Optical networking:

Network elements, devices, technology and transmission issues

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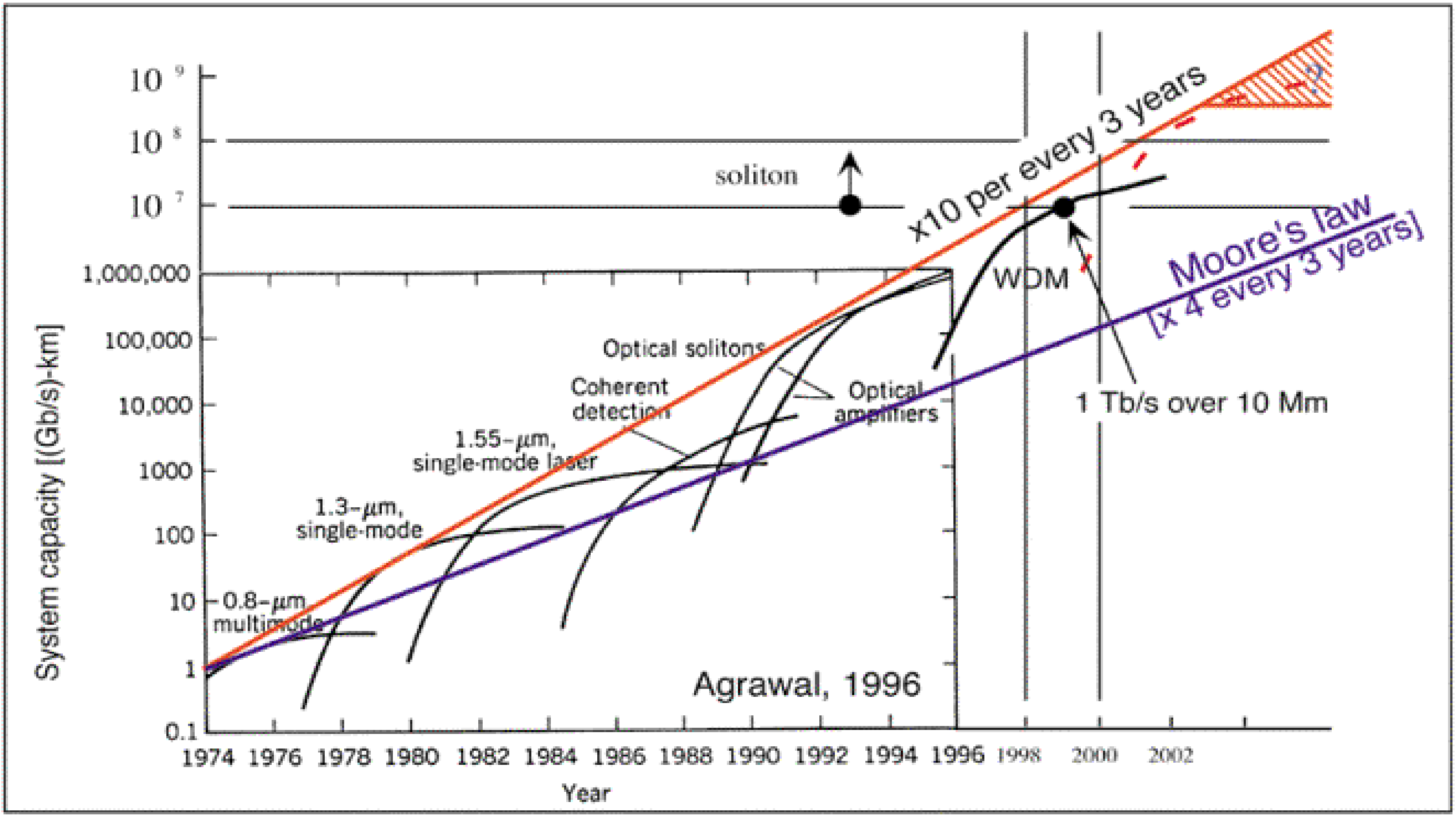
Photonics

Areas of applications

- ***Telecommunications***
- Metrology
- Sensors
- Medicine
- Biotechnology
- Display
- Storage
- Lighting and energy
- Security

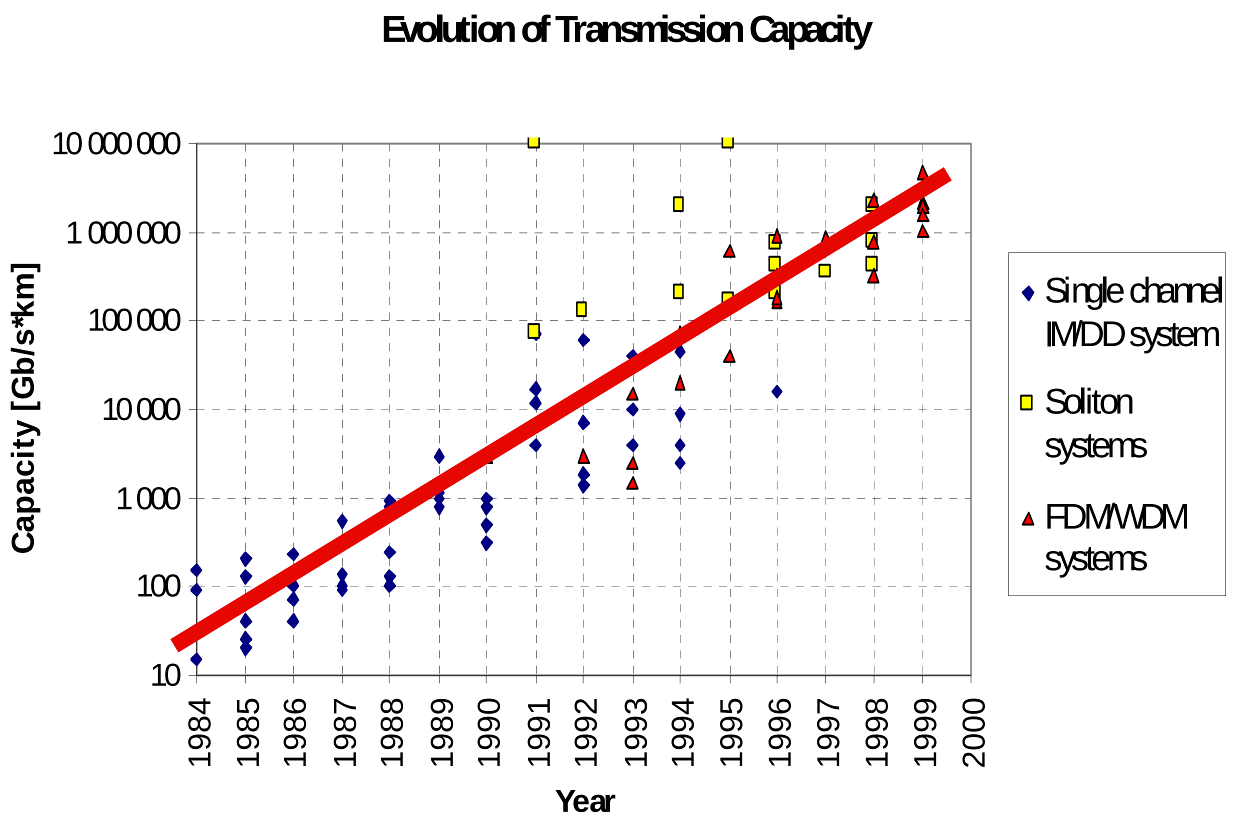
Bara fotonik kan ge kapaciteten
Only photonics can give the capacity

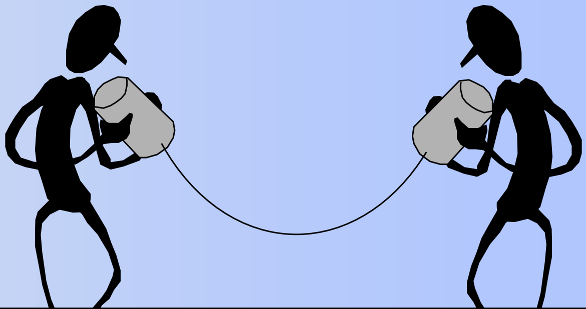


1st generation networks 2nd generation

KTH

Optical Transmission





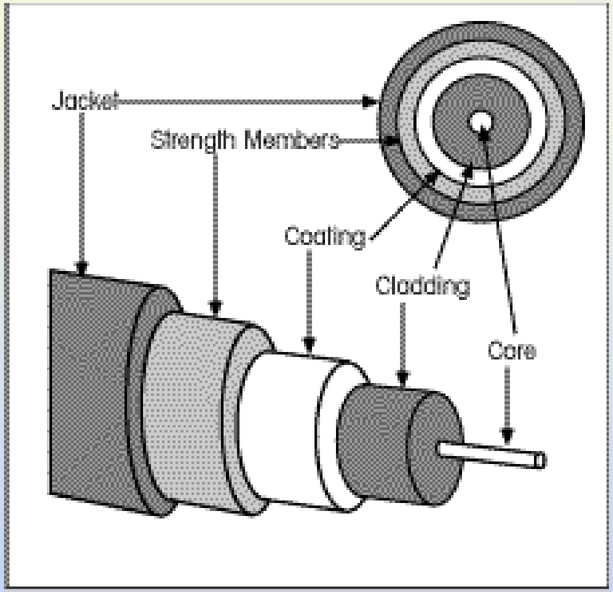
Capacity =Speed *distance

> 1Tbit/s over 1000 km
> 1500 CD-roms/sec
on single fiber

Already today!

Laboratory of
PHOTONICS
and
MICROWAVE Eng.

Capacity of Fiber



Shannon Channel Capacity

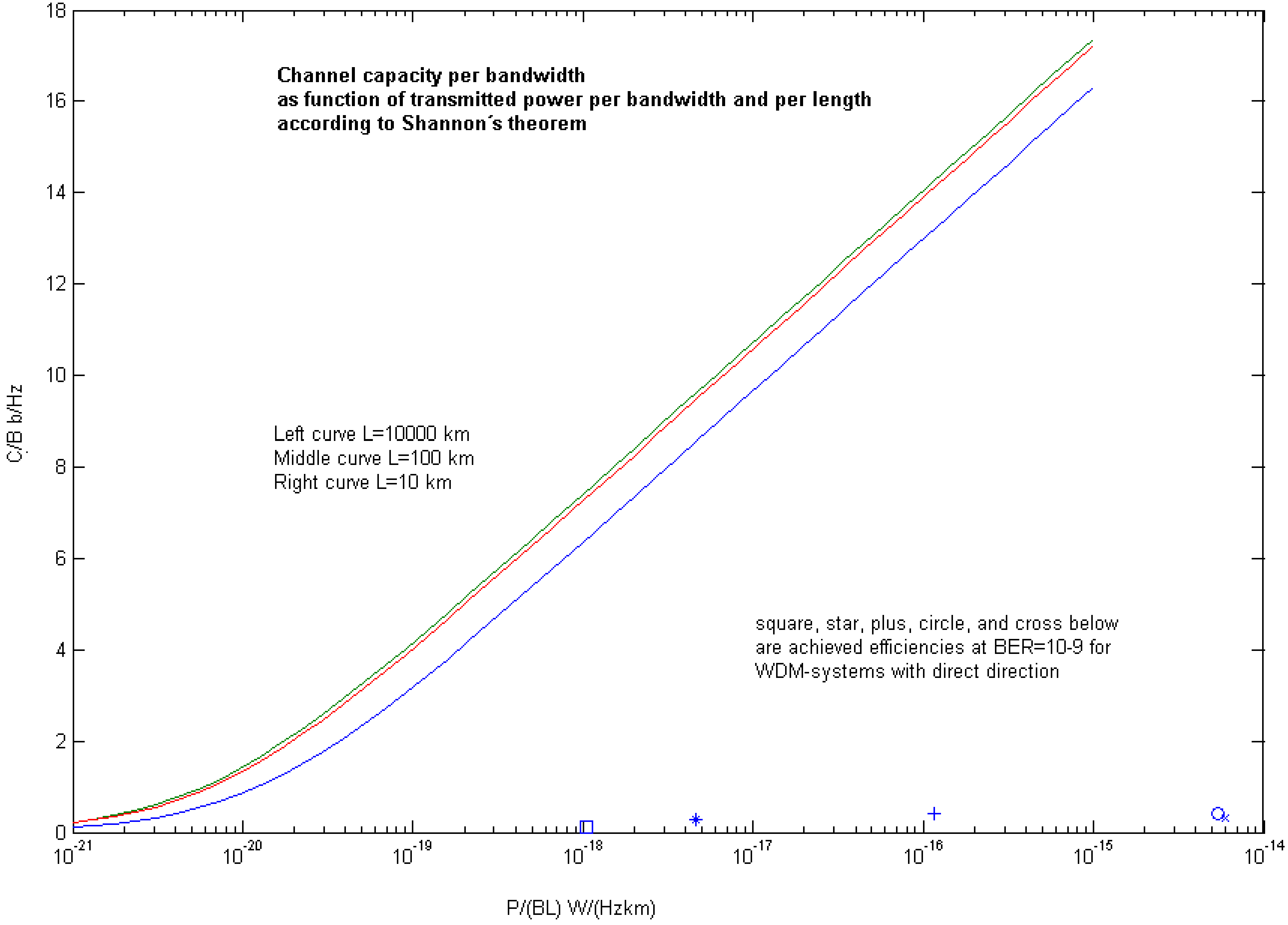
$$C = B \cdot \log_2\left(1 + SNR\right)$$

B = Fiber bandwidth , 5-50 THz
SNR = Signal to Noise Ratio

plug in SNR = 50 (not too unrealistic) gives

C = 250 Tbit/s

Spectral efficiency in b/s/Hz vs power/(bandwidth x length)



Contents

- Review of optical networks
- Optical network elements
- Devices in optical networks
- *Transmission link limitations*
  - ***TDM : Time division multiplexing***
  - ***WDM: Wavelength division multiplexing***
  - ***(SCM : subcarrier multiplexing)***
- *Modulation formats*
- *Photonic packet switching and the time domain*
- Future challenges

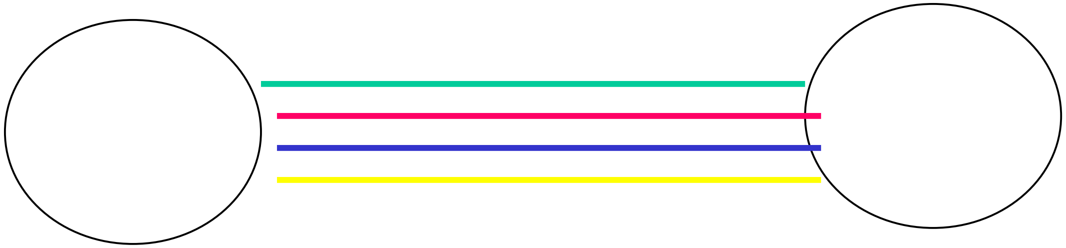
Review of optical networks

First and second generation optical networks

- 1st generation-> point to point, single wavelength
- 2nd generation: routing and switching in the optical domain, ”all optical network”

