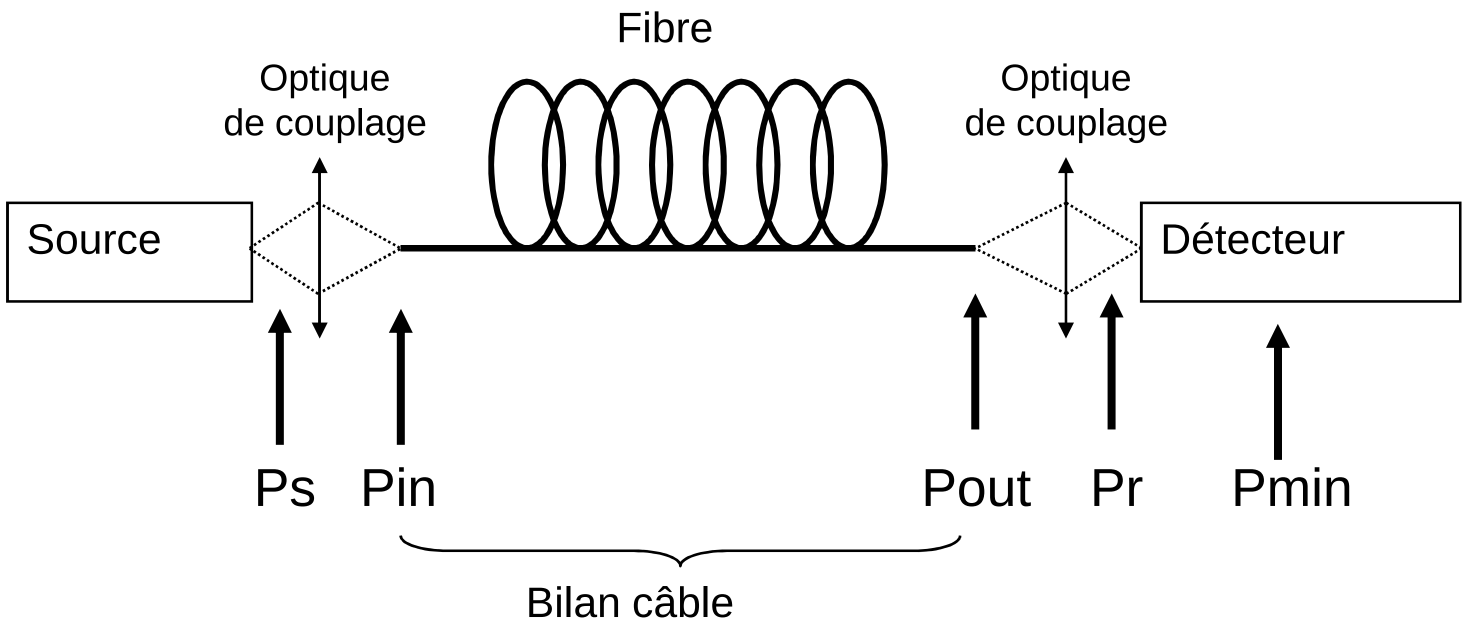
Part 3
Wavelength Division Multiplexing WDM

- ♦ **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



Marge système = Pr - Pmin

Diagramme du bilan en puissance

Pertes en ligne (dB)

Perte de connexion en entrée

Atténuation du câble
ou bilan câble

Dynamique du récepteur

Perte de connexion en sortie

Marge système

Rapport S/B min pour un TEB donné

Niveaux de puissance optique (dBm)

