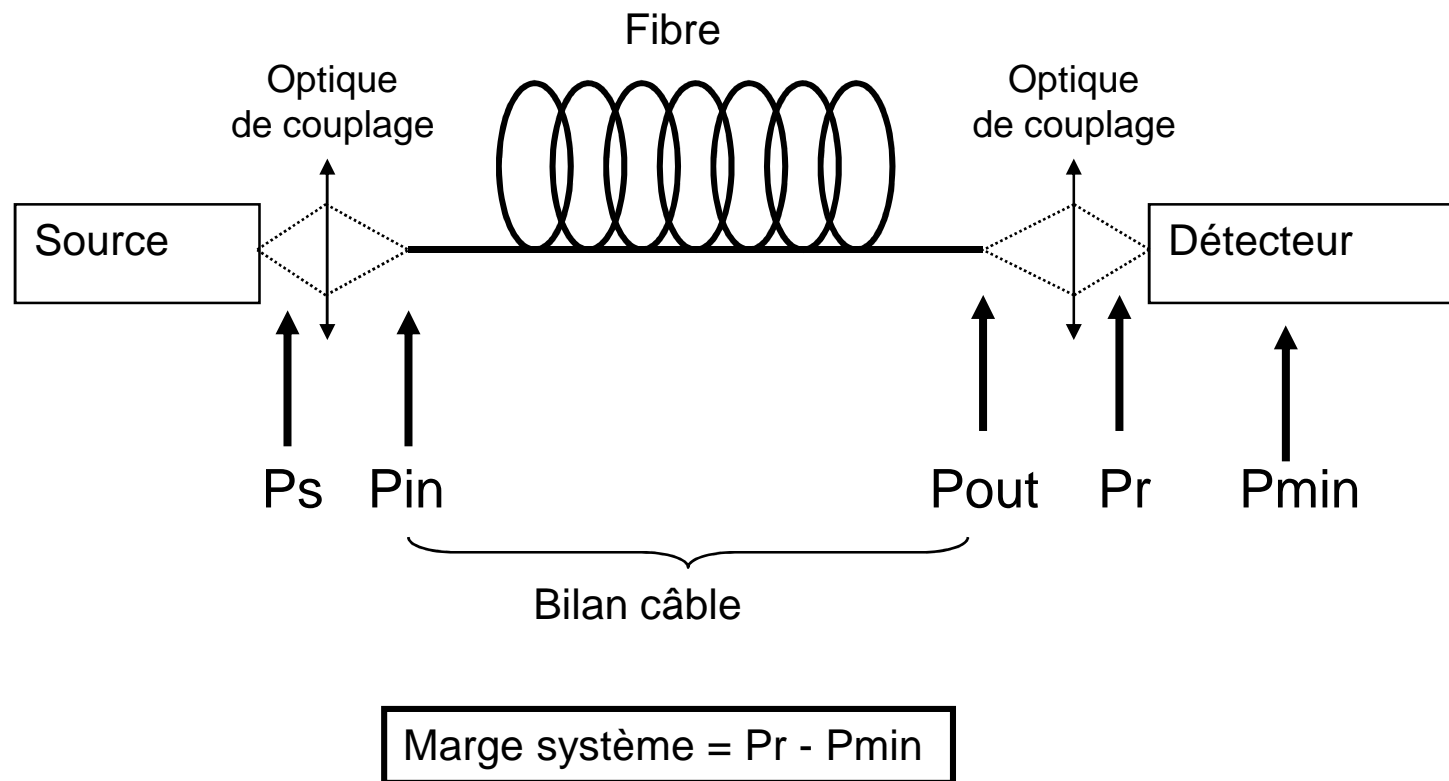
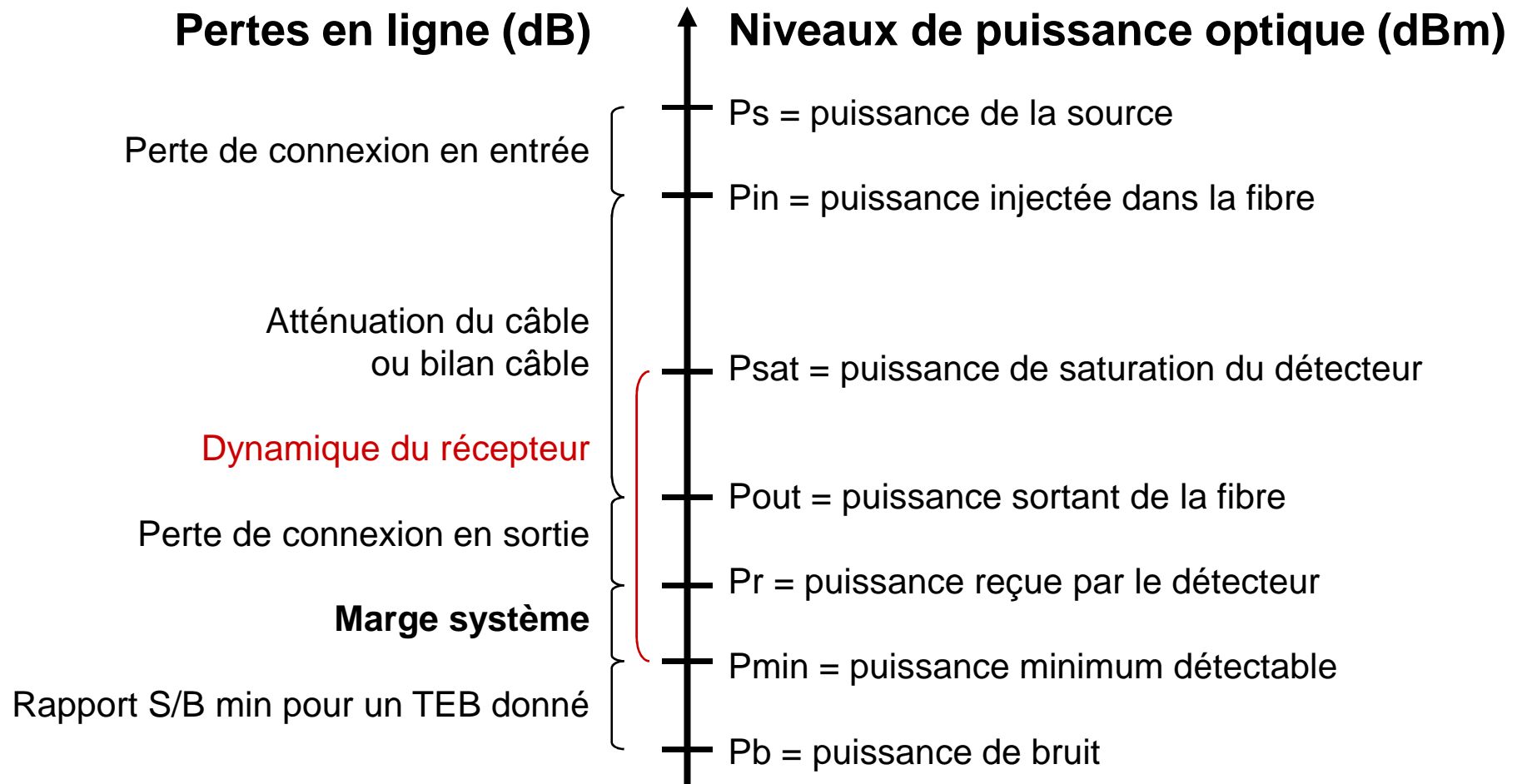


- ◆ **WDM (wavelength division multiplexing) systems : Why ?**
- ◆ **General points on WDM systems**
- ◆ **Limitations due to non-linear effects in the line fiber**
  - Four wave mixing (FWM)
- ◆ **Some specificities of WDM amplification**
  - Gain flatness
  - Considerations on noise
  - Influence of the number of amplifiers and of channels on the S/N ratio
  - Impact of the amplifier input power on its gain response
- ◆ **Description of some WDM transmission systems**
- ◆ **Key advantages of the WDM technique**

# Schéma de principe d'une liaison point à point

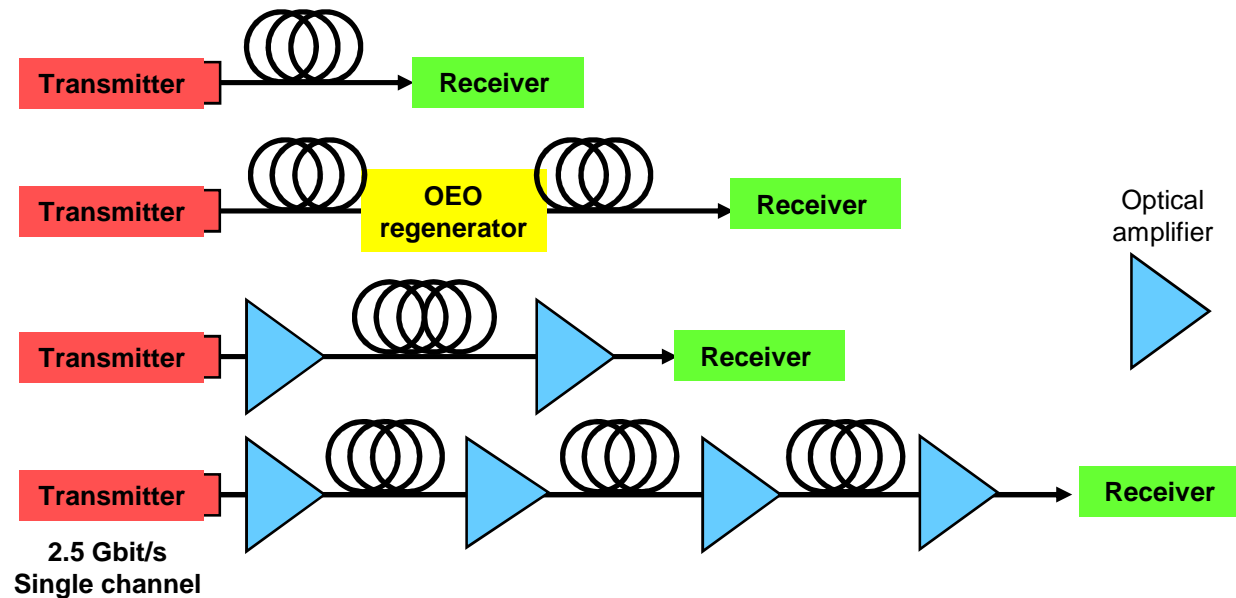


# Diagramme du bilan en puissance



# Evolution of TDM systems on optical fiber

- ◆ Today the bit rate growth doubles every 2.5 years
- ◆ The aim is to increase the bit rate x distance product



And then ?.....

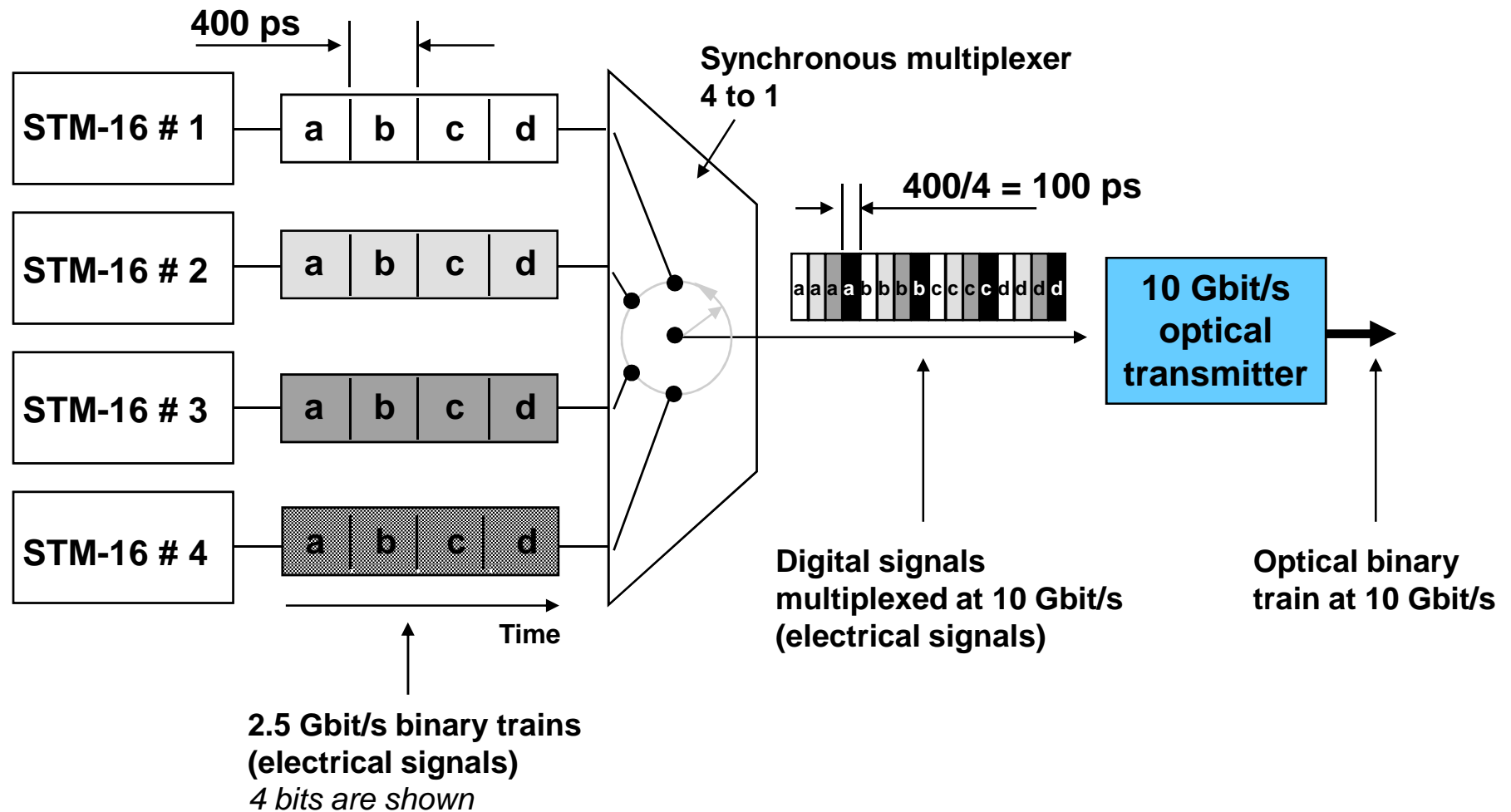
- The 10 Gbit/s (factor of 4) TDM bit rate is beginning to be installed
- The 40 Gbit/s (factor of 16) TDM bit rate is currently being developed

