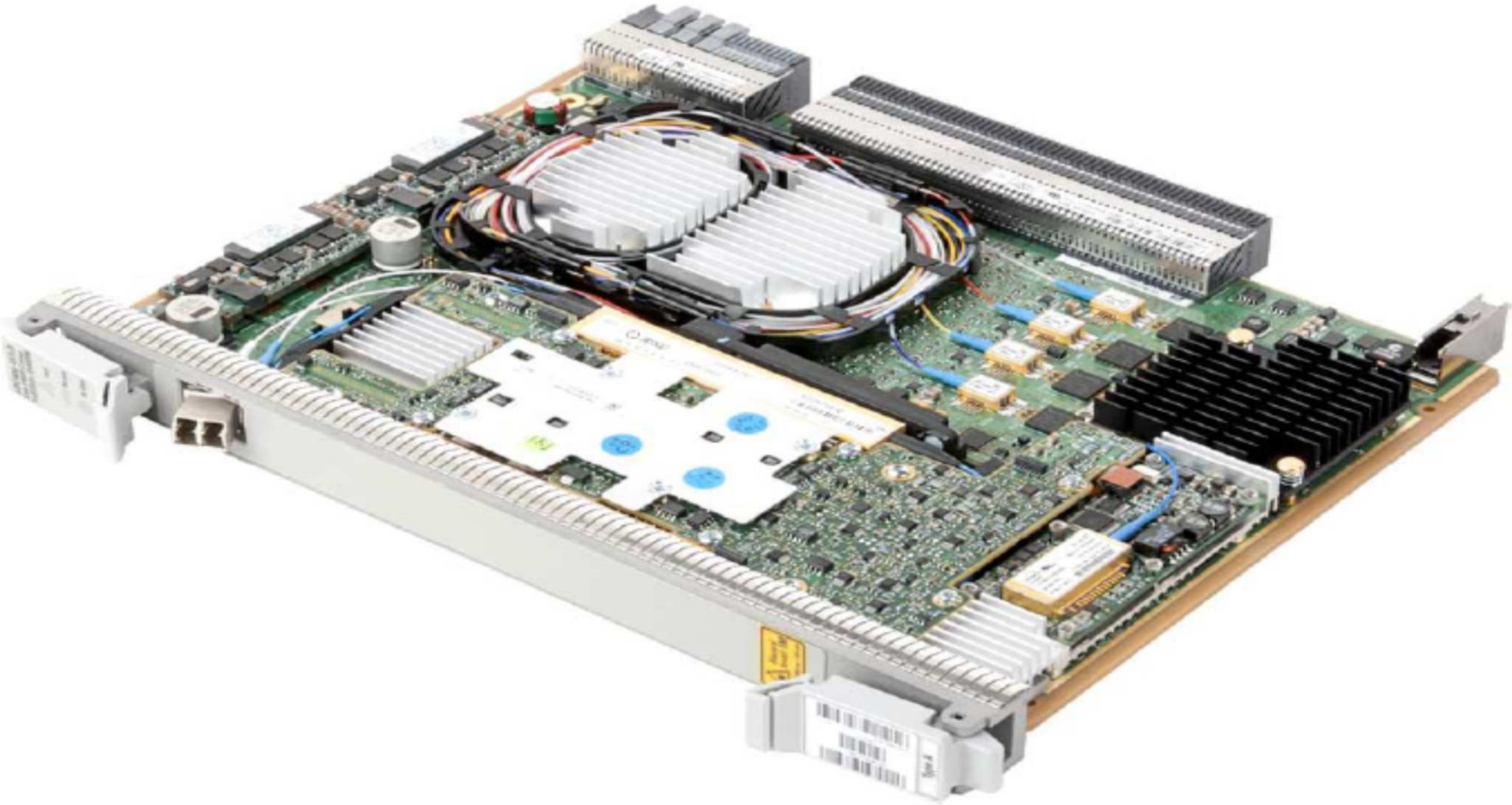
ADC Disp. Comp. Retiming PMD Comp. Phase Recover.

- ***The frequency difference ω_S ω_{LO} is compensated and I e Q are correctly detected***

40 and 100 Gbit/s coherent systems

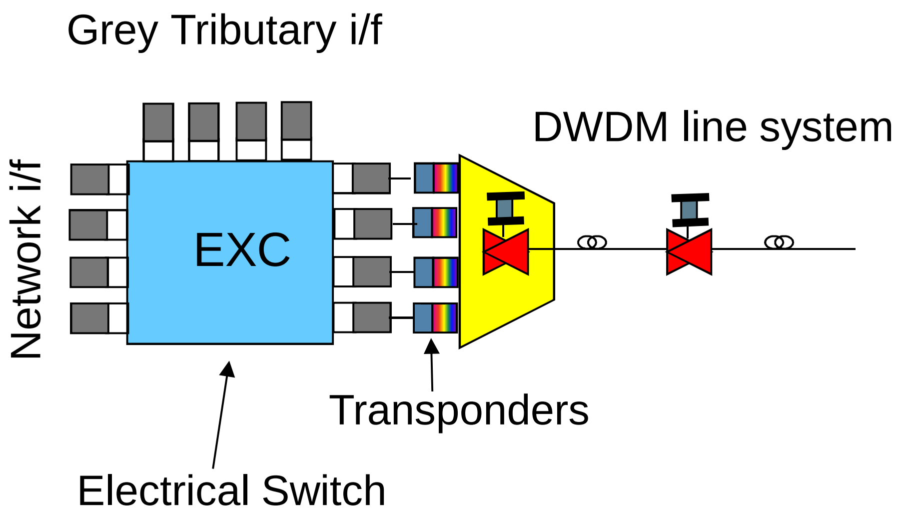
	10G RZ IMDD	40G DQPSK	**40G Coh. DP-BPSK**	**100G Coh. DP-QPSK**
OSNR [dB]	11	14	**11**	**13**
Dispersion [ps/nm]	± 800	± 500 (TDC)	**± 50000**	**>± 40000**
DGD [ps]	30	24	**90**	**90**
50 GHz spacing	Yes	Yes	**Yes**	**Yes**
Max number ROADM	>20	16	**16**	**~20**
Reach on G.652 [km]	1600	1000	**>2000**	**~2000**
Spectral efficiency (50 GHz grid) [(bit/s)/Hz]	0.2	0.8	**0.8**	**2**
Max Capacity (C-band) [Gbit/s]	800	3200	**3200**	**8000**
Compatibility 10 G NRZ	-	XXXX	**XXX**	**XX**
Uncompensated links	No	No	**Yes**	**Yes**
High PMD links	No	No	**Yes**	**Yes**
Complexity	X	XXXX	**XXXXX**	**XXXXXX**