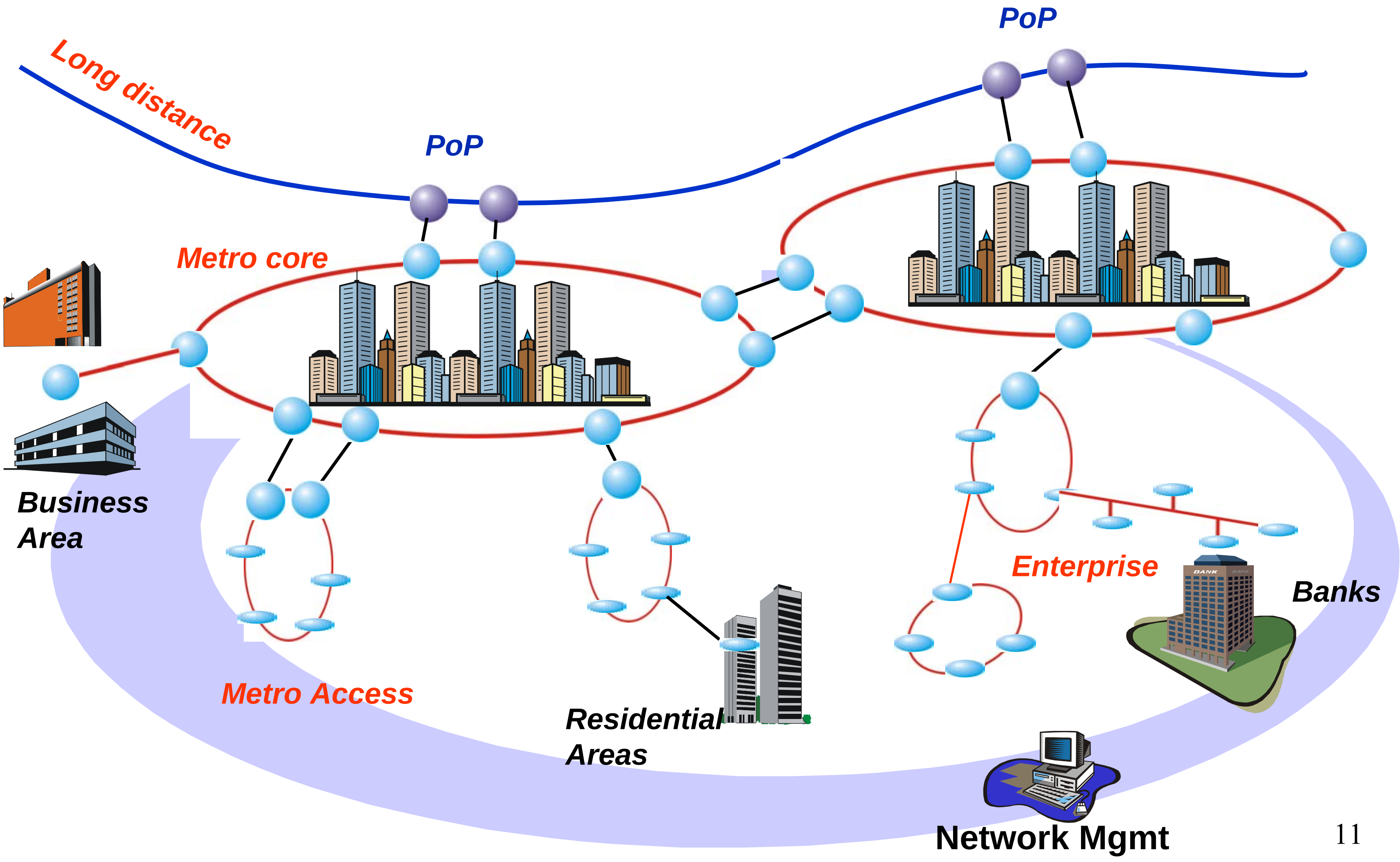
1st generation networks

Point to point WDM

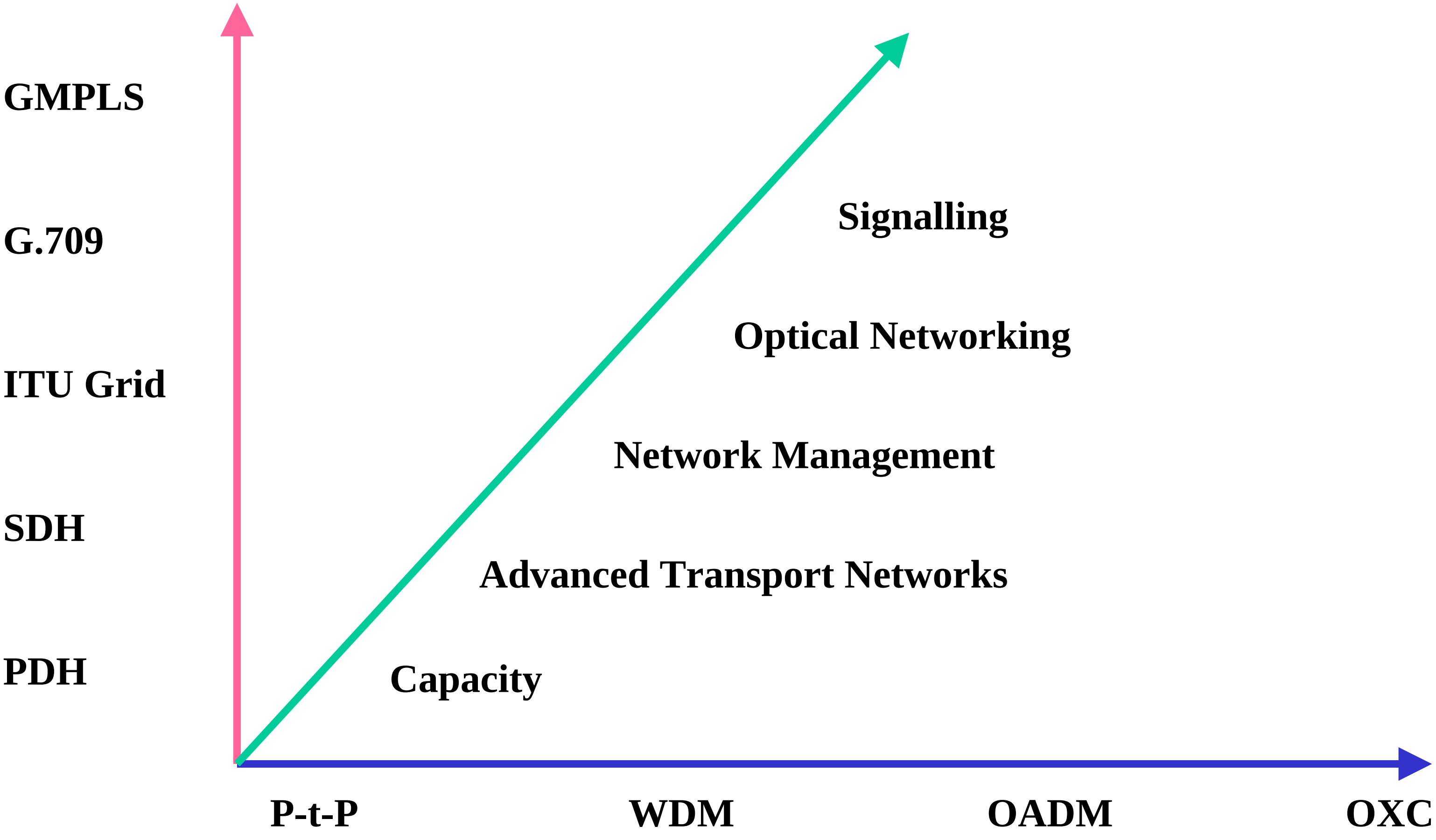


2^{nd} generation networks

Metro DWDM Network



Development in Optical Networking



GMPLS

G.709

ITU Grid

SDH

PDH

Signalling

Optical Networking

Network Management

Advanced Transport Networks

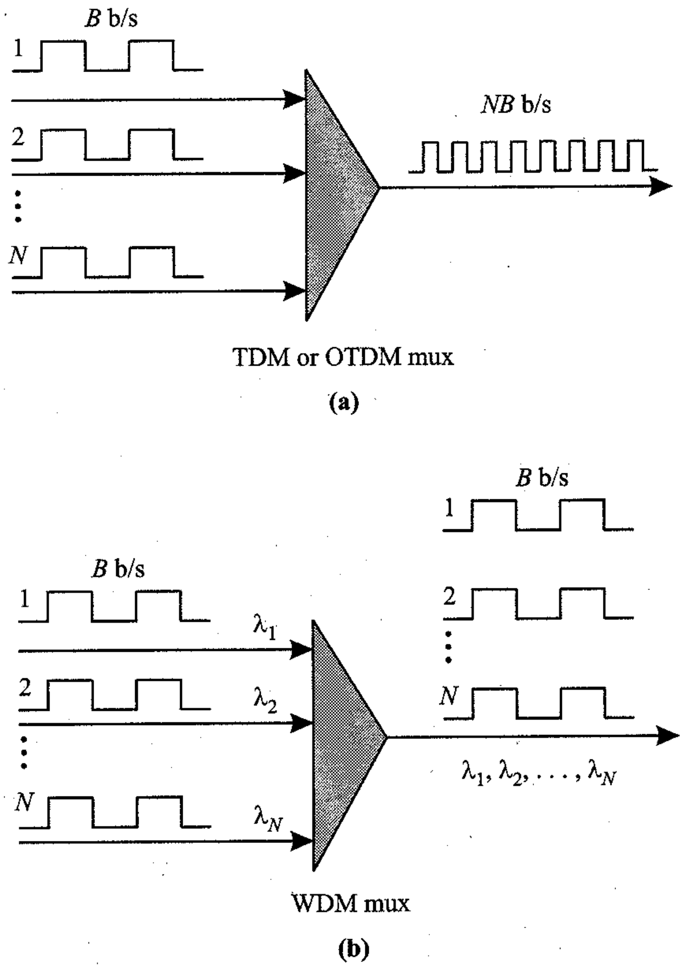
Capacity

P-t-P

WDM

OADM

OXC

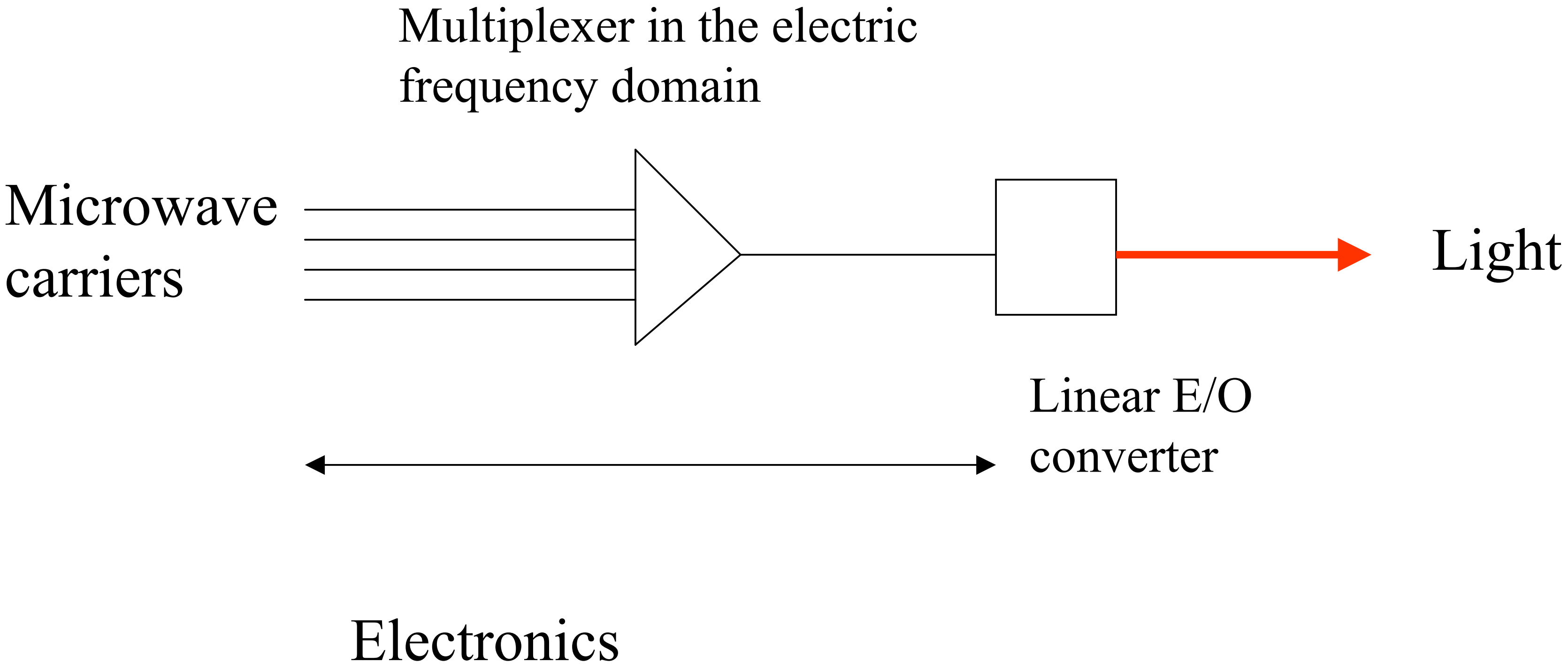


TDM

WDM

Figure 1.3 Different multiplexing techniques for increasing the transmission capacity on an optical fiber. (a) Electronic or optical time division multiplexing, and (b) wavelength division multiplexing. Both multiplexing techniques take in N data streams, each of B b/s, and multiplex them into a single fiber with a total aggregate rate of NB b/s.

SCM : subcarrier multiplexing



Multiplexer in the electric frequency domain

Microwave carriers

Light

Linear E/O converter

Electronics

3rd

Optical networks

TDM vs WDM

WDM: # of channels?

≈1000 reported (difficult!) => e g 5 GHz channel separation

Potential still unexplored!!!

TDM: # of channels?

Example: 160 Gb/s at 1 Mb/s => easily 160 000 channels

≈ WDM gives the transmission capacity, TDM the switching capability , at least now

The layer concept

7 Application

6 Presentation

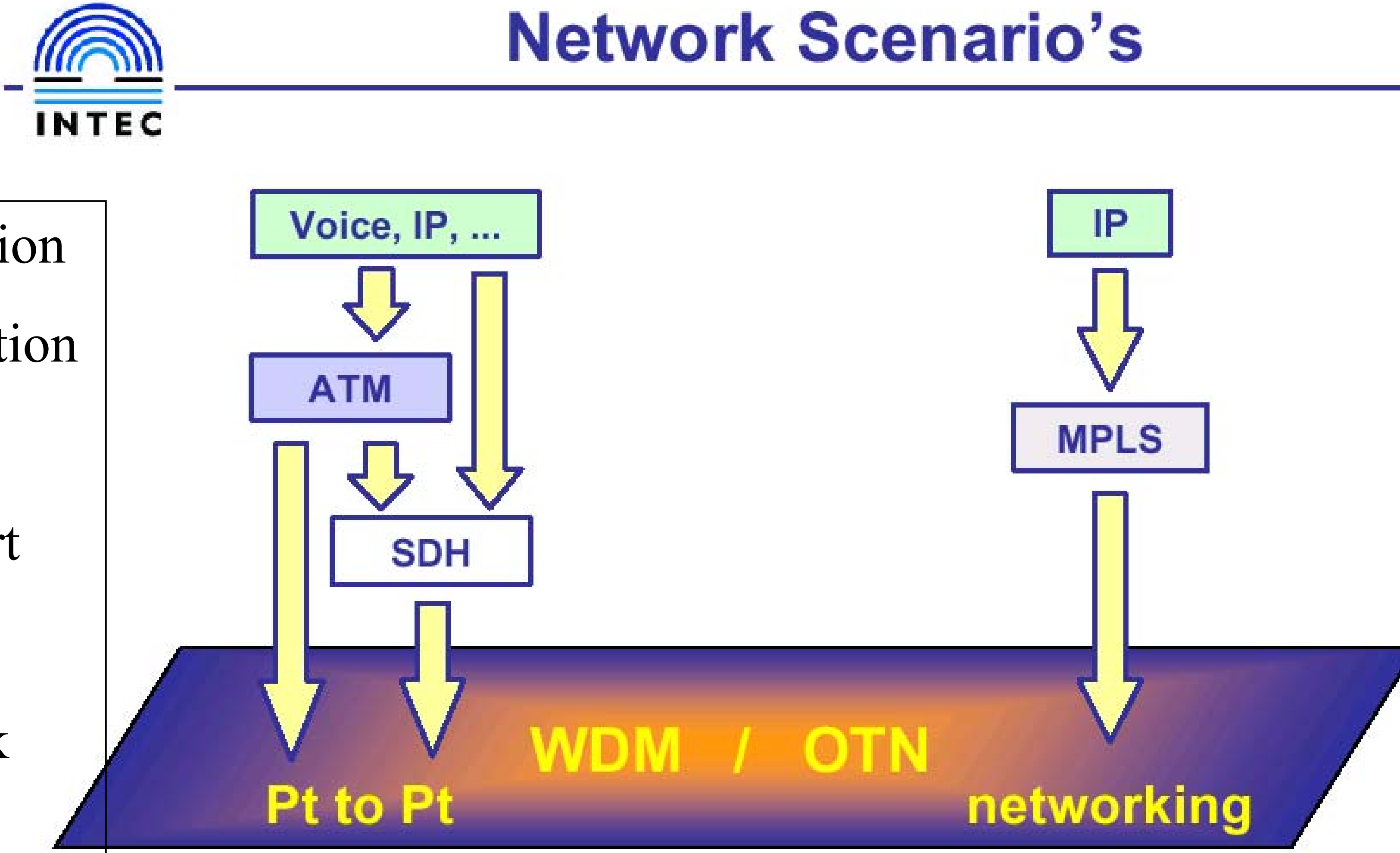
5 Session

4 Transport

3 Network

2 Data link

1 Physical



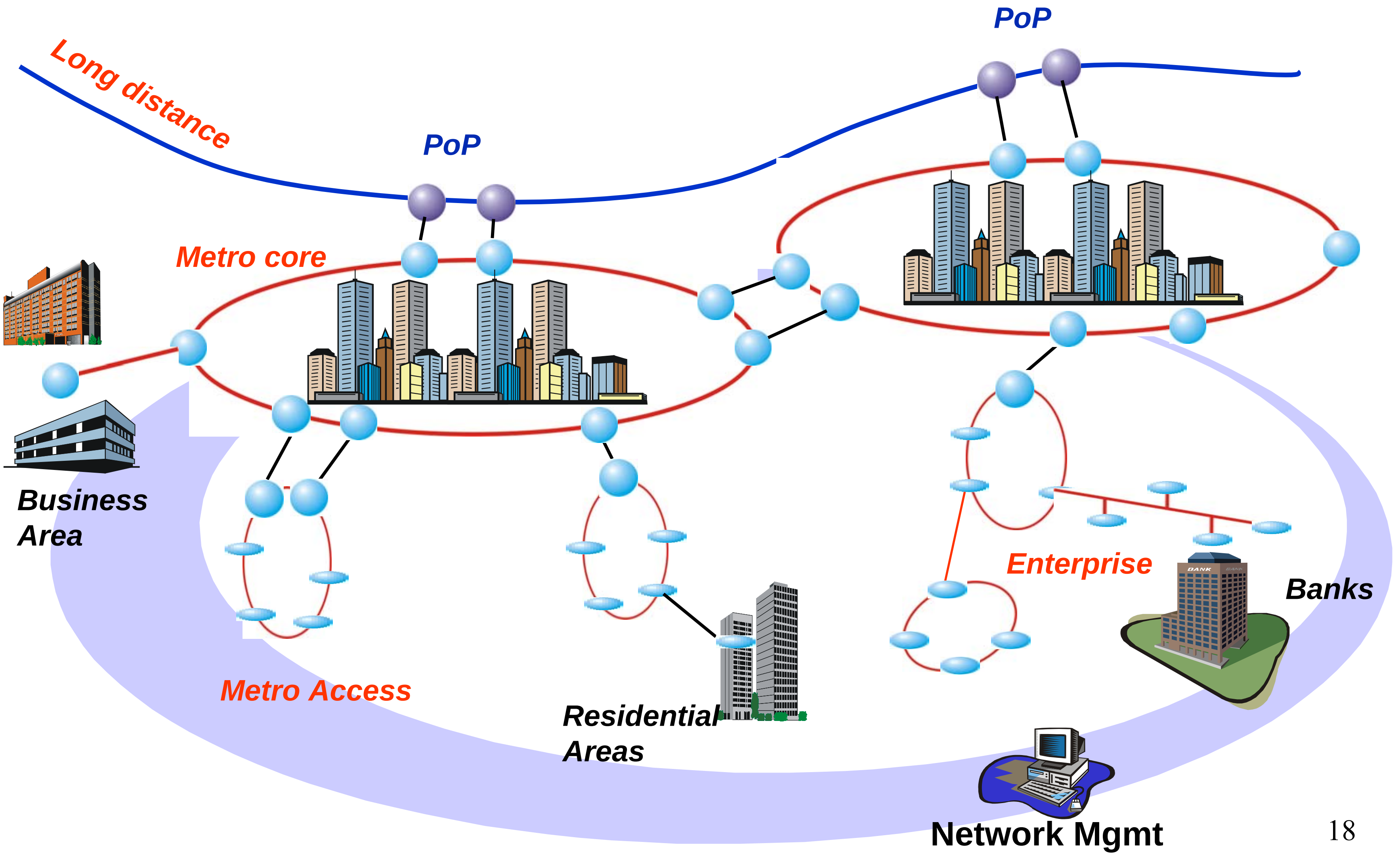
Network Scenario's

Second generation networks

- ***”All” optical WDM networks***
- ***But the all optical network is an analog one (cf your digital computer)=> problems with scalability (will go into that later)***