## Current status of terrestrial networks

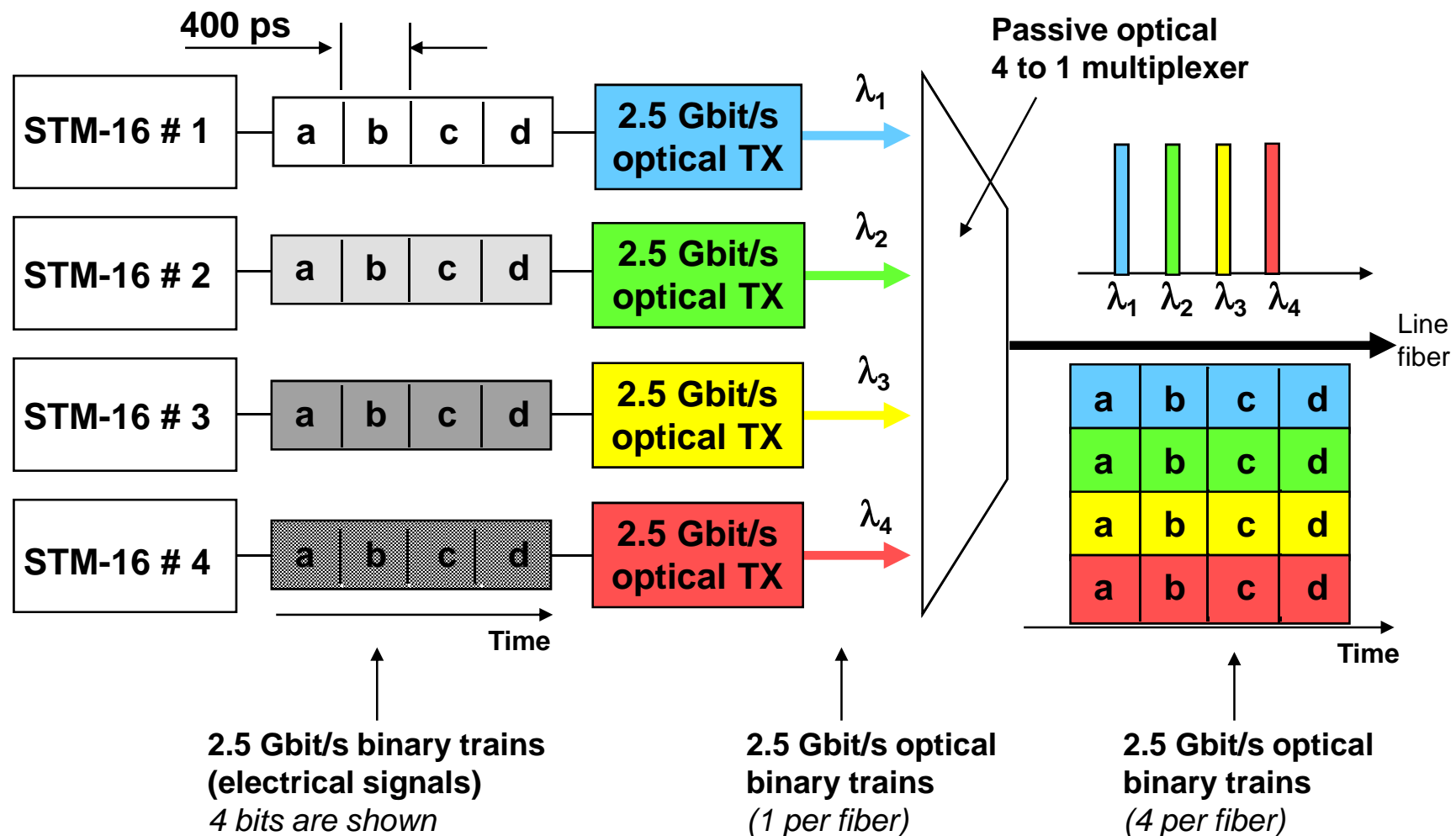
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- ◆ **Systems already installed and operational**
  - **Based on standard singlemode SMF G.652 type fiber used at 1550 nm**
    - Minimum fiber attenuation ( $\approx 0.2\text{-}0.3$  dB/km)
    - Possibility of optical amplification (EDFA)
  - **TDM bit rates**
    - Currently 2.5 Gbit/s
    - Beginning of 10 Gbit/s
- ◆ **2.5 Gbit/s TDM systems specificities**
  - **Direct modulation**
  - **Booster and/or preamplifier**
  - **Distance without regeneration  $\approx 150$  km**
- ◆ **Short term evolution**
  - **Constraint due to limited number of already installed fibers**
  - **Increased capacity : on the way to 10 Gbit/s multichannel systems**
  - **Longer distance without regeneration**

# TDM : Time Division Multiplexing



# WDM : Wavelength Division Multiplexing



### ♦ **Interests of Wavelength Division Multiplexing**

- **Very high transmission capacity on line fiber**
  - 2.5 or 10 Gbit/s per channel (wavelength)
  - Possibility of a large number of channels (typically 16 to 64 channels)
  - Equivalent global capacity carried : 40 to 640 Gbit/s
- **No need for very high speed electronic circuits**
  - 2.5 Gbit/s electronics for N x 2.5 Gbit/s systems (capacity up to 160 Gbit/s)
  - 10 Gbit/s electronics for N x 10 Gbit/s (capacity up to 640 Gbit/s)
- **Possibility to exploit already installed standard SMF fiber used at 1.55  $\mu\text{m}$** 
  - Can stand the high chromatic dispersion of this fiber for bit rates up to 2.5 Gbit/s

### ♦ **Constraints of WDM**

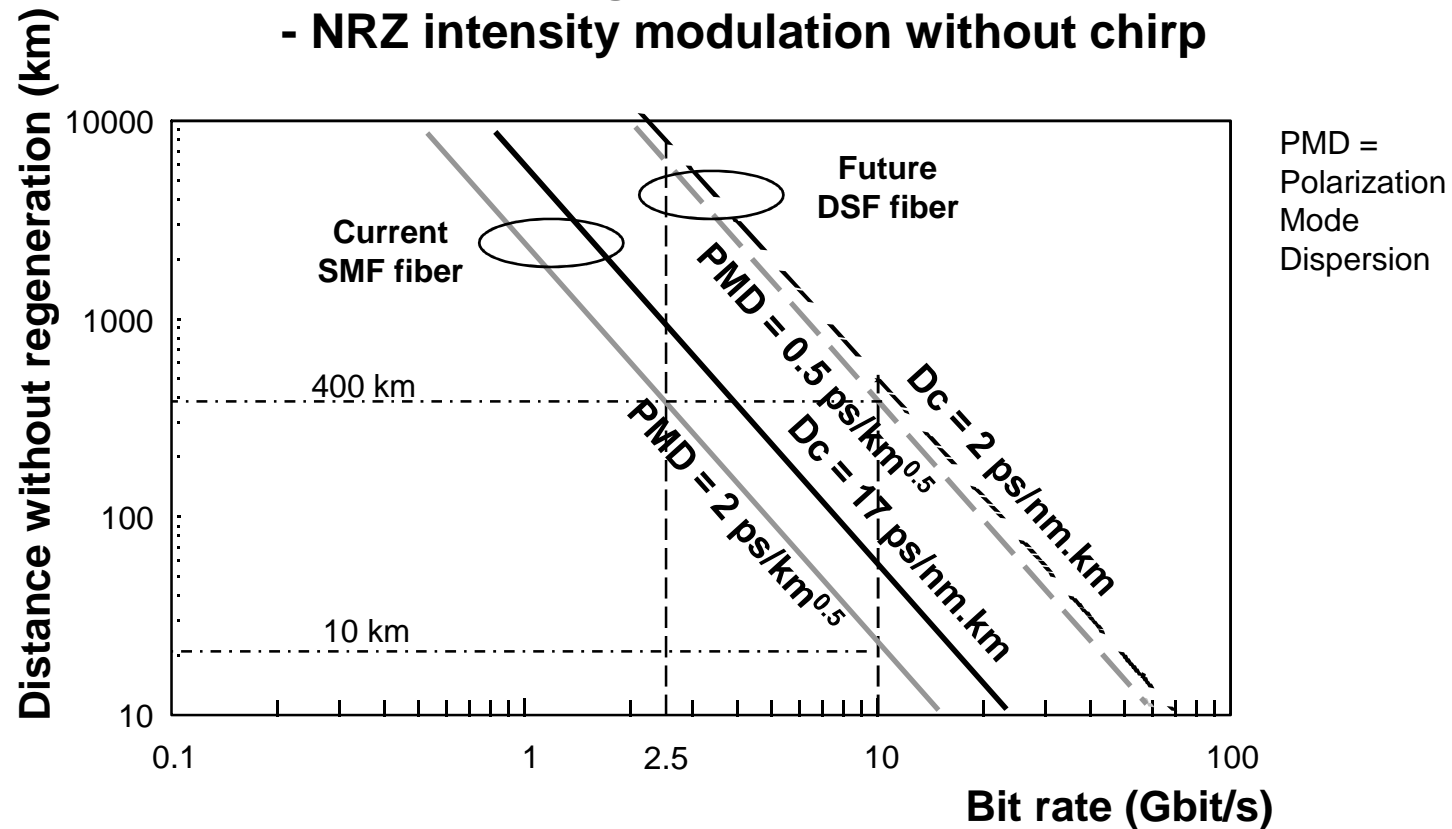
- **Sensitivity to non-linear effects generated into the line fiber (FWM)**
- **Specificities of optical amplifiers used (gain flatness...)**
- **Very high wavelength stability of the sources (laser diodes) used**



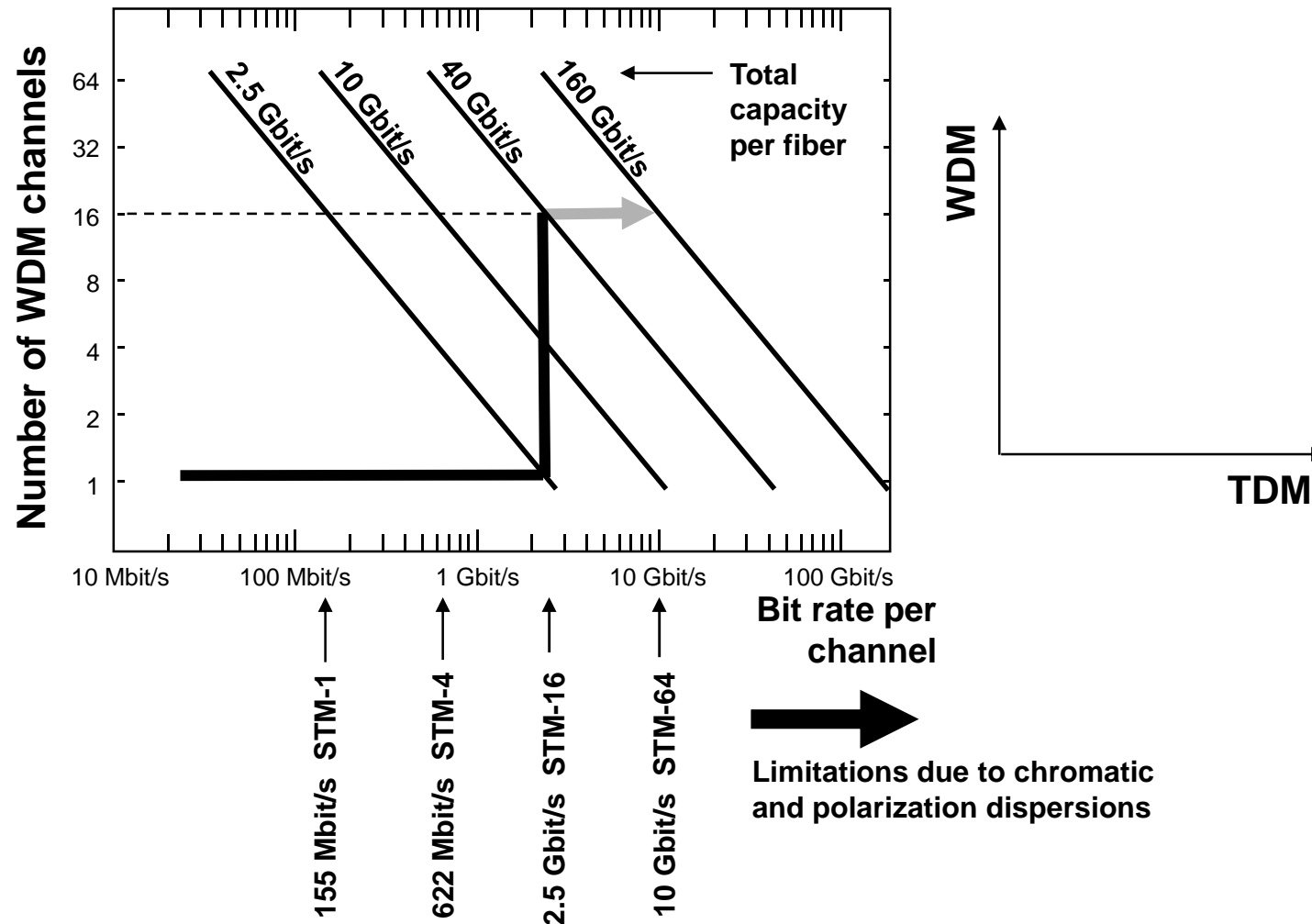
# Transmission limitations

## Chromatic and polarization dispersions

- Hypothesis :**
- Single channel transmission
  - Linear propagation (no non-linear effects)
  - NRZ intensity modulation without chirp