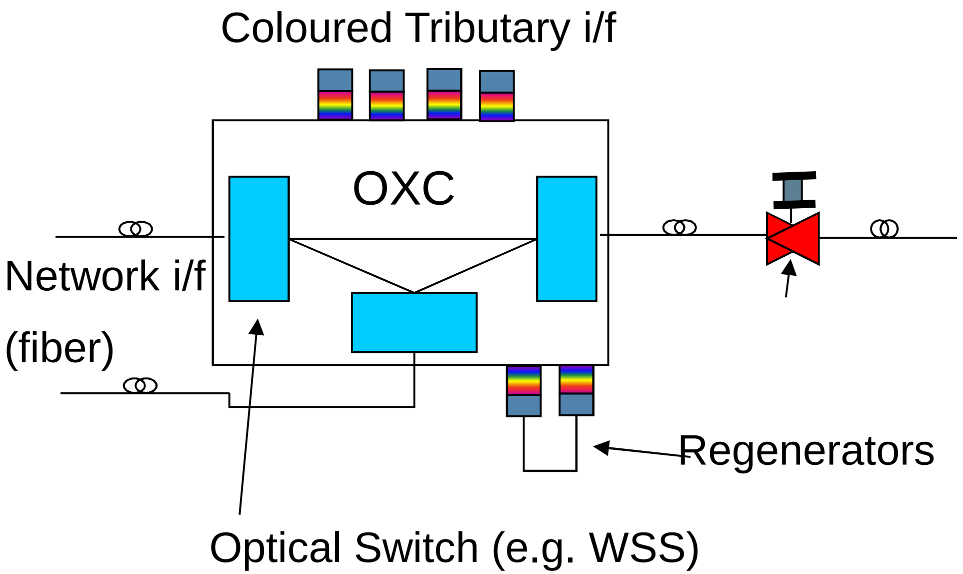
100 Gbit/s line interface board



Switching technologies

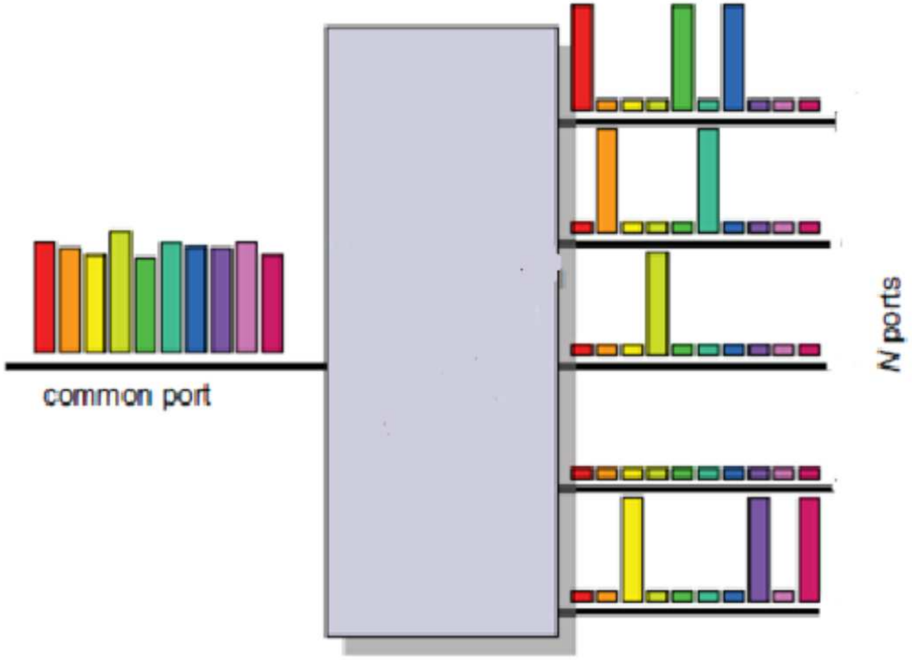
- **Opaque Networks, e.g. SDH or OTN**
  - **Opto-Electronic (OE) conversion in all tributary and line interfaces**
  - **Electrical Switching Matrix (EXC)**
  - **Simple optical link design, but many transponders**
- **Translucent Networks**
  - **Transparent optical connections without OE conversion (if possible)**
  - **Optical Switching nodes OXC or ROADM**
  - **Careful optical design to assure optical continuity and low signal degradation on the entire circuit path (OSNR, PMD, CD, ...)**