2nd generation networks

Metro DWDM Network

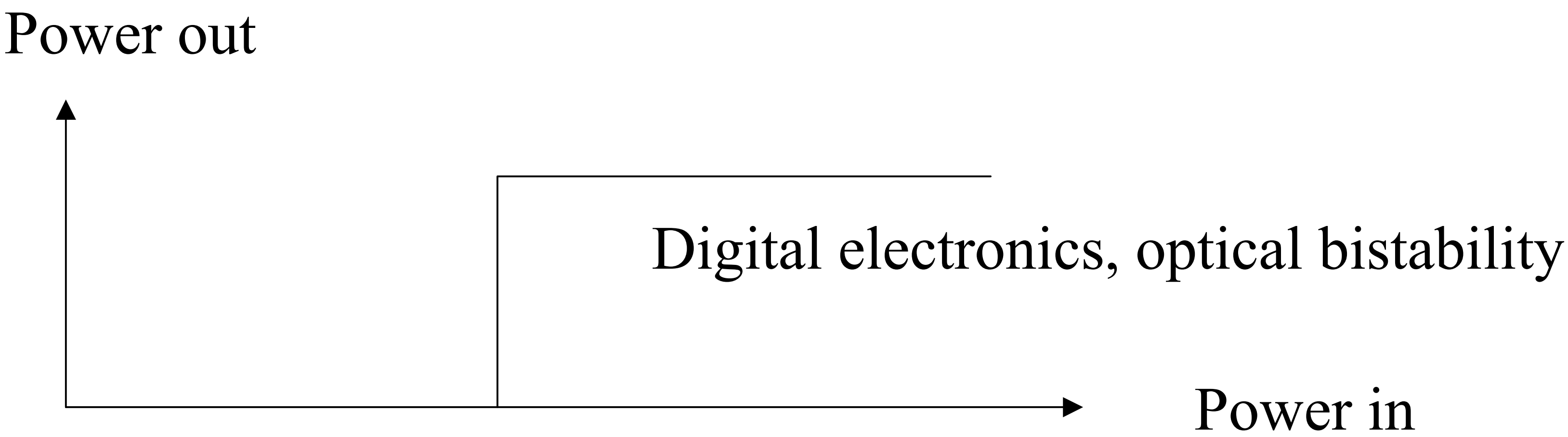


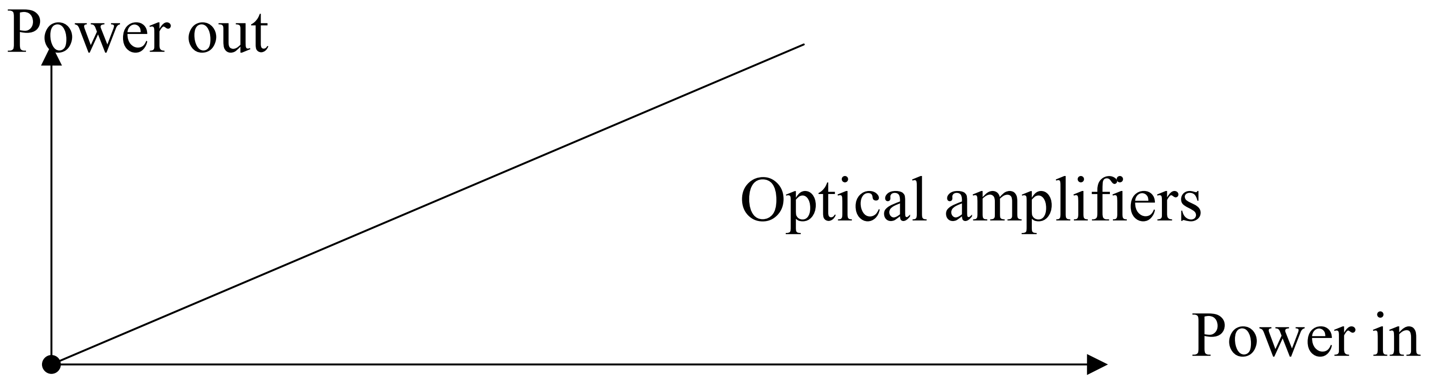
(All) Optical networks

- Networks vs point to point transmission
  - Noise, dispersion and nonlinearity accumulation
  - Crosstalk accumulation
  - Alignment of (de)multiplexers, filters
  - Filter bandwidth narrowing of concatenated (de)multiplexers, filters
  - Equalization of powers due to power and SNR variation in the network
  - Rapid dynamic equalization of amplifier gain
- In general we have linear networks: Scaleability is a problem!!
- Protection
- Granularity
- => Limited scalability! (as compared to point to point transmission with electronic regneration)

Example of limited scalability: Optical amplifiers:

- Compensate for loss -> ”Optical transparency”
- No retiming, pulse shaping etc
- Linear, analog->Noise accumulates





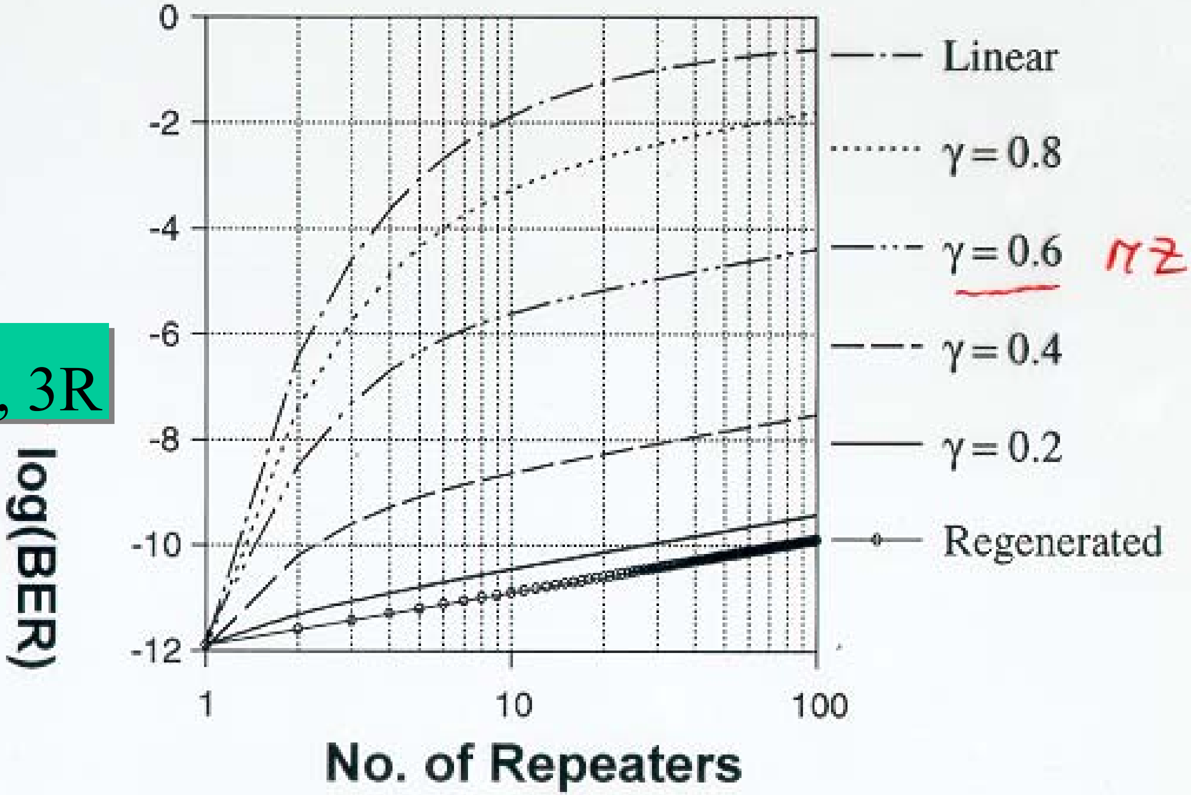
Amplitude Noise Accumulation

Linear system: 1R

$$\mathrm{BER} \sim \exp\left(-\frac{\mathrm{SNR}}{2N}\right)$$

Regenerated system: 2R, 3R

$$\mathrm{BER} \sim N \cdot \exp\left(-\frac{\mathrm{SNR}}{2}\right)$$



MZ

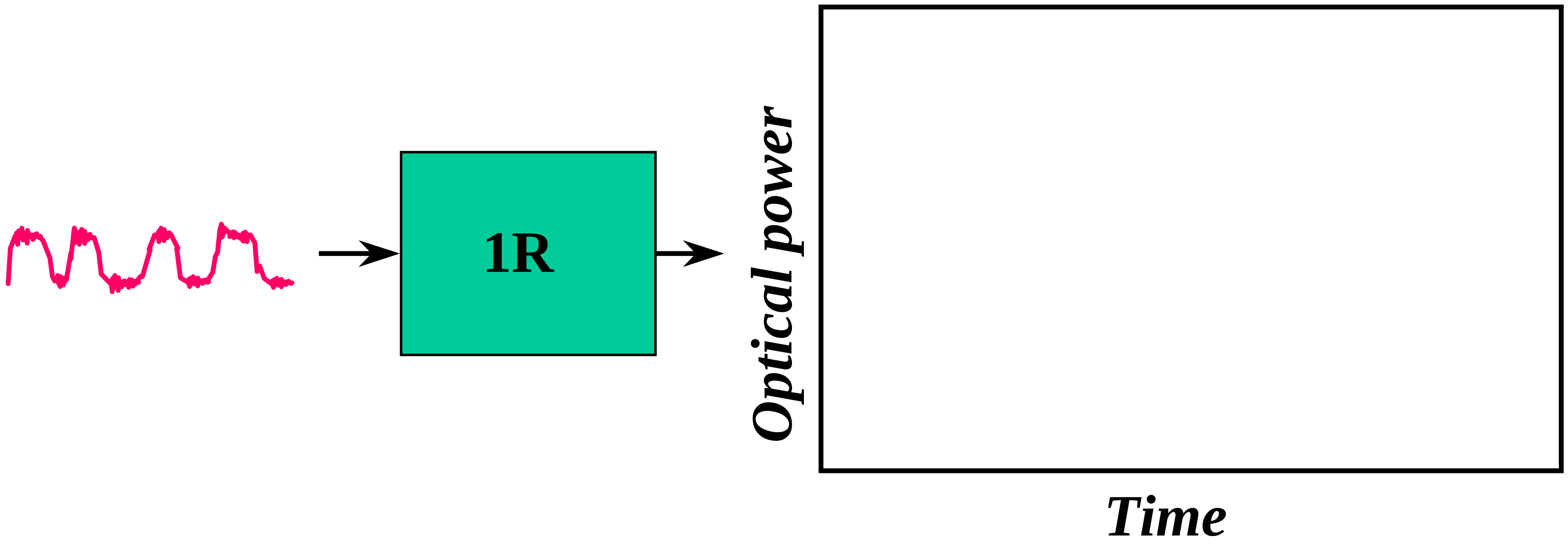
Ex (1-p)^N

Regeneration in optical networks

The signal has to be regenerated after passage of a certain number of nodes

What is 3R and 4R regeneration ?

1R consists in amplification and packet leveling



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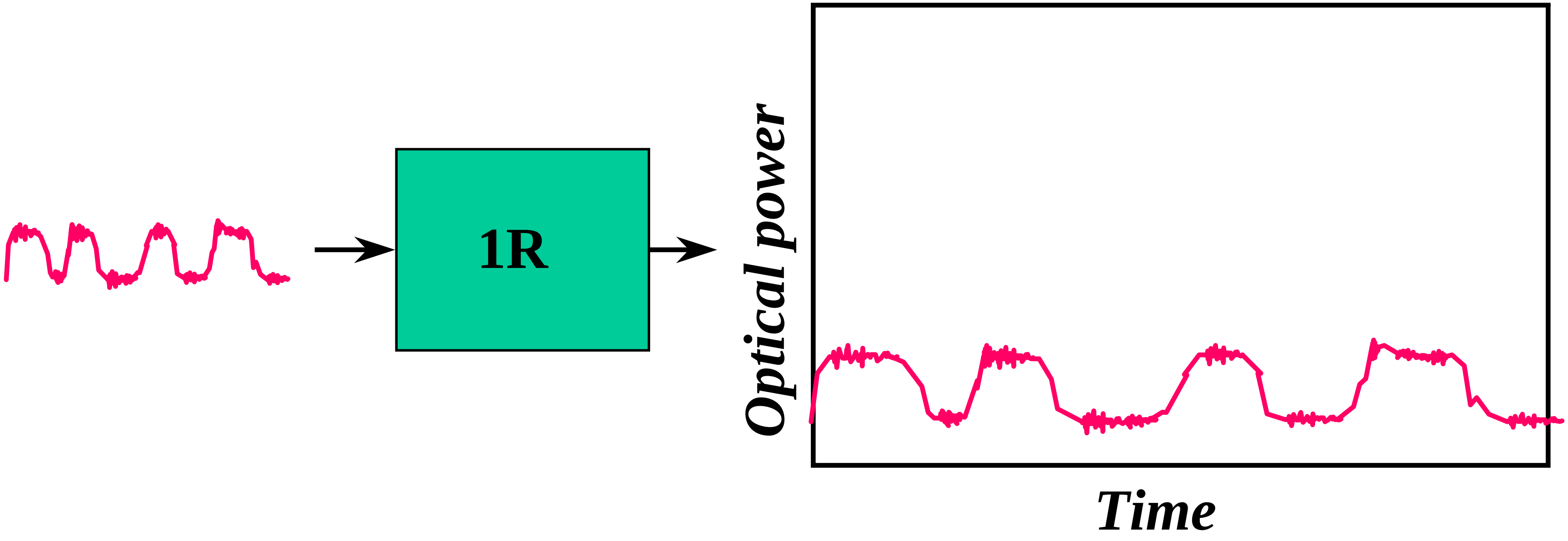

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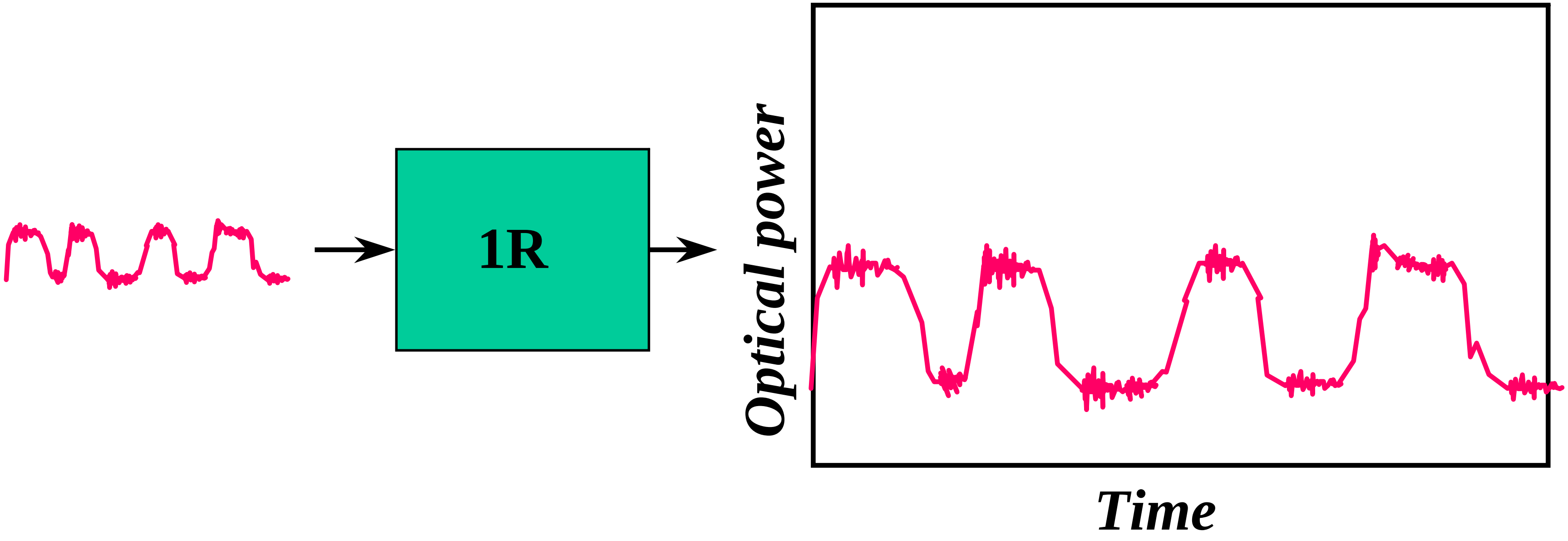

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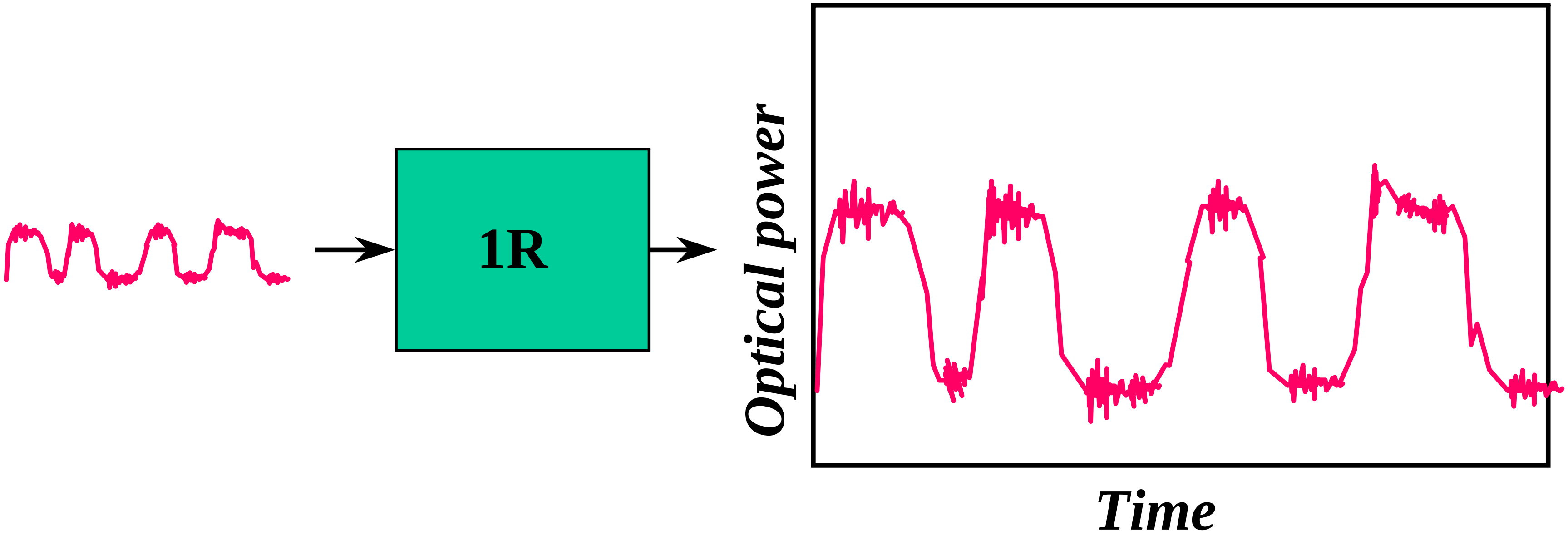

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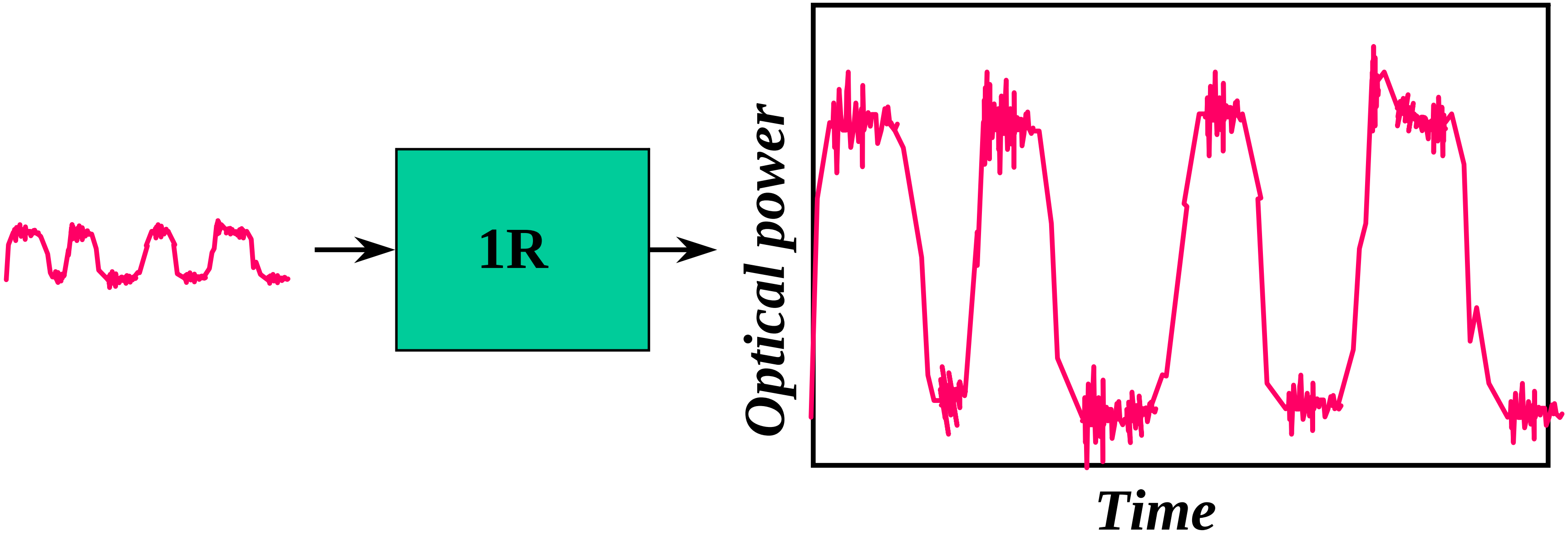