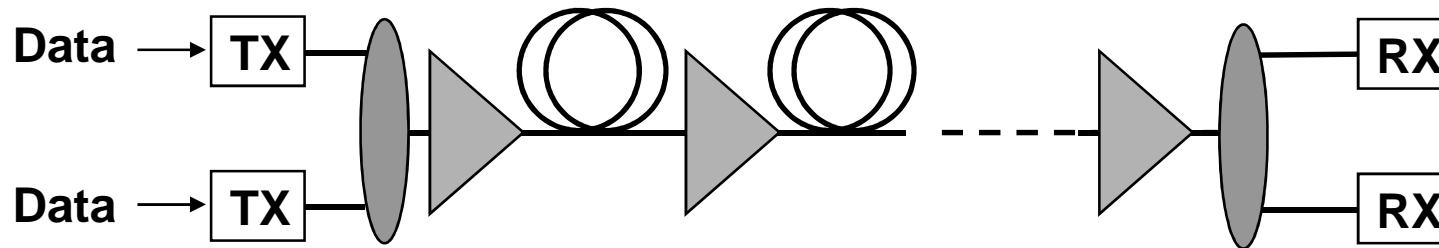


## Strategy for increasing capacity per fiber



## Technical advantages of WDM for high capacity terrestrial systems

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- ◆ **For 2.5 Gbit/s systems : better tolerance on already installed optical cables**
  - To chromatic dispersion (G.652 SMF fibers)
  - To polarization dispersion (G.652 SMF and G.653 DSF fibers)

-> *Longer distance without regeneration : increase by a factor of 4*
- ◆ **Transparency to bit rates and standards, modularity, (N+1) type protection**

# Propagation in WDM systems

## Non-linear effects in fibers

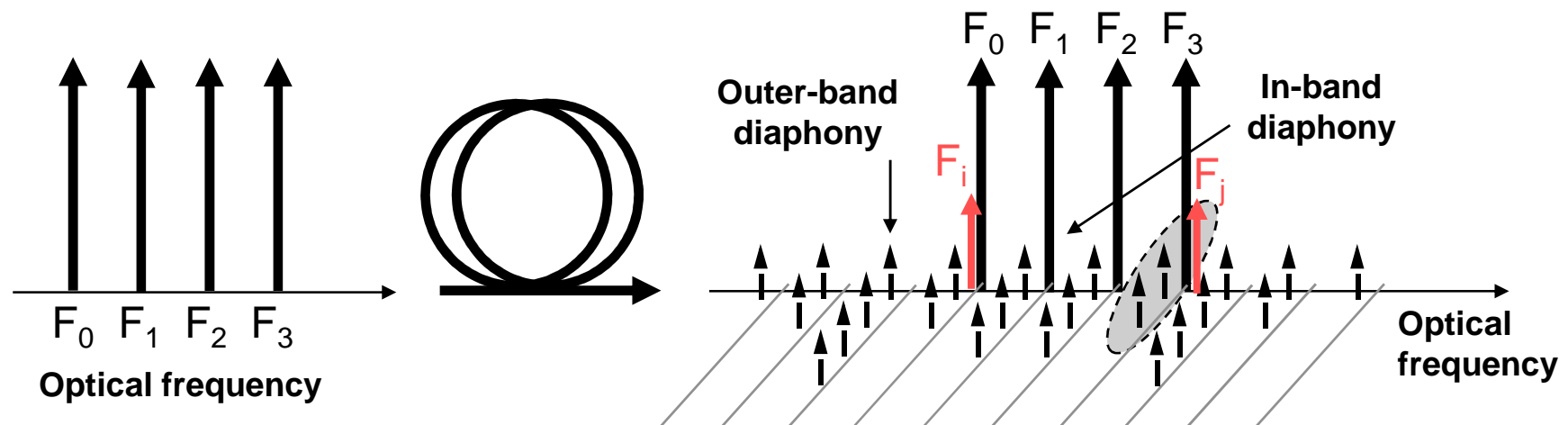
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- ◆ **WDM systems : simultaneous propagation of several optical carriers into the same fiber**
- ◆ **Linear regime ( $P_{\text{channel}} < 0 \text{ dBm} = 1 \text{ mW}$ ) :**
  - *No difference between single channel and multi channel propagation*
- ◆ **Self-phase modulation (SPM) :**
  - Non-linear effect due to fiber core refractive index dependance to optical power density propagating along the fiber
  - Exists both for single channel and multi channel propagation
- ◆ **Non-linear effect limiting WDM systems performance :**
  - Four-wave mixing (FWM)

## Four Wave Mixing (FWM) in WDM systems

- ◆ Four Wave Mixing generates parasitic optical frequencies through 3<sup>rd</sup> order intermodulation :

- $$F_i = F_1 - \Delta F \quad F_j = F_2 + \Delta F \quad \text{where } \Delta F = F_2 - F_1$$



- ◆ FWM diaphony is generated by :
  - A high power per channel ( $> 0$  dBm)
  - A low chromatic dispersion ( $< 2$  ps/nm.km)
  - A narrow or equal spacing between adjacent channels

## Possible solutions for reducing FWM impact

---

### ♦ FWM efficiency decreases with :

- A low optical power per channel (< 0 dBm)
- A large frequency spacing between adjacent channels (> 50 GHz)
- A judicious layout of the channel polarization (orthogonal polarizations between adjacent channels)
- The use of new type of fibers showing a  $\lambda_0$  out of the multiplex range :

– *Design of new line fibers called NZ-DSF (non-zero dispersion shifted fiber) :  
(Lucent TrueWave, Corning LEAF, Alcatel TeraLight...)*

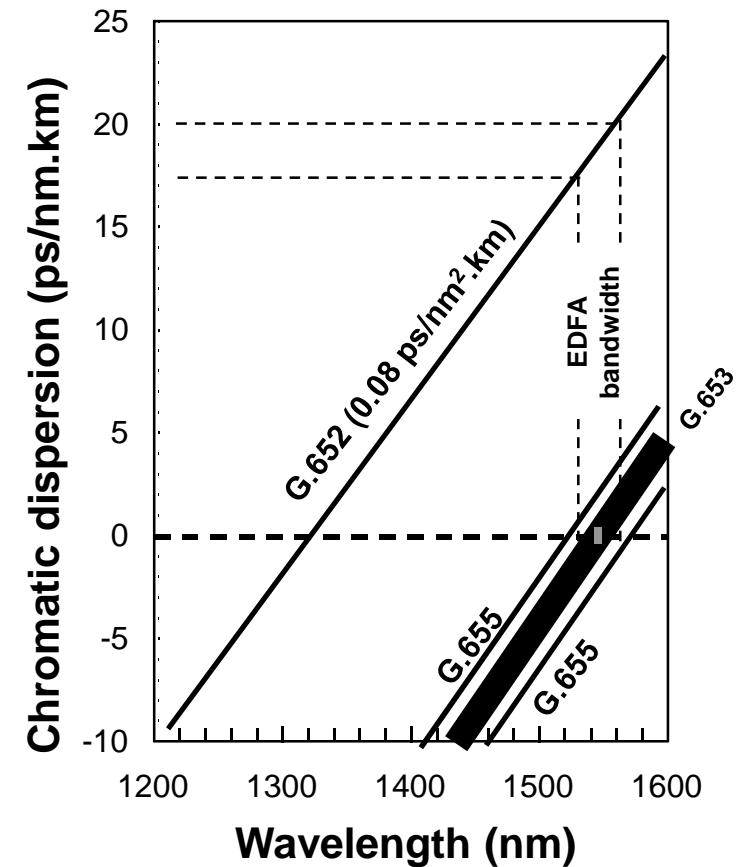
**Best choice**

### ♦ Reducing FWM impact :

- Unequal spacing between channels...  
Non manageable solution for a great number of channels

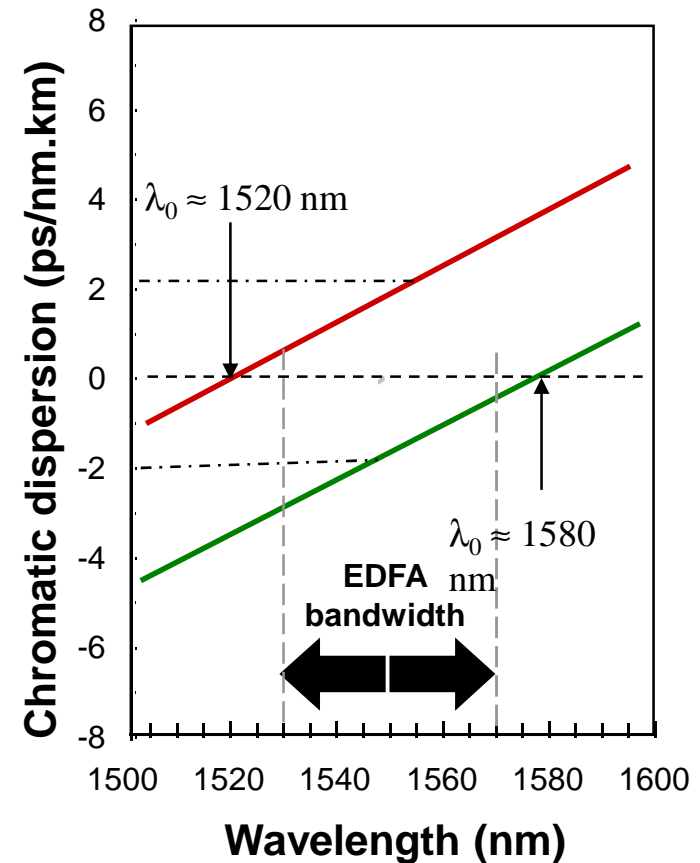
## Standard SMF, DSF and NZ-DSF fibers

- ◆ **Standard SMF fiber (G.652)**
  - Zero chromatic dispersion wavelength ( $\lambda_0$ ) between 1290 and 1320 nm
  - Typical attenuation : 0.25 dB/km
- ◆ **DSF dispersion-shifted fiber (G.653)**
  - $\lambda_0$  between 1530 and 1570 nm
  - Typical attenuation : 0.28 dB/km
- ◆ **NZ-DSF non-zero dispersion-shifted fiber (G.655)**
  - $\lambda_0$  around 1520 or 1580 nm
  - The most promizing fiber ?
  - Beginning to be deployed in the USA



## NZ-DSF fibers for WDM systems

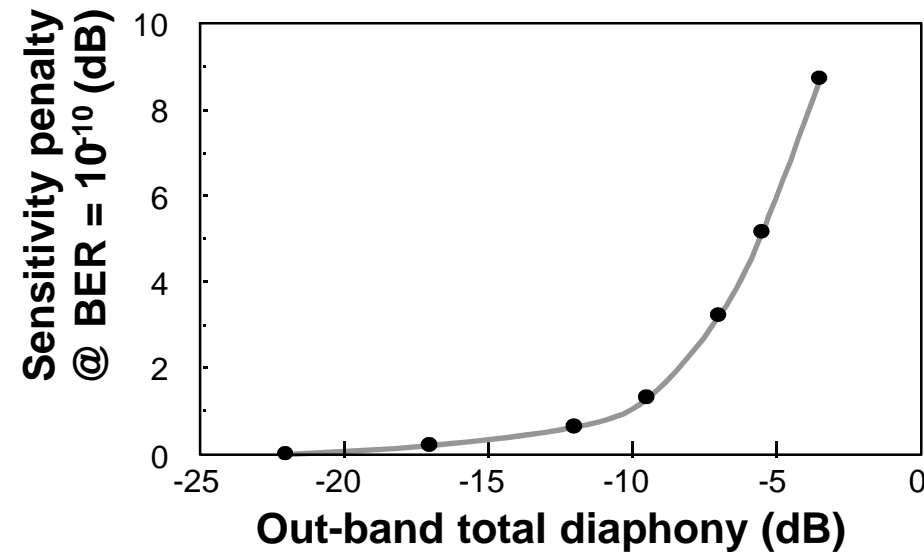
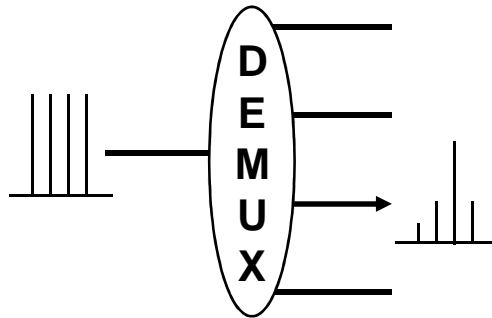
- ◆ **Dispersion shifted fiber (DSF) G.653 :**
  - $\lambda_0$  between 1530 and 1570 nm
  - Worst case :  $\lambda_0$  inside the multiplex range
- ◆ **Development of a new fiber with  $\lambda_0$  outside the multiplex range defined by the EDFA amplification range :**
  - NZ-DSF (G.655)
- ◆ **Two alternatives:**
  - $\lambda_0 \approx 1520$  nm @  $D \approx +2$  ps/nm.km
  - $\lambda_0 \approx 1580$  nm @  $D \approx -2$  ps/nm.km
    - Avoids modulation instabilities
    - Allows dispersion compensation through several SMF fibers concatenation
- ◆ **Fiber of the future ?**