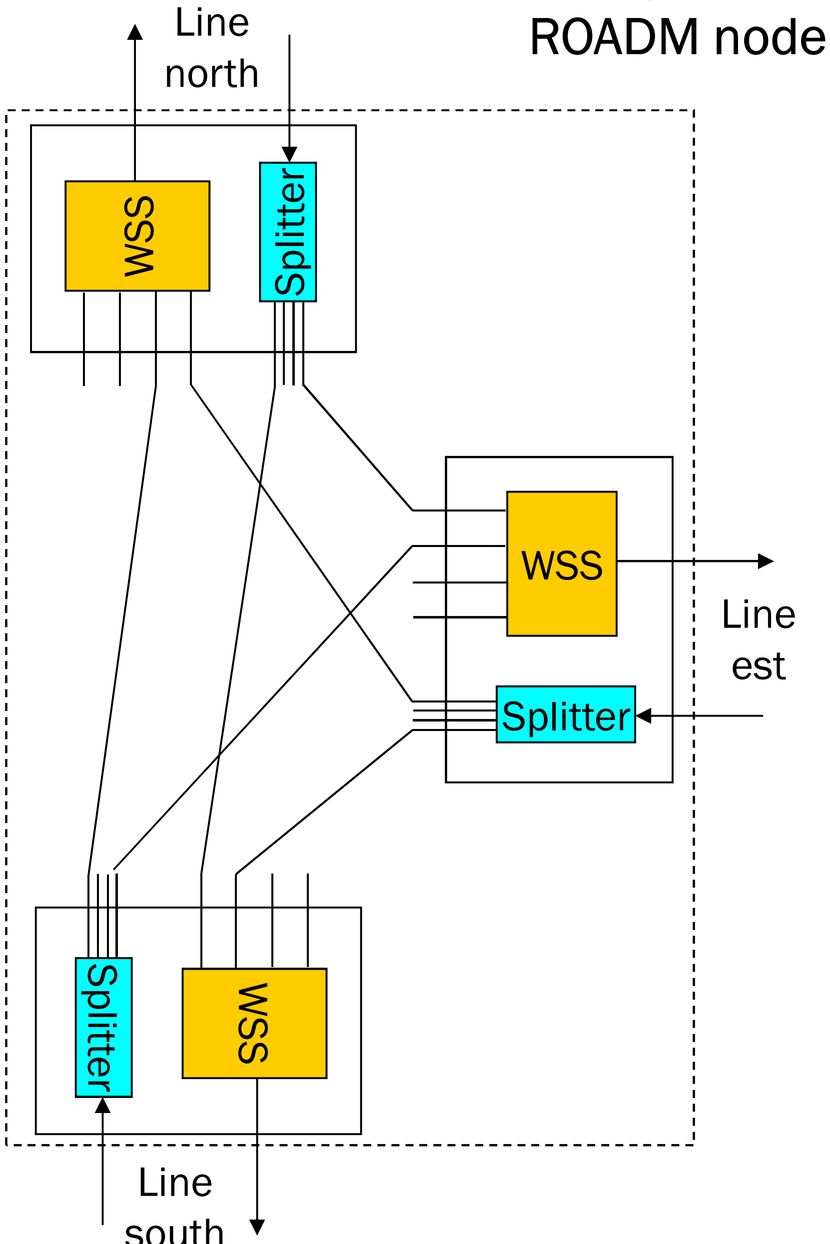


Wavelength Selective Switch and ROADM nodes

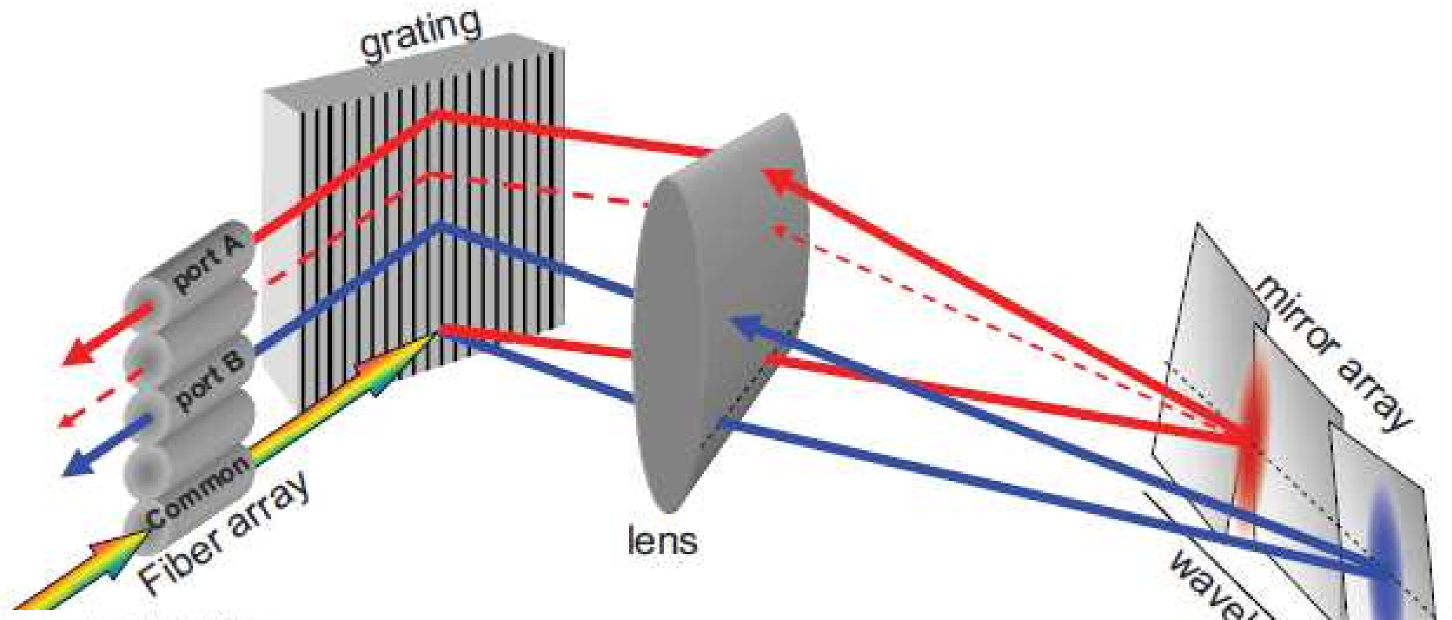
WSS functional scheme

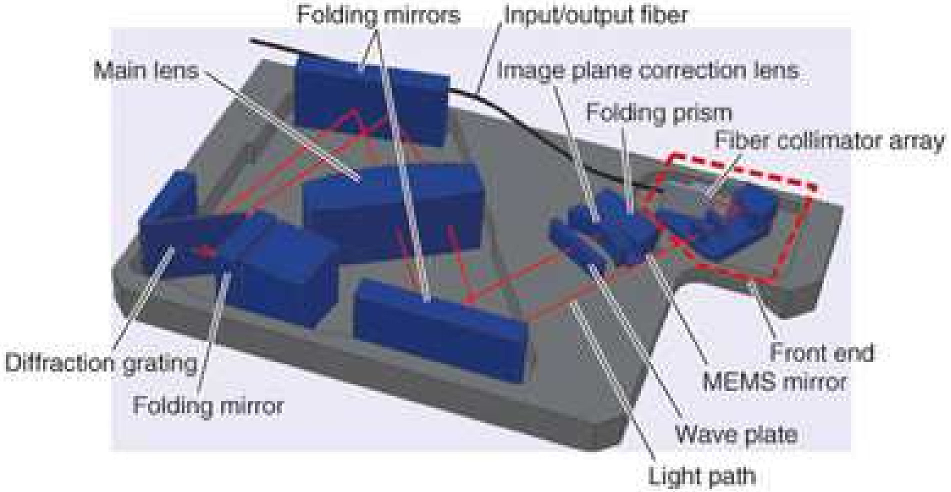


Degree 3 ROADM node

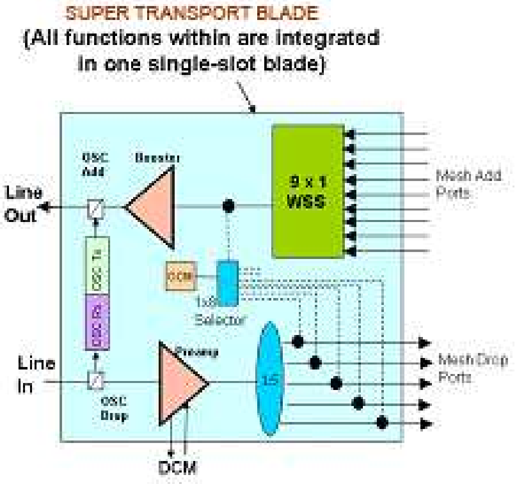


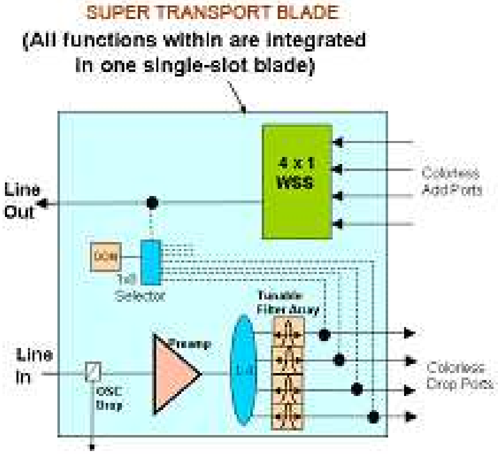
WSS structure

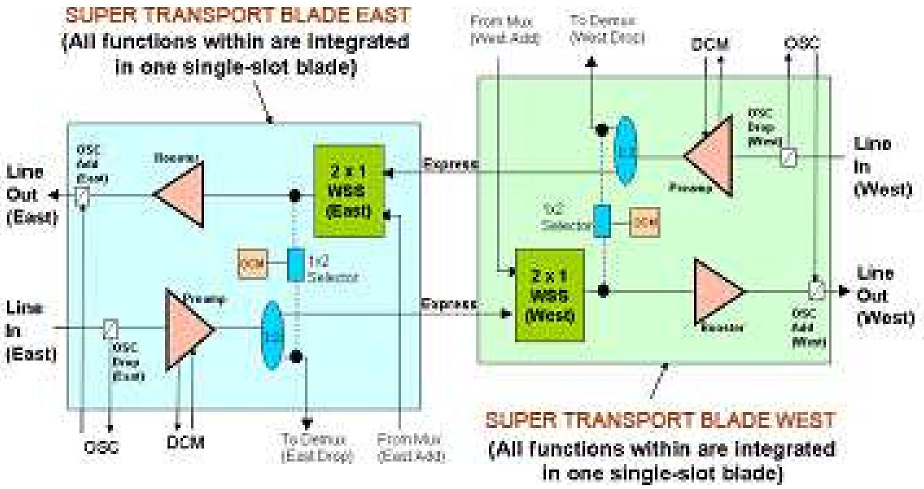


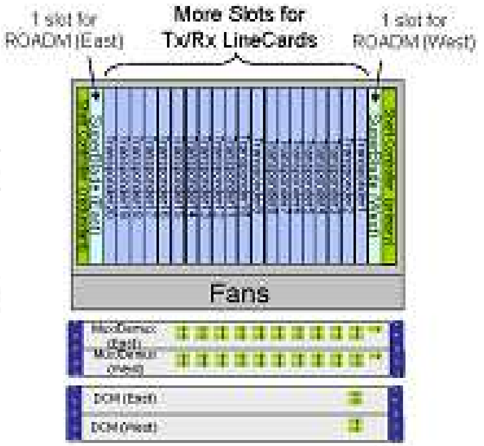


ROADM line card

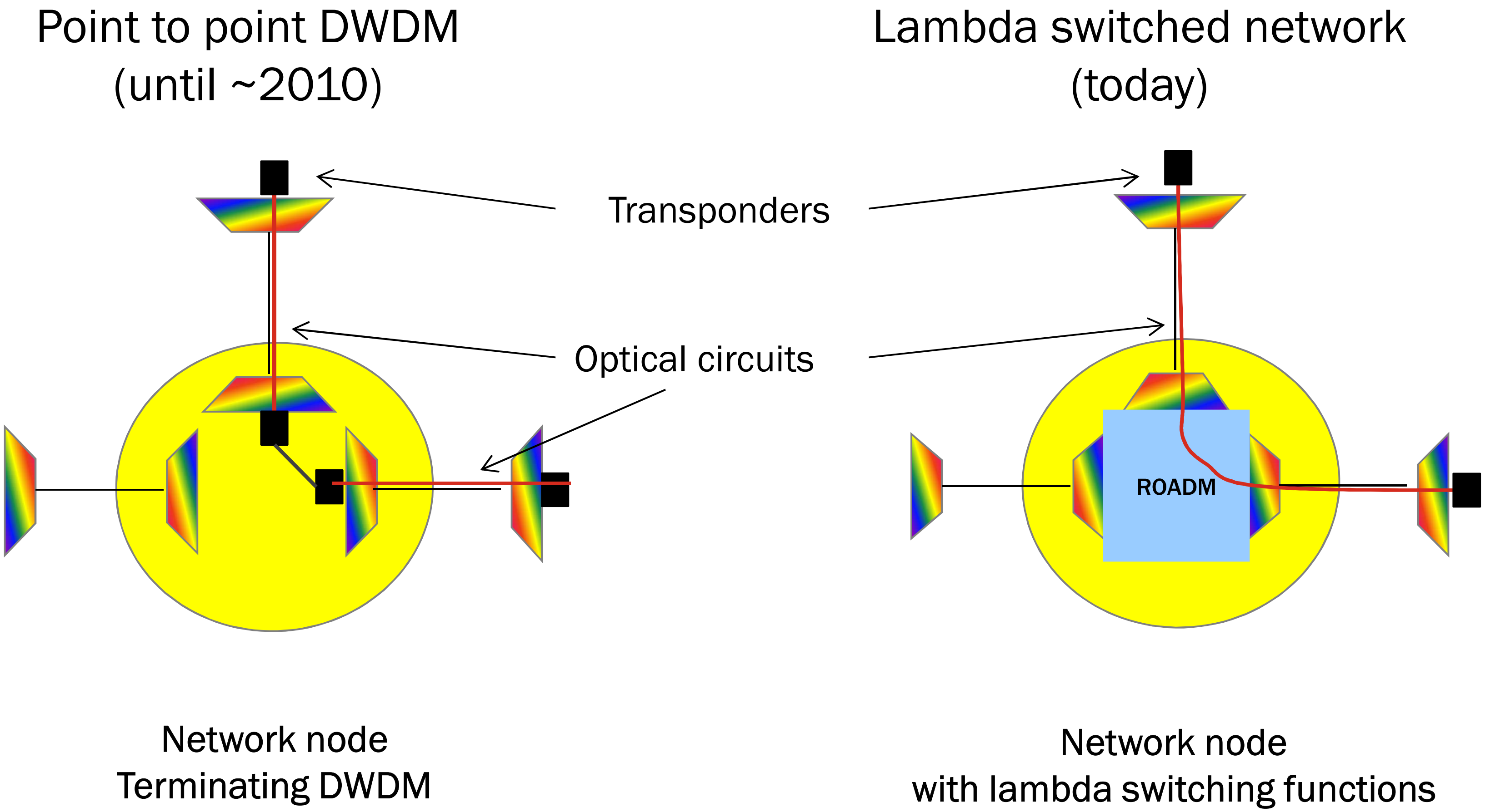








From point to point DWDM to lambda-switched networks


Point to point DWDM
(until ~2010)

Lambda switched network
(today)