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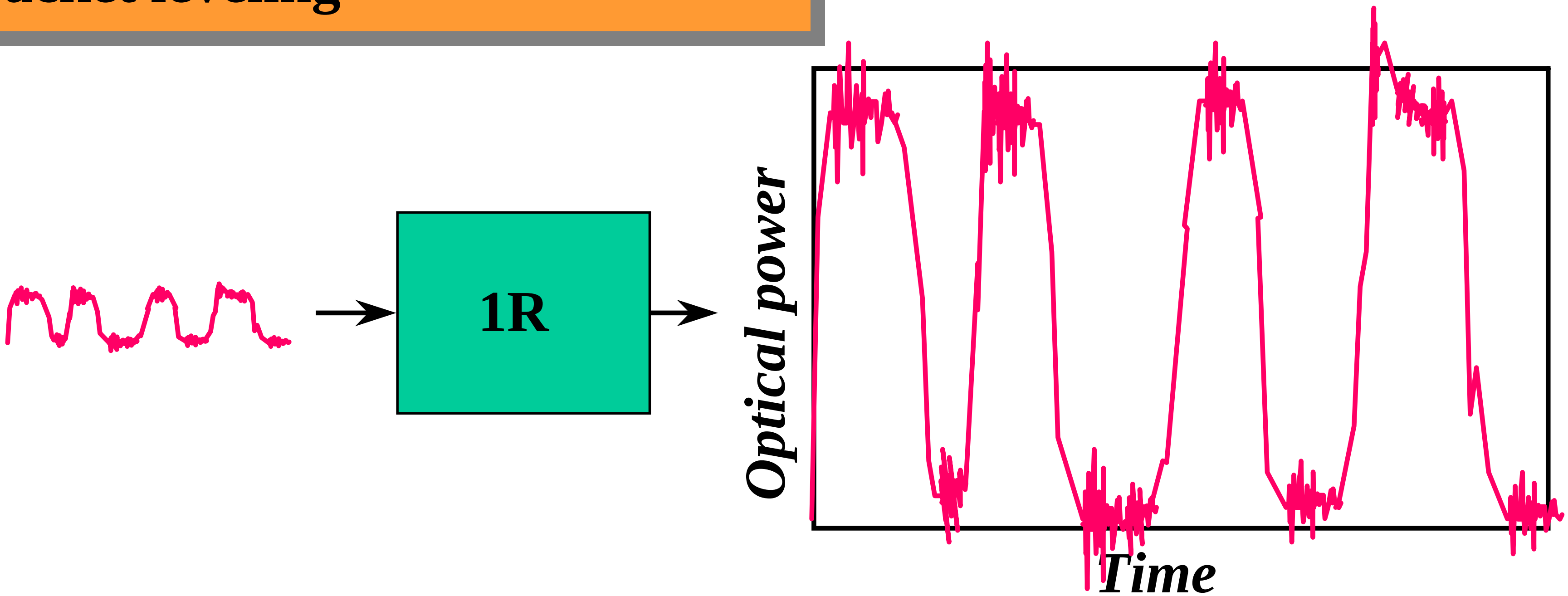

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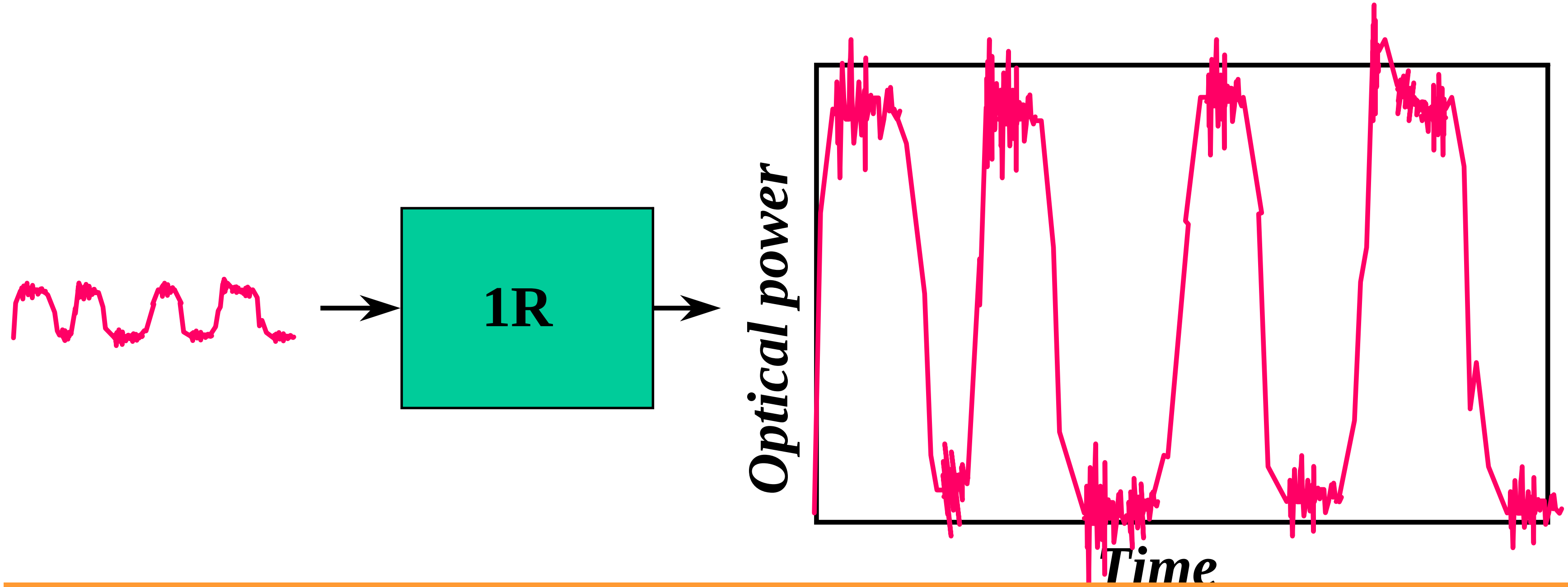
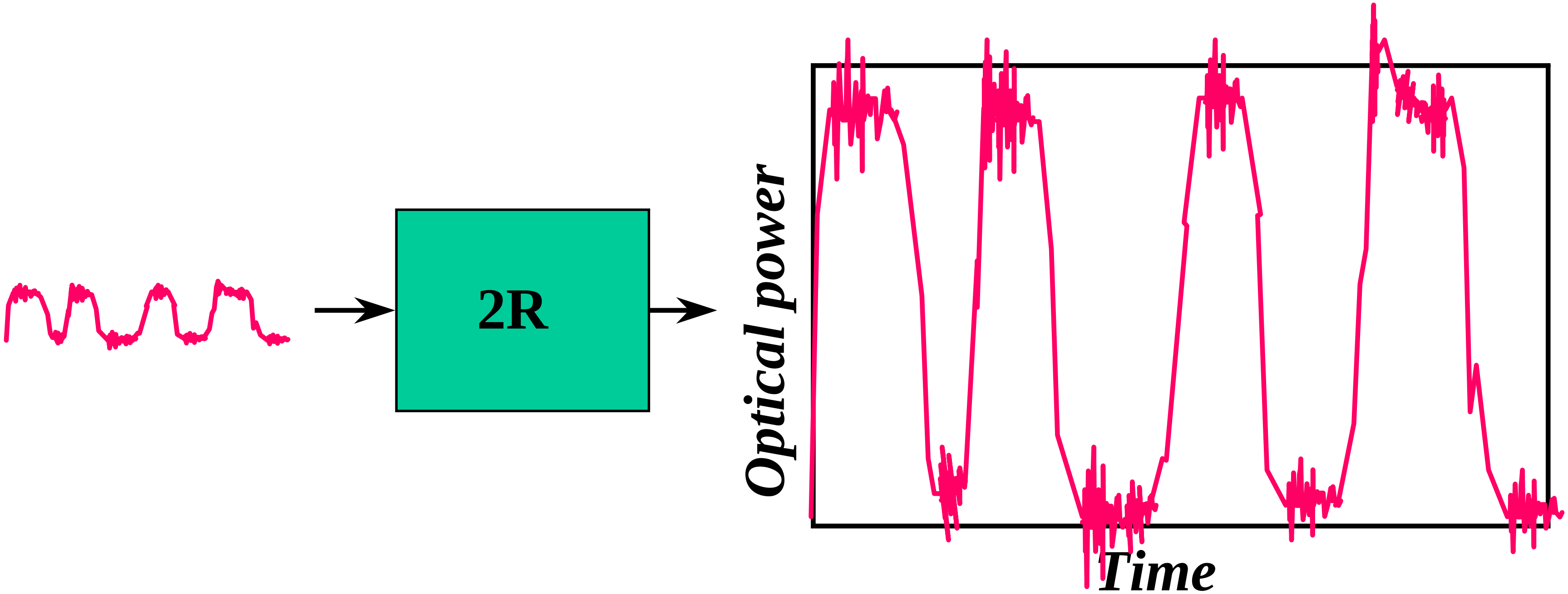


It is performed by fiber or semiconductor optical amplifiers (or electronic amplifiers)

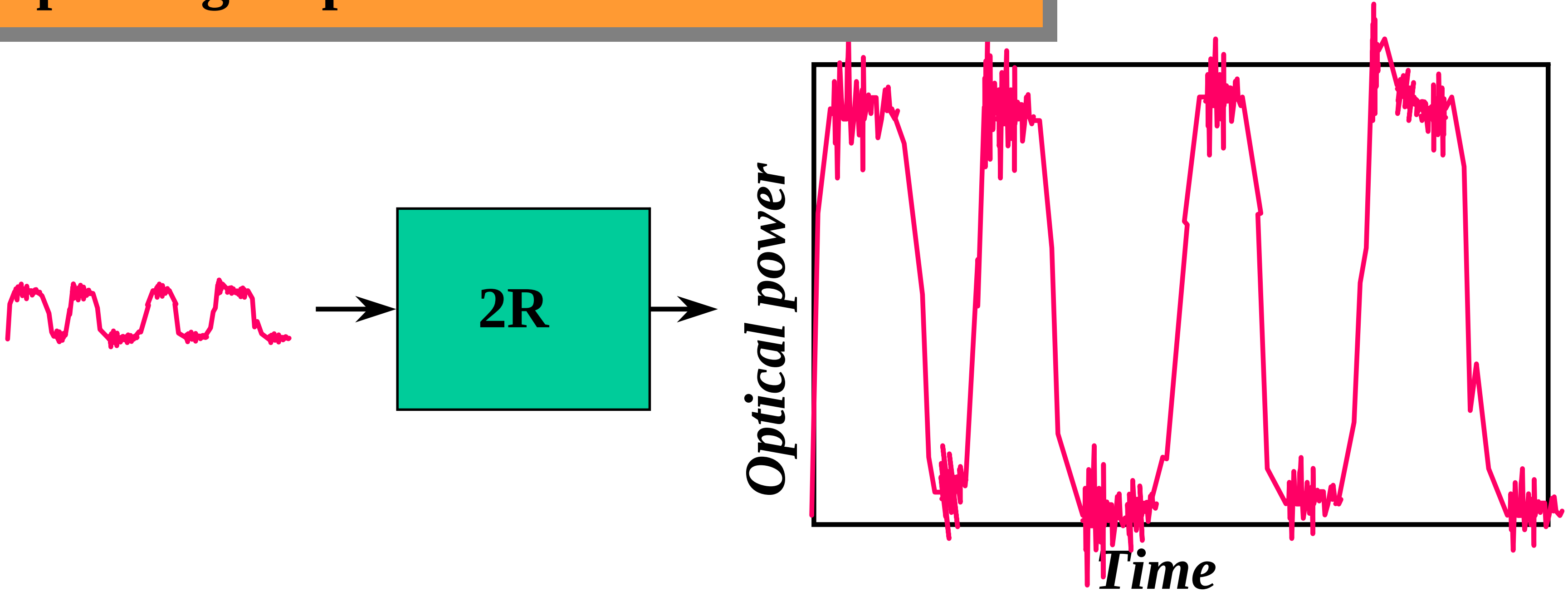
What is 3R and 4R regeneration ?

2R ...



What is 3R and 4R regeneration ?

2nd R consists in reshaping and improving amplitude noise



2R

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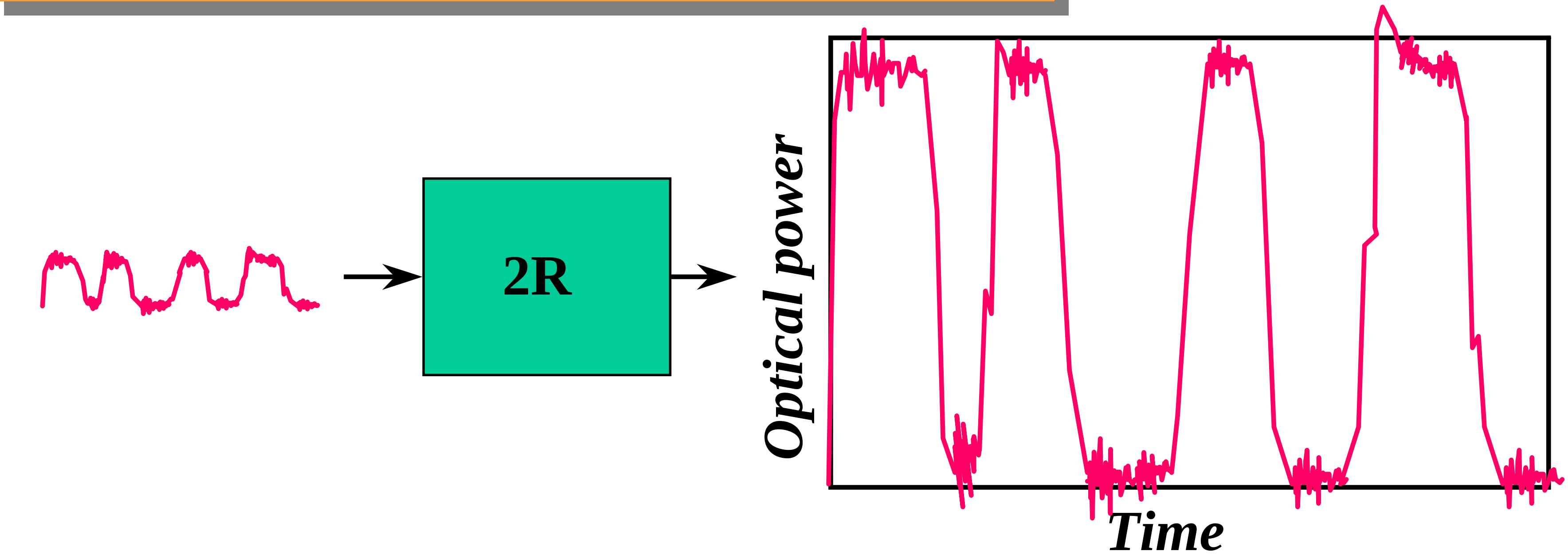

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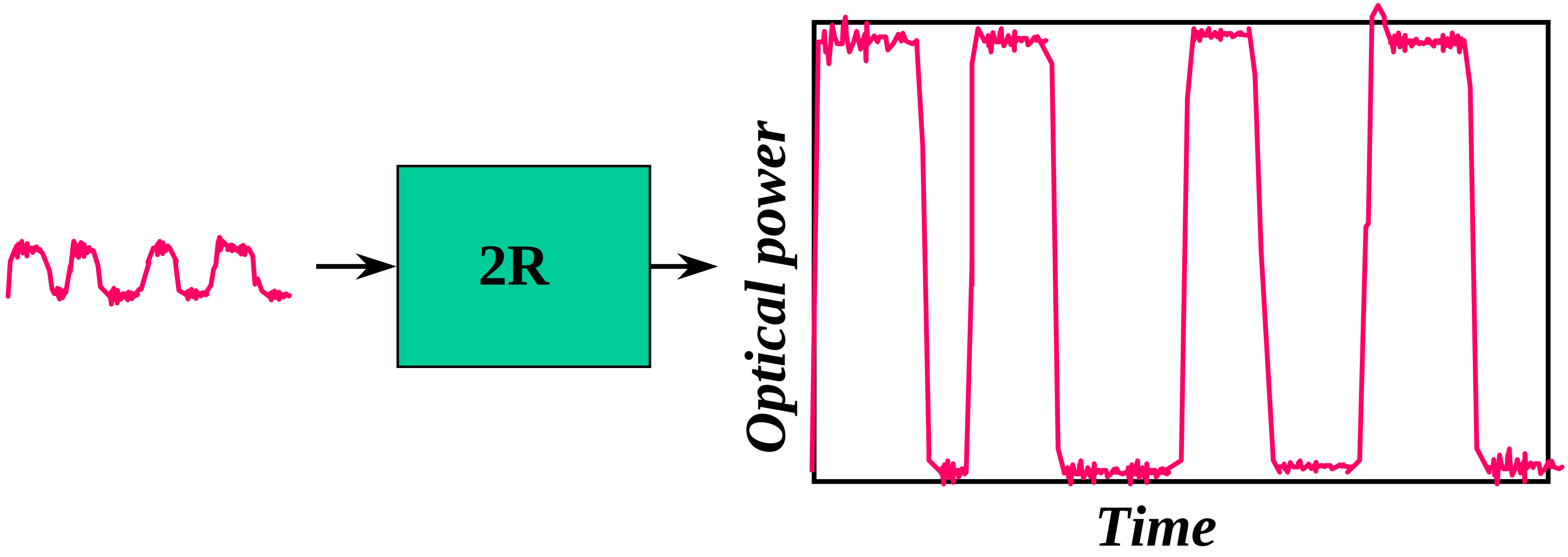