## Diaphony specification of the WDM demultiplexers

4 channel system  
without amplifier



- ◆ 0.5 dB penalty for a -13 dB diaphony
- ◆  $\text{Diaphony}_{\text{channel}} < -20 \text{ dB}$  for 8 channels with flat spectrum at demultiplexer input
- ◆  $\text{Diaphonie}_{\text{channel}} < -25 \text{ dB}$  for 8 channels after the amplifiers chain

## Considerations regarding channel spacing

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### ◆ Lower limit :

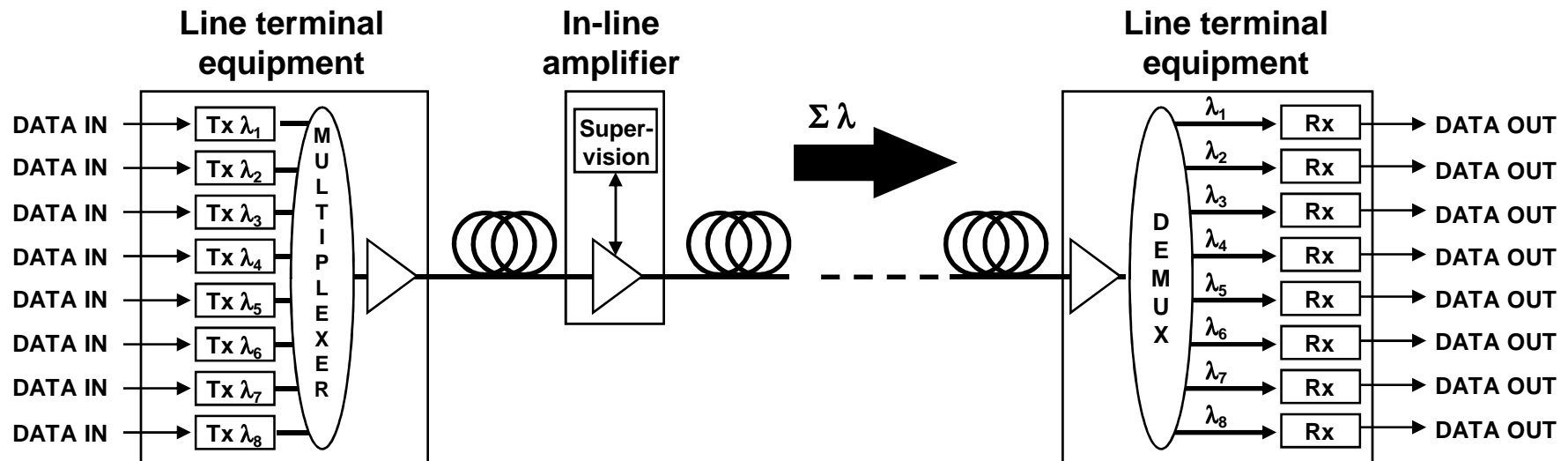
- Wavelength stability of the sources requiring complex and expensive control circuits
- Technological constraints on the demultiplexer (diaphony and wavelength stability)
- Non-linear effects in the line fiber (four wave mixing FWM)

### ◆ Upper limit :

- Non uniform gain curve of the optical amplifiers
- Total optical bandwidth for increasing number of channels

***-> A 50 to 100 GHz spacing is a good trade-off  
(according to the ITU-T G.692 standard recommandation)***

# WDM amplification Requirements and specificities



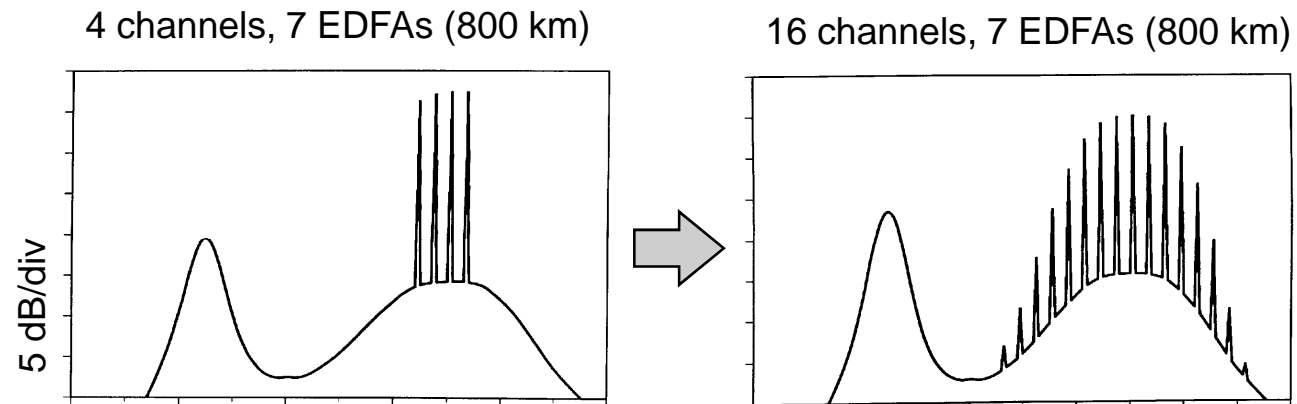
## ♦ WDM optical amplifiers must show :

- **A uniform per channel output power taking into account**
  - Receiver dynamics
  - Non-linear effects in the line fiber
- **A uniform S/N ratio**
  - For keeping a good bit error rate (BER) performance whatever the number of channels

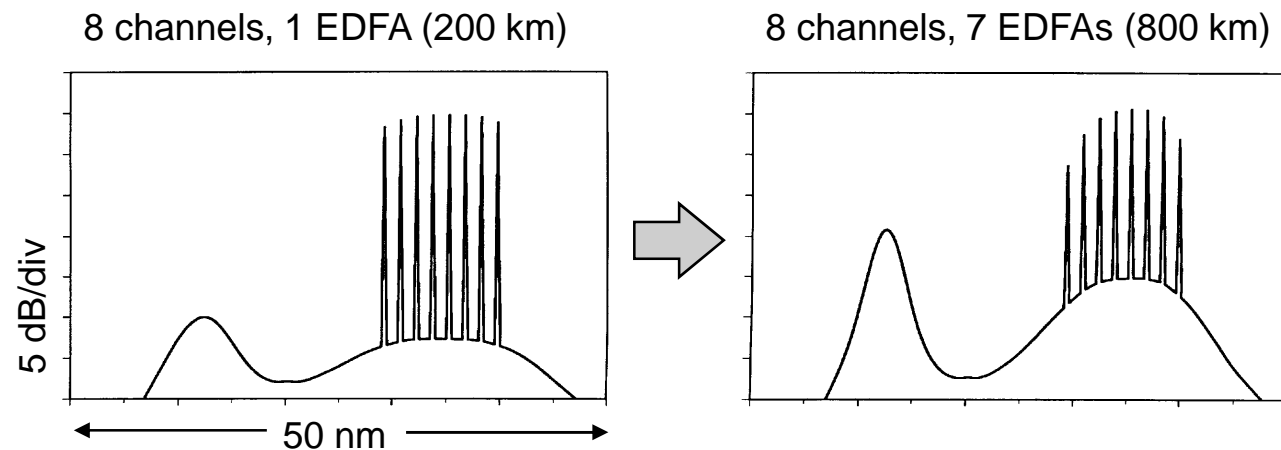
# WDM amplification

## Limitation due to self-filtering gain curve $G(\lambda)$

**Increasing the number of channels :**



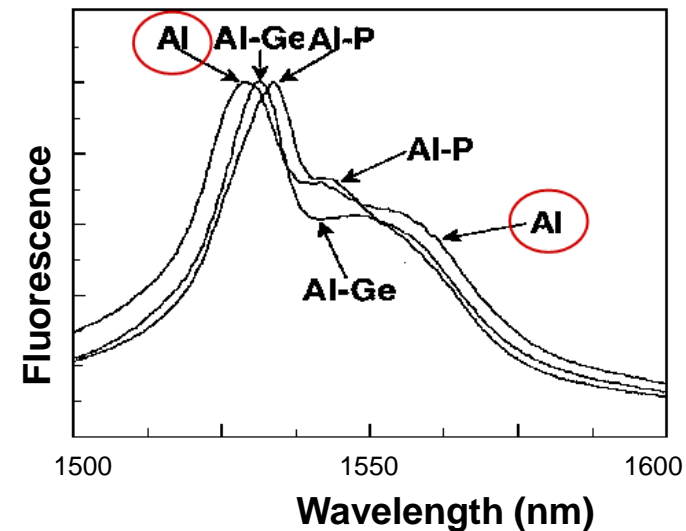
**Increasing the number of amplifiers :**