Transponders

Optical circuits

Network node
Terminating DWDM

Network node
with lambda switching functions

Coherent systems references

[1] K. Roberts, M. O'Sullivan, K. Wu, H. Sun, A. Awadalla, D. J. Krause, C. Laperle, "Performance of Dual-Polarization QPSK for Optical Transport Systems", J. Lightw. Technol., vol. 27, no. 16, August 15, 2009, pp. 3546-3559

[2] Peter J. Winzer et al., "100-Gb/s DQPSK Transmission: From Laboratory Experiments to Field Trials", J. Lightw. Technol., vol. 26, 2008 p.64

[3] 1.C. R. S. Fludger , T. Duthel , D. van den Borne , C. Schulien , E.-D. Schmidt , T. Wuth , J. Geyer , E. De Man , G.-D. Khoe and H. de Waardt "Coherent equalization and POLMUX-RZ-DQPSK for robust 100-GE transmission", J. Lightw. Technol., vol. 26, p.64 , 2008

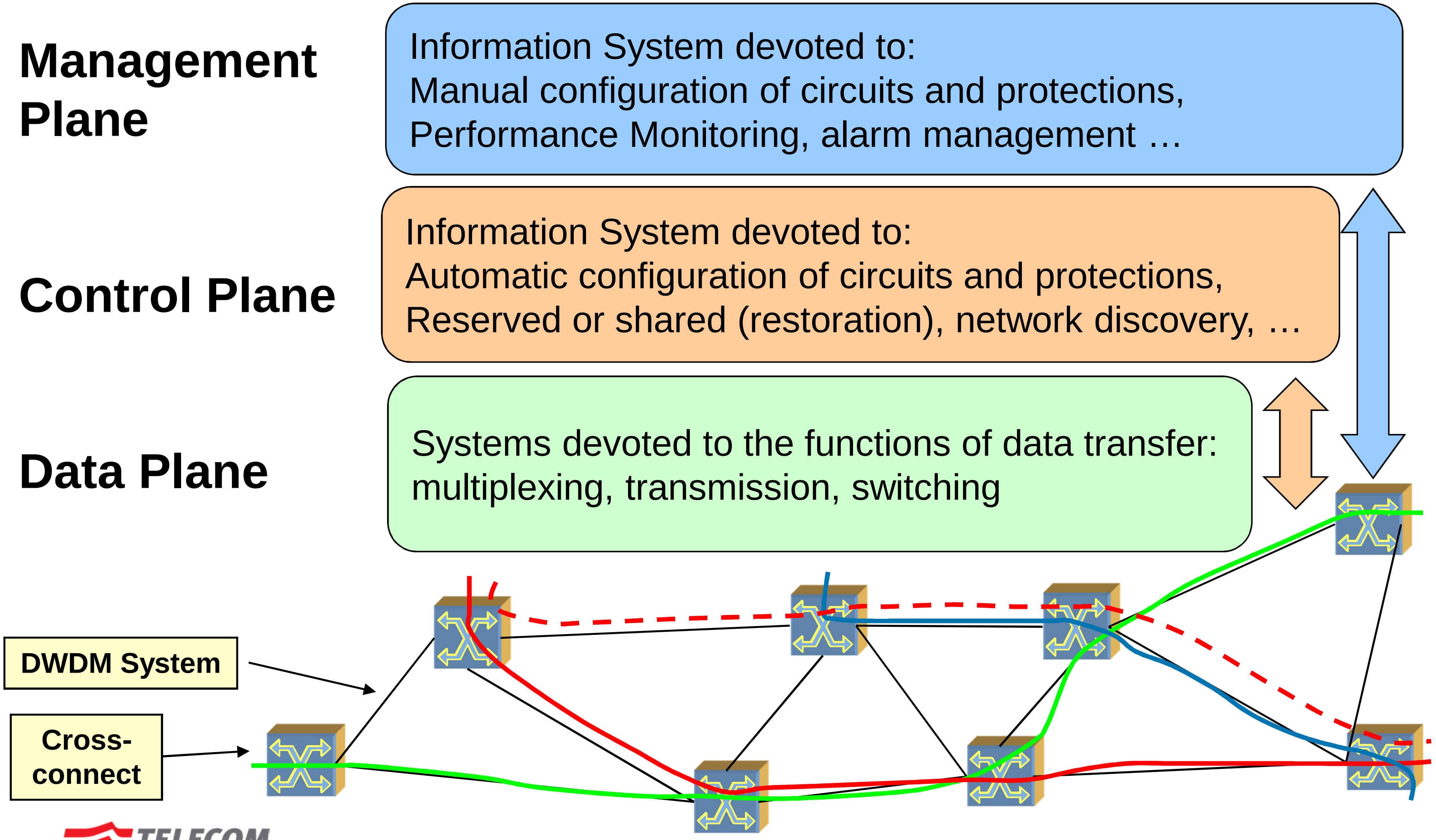
[4] S. J. Savory, "Digital filters for coherent optical receivers", Opt. Exp., vol. 16, no.2, Jan 2008, p. 804

[5] Kazuro Kikuchi, "Coherent transmission systems", Tutorial paper Th.2.A.1, Proceedings ECOC 2008, Brussels 2008

Summary

- Photonic Networks technologies
- **Transport Networks basic functions**
- The Kaleidon photonic backbone

Functional outline of a backbone network, ASON: Automatically Switched Optical Network



Management Plane

Information System devoted to:
Manual configuration of circuits and protections,
Performance Monitoring, alarm management …

Control Plane

Information System devoted to:
Automatic configuration of circuits and protections,
Reserved or shared (restoration), network discovery, …

Data Plane

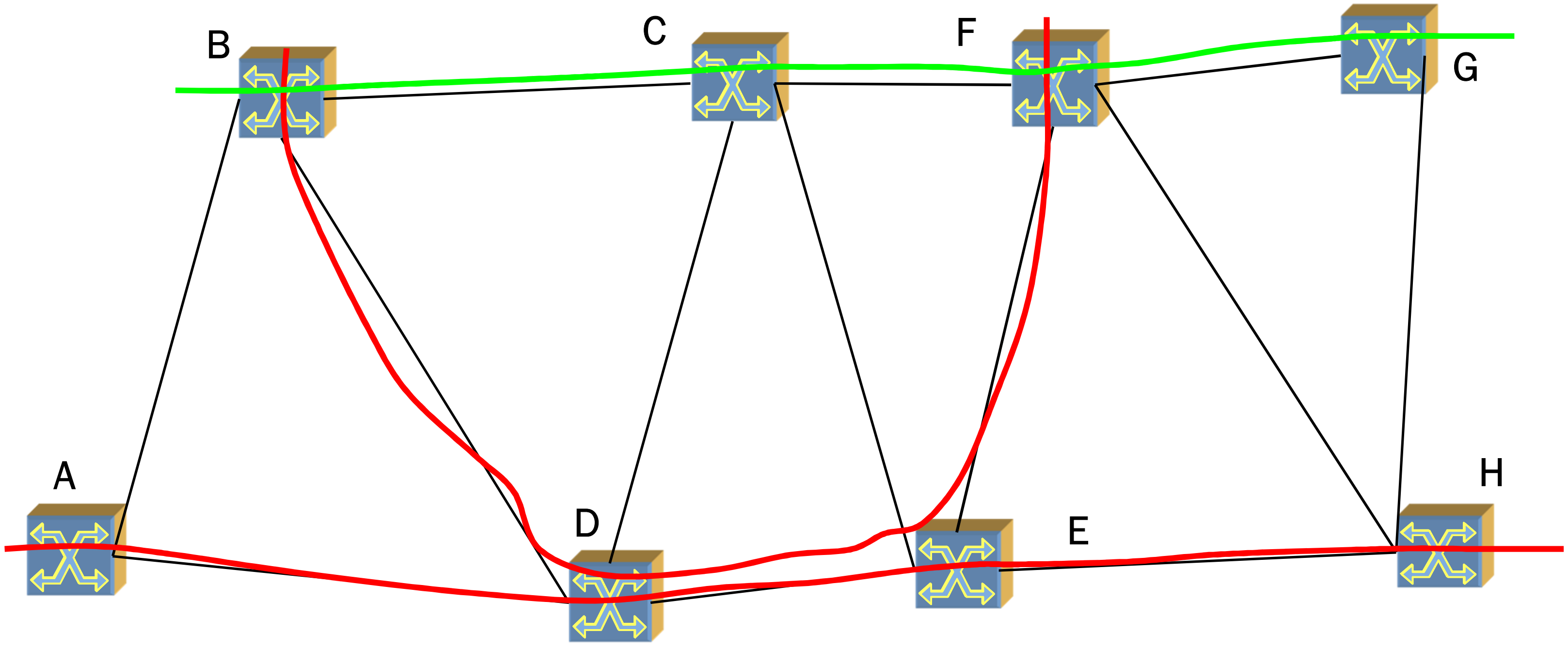
Systems devoted to the functions of data transfer:
multiplexing, transmission, switching