Ps = puissance de la source

Pin = puissance injectée dans la fibre

Psat = puissance de saturation du détecteur

Pout = puissance sortant de la fibre

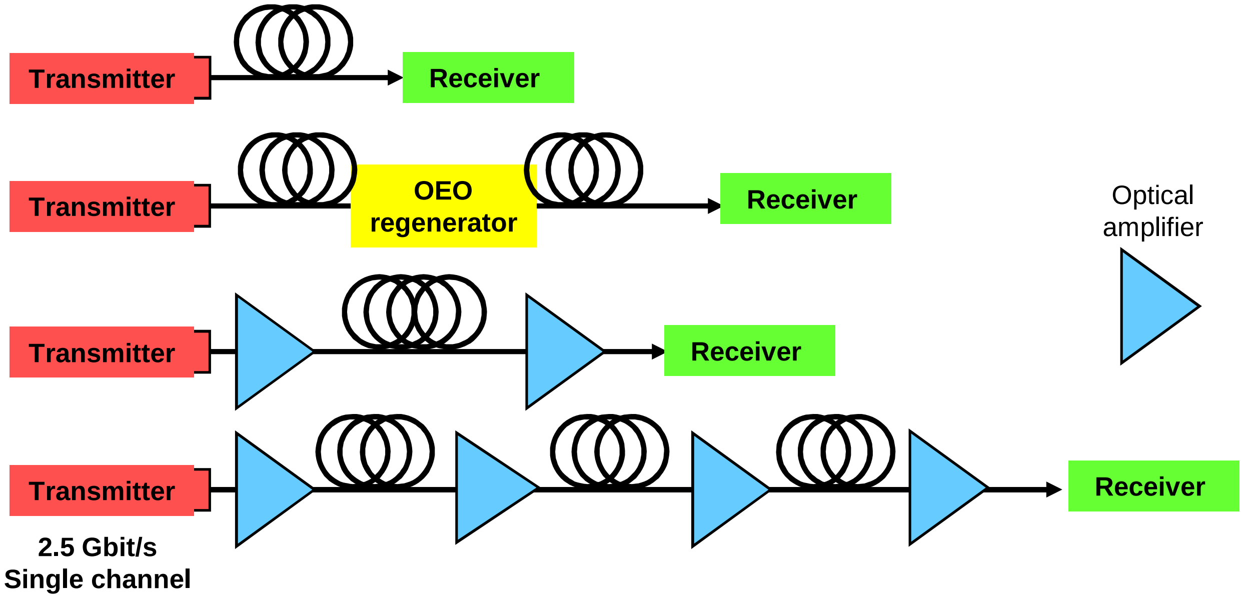
Pr = puissance reçue par le détecteur

Pmin = puissance minimum détectable

Pb = puissance de bruit

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



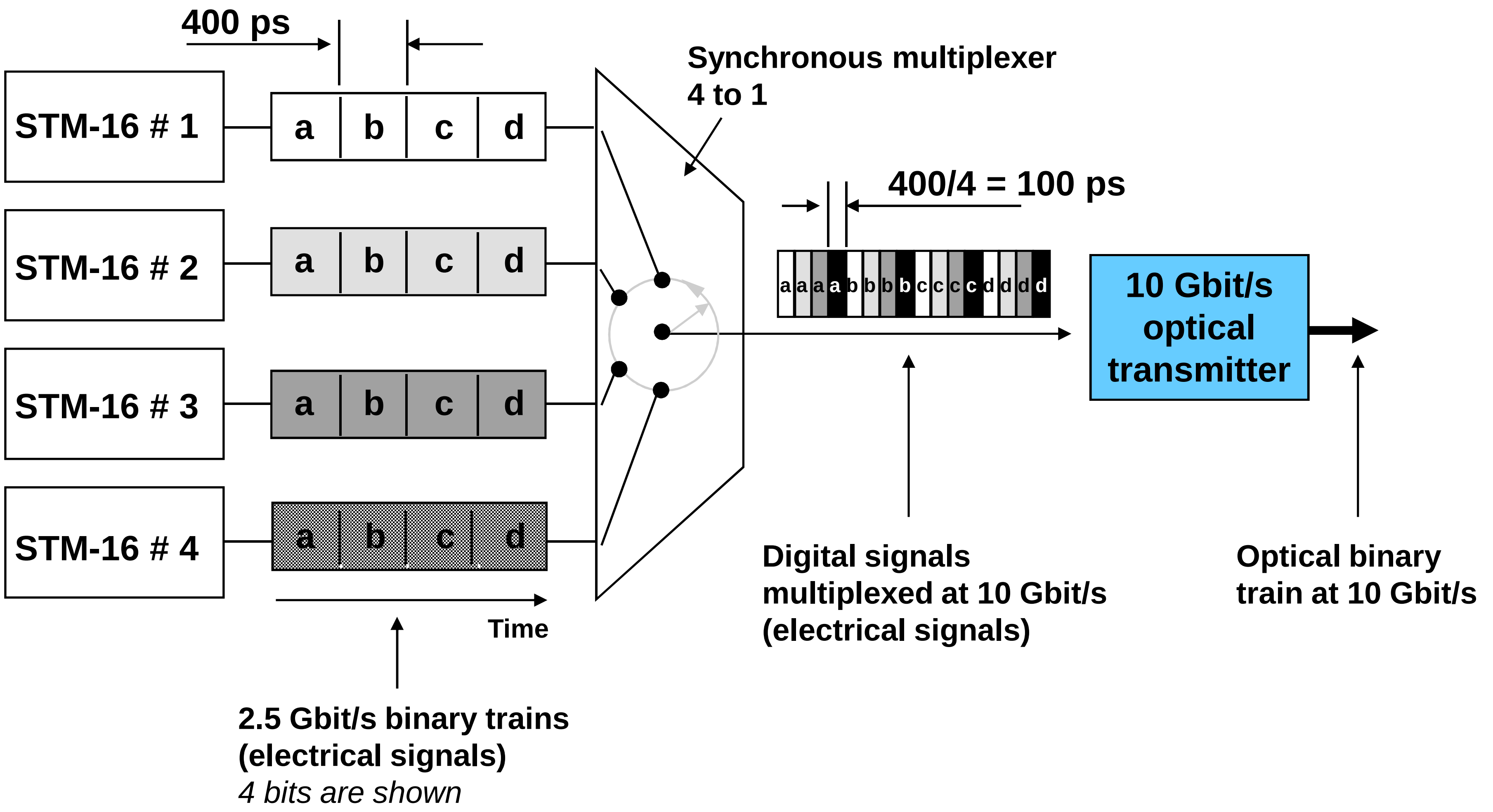
And then ?.....

- 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

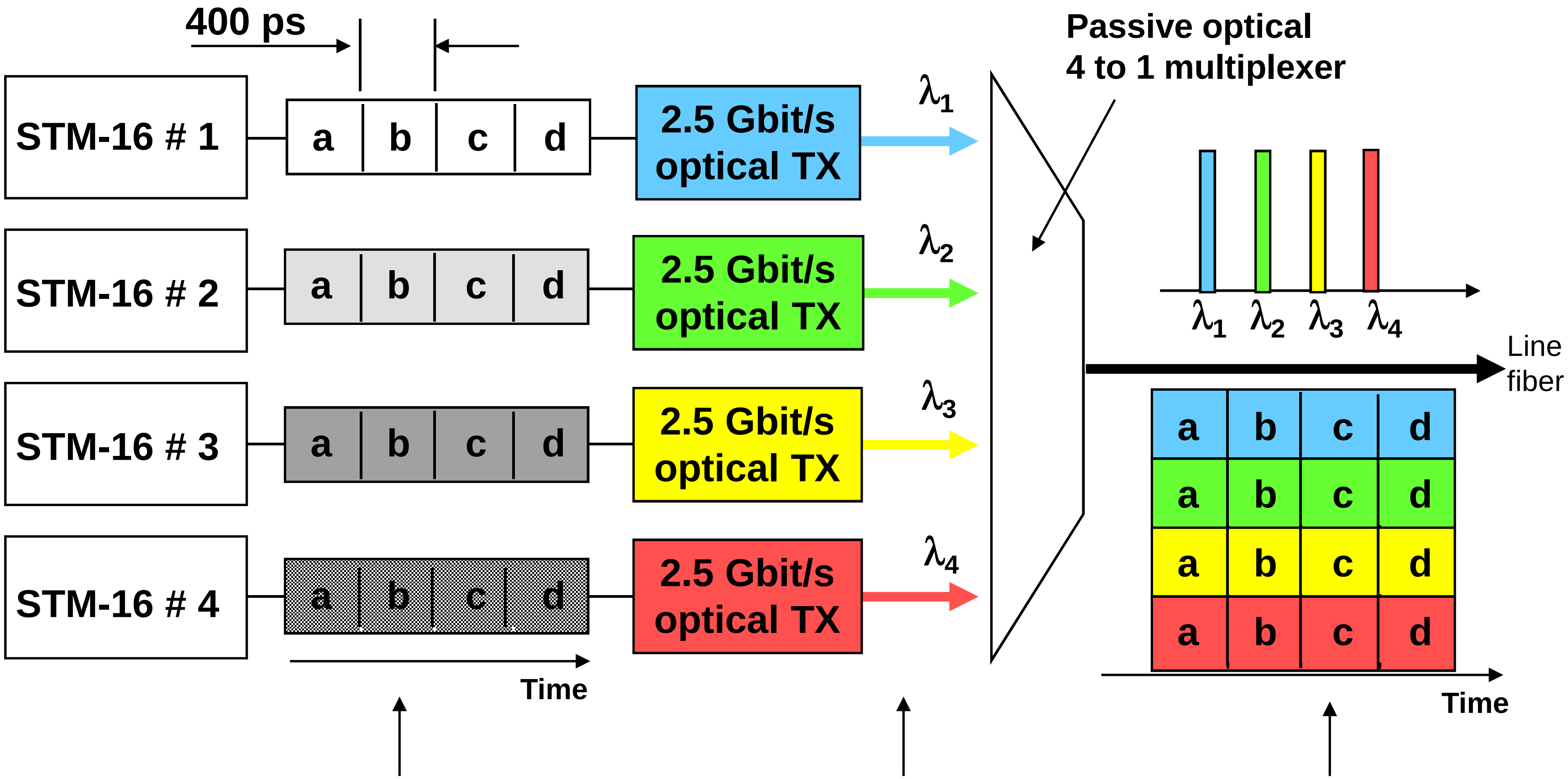
Current status of terrestrial networks

- **Systems already installed and operational**
  - **Based on standard singlemode SMF G.652 type fiber used at 1550 nm**
    - Minimum fiber attenuation (≈ 0.2-0.3 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 ≈ 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