# Gain curve flatness

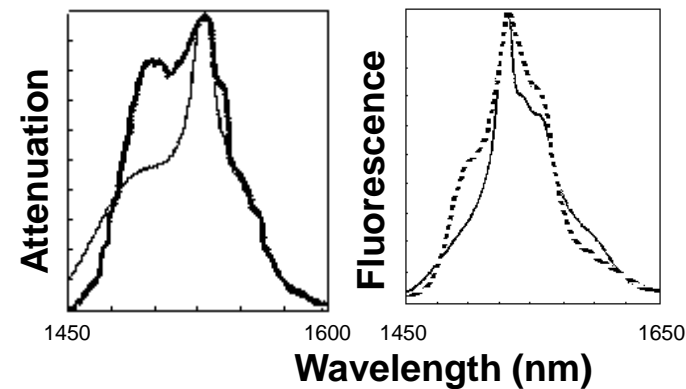
## Co-dopants and new host materials

**Various co-dopants  
in silica-based  
Erbium doped fibers**  
-> Interest of Al doping



**Silica and fluoride glass  
used as host materials  
for Erbium doping**

- Erbium doped silica fiber
- Erbium doped fluoride glass fiber

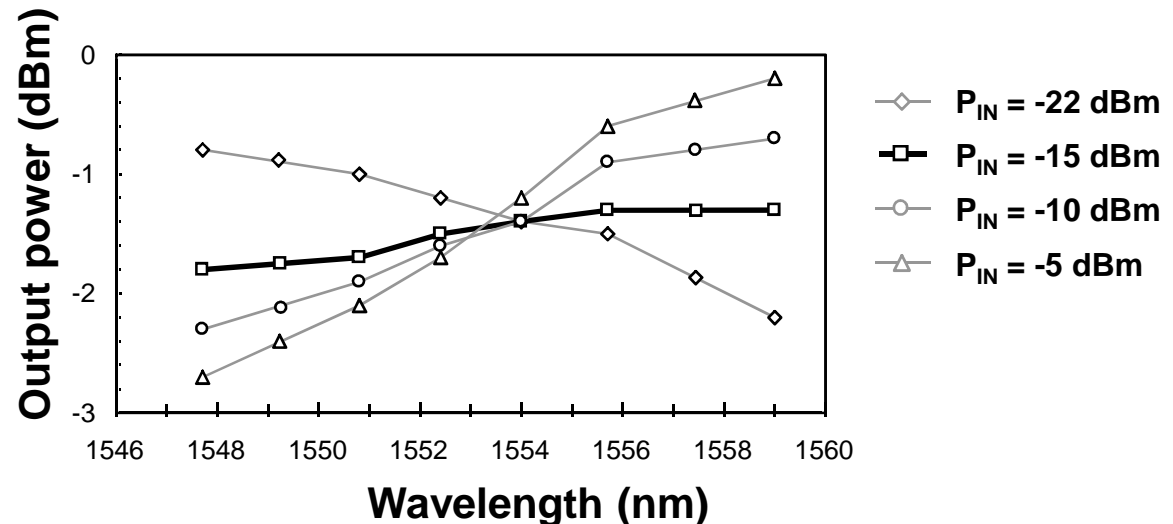


## Gain curve flatness

### The input power impact

#### Influence of the input power (constant pump power)

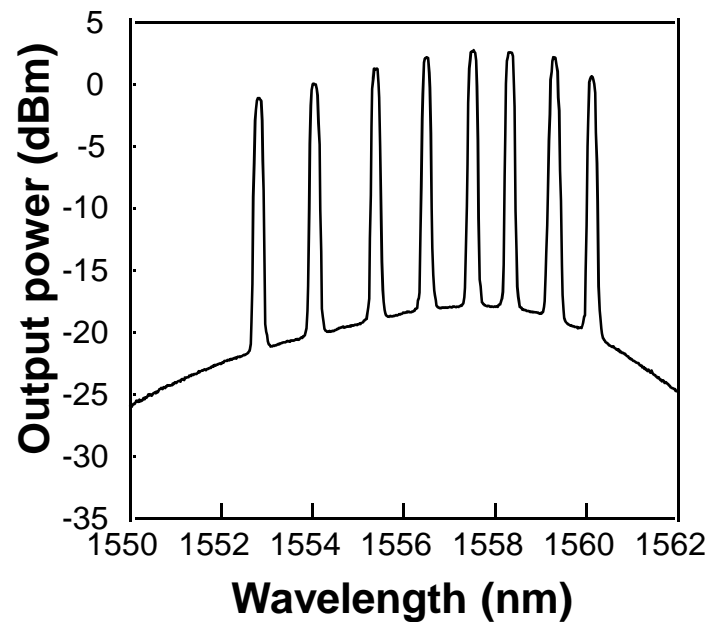
One EDFA with  
Aluminum co-dopant



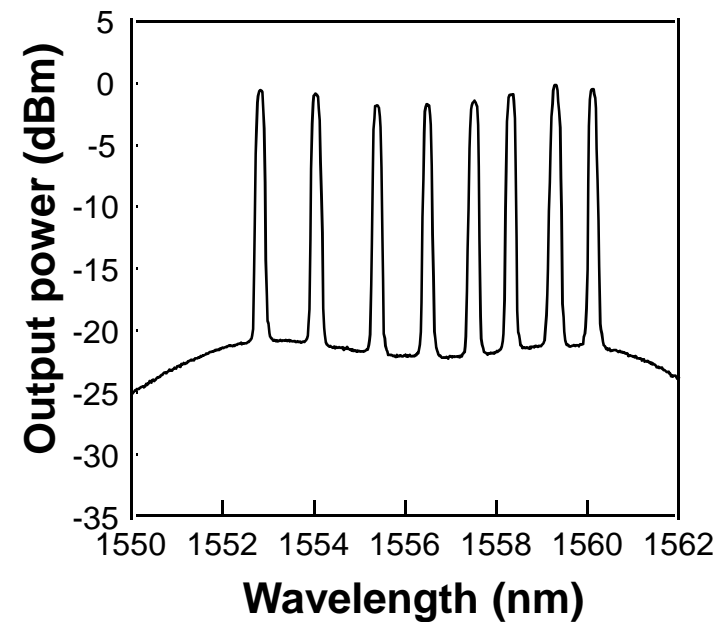
- ◆ **Gain curve flatness is directly depending on the overall optical power entering the amplifier :**
  - A too weak input power leads to a lower gain at longer wavelengths
  - The right gain flatness requires a permanent input power control for adjusting it at the optimum level

### Chain of 10 EDFAs : impact of the gain flattening filter

**Without filter**



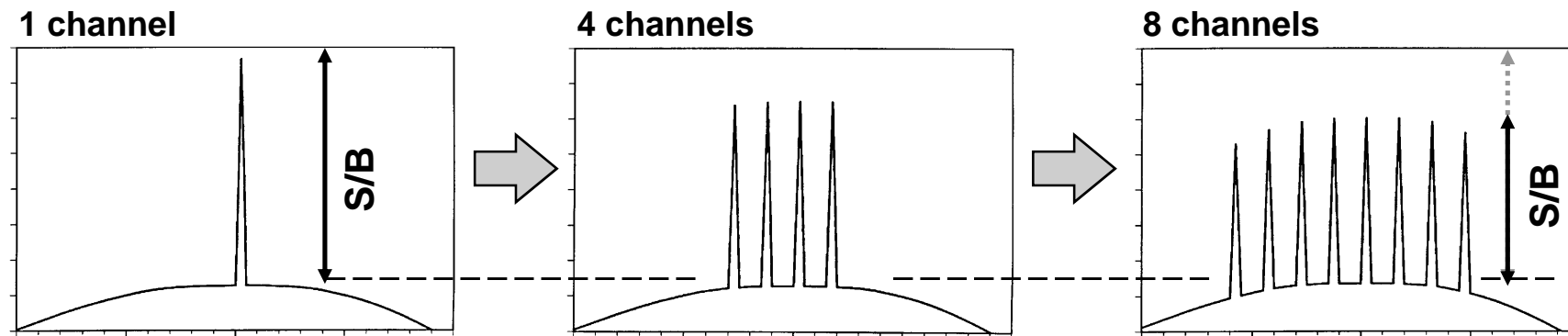
**With 1 filter**



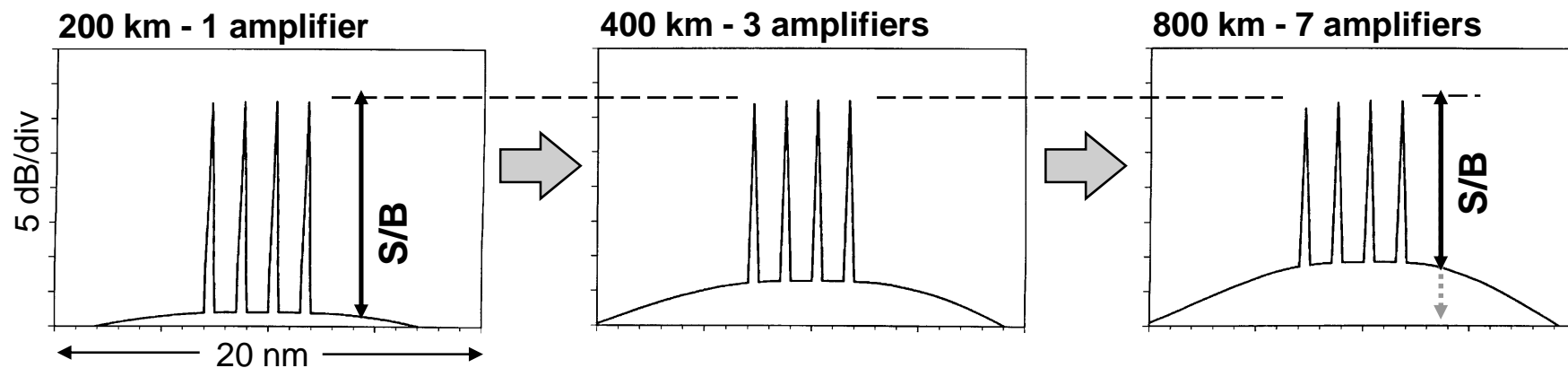
# Limitations of the WDM amplification

## Noise considerations

### Increasing the number of channels :



### Increasing the number of in-line amplifiers :



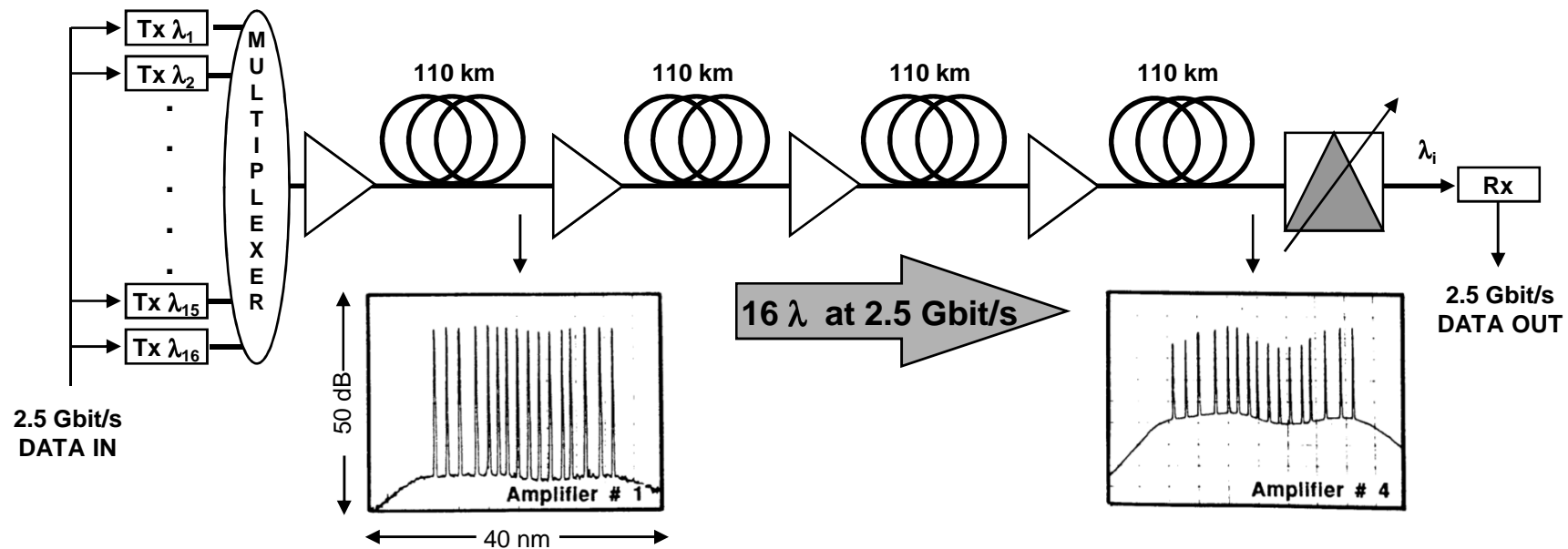


## **Practical implementation of WDM optical amplifiers**

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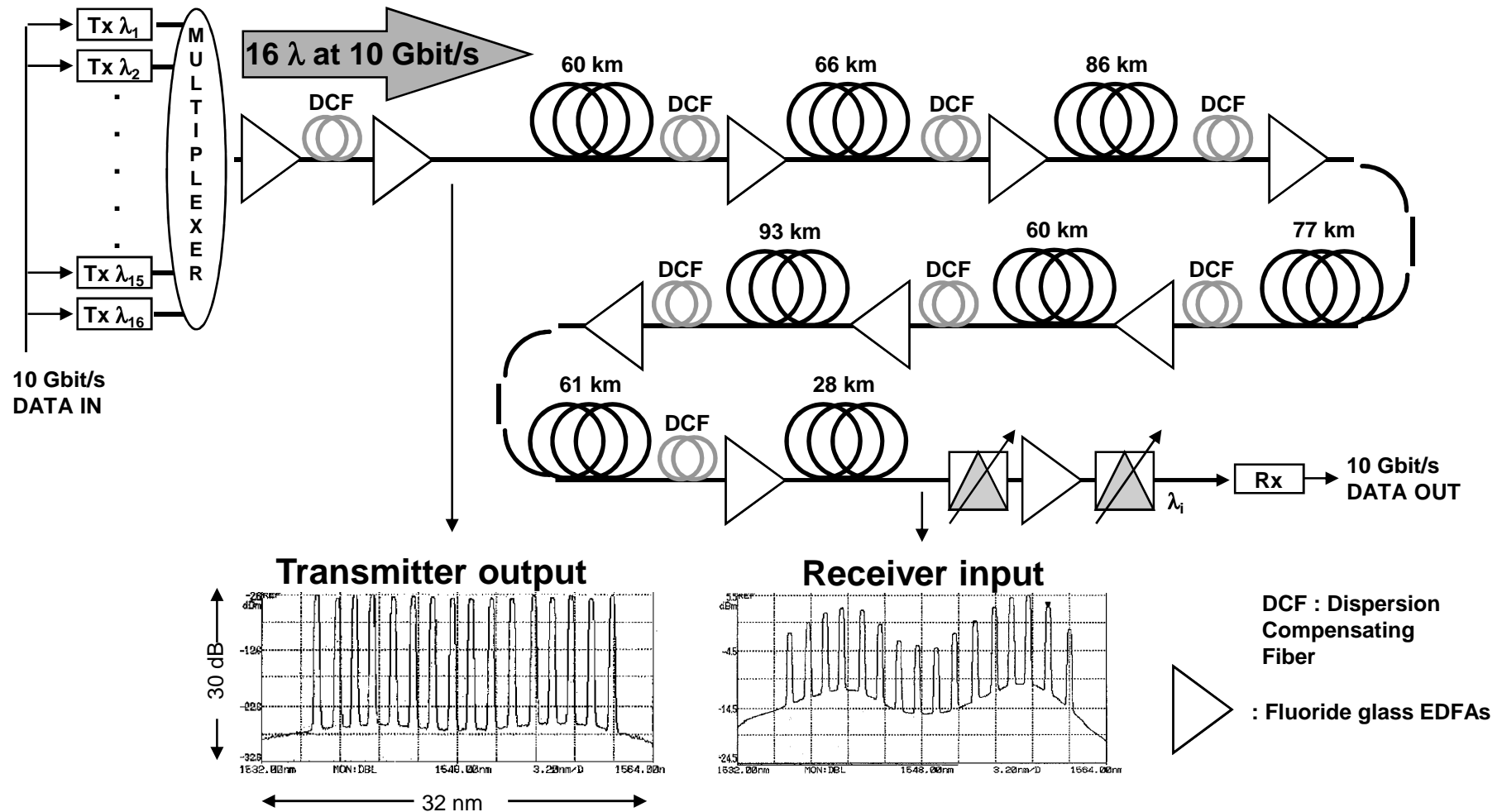
- ◆ **The WDM EDFA response (gain flatness, per channel output power) is directly depending on the overall input power**
- ◆ **WDM amplifiers are designed to be used at a specific input power for optimizing gain flatness**
- ◆ **Overall input power can vary :**
  - **Non uniform in-line loss between amplifiers**
  - **Variation of the number of channels due to :**
    - Progressive increase of the number of channels (system upgrade)
    - Possible defect of a transmitter electronic board
    - Wavelength routing networks integrating OADM (optical add-drop multiplexing) function