Control Plane functions

- ***Routing:***
  - ***Circuits' optimum path computation based either on elementary criteria (e.g. minimum distance) or on sophisticated Traffic Engineering approaches. Standard GMPLS protocol: OSPF-TE, RFC3630***
- ***Signaling:***
  - ***Cross-connections creation that allows circuits establishment. Standard GMPLS protocol: RSVP-TE, RFC3209***
- ***Discovery:***
  - ***Automatic Network inventory: automatic identification of new nodes or new network resources. Standard GMPLS protocol: LMP, RFC4209***

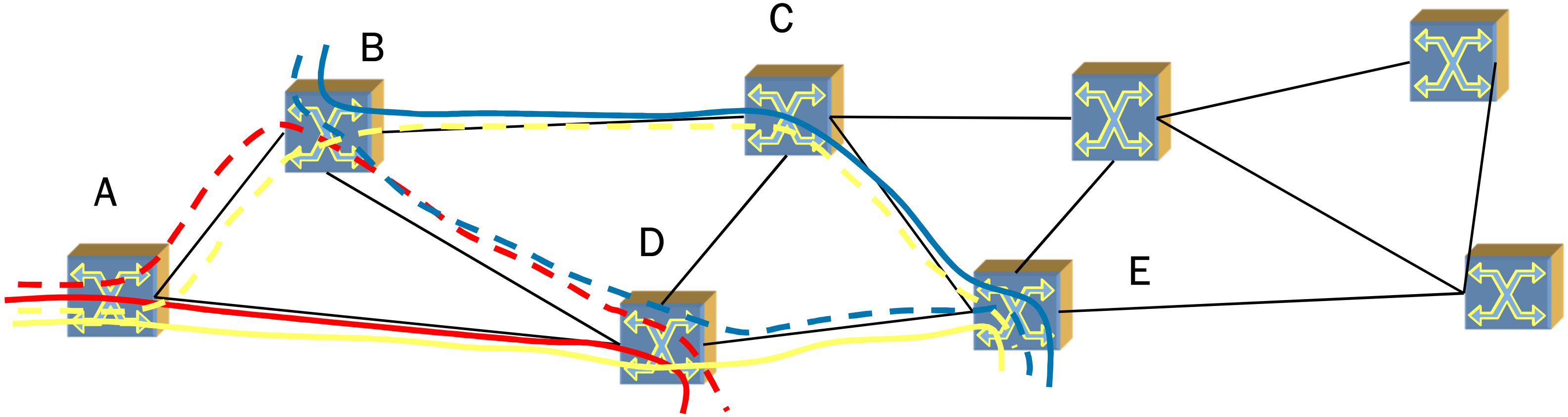
Wavelength continuity constraint

- ***Shortest Path routing is commonly used (Dijkstra algorithm). A given weight function is minimized: distance, number of hops, administrative weight …***
- ***In transparent optical networks wavelength continuity must be preserved from source to destination node (unless λ conversion is performed)***
- ***Blocking may occur if the selected λ is already used in one or more links***

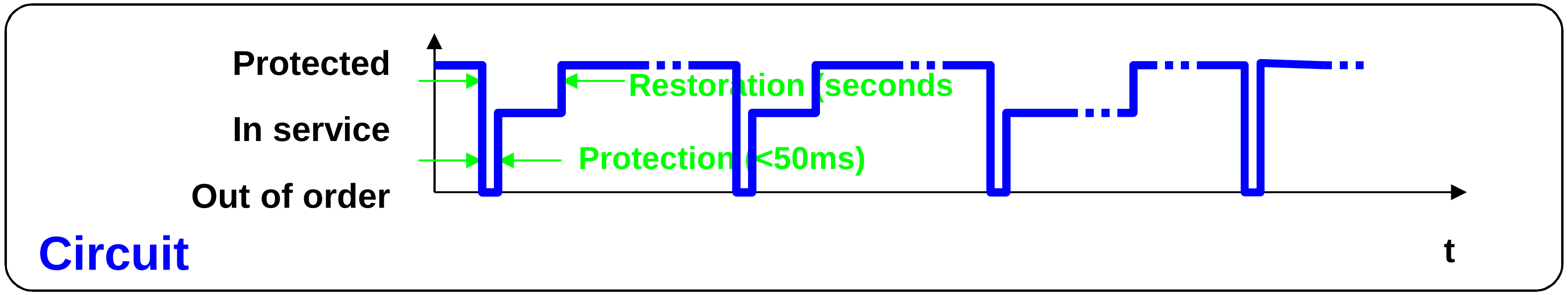


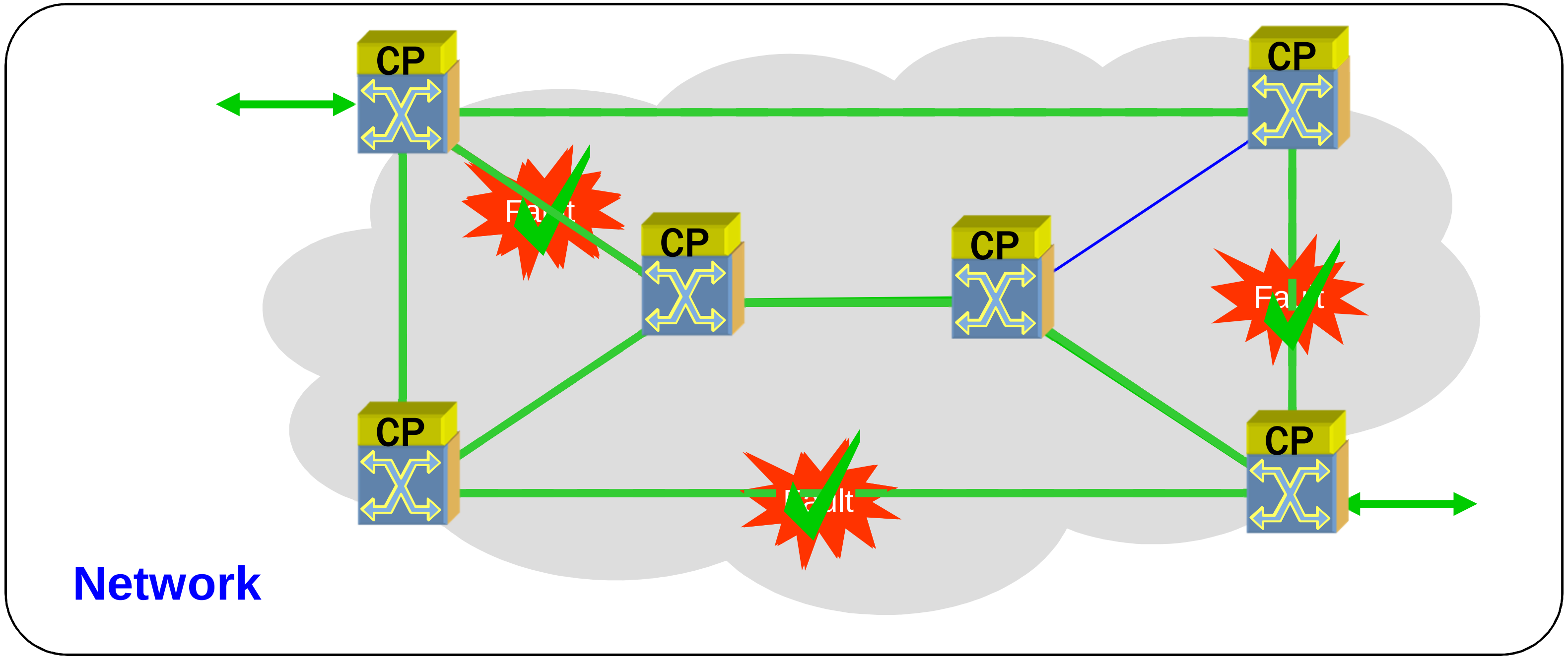
Dedicated and shared protection

- ***Dedicated Protection:** a disjoint path circuit is fully dedicated to protection of a single working circuit*
- ***In meshed networks, a single protection circuit can be shared among many working circuits, i.e. a single protection resource is allocated for multiple circuits***
- ***This resilience scheme is called "Restoration" which is of two kinds:***
  - ***"Pre-planned": protection circuit is shared, but it is calculated in advance***
  - ***"On the fly": protection circuit is calculated in real time at the time of fault***



Protection and Restoration combined





Summary

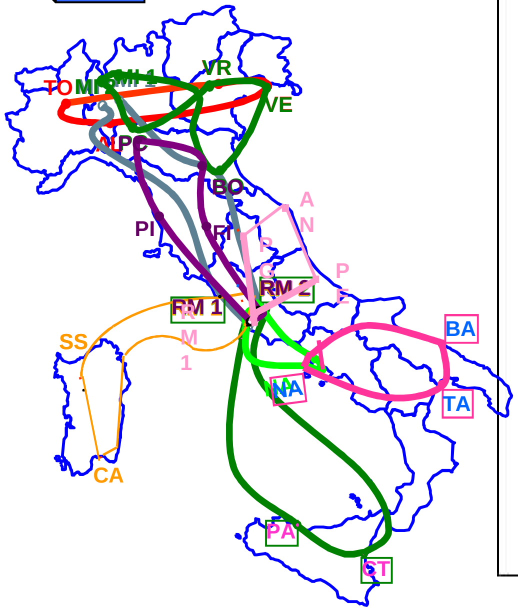
- Photonic Networks technologies
- Transport Networks basic functions
- **The Kaleidon photonic backbone**

Why a new Photonic Backbone?