2.5 Gbit/s binary trains (electrical signals)
4 bits are shown

2.5 Gbit/s optical binary trains
(1 per fiber)

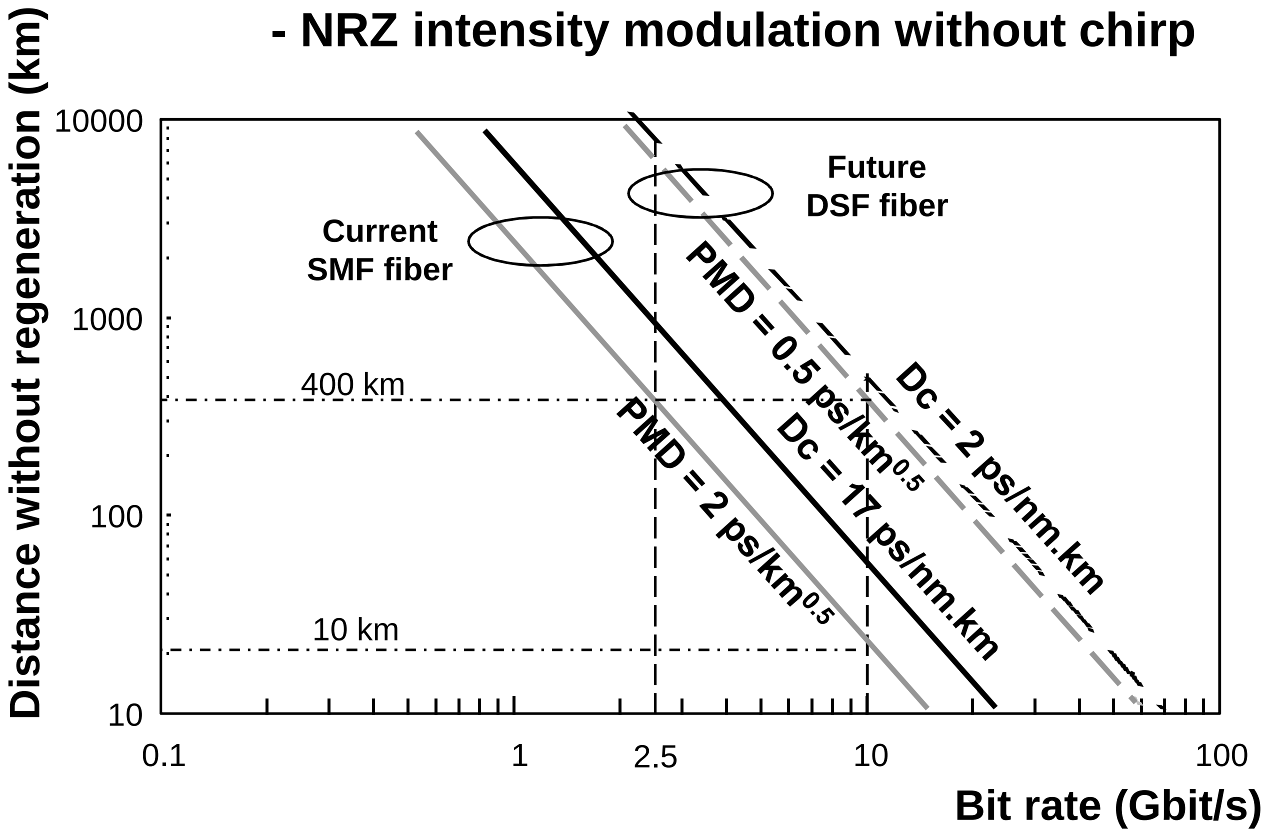
2.5 Gbit/s optical binary trains
(4 per fiber)

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 µm**
    - Can stand the high chromatic dispersion of this fiber for bit rates up to 2.5 Gbit/s

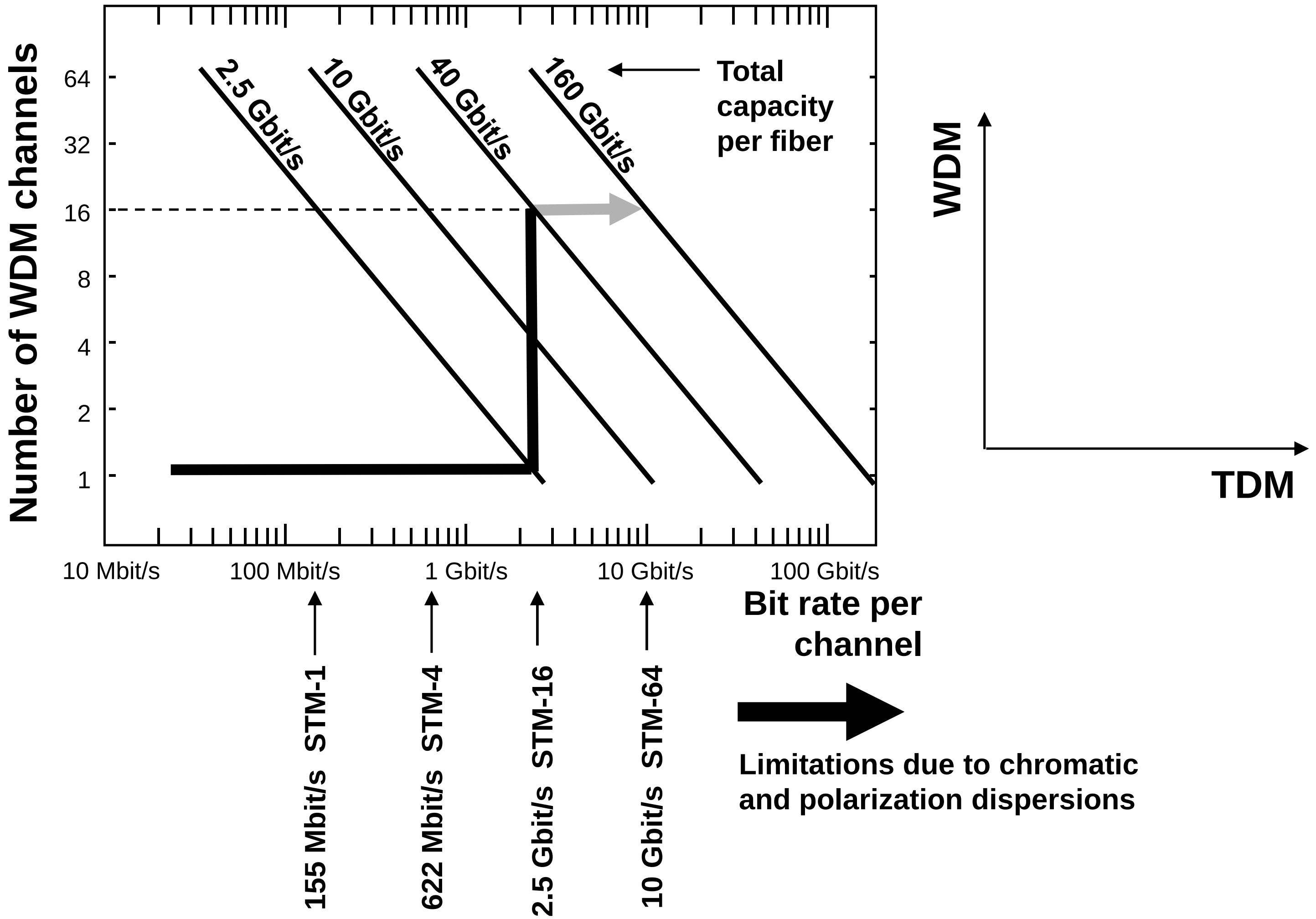
- **Constraints of WDM**
  - **Sensitivity to non-linear effects generated into the line fiber (FWM)**
  - **Specificities of optical amplifiers used (gain flatness…)**
  - **Very high wavelength stability of the sources (laser diodes) used**