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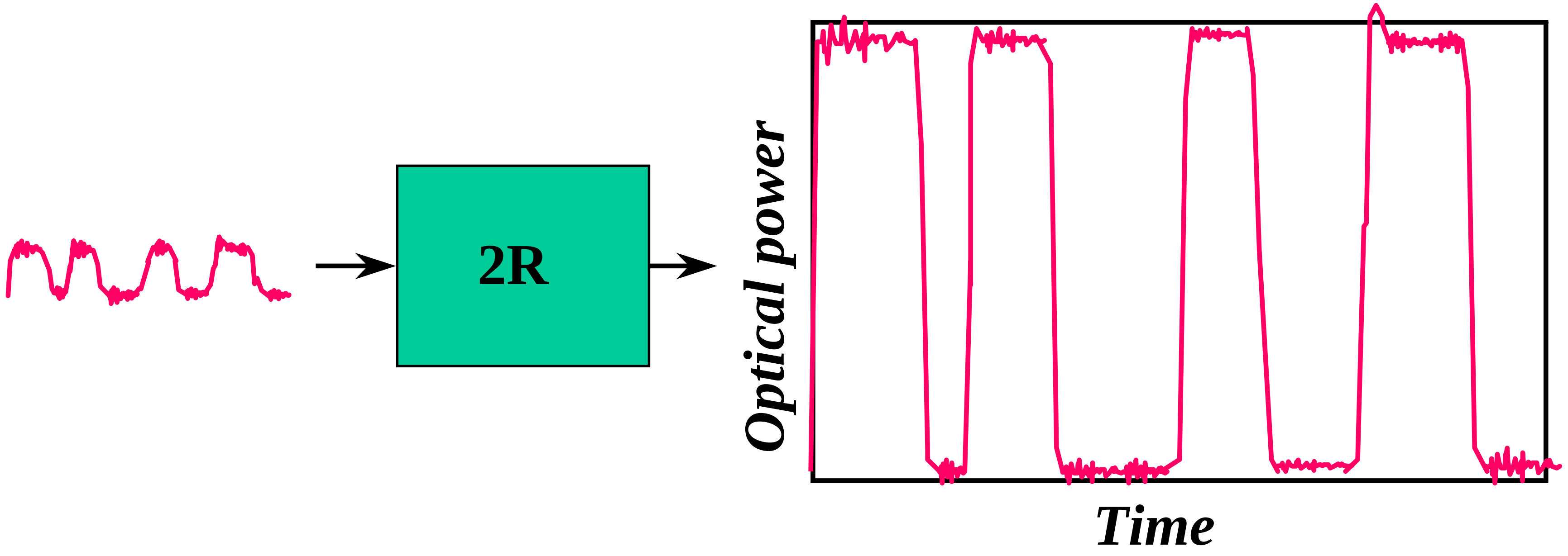

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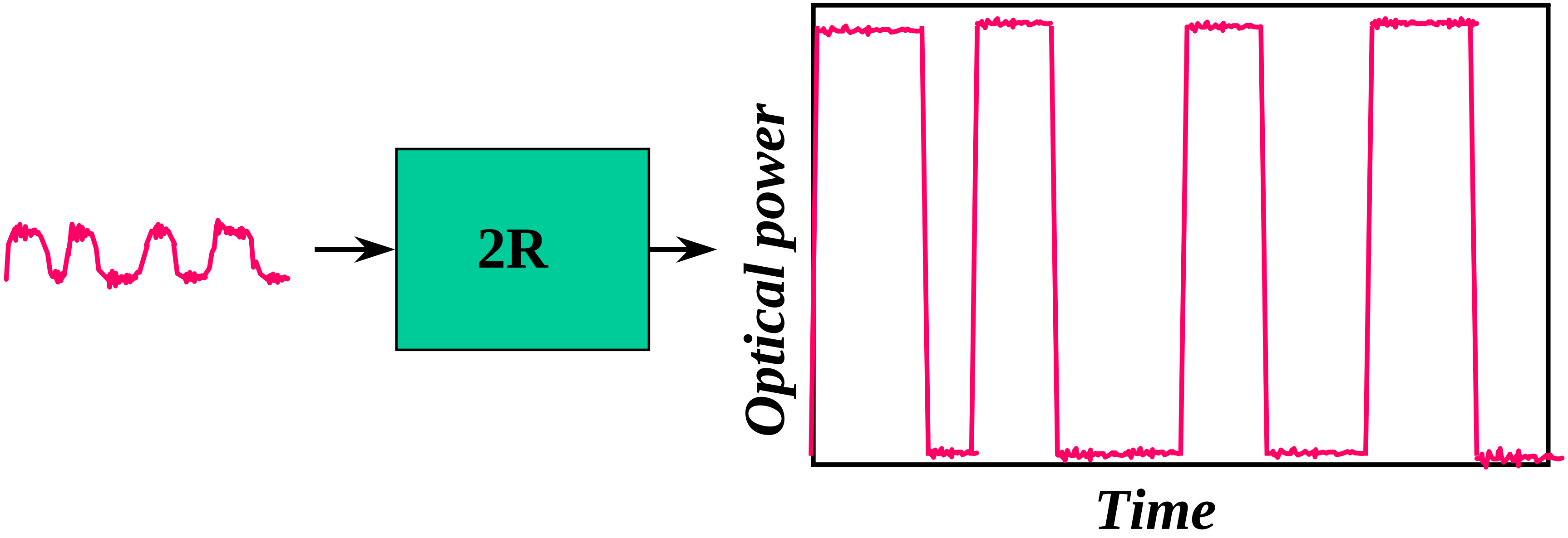
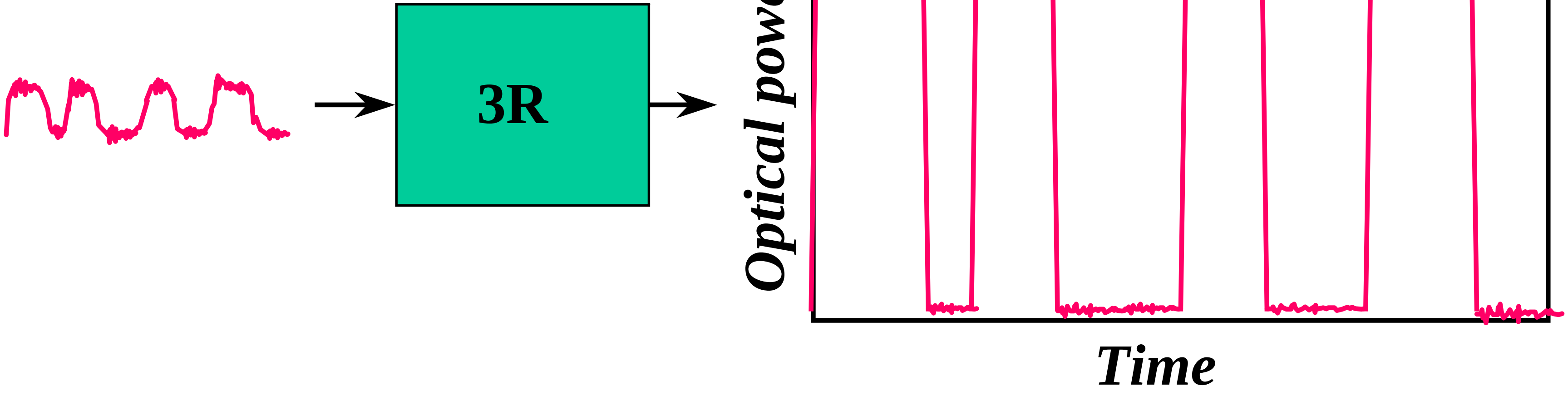


It is done by using non-linear devices: SOA , SOA based Mach-Zehnder, Q-switched laser, etc

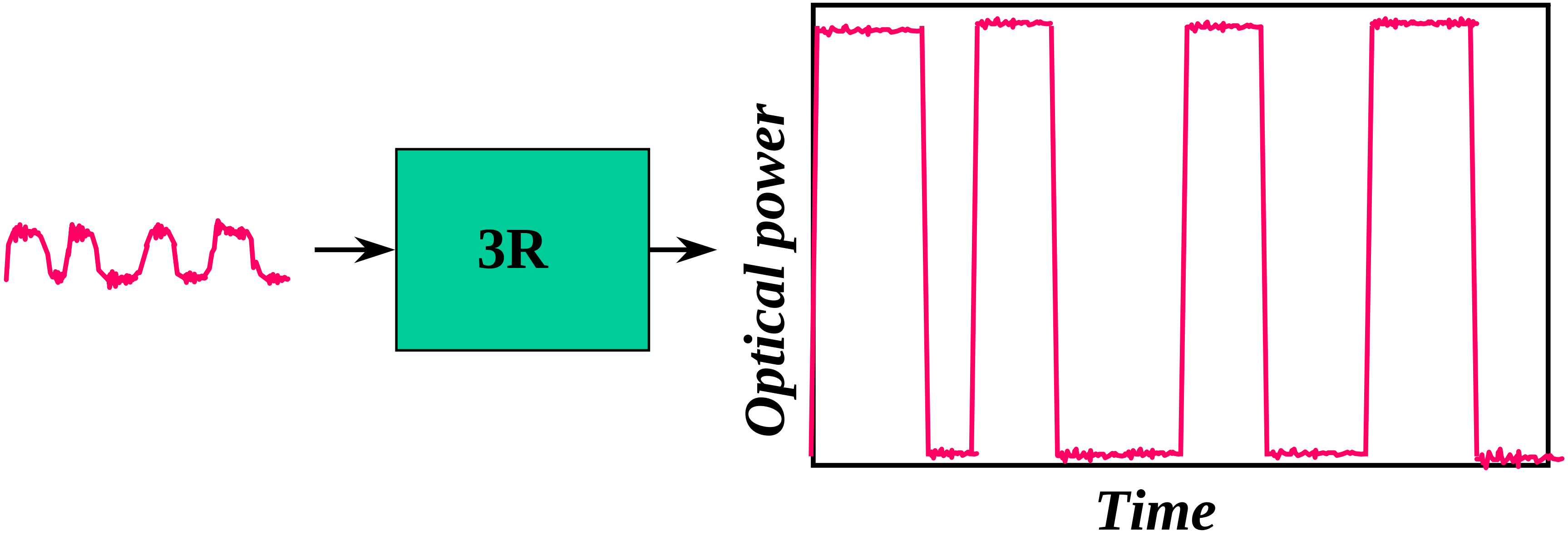
What is 3R and 4R regeneration ?

3R ...



What is 3R and 4R regeneration ?

3rd R consists in retiming the signal to correct jitter



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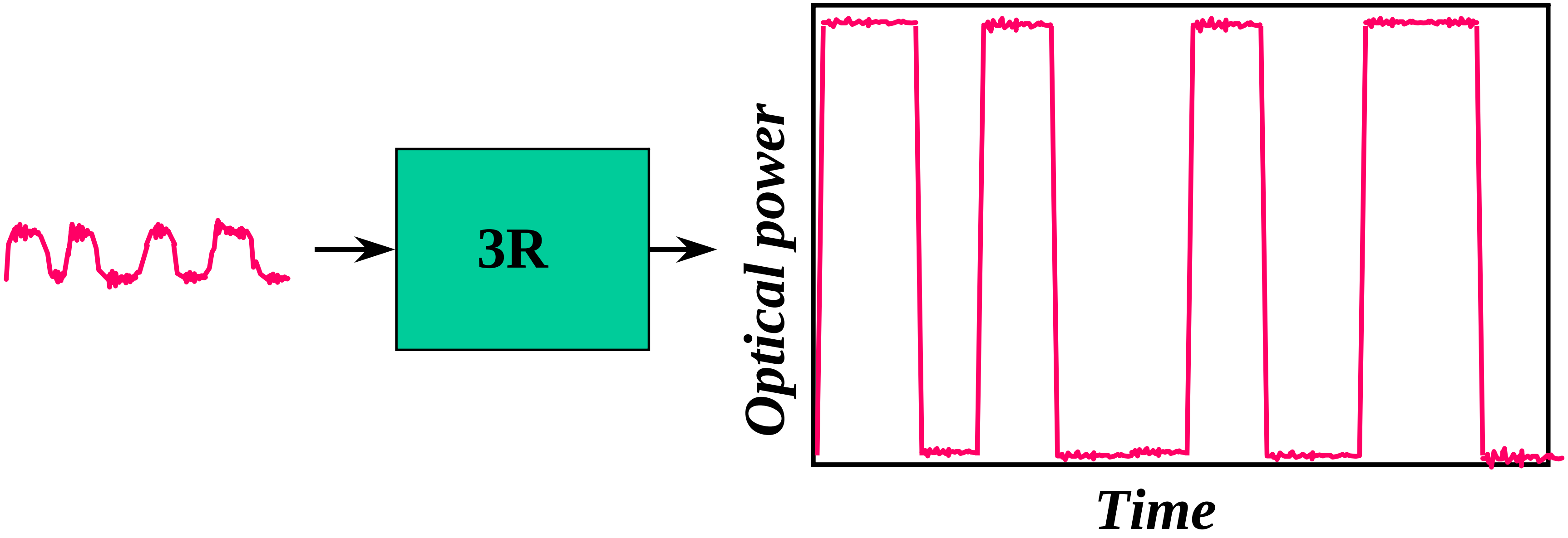

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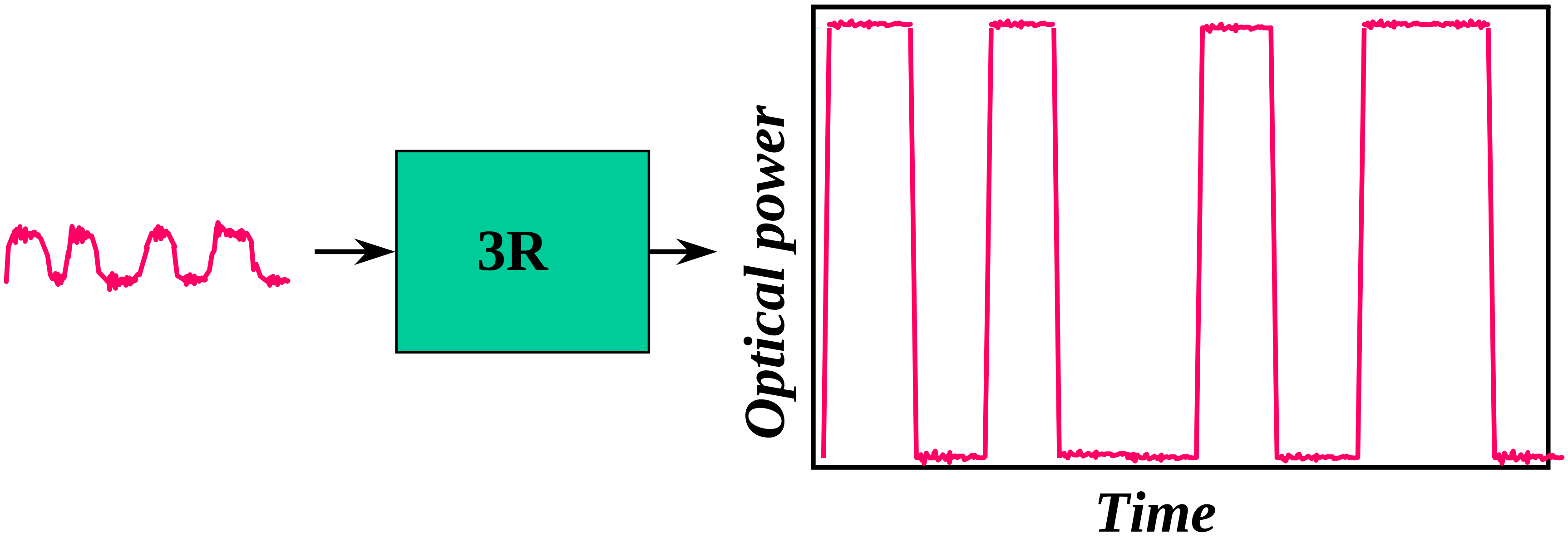

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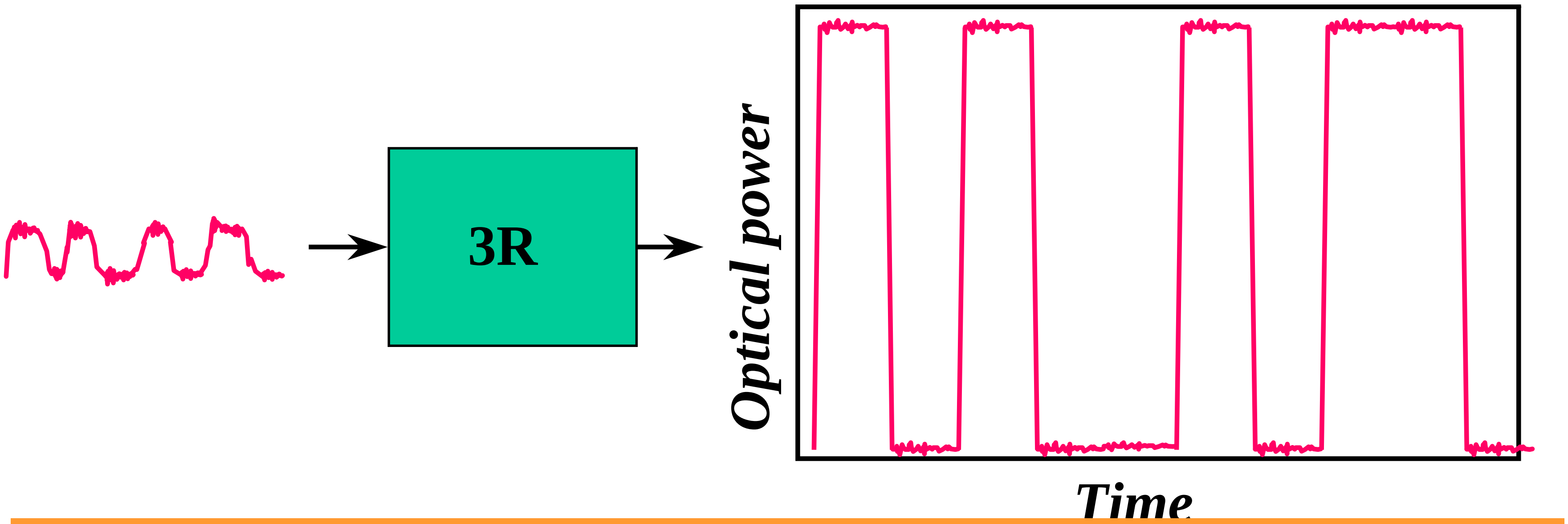
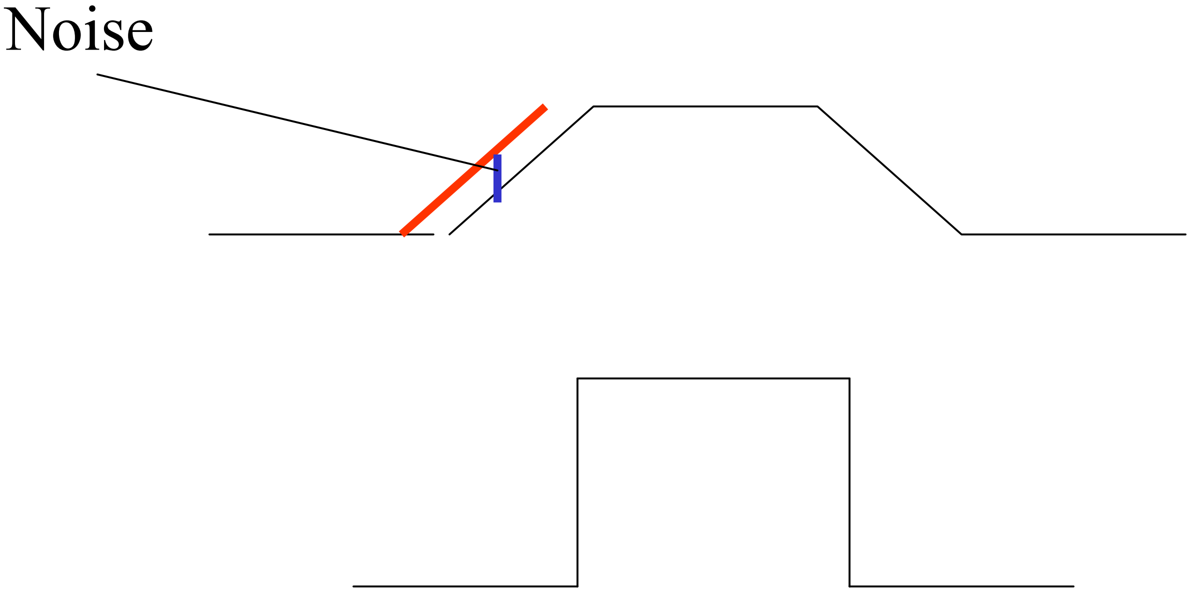