## Transmission of 16 channels at 2.5 Gbit/s over 440 km of standard G.652 fiber

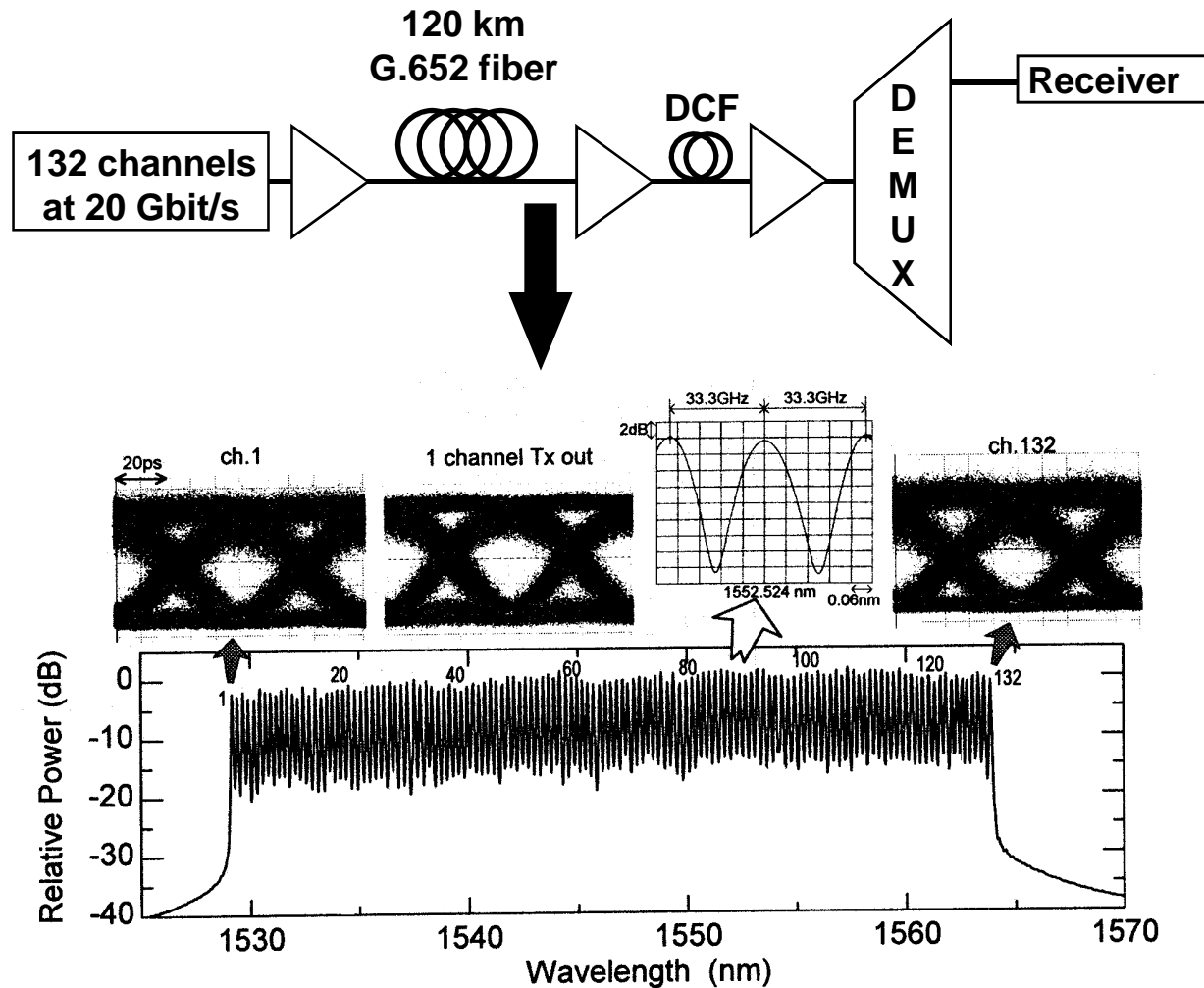


- ◆ **Use of wide band fluoride glass amplifiers :**
  - 16 WDM channels, 200 GHz spacing, i.e. 1.6 nm (1533.7  $\Rightarrow$  1558.2 nm)
- ◆ **2.5 Gbit/s per channel bit rate :**
  - Overall capacity of 40 Gbit/s with excellent tolerance to chromatic and polarization dispersions

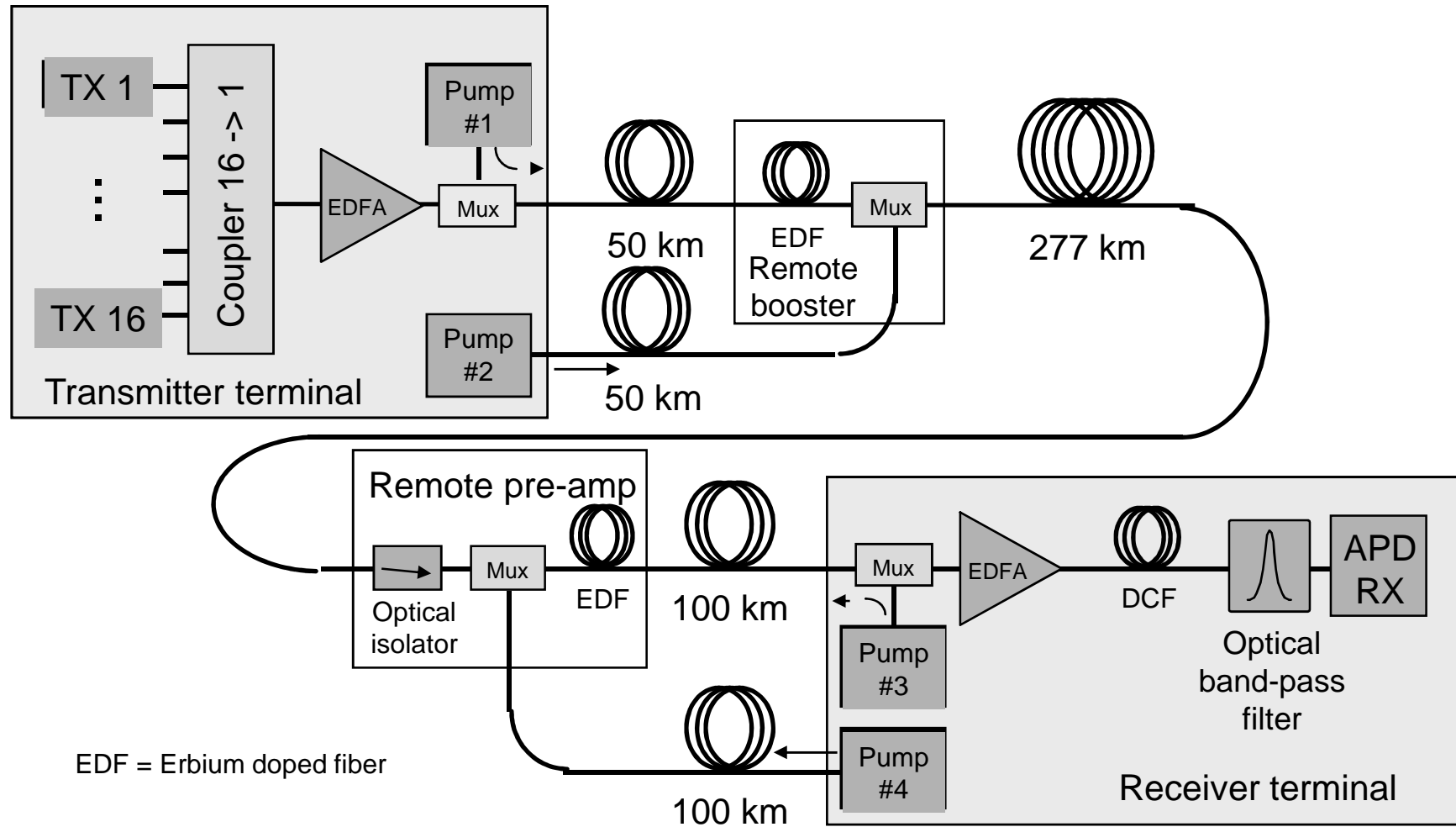
## Transmission of 16 channels at 10 Gbit/s over 531 km of standard G.652 fiber



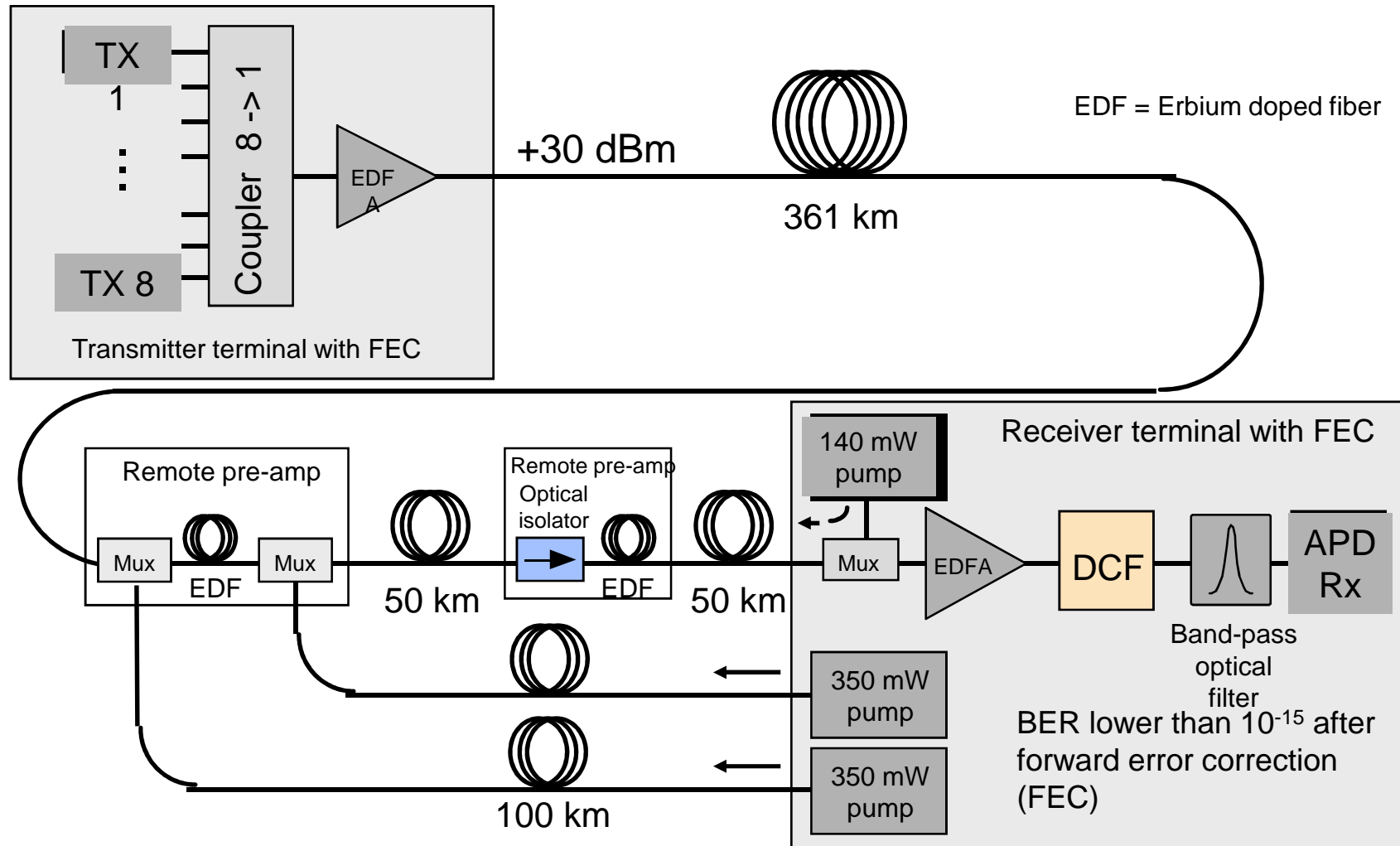
## NEC experiment at 2.6 Tbit/s : 132 channels at 20 Gbit/s over 120 km of SMF fiber