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

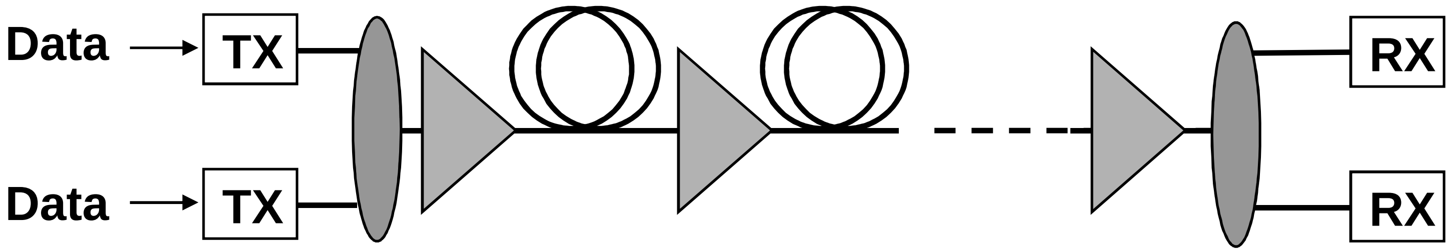


PMD = Polarization Mode Dispersion

Strategy for increasing capacity per fiber



Technical advantages of WDM
for high capacity terrestrial systems



- **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

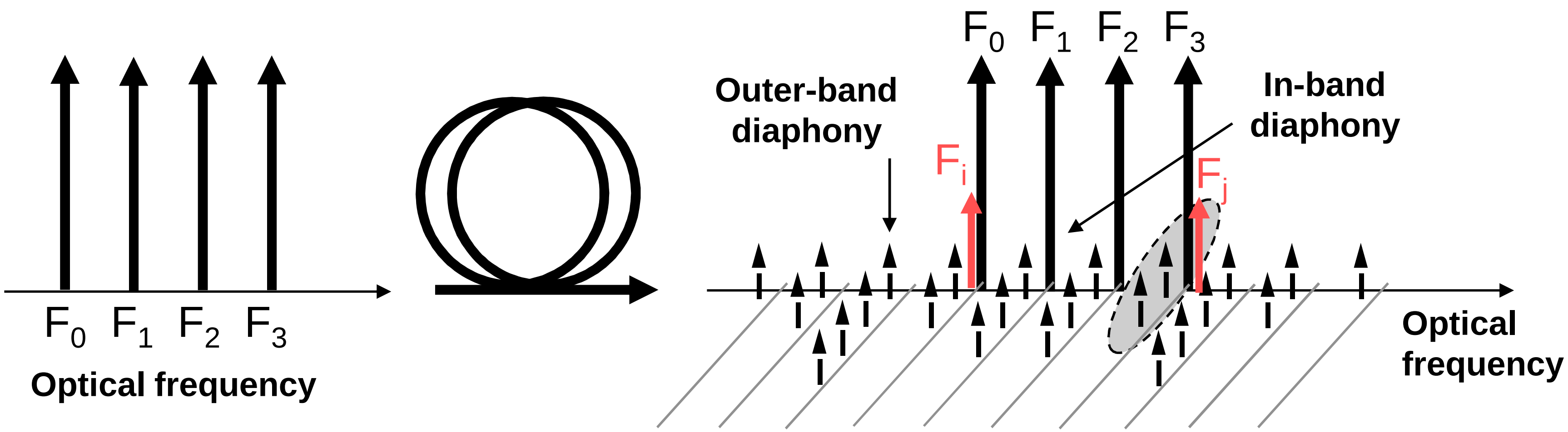
- **Transparency to bit rates and standards, modularity, (N+1) type protection**

Propagation in WDM systems
Non-linear effects in fibers

- **WDM systems : simultaneous propagation of several optical carriers into the same fiber**
- **Linear regime ($P_{channel}$ < 0 dBm = 1 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 3rd order intermodulation :
  - $F_i = F_1 - \Delta F \quad F_j = F_2 + \Delta F$ 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

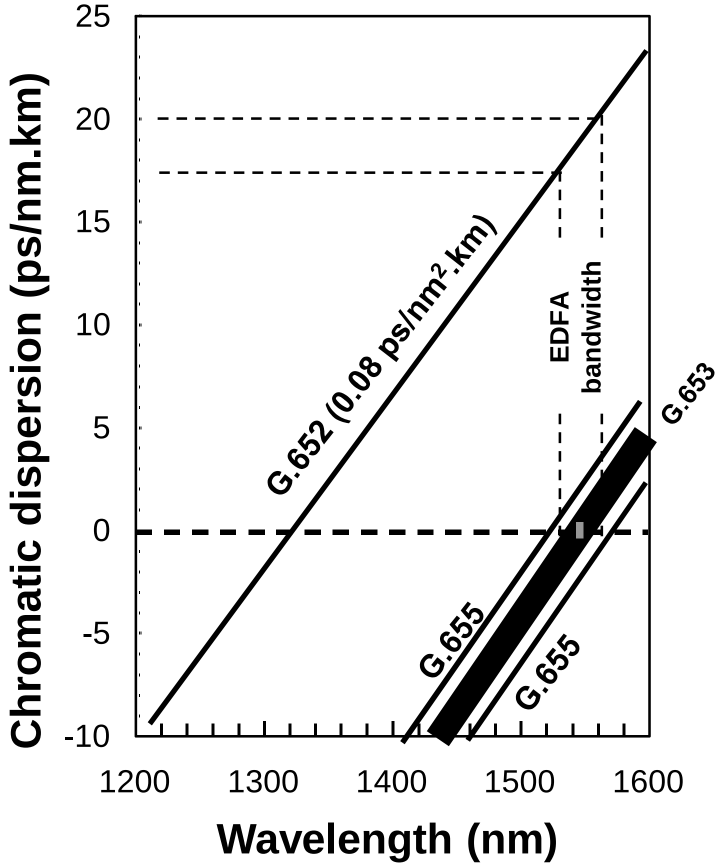
- **FWM efficiency decreases with :**
  - **A low optical power per channel (< 0 dBm)**
  - **A large frequency spacing between adjacent channels (> 50 GHz)**
  - **A judicious layout of the channel polarization (orthogonal polarizations between adjacent channels)**
  - **The use of new type of fibers showing a λ_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