It requires clok recovery (E standard or self-pusating laser) followed by gating or switching

Trade off bandwidth vs jitter



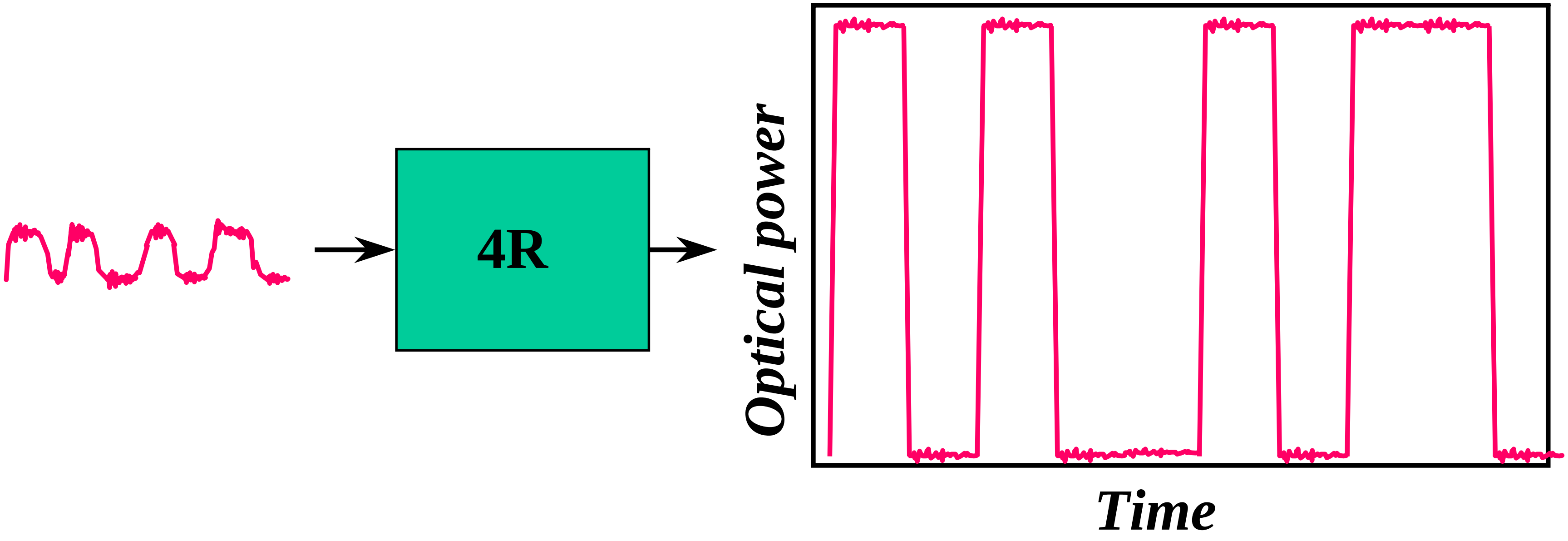
Low bandwidth

High bandwidth

Drawback?

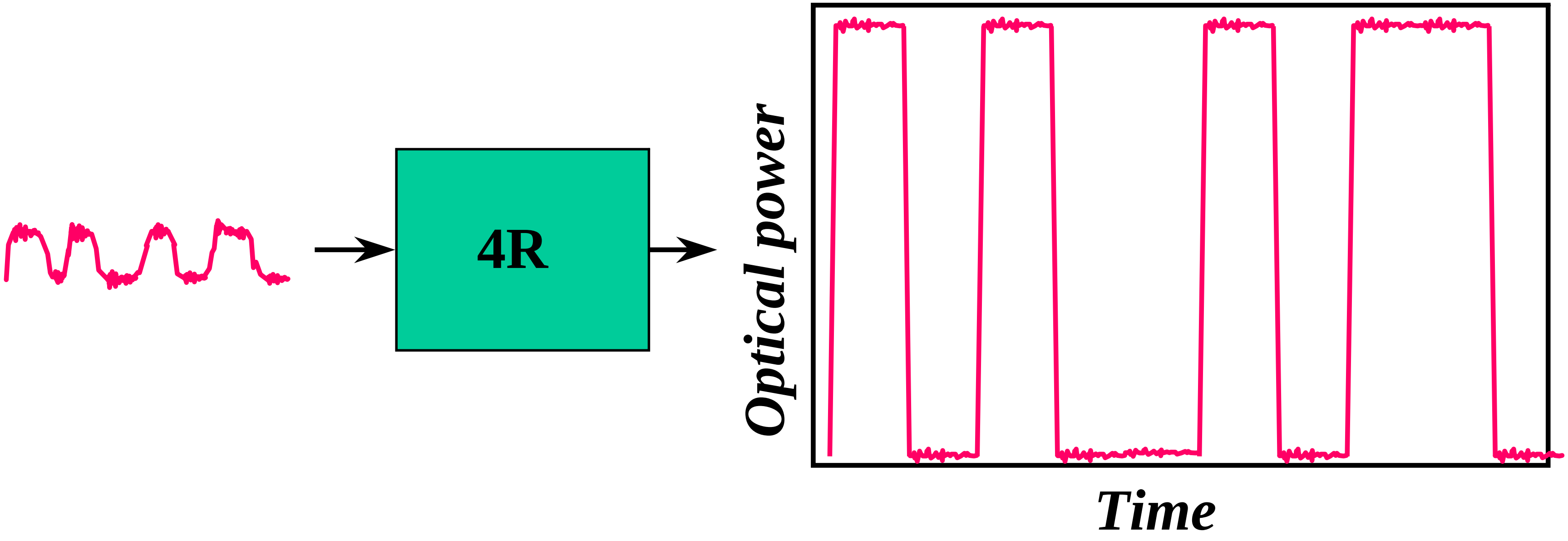
What is 3R and 4R regeneration ?

4th is specific to optical regeneration ...



What is 3R and 4R regeneration ?

4th R consists in wavelength regeneration or reallocation



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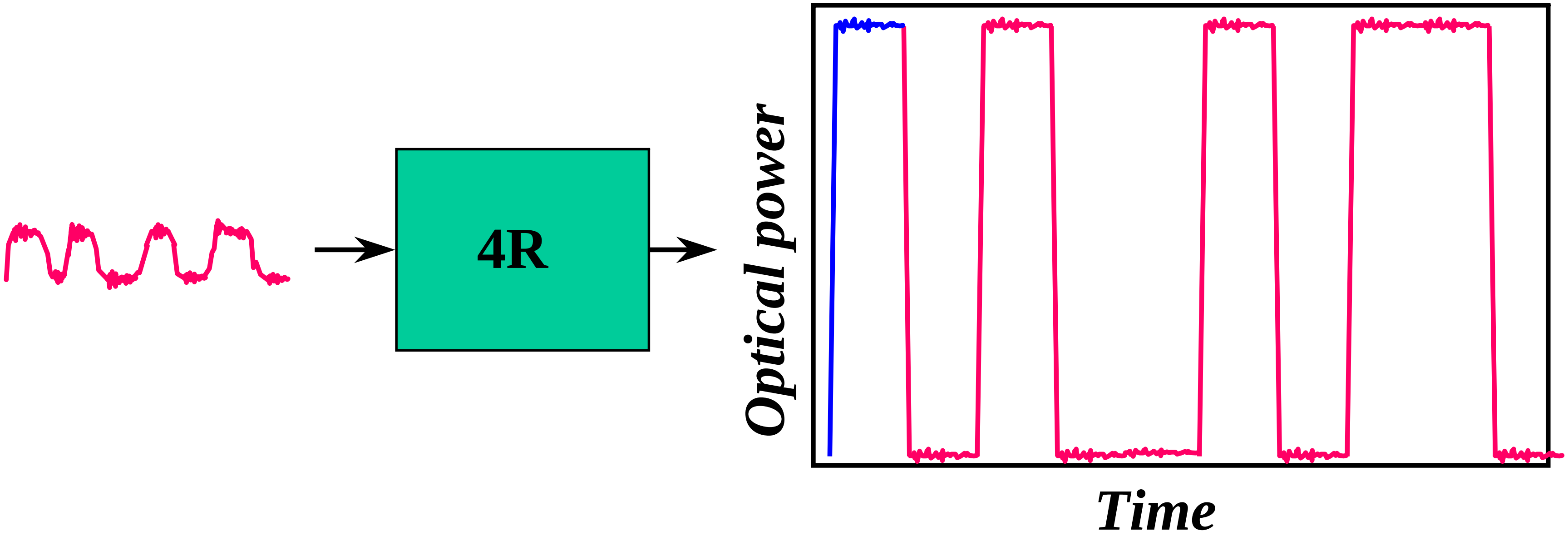

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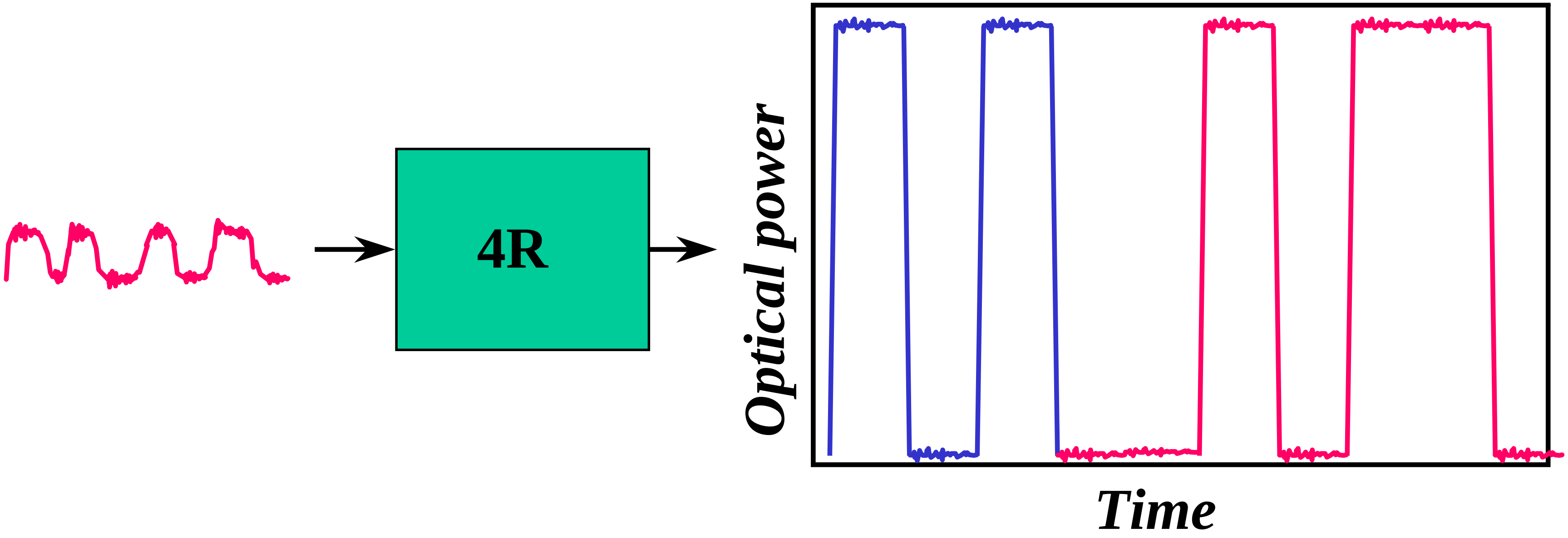

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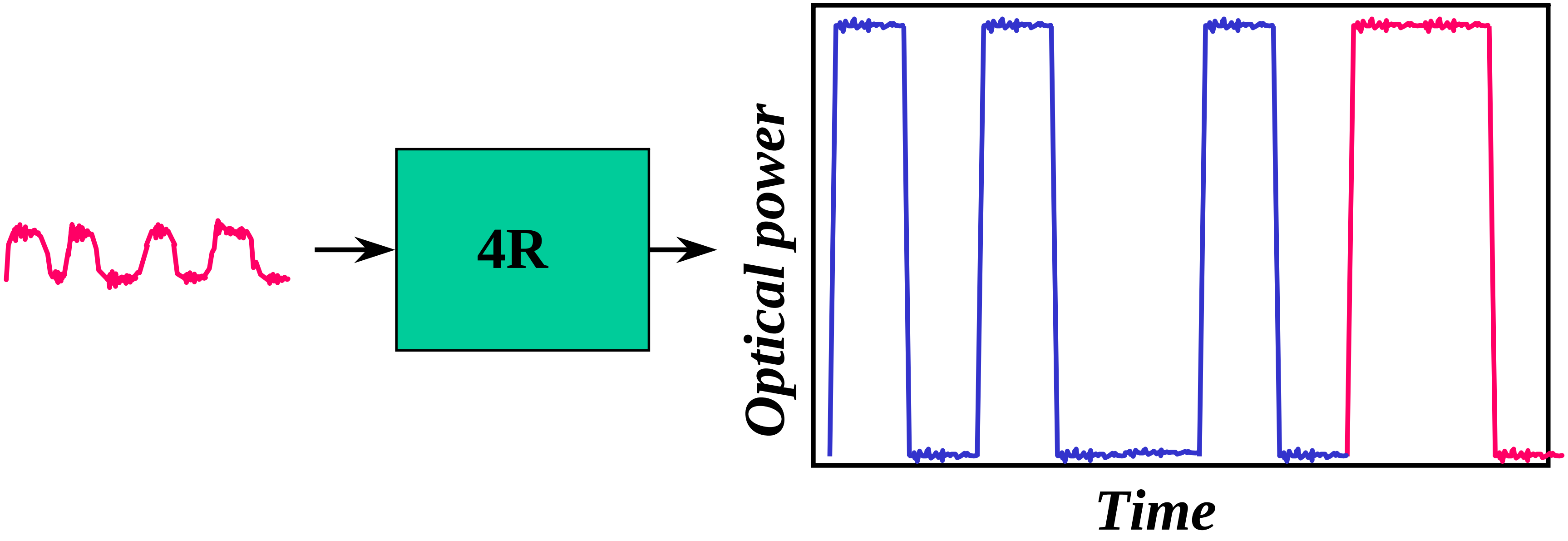

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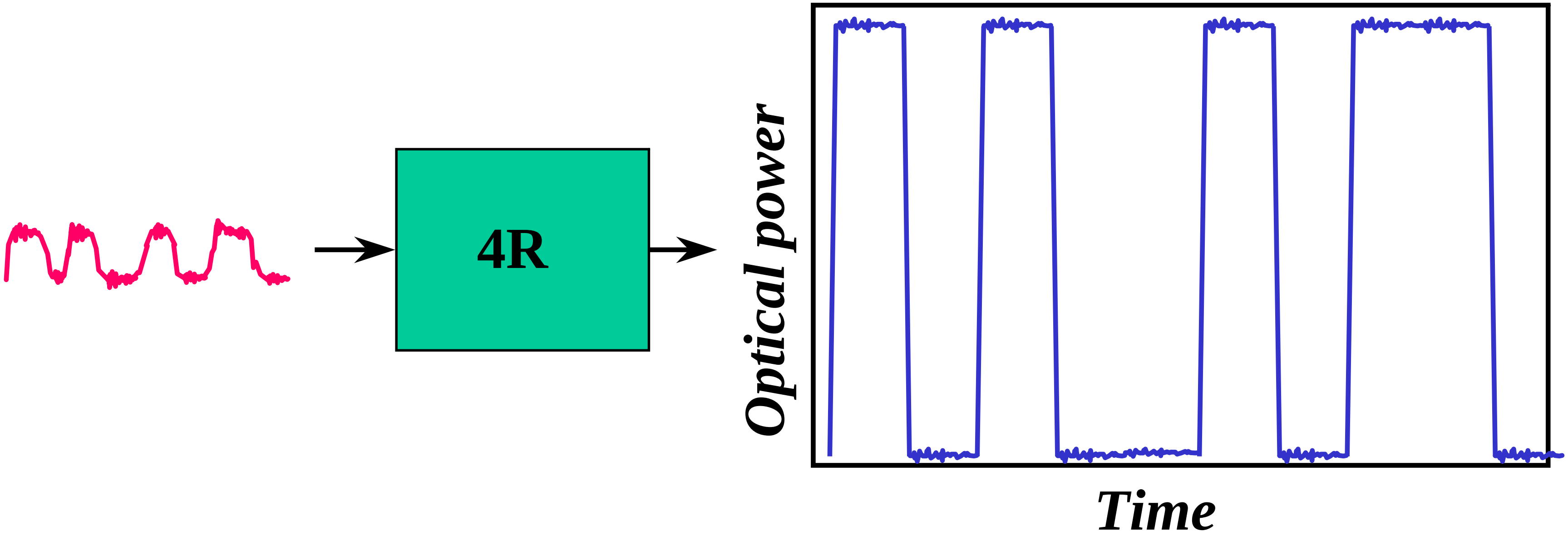


Optical network elements

Network elements:

- Optical cross connects (OXCs)
- Optical add drop multiplexers (OADMs)
- Optical line amplifiers (OLAs)
- Optical line terminals (OLTs)
- ………..