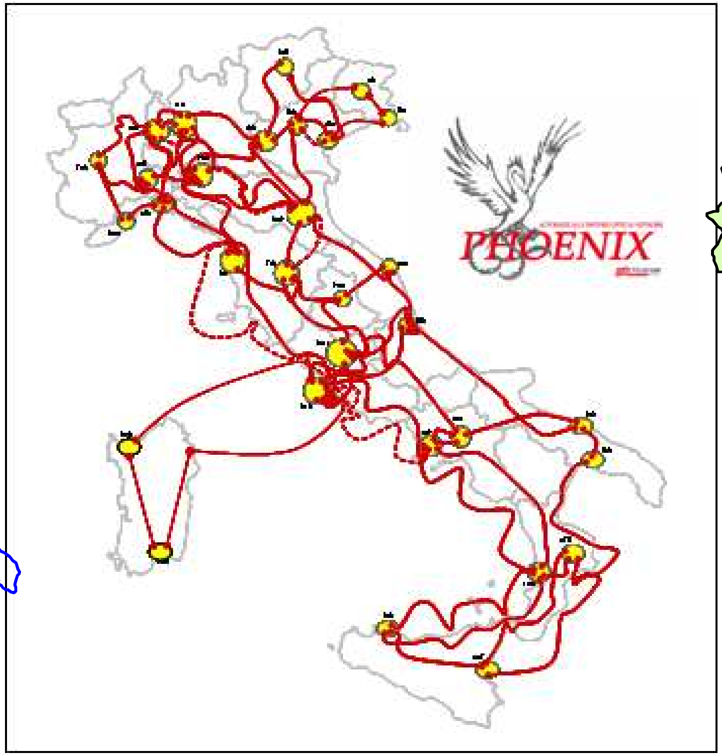
- To cope with a remarkable traffic increase
  - from the domestic networks (especially the IP backbone)
  - from International networks
  - from the emerging λ wholesale market
- To decrease costs (both CAPEX and OPEX)
- To enhance reliability for critical services
- To reorganize the transport backbone into a single easily manageable platform, switching over multiple legacy DWDM systems

The domestic client networks

ARIANNA
rete trasmissiva nazionale



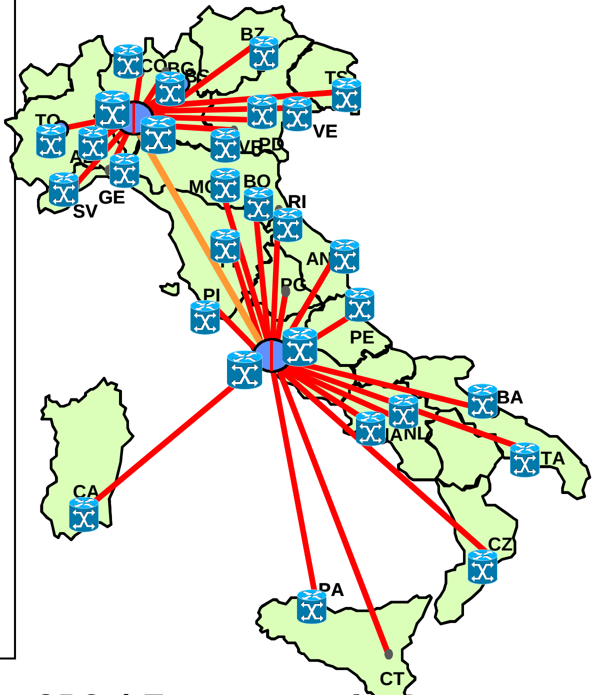
- *2.5 Gbit/s SDH ring architecture*
- *Today used for structured VC4 services*
- *Excellent reliability (MS-SPRing)*



- *ASON meshed network*
- *SDH cross-connects and DWDM links*
- *Control Plane, centralized routing*

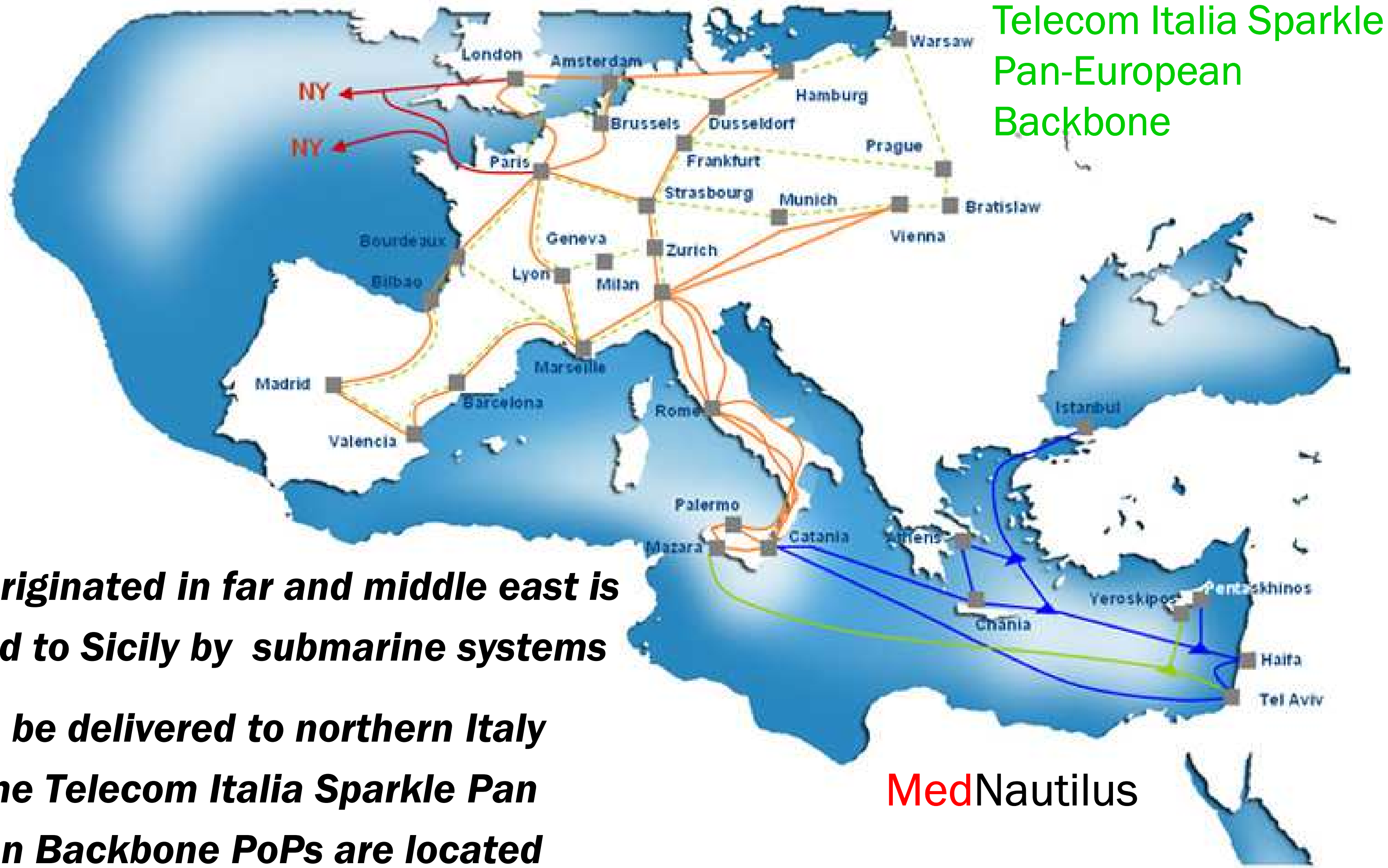
IP backbone architecture

OPB: Optical Packet Backbone



- *CRS 1 Tera-routers in the core*
- *10 Gbit/s POS interfaces for all links*
- *40 Gbit/s POS interfaces in the core*

Carrying international traffic through Italy



- ***Traffic originated in far and middle east is conveyed to Sicily by submarine systems***
- ***It has to be delivered to northern Italy where the Telecom Italia Sparkle Pan European Backbone PoPs are located***