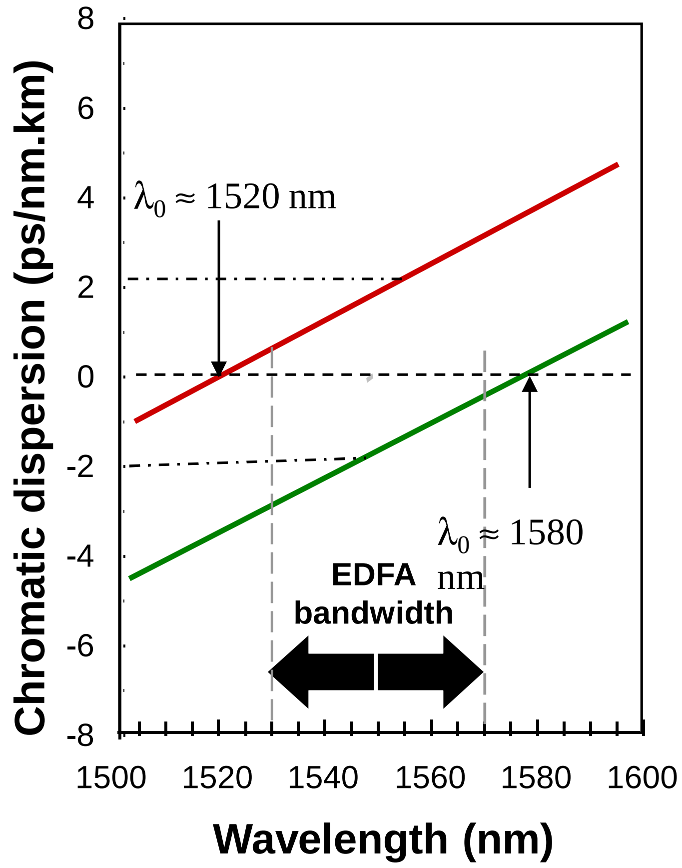
Standard SMF, DSF and NZ-DSF fibers

- **Standard SMF fiber (G.652)**
  - Zero chromatic dispersion wavelength (λ_0) between 1290 and 1320 nm
  - Typical attenuation : 0.25 dB/km
- **DSF dispersion-shifted fiber (G.653)**
  - λ_0 between 1530 and 1570 nm
  - Typical attenuation : 0.28 dB/km
- **NZ-DSF non-zero dispersion-shifted fiber (G.655)**
  - λ_0 around 1520 or 1580 nm
  - The most promizing fiber ?
  - Beginning to be deployed in the USA



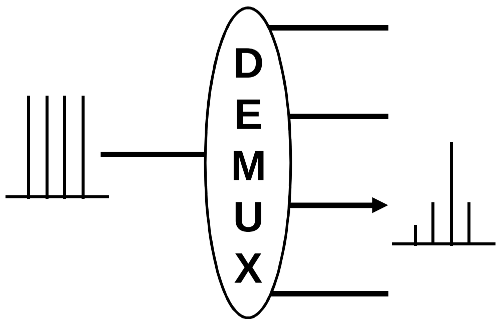
NZ-DSF fibers for WDM systems

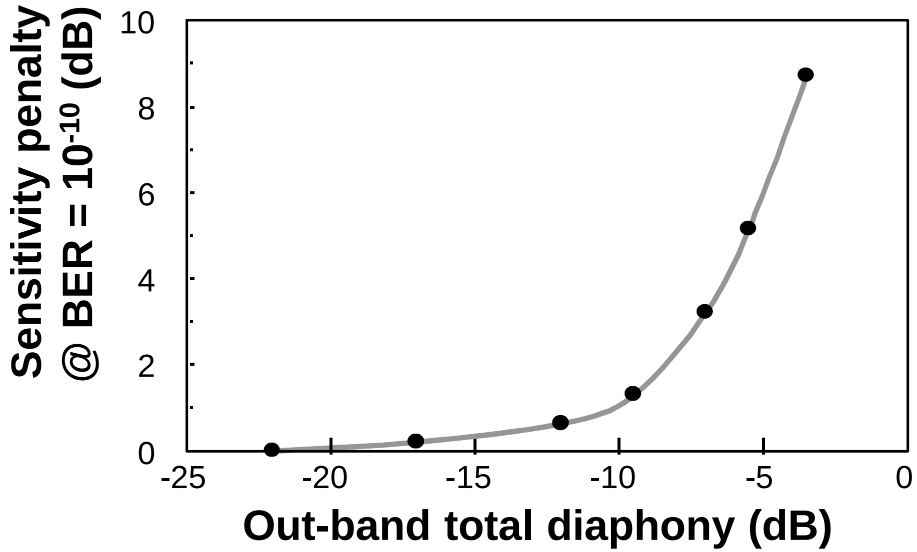
- **Dispersion shifted fiber (DSF) G.653 :**
  - λ_0 between 1530 and 1570 nm
  - Worst case : λ_0 inside the multiplex range
- **Development of a new fiber with λ_0 outside the multiplex range defined by the EDFA amplification range :**
  - NZ-DSF (G.655)
- **Two alternatives:**
  - $\lambda_0 \approx 1520$ nm @ D ≈ +2 ps/nm.km
  - $\lambda_0 \approx 1580$ nm @ D ≈ -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 dB for 8 channels with flat spectrum at demultiplexer input**
- **$\text{Diaphonie}_{\text{channel}}$ < -25 dB for 8 channels after the amplifiers chain**