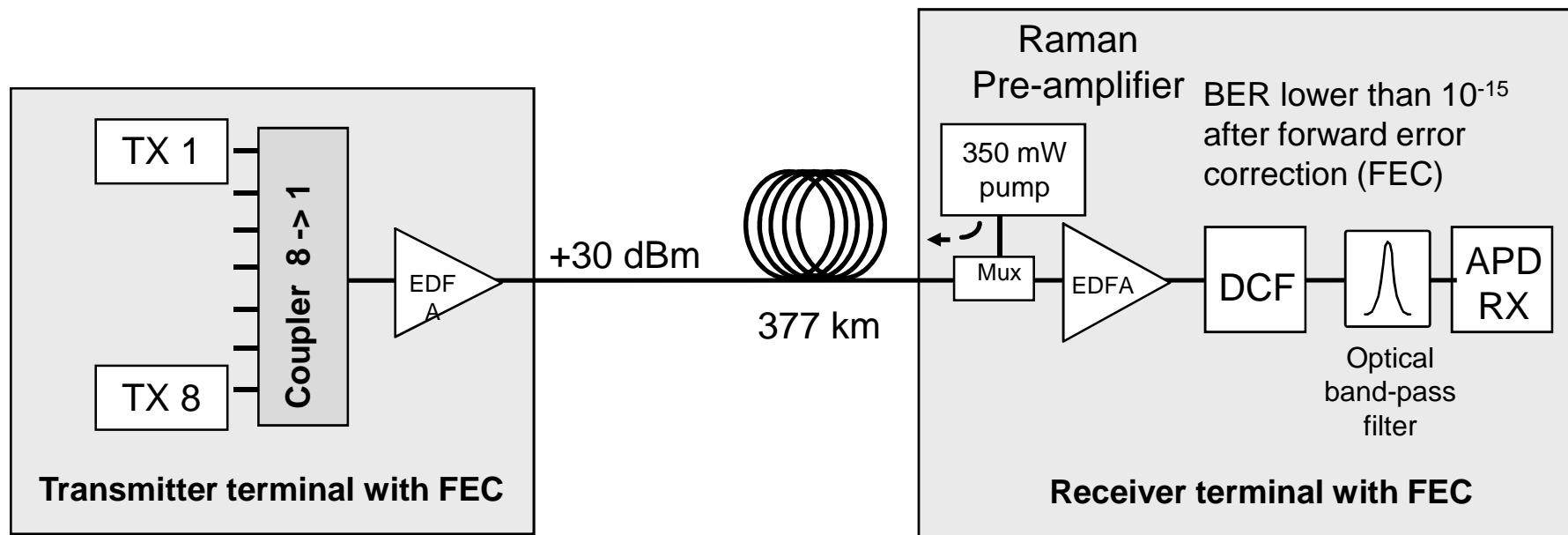
## Demonstration of a non-regenerated WDM system of 16 x 2.5 Gbit/s over 427 km



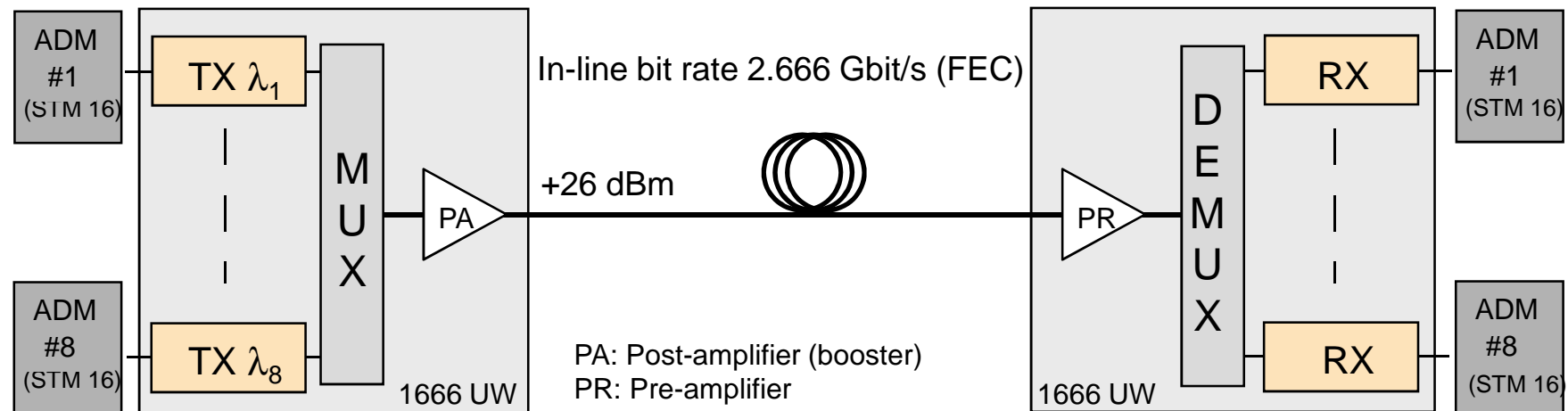
# Demonstration of a non-regenerated WDM system of 8 x 2.5 Gbit/s over 461 km



## Demonstration of a non-regenerated WDM system of 8 x 2.5 Gbit/s over 377 km



## Commercial terminal 8 x 2.5 Gbit/s



- ◆ **Forward Error Correction (FEC)**
- ◆ **High output power booster amplifier (+26 dBm = 400 mW)**
- ◆ **Low noise pre-amplifier**
- ◆ **Channel spacing compliant to ITU-T G.692 standard**
- ◆ **Compatible with SDH and SONET multiplexers**



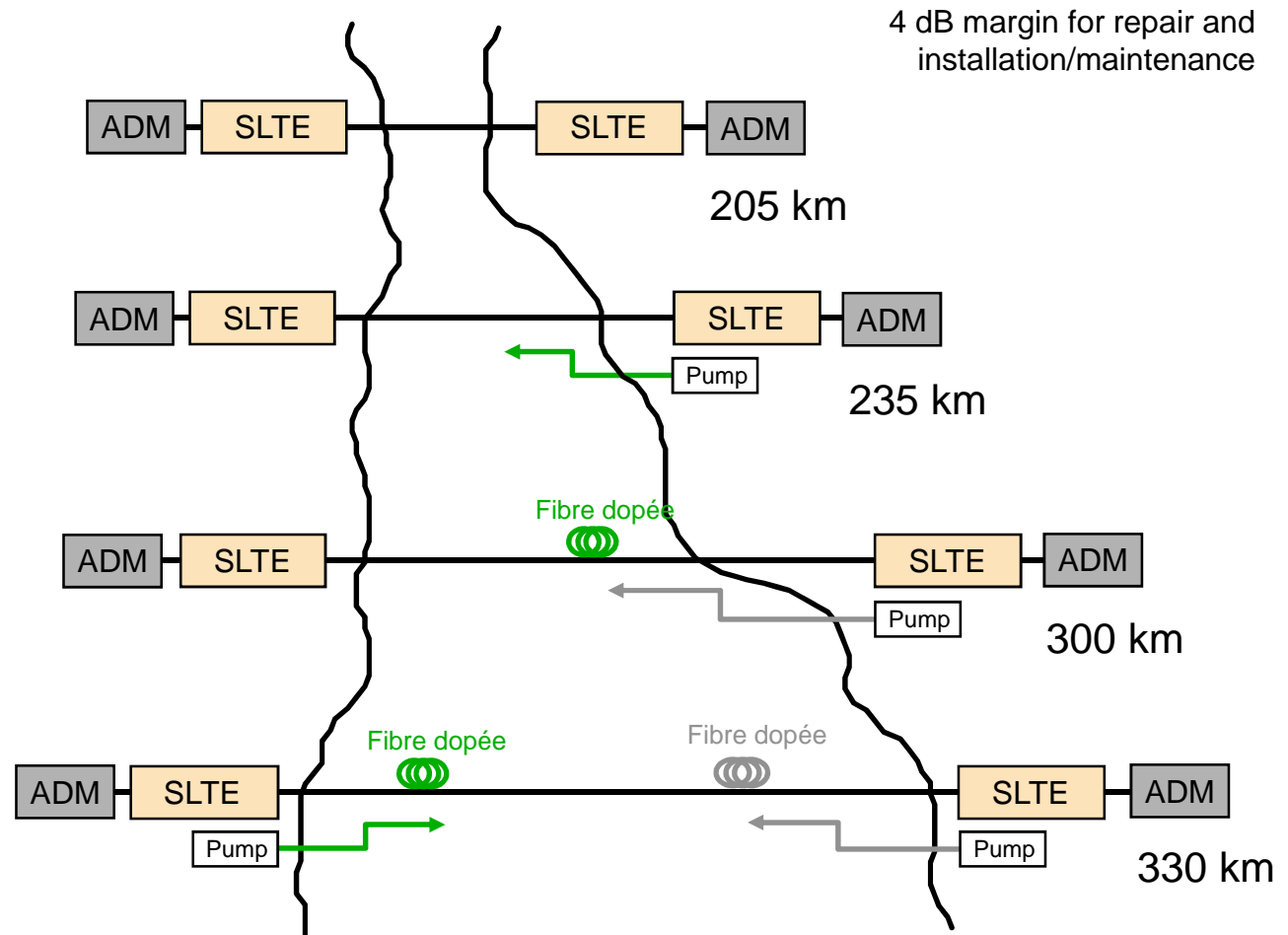
# Operational 16 x 2.5 Gbit/s submarine systems

**Submarine line terminal equipment (SLTE) with FEC and amplifiers**

**+ Pre-amplification and Raman pumping at receiver side**

**+ Remote pre-amplification and Raman pumping at receiver side**

**+ Remote pre-amplification and Raman pumping at both transmitter and receiver sides**



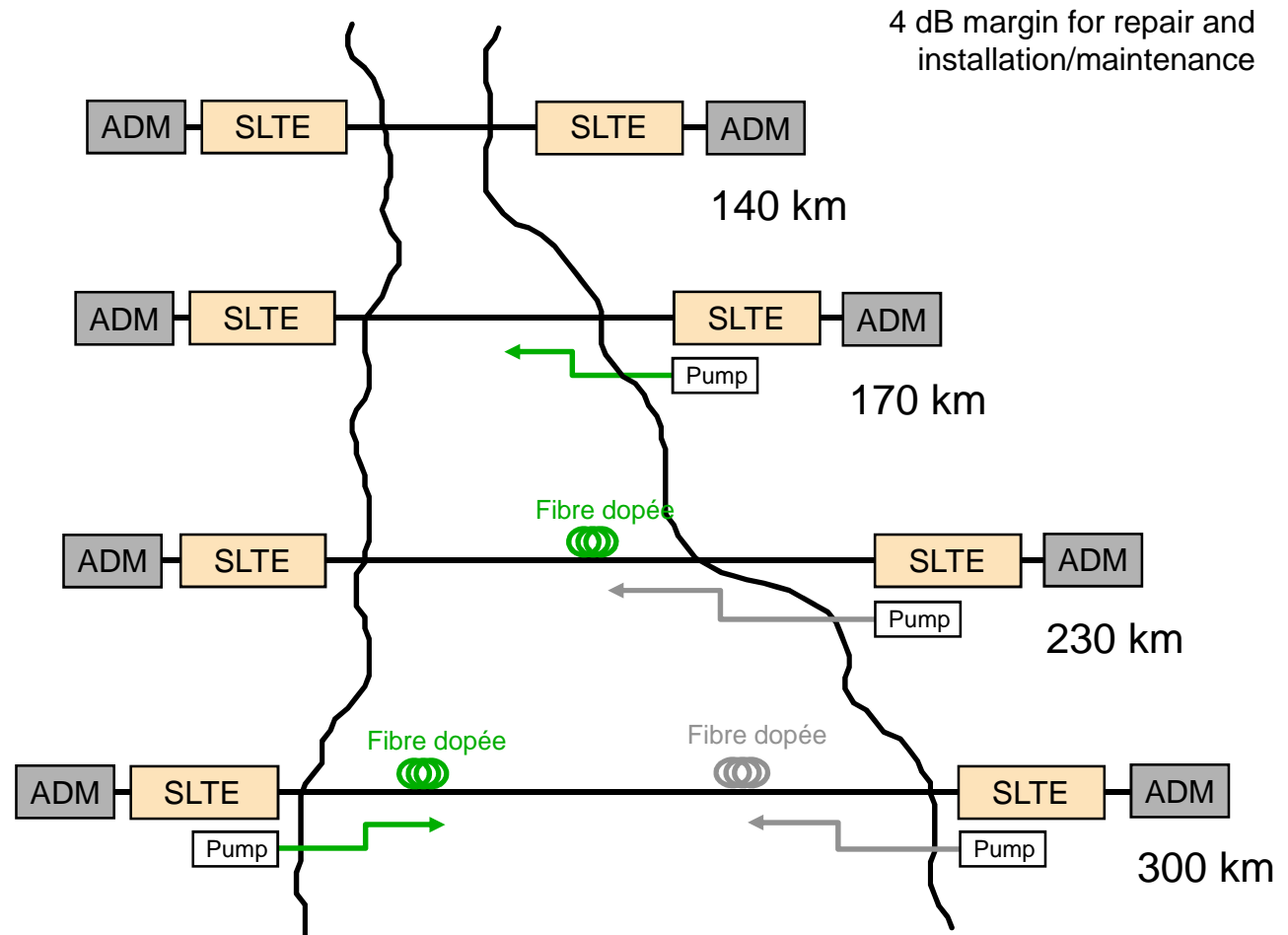
# 16 x 10 Gbit/s submarine systems under development

**Submarine line terminal equipment (SLTE) with FEC and amplifiers**

**+ Pre-amplification and Raman pumping at receiver side**

**+ Remote pre-amplification and Raman pumping at receiver side**

**+ Remote pre-amplification and Raman pumping at both transmitter and receiver sides**



# Optical fiber standards

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## ♦ ITU-T recommendations

- G series « Systems and transmission supports, systems and digital networks »

## ♦ Correspondance with CEI classes

G Series	Fiber type	CEI Class
<b>G.651</b>	50/125 $\mu\text{m}$ type graded-index multimode fiber	
<b>G.652</b>	Standard SMF singlemode fiber for use at 1300 nm and eventually at 1550 nm	<b>B1.1</b>
<b>G.653</b>	DSF dispersion shifted singlemode fiber (DSF)	<b>B.2</b>
<b>G.654</b>	Singlemode fiber with shifted cut-off wavelength	<b>B1.2</b>
<b>G.655</b>	Non-zero dispersion shifted fiber (NZ-DSF)	<b>B.4</b>
<b>G.656</b>	Non-zero dispersion fiber for broadband systems	<b>B.5</b>
<b>G.657</b>	Singlemode fiber for FTTH access networks	<b>B.6</b>