Opportunities of new photonic technologies

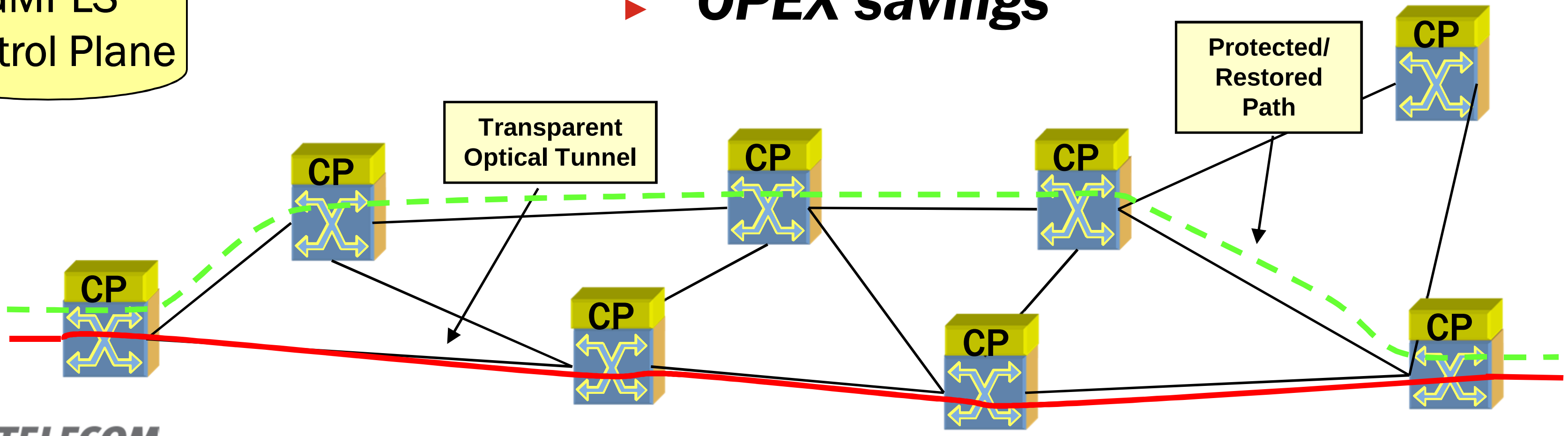
Ultra Long-Haul DWDM

Multi-degree ROADM

Enhanced GMPLS Control Plane

- ***Fewer regenerators***
- ***CAPEX savings***

- ***End-to end provisioning***
- ***OCh protection and restoration***
- ***OPEX savings***



The Photonic Backbone structure

Tentative scheme of the new Backbone

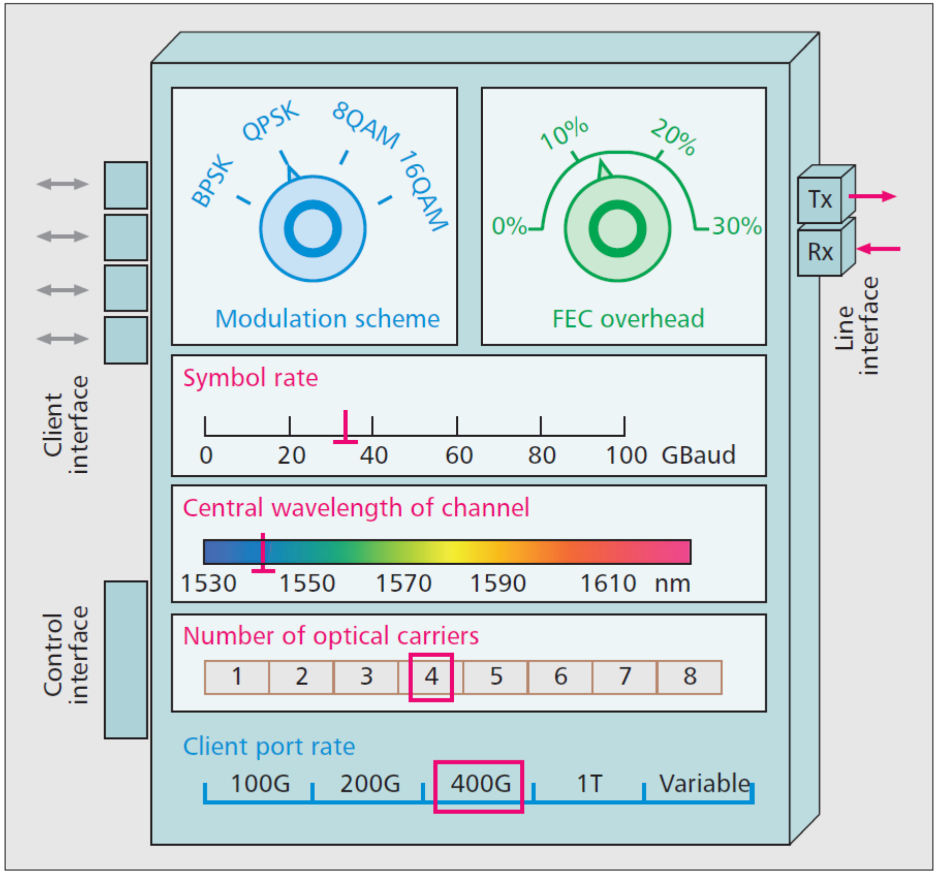
- Network diameter: 2400-3100 km (working-protection paths)
- Maximum number of hops: 11
- Nodal degree: 2÷5 (av. 3.1)

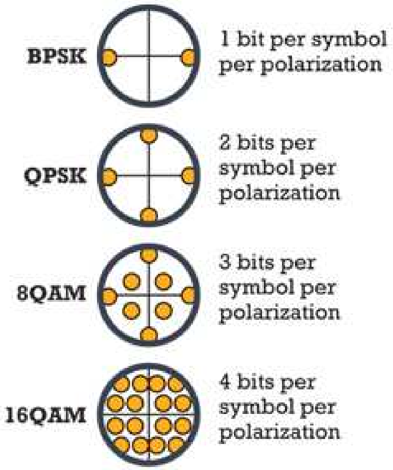
- Technology:
- ~44 λ switching nodes based on ROADMs
- ~71 ULH DWDM systems with 80 lambdas
- G.655 and G.652 fibers
- 40 and 100 Gbit/s optical channels (OCh)

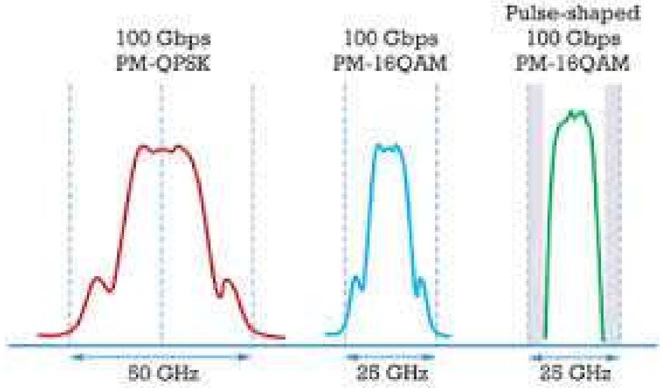
Energy savings and other operational benefits

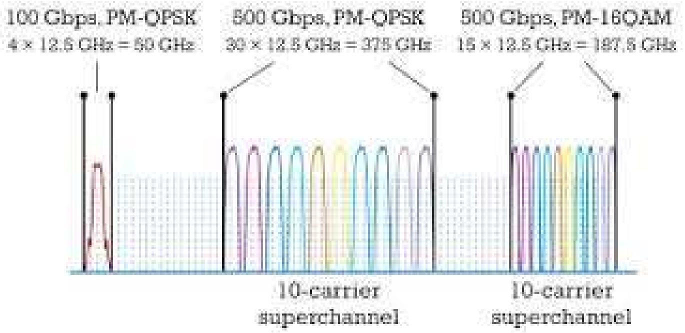
- Compared to transport on point-to-point DWDM systems, energy savings range between 20 and 30%
- Energy saving is mainly due to the regenerator number reduction, while ROADMs power consumption is very low
- Other important benefits are:
  - Remarkable spare parts reduction (due to fewer regenerators);
  - ~40% circuit creation cost reduction;
  - Opportunity of relocating the circuits of legacy networks on the new backbone simplifying the transport in the backbone