Considerations regarding channel spacing

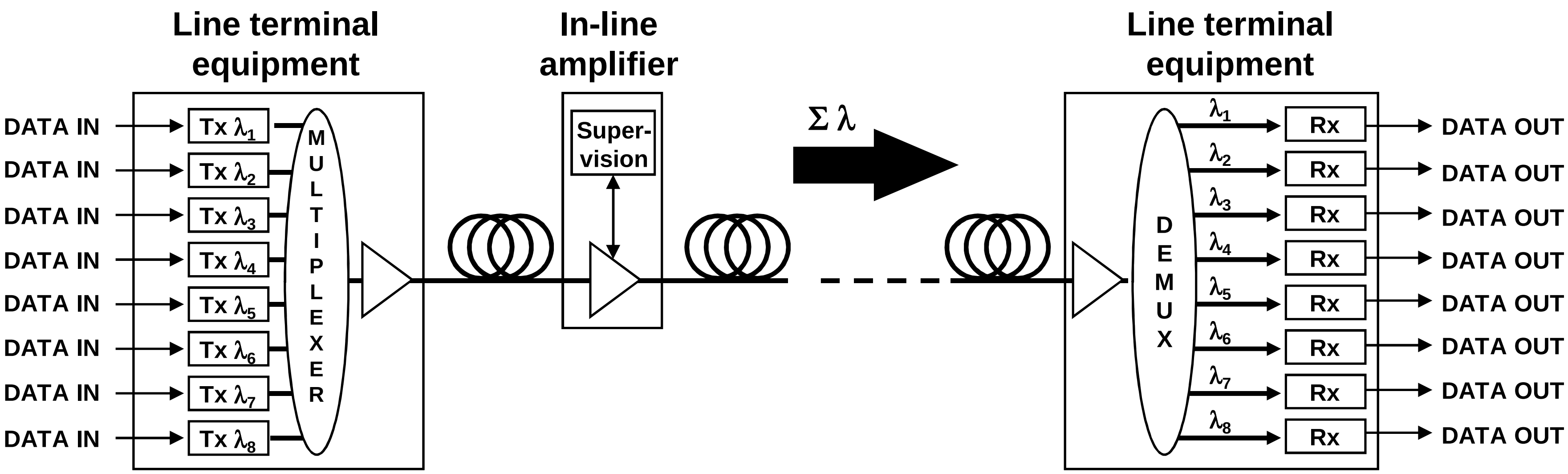
- ♦ **Lower limit :**
  - Wavelength stability of the sources requiring complex and expensive control circuits
  - Technological constraints on the demultiplexer (diaphony and wavelength stability)
  - Non-linear effects in the line fiber (four wave mixing FWM)

- ♦ **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)

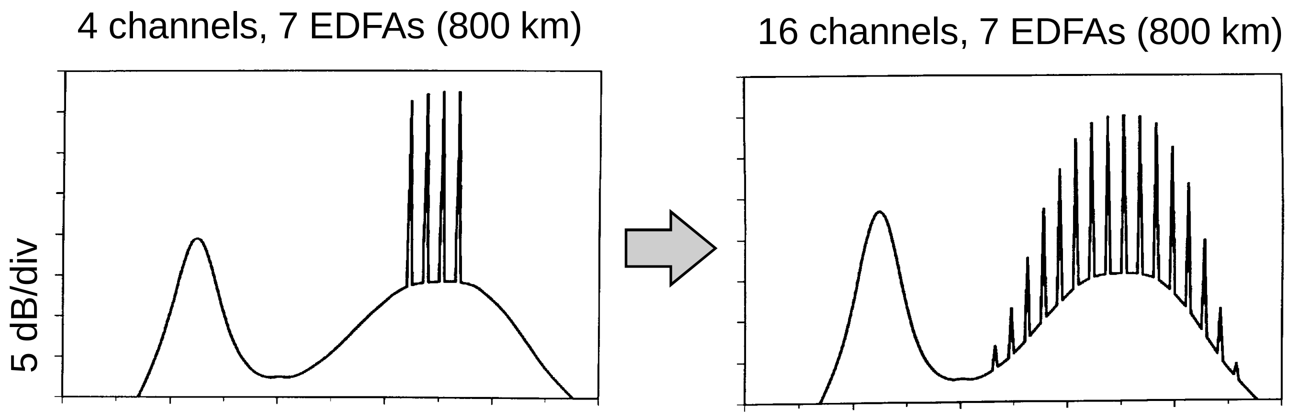
WDM amplification
Requirements and specificities



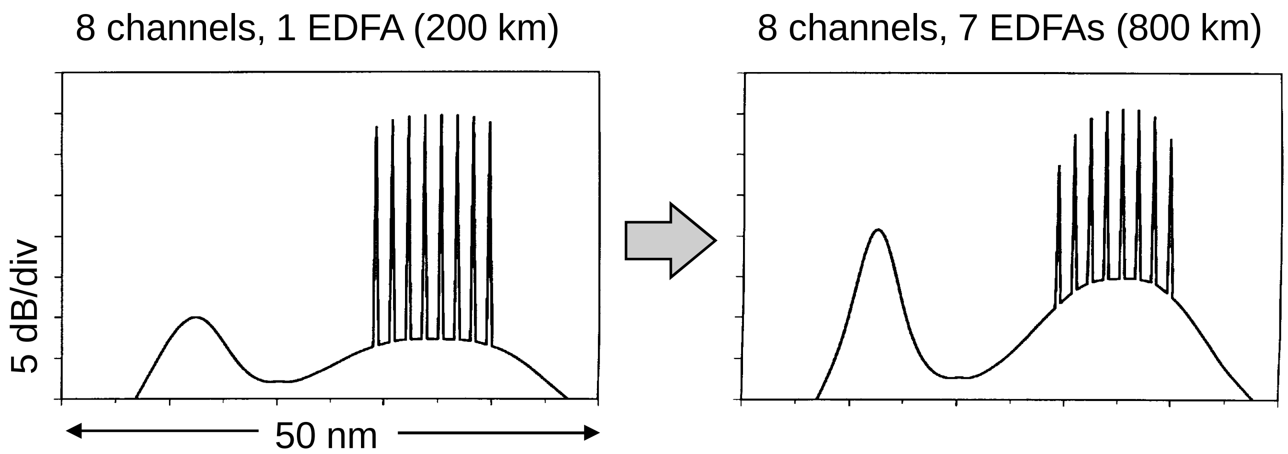
- **WDM optical amplifiers must show :**
  - **A uniform per channel output power taking into account**
    - Receiver dynamics
    - Non-linear effects in the line fiber
  - **A uniform S/N ratio**
    - For keeping a good bit error rate (BER) performance whatever the number of channels

WDM amplification
Limitation due to self-filtering gain curve G(λ)

Increasing the number of channels :

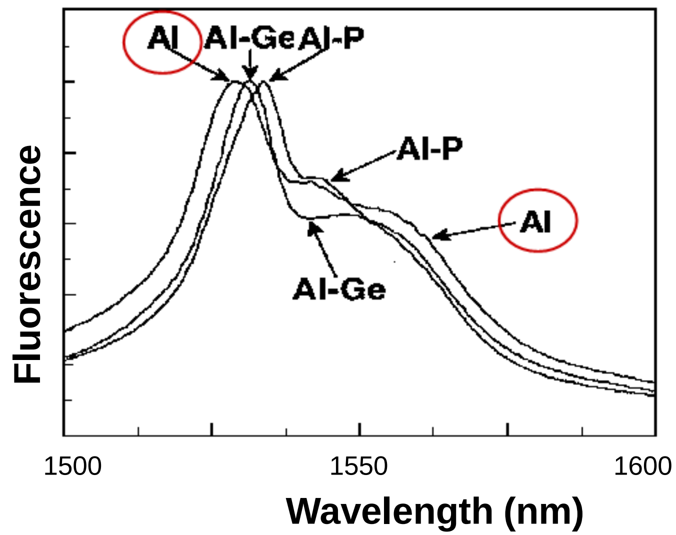


Increasing the number of amplifiers :