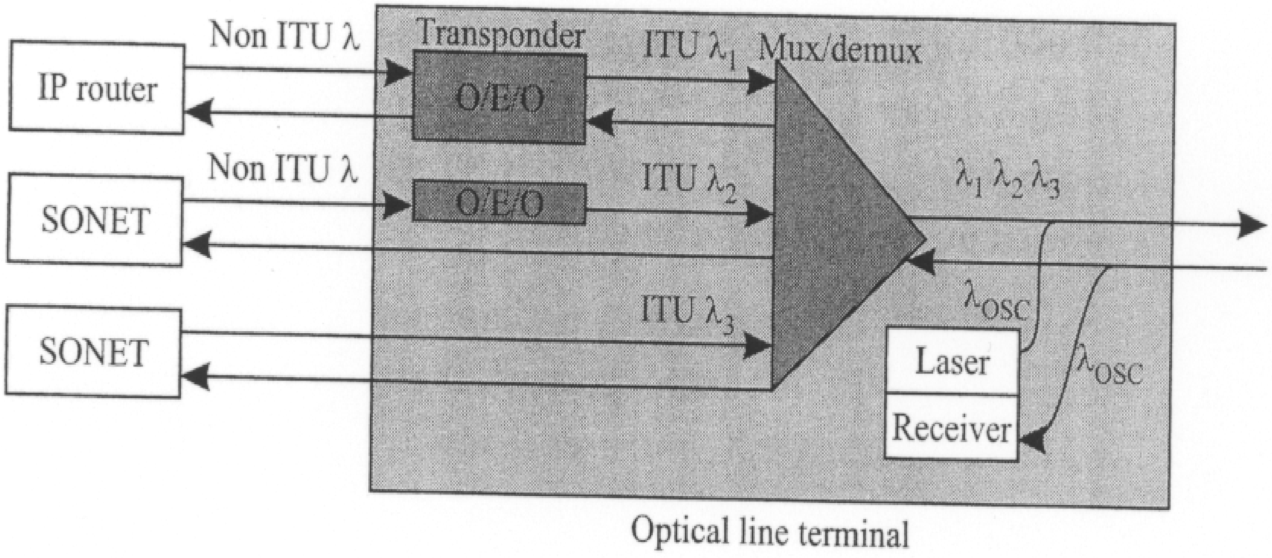


Figure 7.2 Block diagram of an optical line terminal. The OLT has wavelength multiplexers and demultiplexers and adaptation devices called transponders. The transponders convert the incoming signal from the client to a signal suitable for transmission over the WDM link and an incoming signal from the WDM link to a suitable signal toward the client. Transponders are not needed if the client equipment can directly send and receive signals compatible with the WDM link. The OLT also terminates a separate optical supervisory channel (OSC) used on the fiber link.

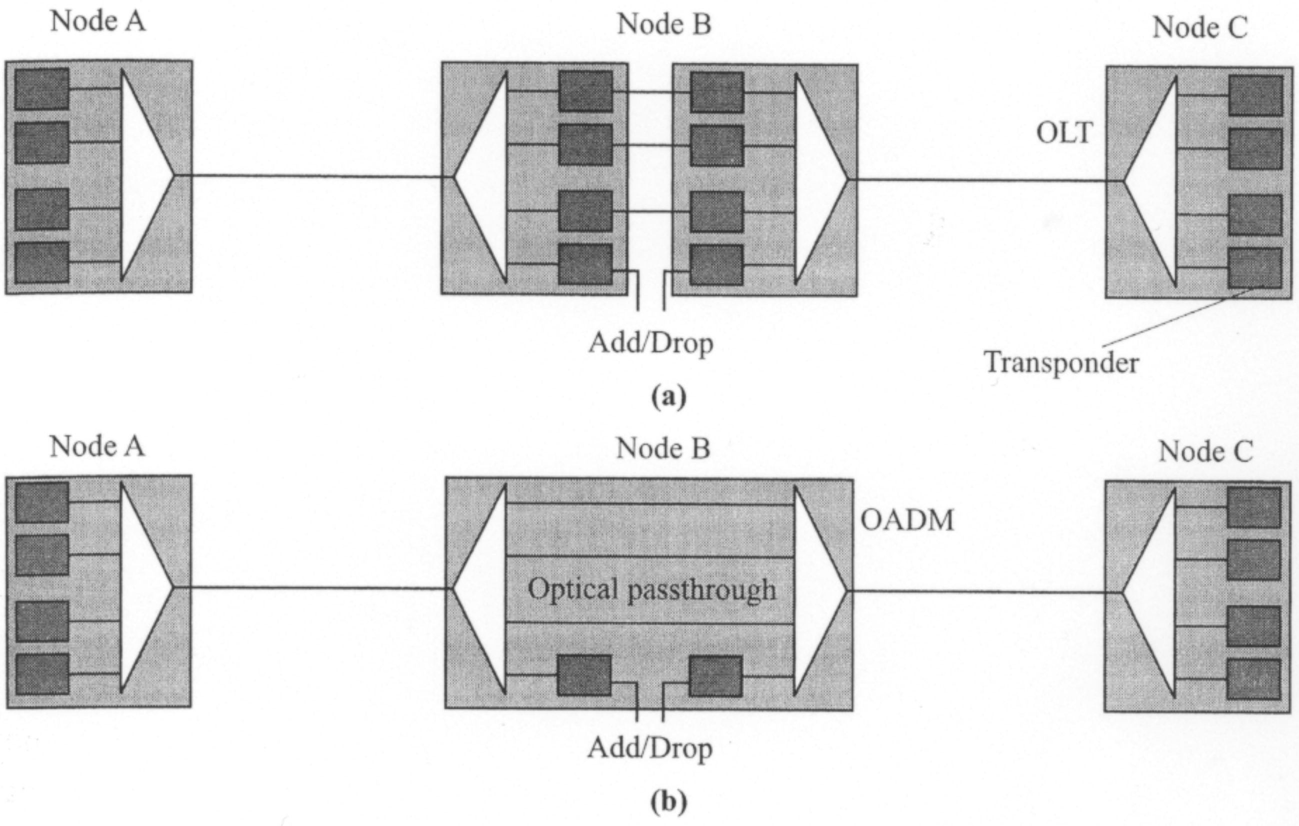


Figure 7.4 A three-node linear network example to illustrate the role of optical add/drop multiplexers. Three wavelengths are needed between nodes A and C, and one wavelength each between nodes A and B and between nodes B and C. (a) A solution using point-to-point WDM systems. (b) A solution using an optical add/drop multiplexer at node B.

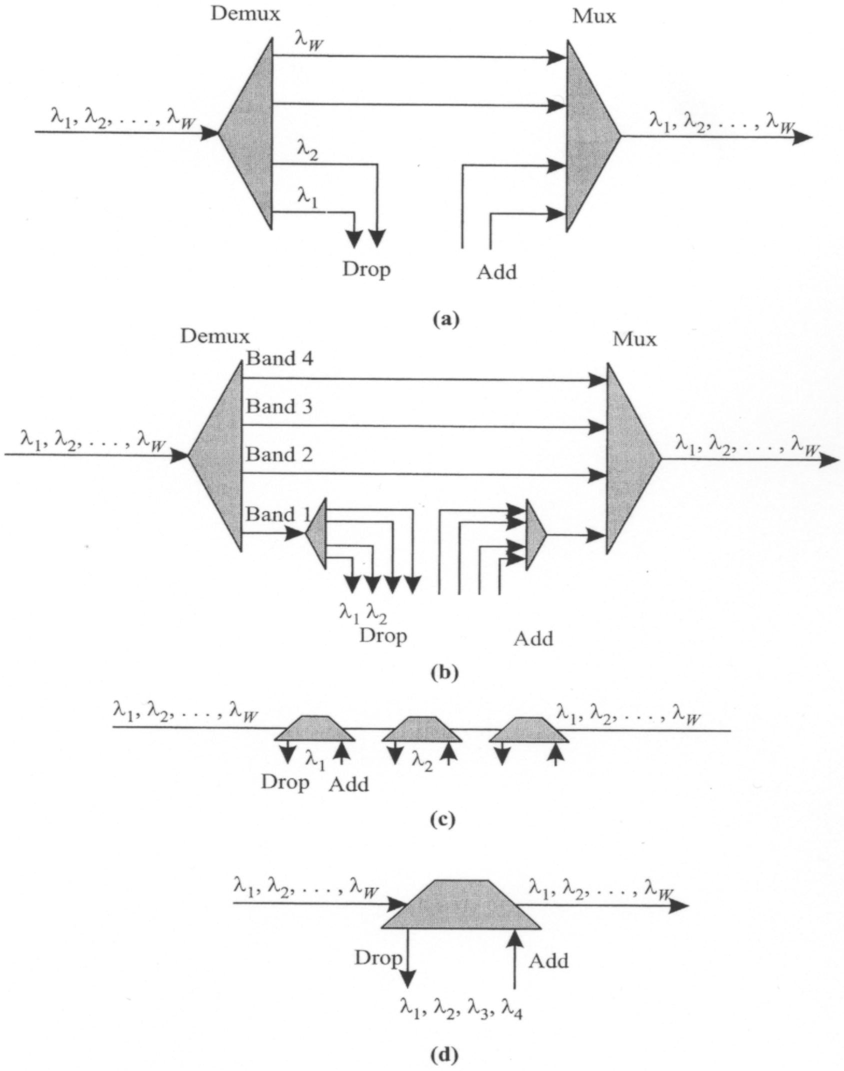


Figure 7.5 Different OADM architectures. (a) Parallel, where all the wavelengths are separated and multiplexed back; (b) modular version of the parallel architecture; (c) serial, where wavelengths are dropped and added one at a time; and (d) band drop, where a band of wavelengths are dropped and added together. *W* denotes the total number of wavelengths.

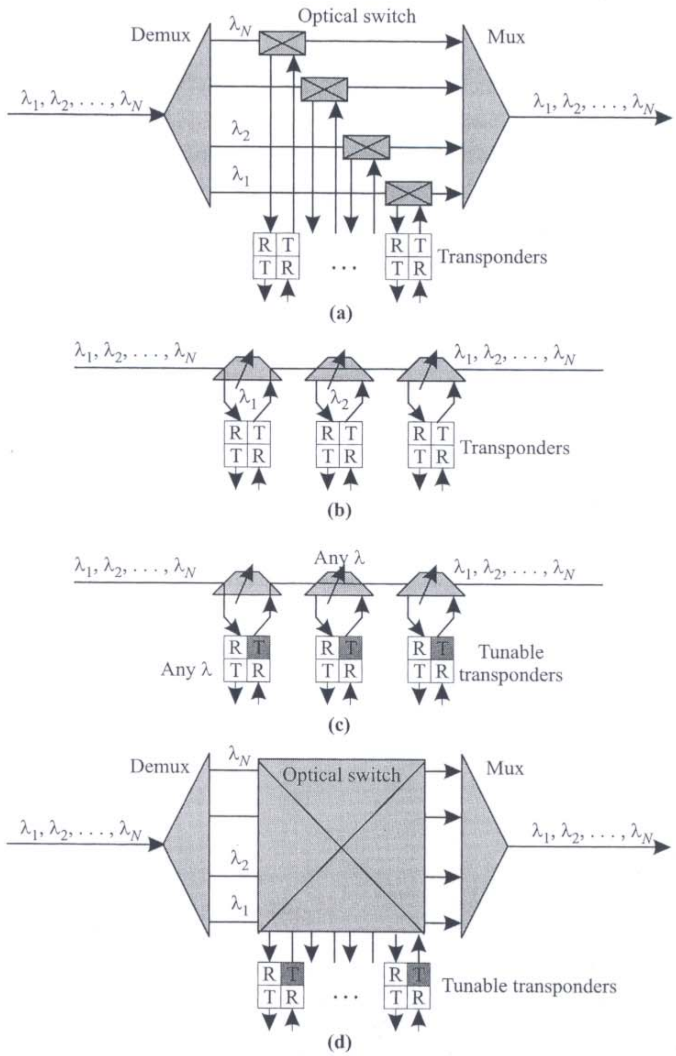


Figure 7.7 Reconfigurable OADM architectures. (a) A partially tunable OADM using a parallel architecture with optical add/drop switches and fixed-wavelength transponders. T indicates a transmitter and R indicates a receiver. (b) A partially tunable OADM using a serial architecture with fixed-wavelength transponders. (c) A fully tunable OADM using a serial architecture with tunable transponders. This transponder uses a tunable laser (marked T in the shaded box) and a broadband receiver. (d) A fully tunable OADM using a parallel architecture with tunable transponders.

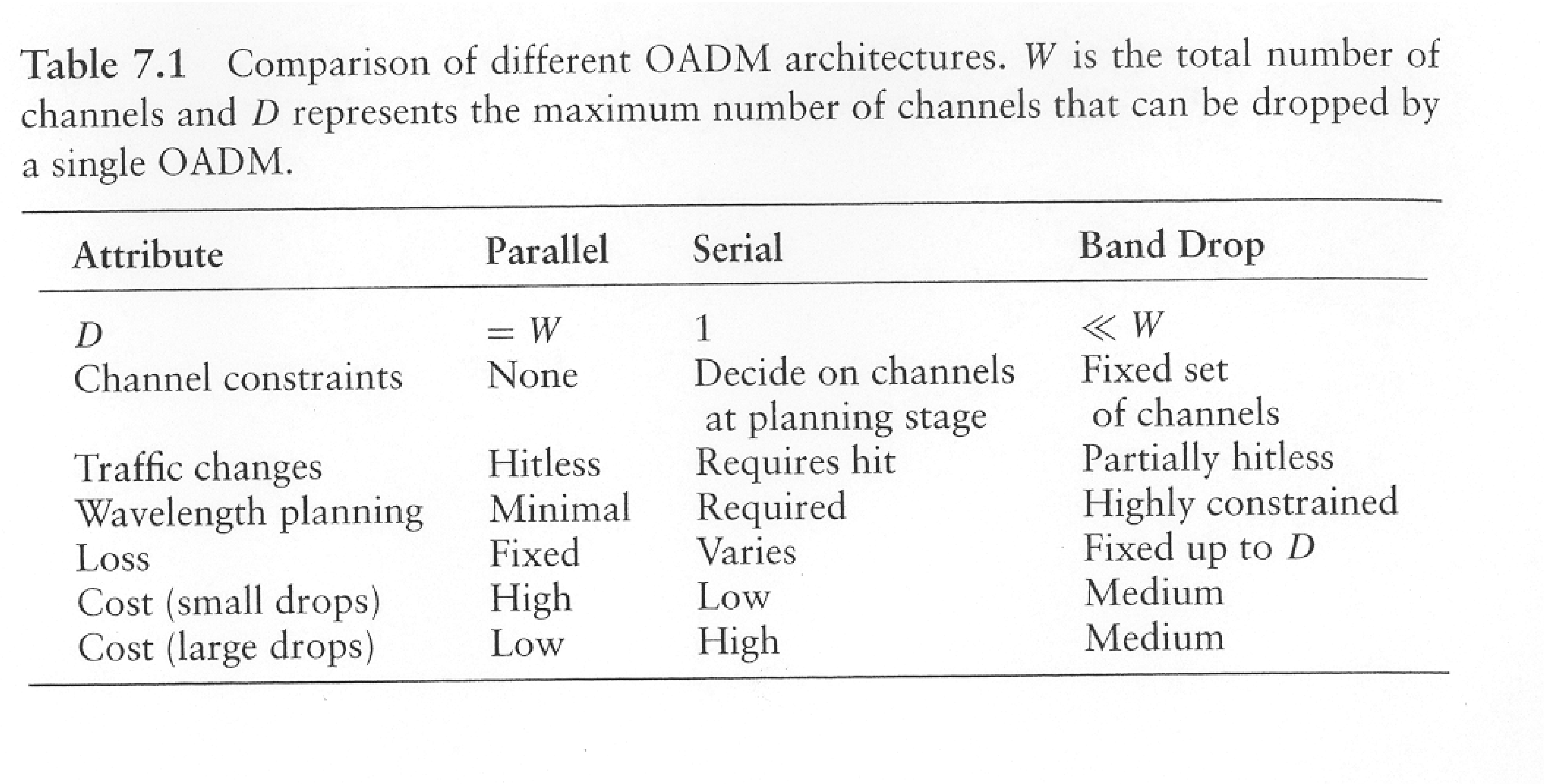


Table 7.1 Comparison of different OADM architectures. W is the total number of channels and D represents the maximum number of channels that can be dropped by a single OADM.

Attribute	**Parallel**	**Serial**	**Band Drop**
D	$= W$	1	$\ll W$
Channel constraints	None	Decide on channels at planning stage	Fixed set of channels
Traffic changes	Hitless	Requires hit	Partially hitless
Wavelength planning	Minimal	Required	Highly constrained
Loss	Fixed	Varies	Fixed up to D
Cost (small drops)	High	Low	Medium
Cost (large drops)	Low	High	Medium

Optical cross connects

- Needed for complex mesh topologies and large number of wavelengths
- Functions:
  - Service provisioning
  - Protection switching
  - Bit rate transparency (if it is all optical)
  - Performance monitoring
  - Wavelength conversion
  - Multiplexing and grooming

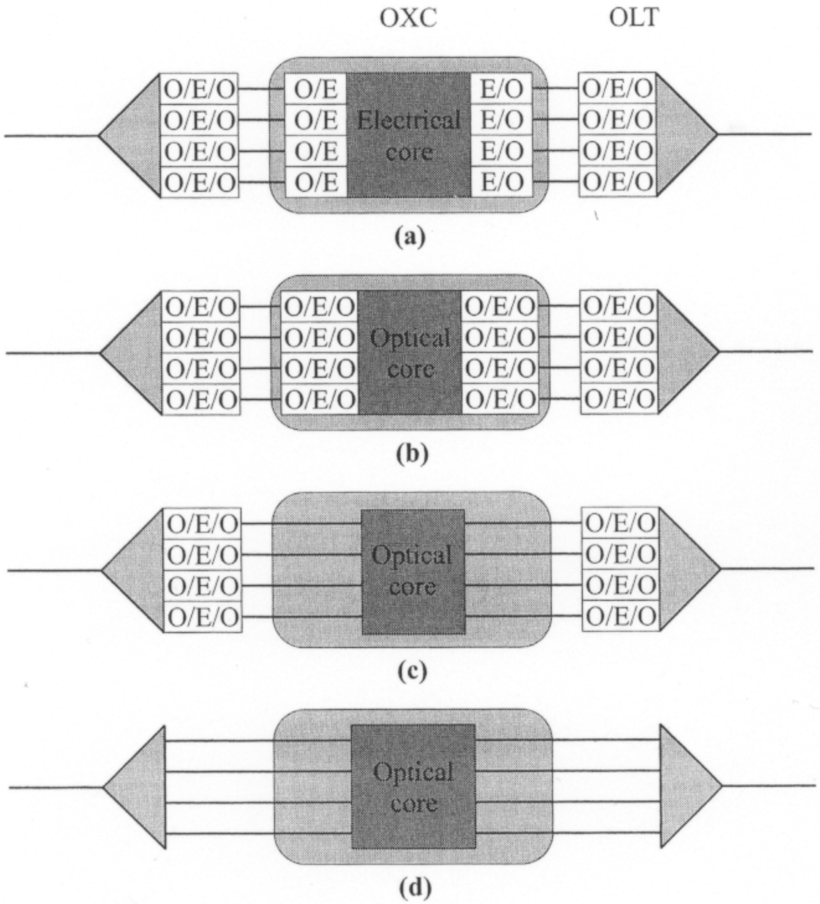
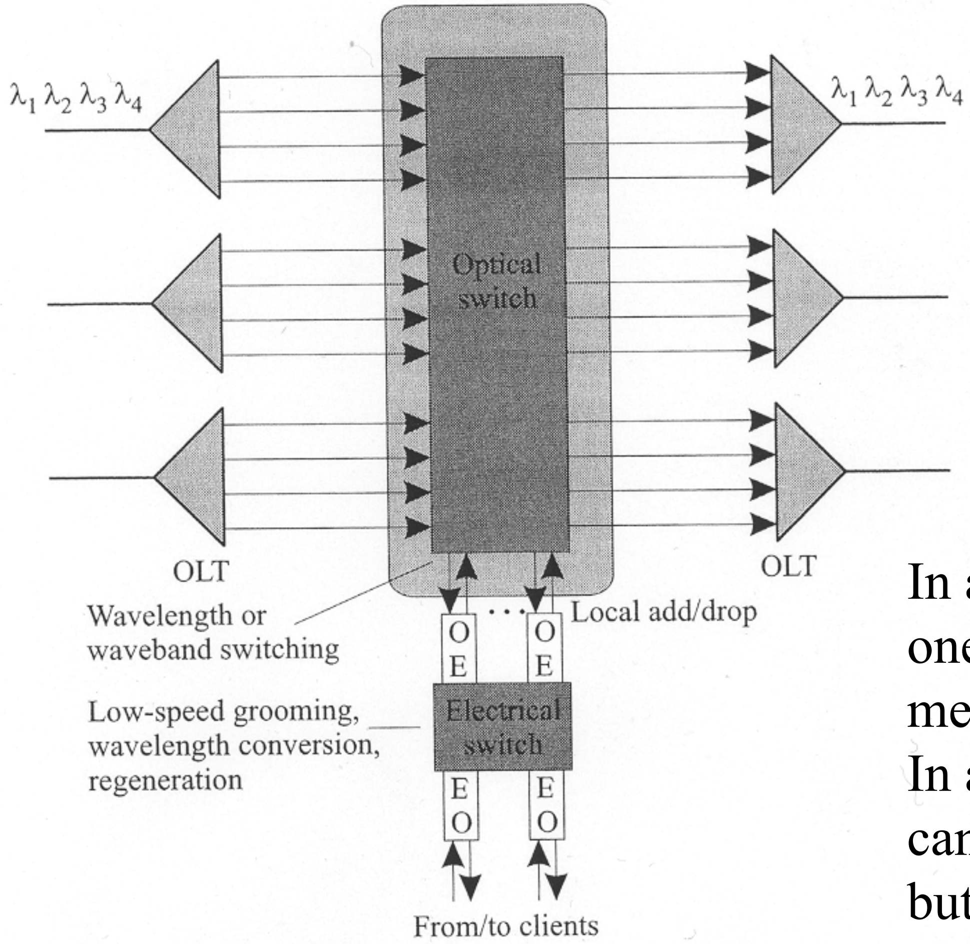


Figure 7.9 Different scenarios for OXC deployment. (a) Electrical switch core; (b) optical switch core surrounded by O/E/O converters; (c) optical switch core directly connected to transponders in WDM equipment; and (d) optical switch core directly connected to the multiplexer/demultiplexer in the OLT. Only one OLT is shown on either side in the figure, although in reality an OXC will be connected to several OLTs.