## WDM system standardization

### Allocation of central frequencies

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- ◆ Since October 1998, the allocation of central frequencies of WDM channels is defined by the G.692 ITU-T recommendation :

- Frequency spacing between adjacent channels :

*Uniform spacing for G.652/G.655 fiber systems :*

Two values are usually used in current systems :

- WDM : 100 GHz spacing (around 0.8 nm at  $\lambda = 1550$  nm)
- Dense WDM (DWDM) : 50 GHz spacing (around 0.4 nm at  $\lambda = 1550$  nm)

Currently under study :

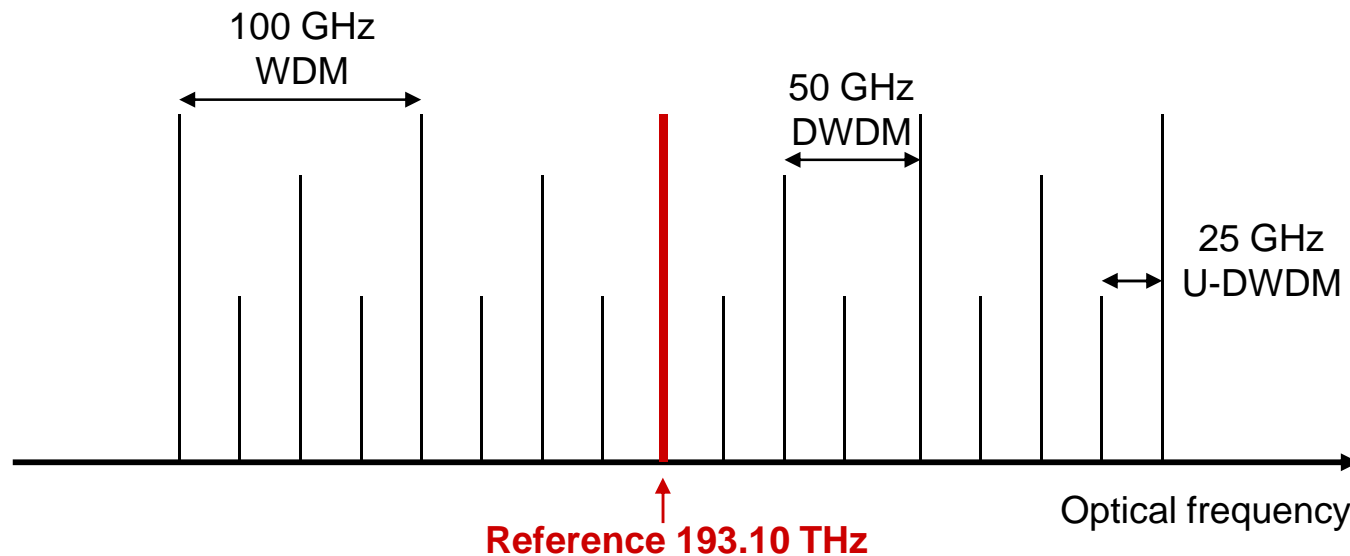
- Ultra-dense WDM (U-DWDM) : 25 GHz spacing (0.2 nm at  $\lambda = 1550$  nm)

*The study of non-uniform spacing for G.653 fiber systems has been stopped : not manageable for large number of channel systems*

- Reference for the choice of the central frequency :
  - Whatever the spacing, the reference frequency is 193.10 THz

## Definition of central frequencies

### ◆ Definition of central frequencies of WDM systems



### ◆ Relation between frequency spacing $\Delta f$ and wavelength spacing $\Delta \lambda$

$$\Delta \lambda = \frac{\lambda^2}{c} \Delta f$$

## Definition of WDM spectral bands

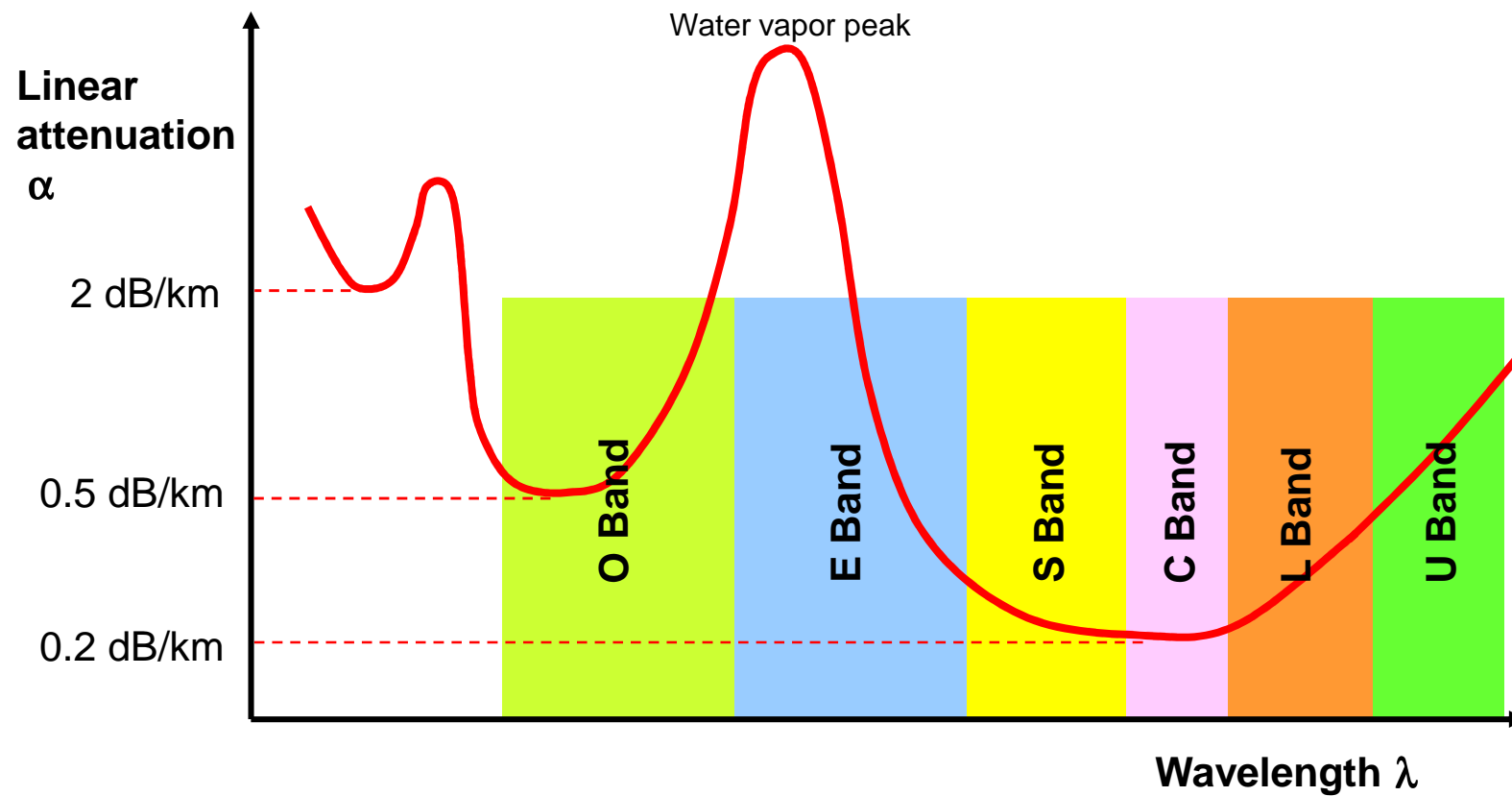
### ♦ Normalized spectral bands for WDM systems

- Transmission bands for singlemode fibers defined by the G.692 standard

Band name	O Band (Original)	E Band (Extended)	S Band (Short)	C Band (Conventional)	L Band (Long)	U Band (Ultra long)
Spacing in nm	1260-1360	1360-1460	1460-1530	1530-1565	1565-1625	1625-1675
Comments	Original band of G.652 fibers	Band of « water peak » for fibers with low water vapor absorption	In this band, some wavelengths are used for EDFA pumping, others for supervision channel	Band used for high performance transmission systems	Used for maintenance purpose. Not yet used for transmission	Not yet exploited band

## WDM spectral bands

- ◆ Representation of spectral bands on the attenuation curve of silica based ( $\text{SiO}_2$ ) fibers



## Potential number of channels in the 1.5 $\mu\text{m}$ wavelength range

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♦ Three bands are defined in the 1460 - 1625 nm range :

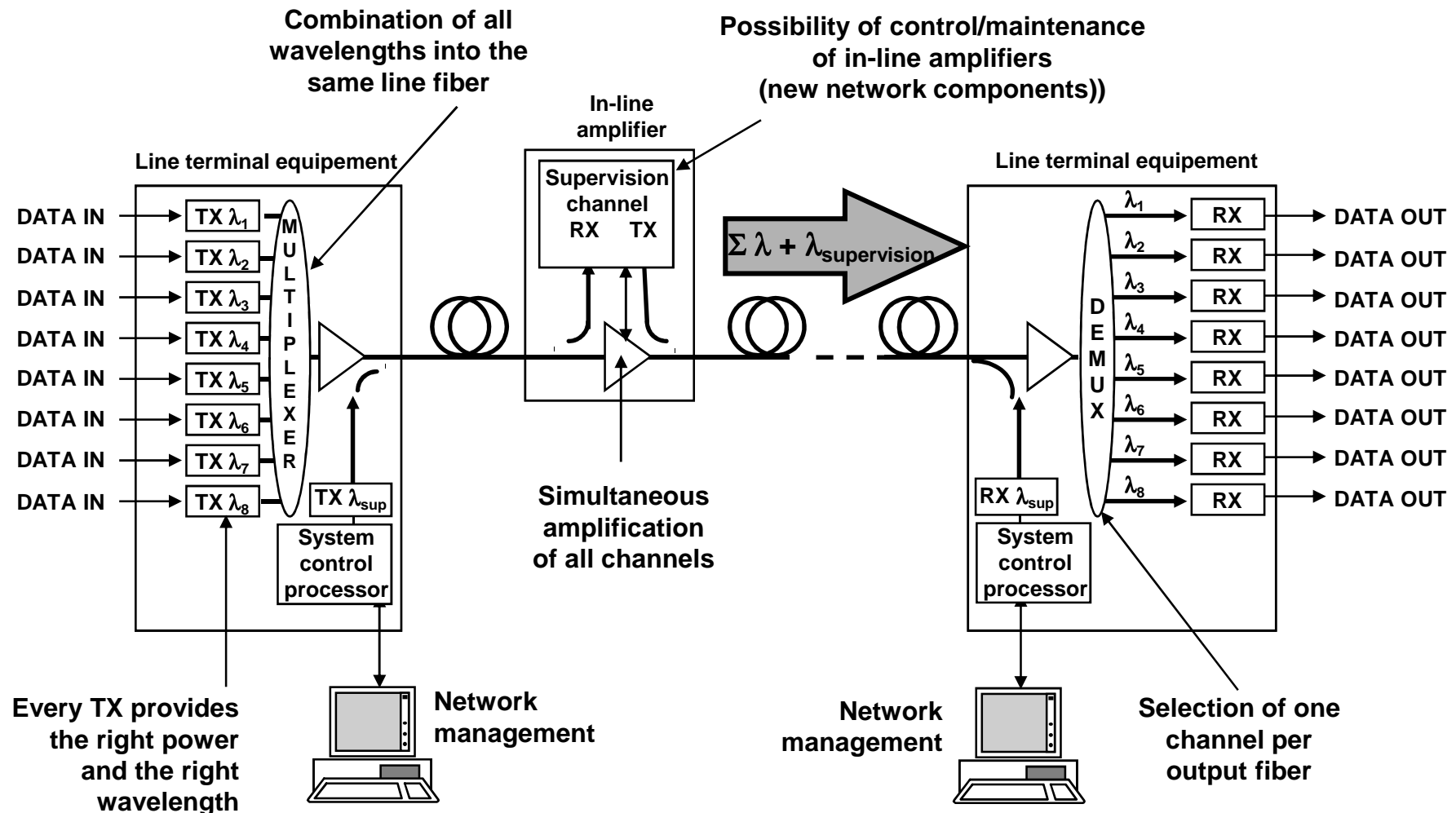
- S Band : 1460 - 1530 nm (70 nm width)
- C Band : 1530 - 1565 nm (35 nm width)
- L Band : 1565 - 1625 nm (60 nm width)

♦ Potential number of channels :

Band	Spacing		
	100 GHz	50 GHz	25 GHz
S	87 channels	175 channels	350 channels
C	43 channels	87 channels	175 channels
L	75 channels	150 channels	300 channels
Total	205 channels	412 channels	825 channels



# New functions and new components in WDM networks



# Wavelength division multiplexing

## Key advantages

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- ◆ **Capacity increase of existing networks**
  - Single-channel to multi-channel system upgrade
  - Exploiting existing infrastructure of standard SMF fibers for their use in WDM at 10 Gbit/s per channel
- ◆ **Network connectivity and flexibility improvement**
  - Finer granularity of WDM channels (reduced inter-channel spacing)
  - Better compliance to traffic configuration
- ◆ **Possibility of step to step network implementation**
  - Progressive upgrade depending on demand
- ◆ **Global optimization of network manufacturing cost**
  - Cost optimized for the final network aimed