Gain curve flatness
Co-dopants and new host materials

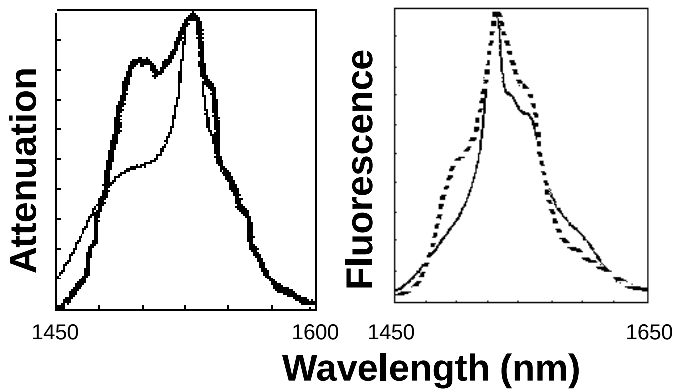
Various co-dopants in silica-based Erbium doped fibers
-> Interest of Al doping



Silica and fluoride glass used as host materials for Erbium doping

Erbium doped silica fiber

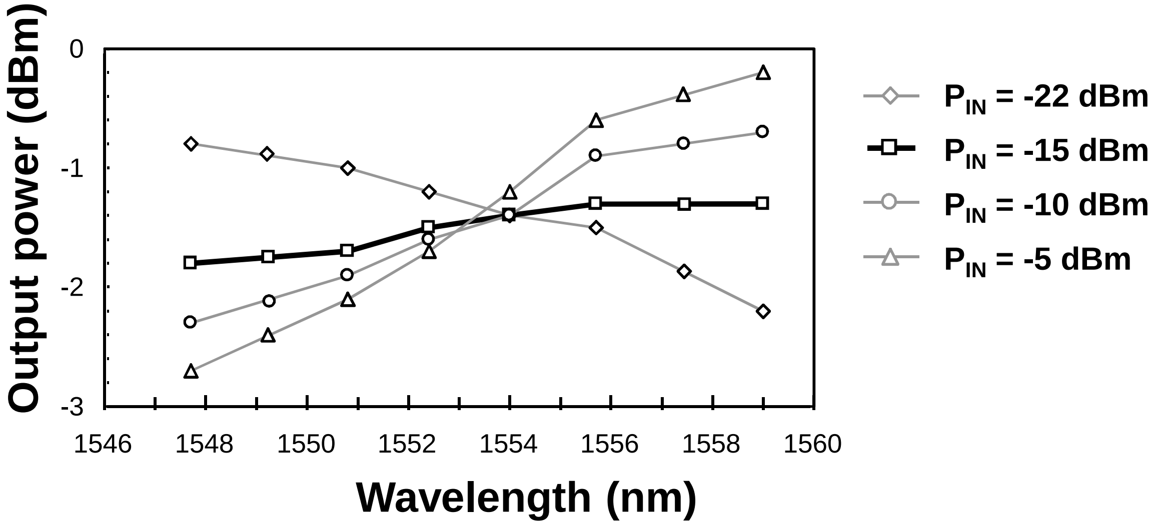
Erbium doped fluoride glass fiber



Gain curve flatness
The input power impact

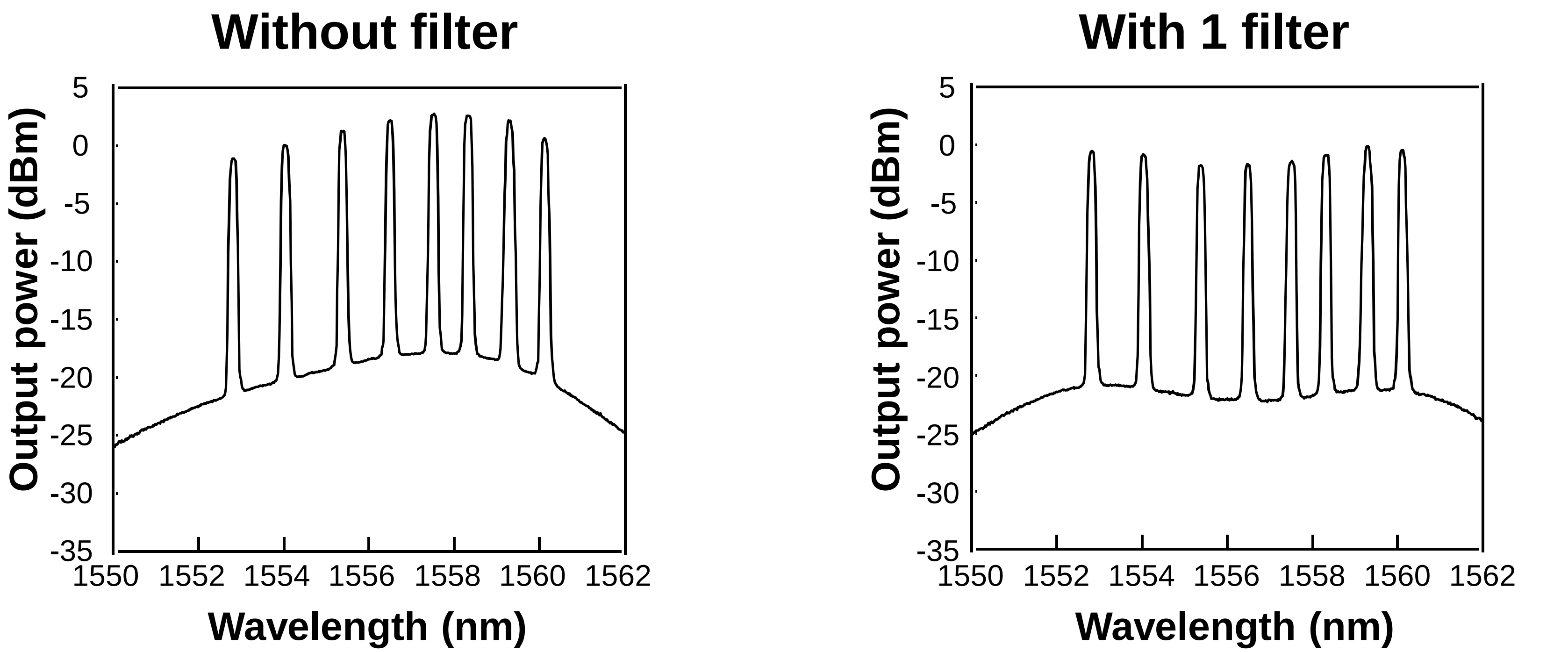
Influence of the input power
(constant pump power)