Grooming, regeneration, wavelength conversion



In an electronic switch
one can monitor signals,
measure BER, groom, etc
In an optical one, optical power
can conveniently be measured,
but not much more

Figure 7.11 A realistic "all-optical" network node combining optical core crossconnects with electrical core crossconnects. Signals are switched in the optical domain whenever possible but routed down to the electrical domain whenever they need to be groomed, regenerated, or converted from one wavelength to another.

Table 7.2 Comparison of different OXC configurations. Some configurations use optical to electrical converters as part of the crossconnect, in which case, they are able to measure electrical layer parameters such as the bit error rate (BER) and invoke network restoration based on this measurement. For the first two configurations, the interface on the OLTs is typically a SONET short-reach (SR), or very-short-reach (VSR) interface. For the opaque photonic configuration, it is an intermediate-reach (IR) or a special VSR interface. The cost, power, and footprint comparisons are made based on characteristics of commercially available equipment at OC-192 line rates.

Attribute	Opaque Electrical Figure 7.9(a)	Opaque Optical with ? O/E/Os Figure 7.9(b)	Opaque Optical Figure 7.9(c)	All-Optical Figure 7.9(d)
Low-speed grooming	Yes	No	No	No
Switch capacity	Low	High	High	Highest
Wavelength conversion	Yes	Yes	Yes	No ?
Switching triggers	BER	BER	Optical power	Optical power
Interface on OLT	SR/VSR	SR/VSR	IR/serial VSR	Proprietary
Cost per port	Medium	High	Medium	Low ?
Power consumption	High	High	Medium	Low ?
Footprint	High	High	Medium	Low ?

Example of optical network node

OXC

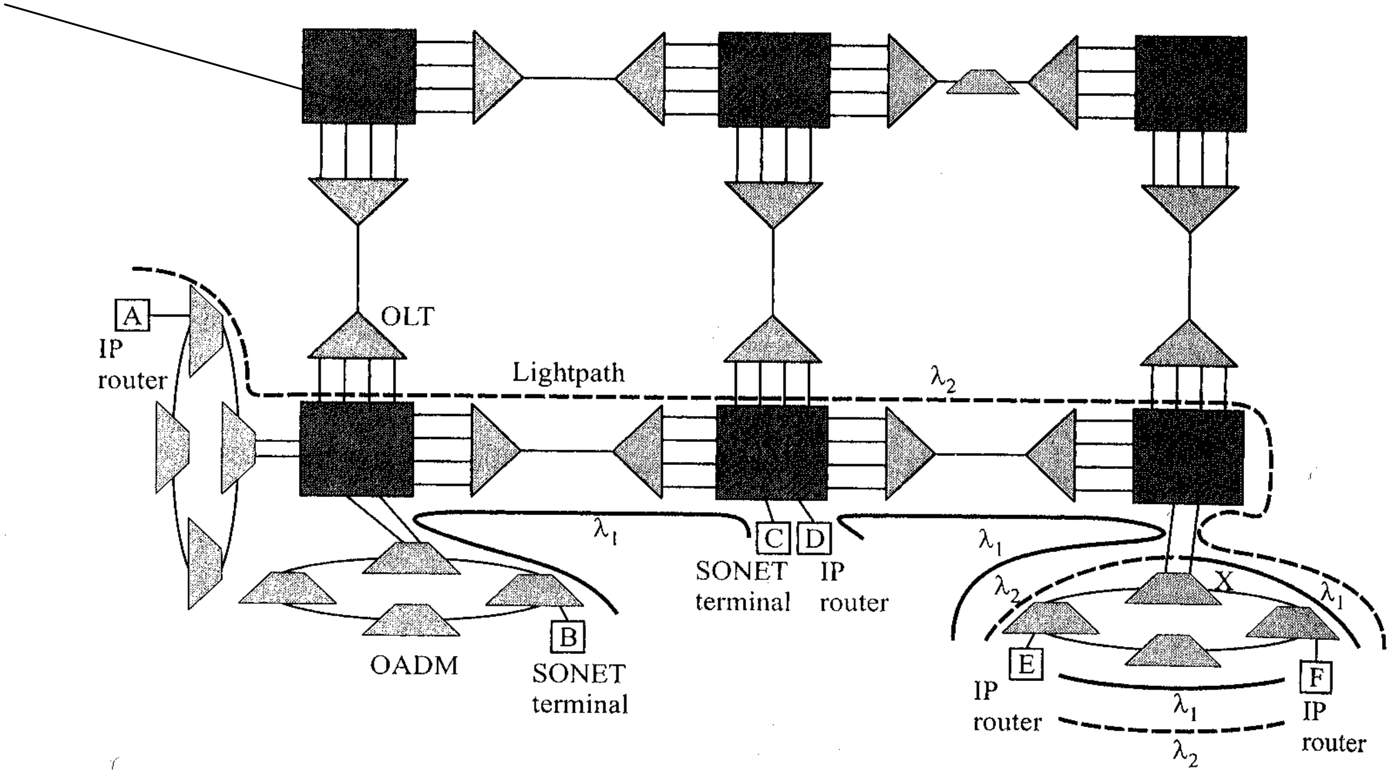
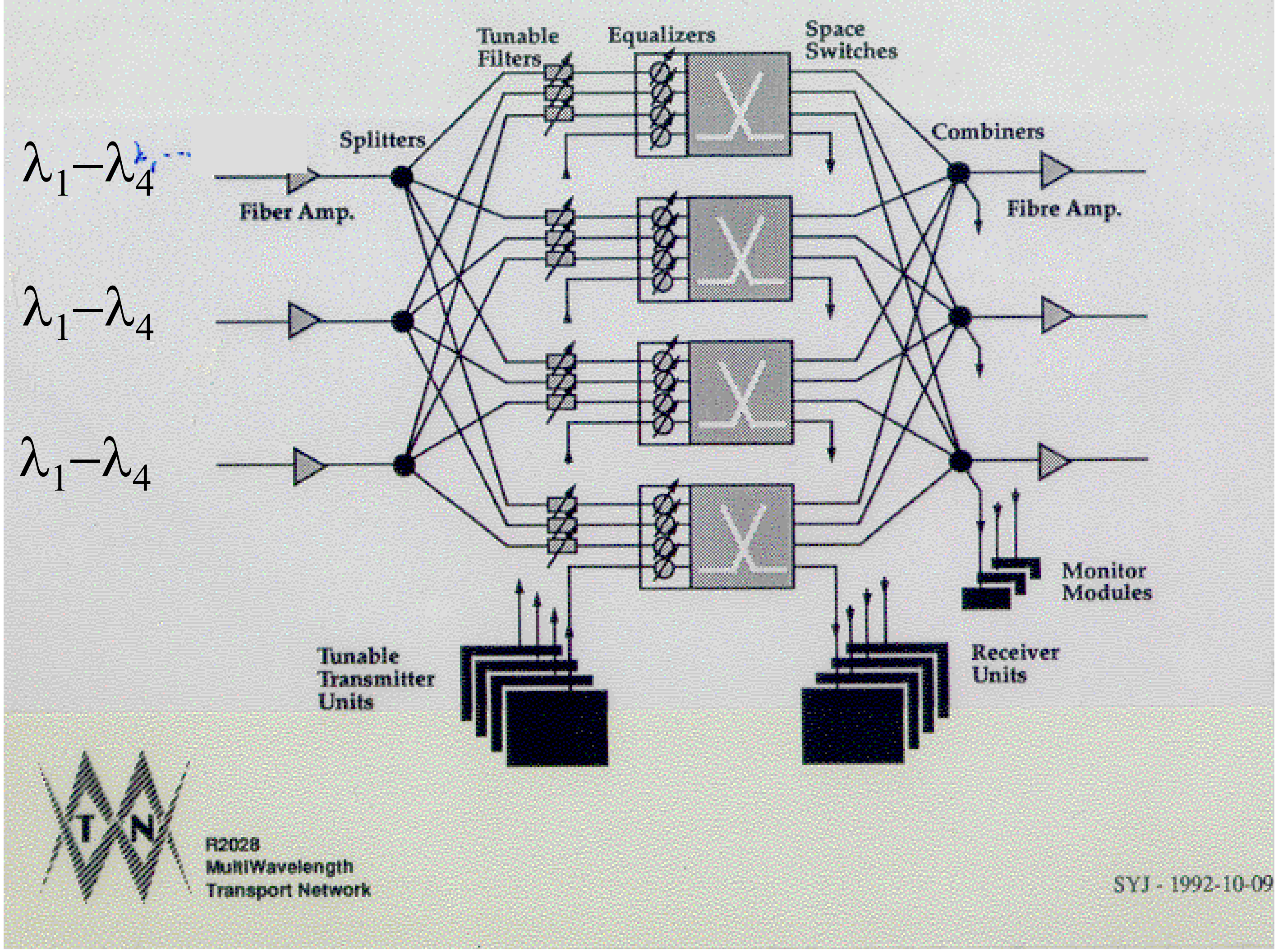


Figure 7.1 A wavelength-routing mesh network showing optical line terminals (OLTs), optical add/drop multiplexers (OADMs), and optical crossconnects (OXCs). The network provides lightpaths to its users, such as SONET boxes and IP routers. A lightpath is carried on a wavelength between its source and destination but may get converted from one wavelength to another along the way.

Ericsson & KTH 1992 (!)

Wavelength Routing Optical Cross-Connect



$\lambda_1 - \lambda_4$

$\lambda_1 - \lambda_4$

$\lambda_1 - \lambda_4$

Table 11.1 Summary of demonstrated and planned wavelength routing testbeds. The testbeds in the first grouping (MWTN–NTONC) have been demonstrated and those in the second grouping (COBNET–METON) are under construction. (OWXC = all-optically implemented wavelength crossconnects; EWXC = electronically implemented wavelength crossconnects; OADM = optical add/drop multiplexer; OEADM = optoelectronic add/drop multiplexer (includes regeneration).)

Name	Architecture	Topology	Router Ports	Wavelengths	Channel Spacing (nm)	Bit Rate	Distance (km)
MWTN	OWXC	Ring/mesh	4	4	4	622 Mb/s	230
AON	Static	Star	8	20	0.4	2.5 Gb/s	100
ONTC	OWXC	Linked rings	2	4	4	155 Mb/s	150
NTT	OADM	Ring	2	15	0.8	622 Mb/s	120
Alcatel	OEADM	Ring	2	4	1.6	2.5 Gb/s	160
MONET	OWXC	Mesh/ring	4	8	1.6	10 Gb/s	2000
NTONC	OADM	Dual ring	2	4	4	2.5 Gb/s	700
COBNET	EWXC/ OWXC	Ring	Many/2	12	1.6		
PHOTON	OWXC	Mesh	2	8	3.2	2.5 Gb/s, 10 Gb/s	500
METON	OWXC	Mesh/ring	4	6	3.2	622 Mb/s, 2.5 Gb/s	230

Name	Architects
MWTN	BT, Ericsson, Pirelli, Ellemtel, Televerket, Italel, CSELT, CNET, U. Essex, U. Paderborn
AON	AT&T, MIT, Digital Equipment Corp. (DEC)
ONTC	Bellcore, Columbia U., Hewlett-Packard, Hughes, Northern Telecom, Rockwell, United Tech.
MONET	AT&T, Bellcore, Bell Atlantic, Bell South, Pacific Telesis
NTONC	LLNL, Columbia, Hewlett-Packard, Hughes, Northern Telecom, Rockwell, United Tech.
COBNET	BNR Europe, BT, EPF Lausanne, ETH Zurich, GEC Marconi, IBM France, IBM Zurich, Italtel Sit, Siemens AG, Siemens ATEA, U. Dortmund
PHOTON	Siemens, Centro de Estudos Telecom., Deutsche Telekom, Heinrich Hertz, Interuniv. Microelectron. Ctr., Austria PTT, Philips, TU, BBC, Telecom Australia
METON	Ericsson, Thomson, Telia, CNET, Tech. U. Denmark, Heinrich Hertz, CSELT, Deutsche Telekom, Royal Inst. of Tech., Nat. Microelectron. Res. Ctr.

Devices in optical network elements

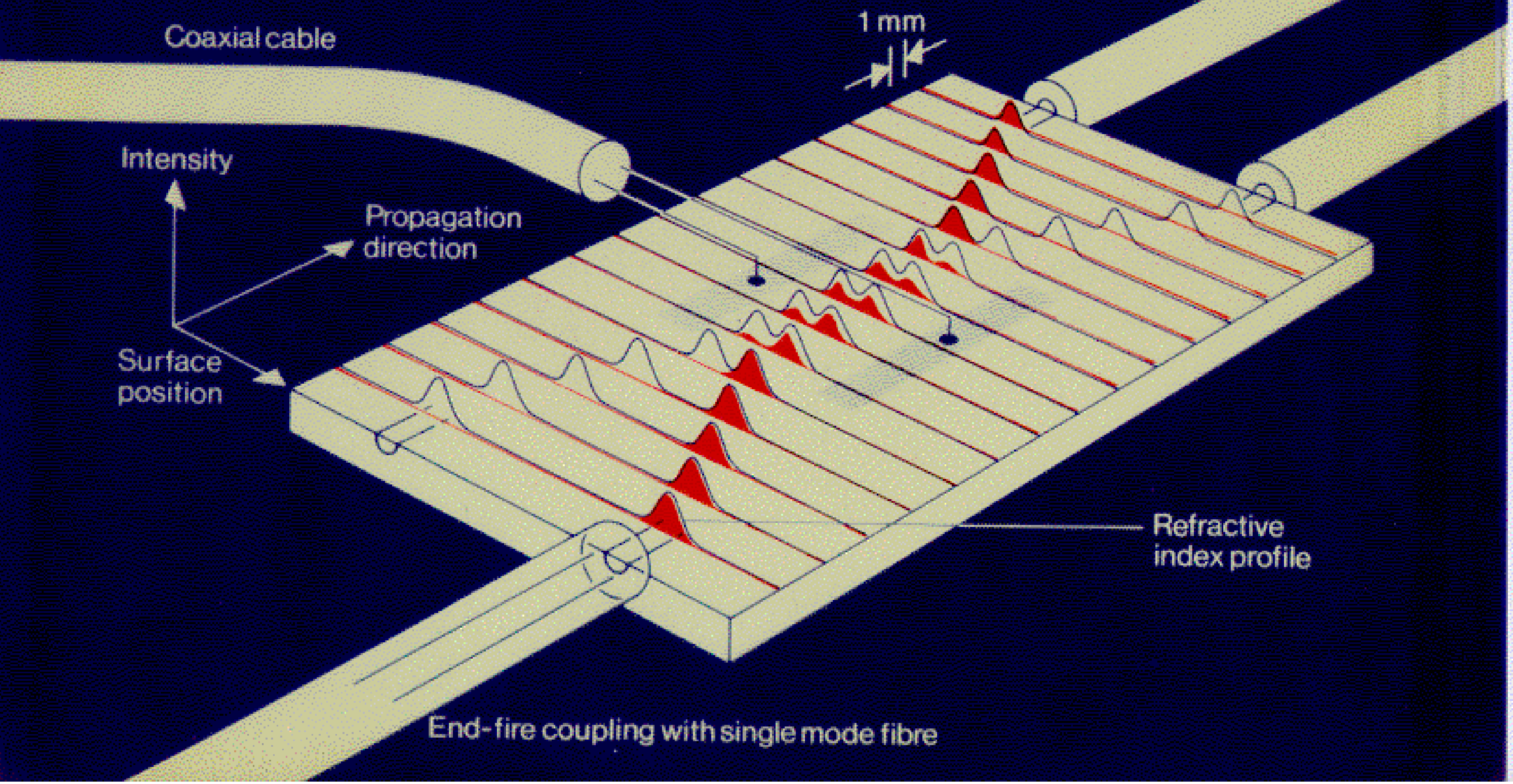
Requirements??

Photonics in information transfer and in general

- Functionality
  - Photonics lacks, *currently*, RAM type memory and signal processing capability
- Physical size (”footprint”)
  - 100s to 1000s of wavelengths in length, order of wavelength in transverse dimension
  - Compare electronics (FET gate lengths < 100 nm), but interconnects important for photonics as well as electronics
- Cost
  - Too expensive (too much handcraft..)
- *But there are ways to resolve this*

Electrooptical Directional Coupler - EDC

ERICSSON



First 4x4 polarization independent switch ($LiNbO_3$)

Ericsson, 1988