Bandwidth variable transponders



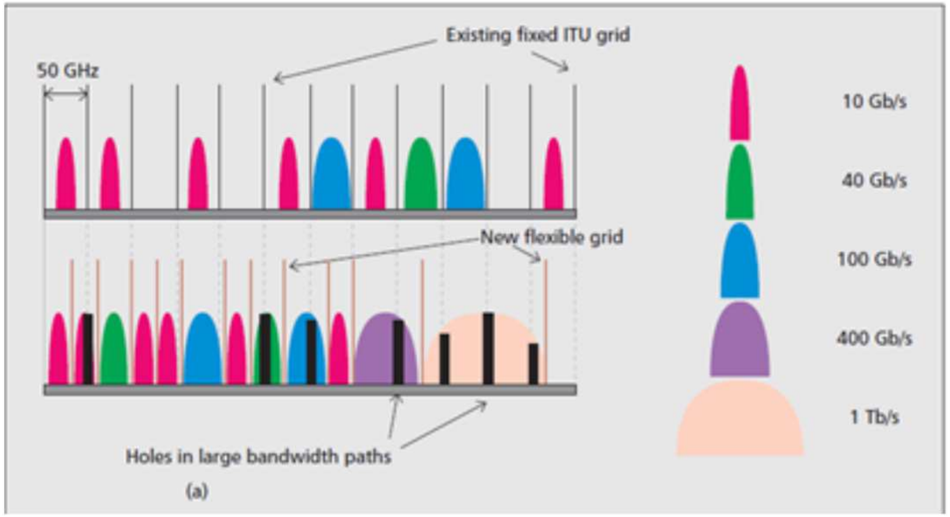




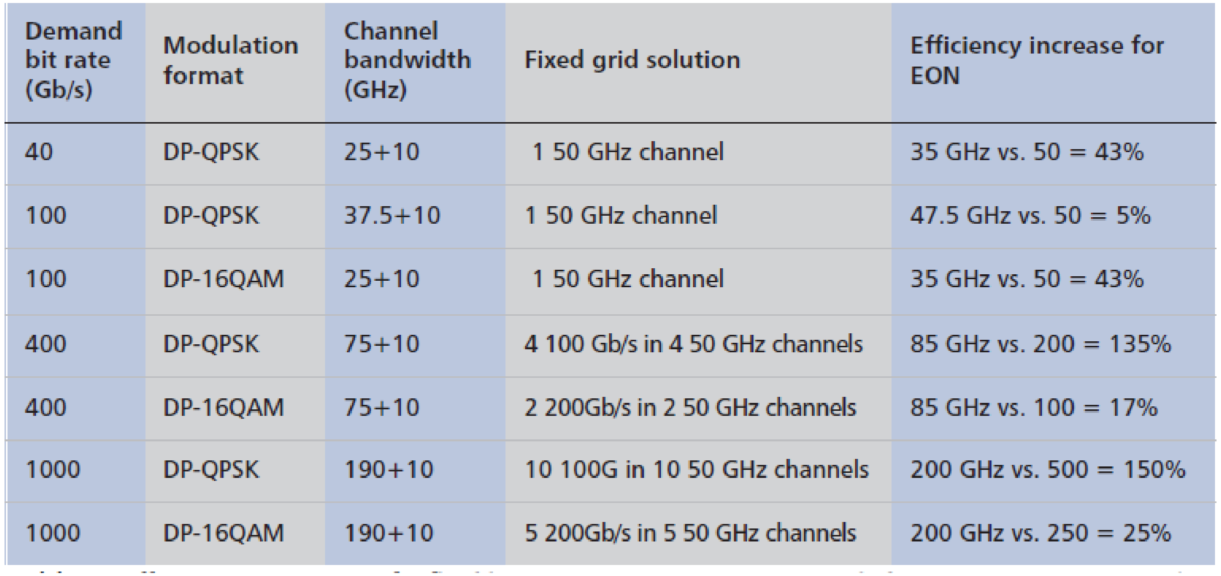


From S. Gringeri, et al., “Extending Software Defined Network Principles to Include Optical Transport”, IEEE Communications Magazine March 2013

Bandwidth variable superchannel Flexible grid

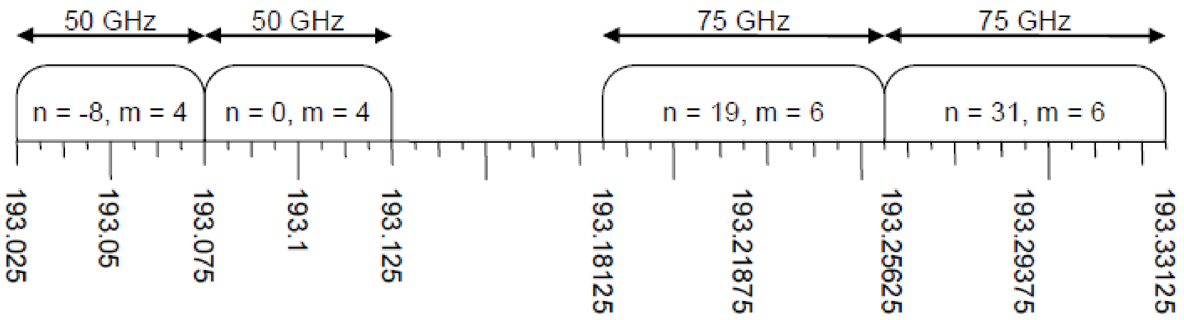


From O. Gerstel, et al., “Elastic Optical Networking: A New Dawn for the Optical Layer?”, IEEE Communications Magazine February 2012

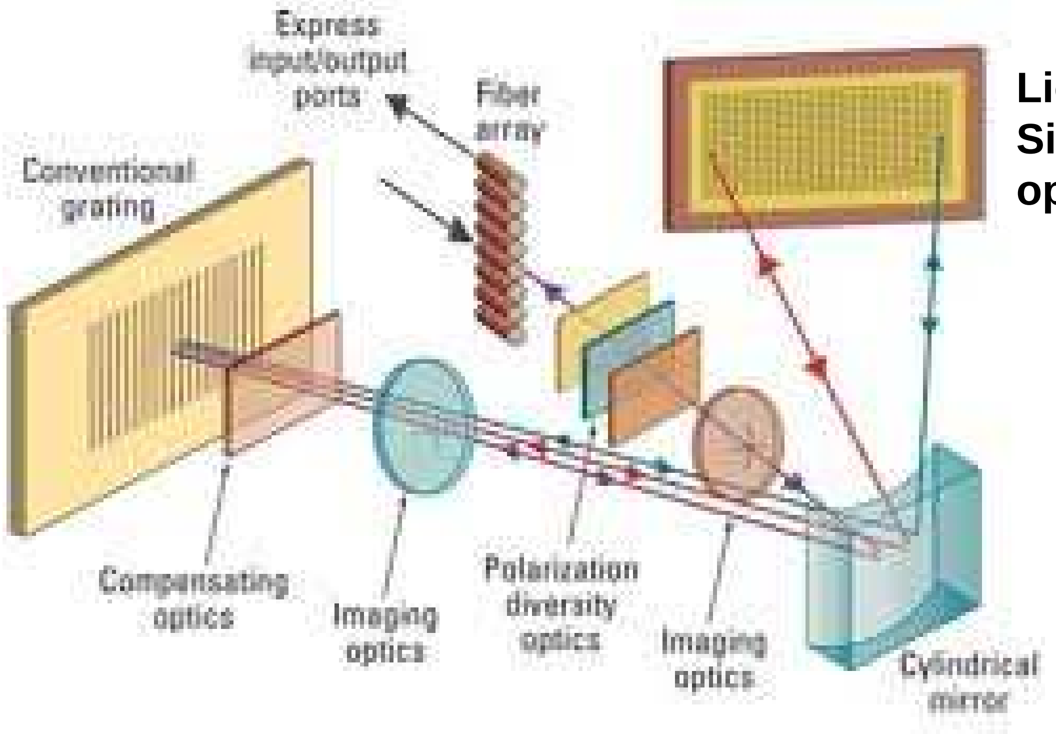


Demand bit rate (Gb/s)	Modulation format	Channel bandwidth (GHz)	Fixed grid solution	Efficiency increase for EON
40	DP-QPSK	25+10	1 50 GHz channel	35 GHz vs. 50 = 43%
100	DP-QPSK	37.5+10	1 50 GHz channel	47.5 GHz vs. 50 = 5%
100	DP-16QAM	25+10	1 50 GHz channel	35 GHz vs. 50 = 43%
400	DP-QPSK	75+10	4 100 Gb/s in 4 50 GHz channels	85 GHz vs. 200 = 135%
400	DP-16QAM	75+10	2 200Gb/s in 2 50 GHz channels	85 GHz vs. 100 = 17%
1000	DP-QPSK	190+10	10 100G in 10 50 GHz channels	200 GHz vs. 500 = 150%
1000	DP-16QAM	190+10	5 200Gb/s in 5 50 GHz channels	200 GHz vs. 250 = 25%

The new Flexible grid



Flexible grid example (ITU-T G.6941 Recommendation)



Liquid Crystal over Silicon (LCoS) optical processor

Photonic networks References

[1] R. S. Tucker et al., "Evolution of WDM Optical IP Networks: A Cost and Energy Perspective", IEEE JLT, VOL. 27, no. 3, February 1, 2009

[2] S. Gringeri et al., "Flexible Architectures for Optical Transport Nodes and Networks", IEEE Communications Magazine, July 2010

[3] O. Gerstel, et al., "Elastic Optical Networking: A New Dawn for the Optical Layer?", IEEE Communications Magazine February 2012

[4] S. Gringeri, et al., "Extending Software Defined Network Principles to Include Optical Transport", IEEE Communications Magazine March 2013