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

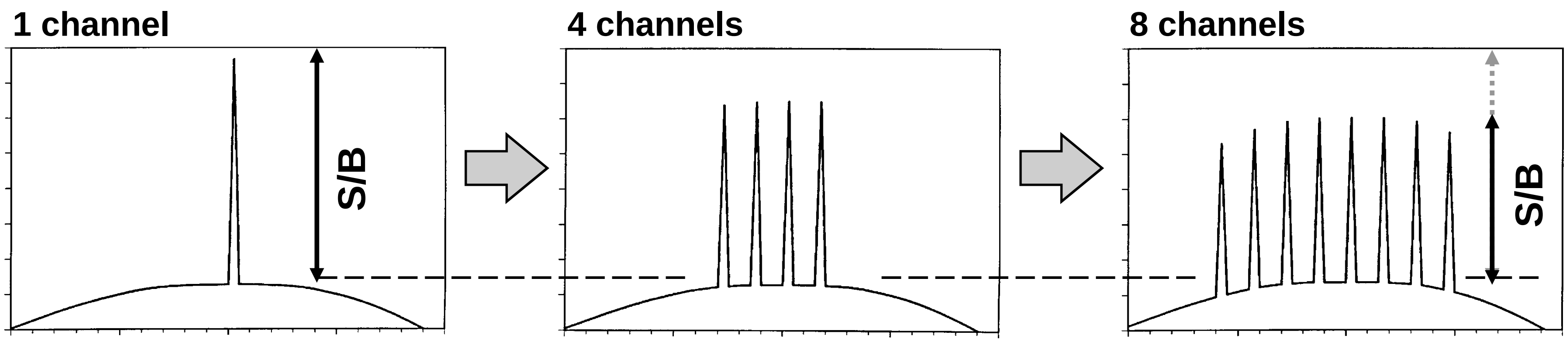
Chain of 10 EDFAs : impact of the gain flattening filter



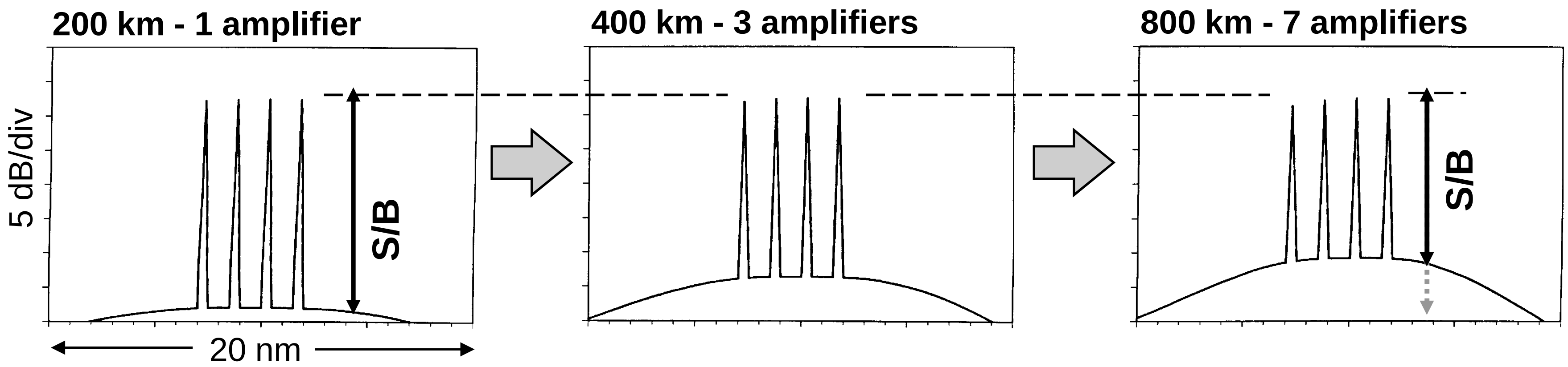
Limitations of the WDM amplification

Noise considerations

Increasing the number of channels :



Increasing the number of in-line amplifiers :



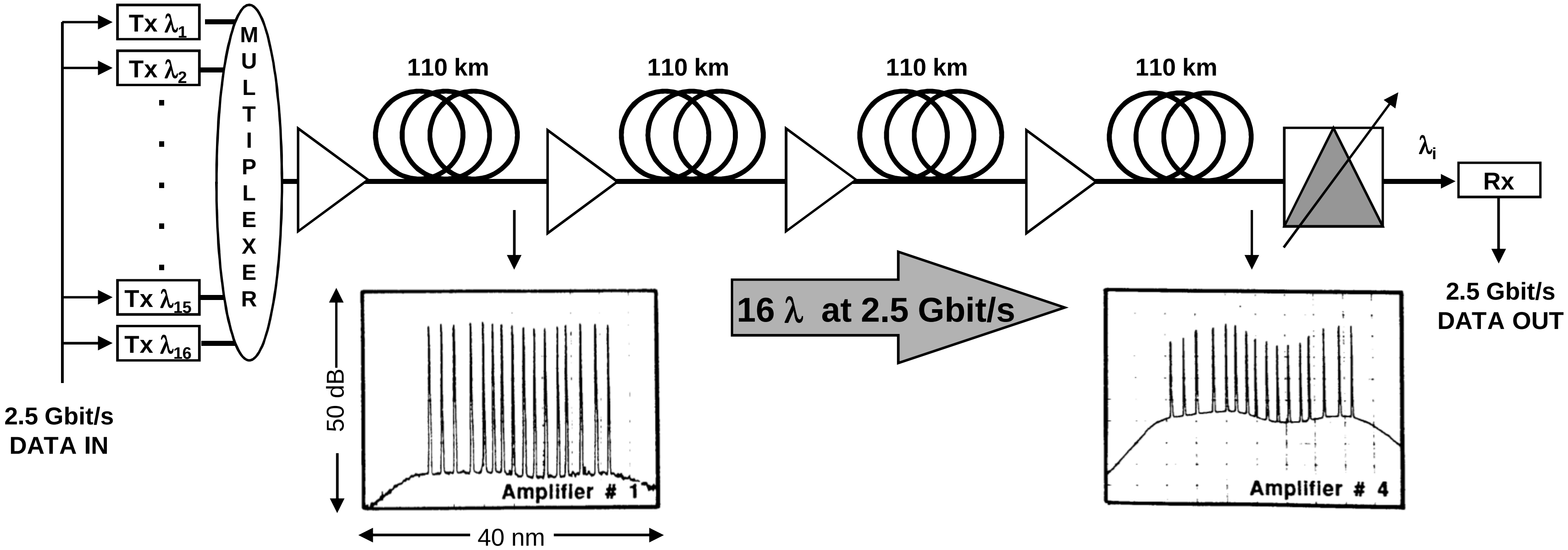
Practical implementation of WDM optical amplifiers

- **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**

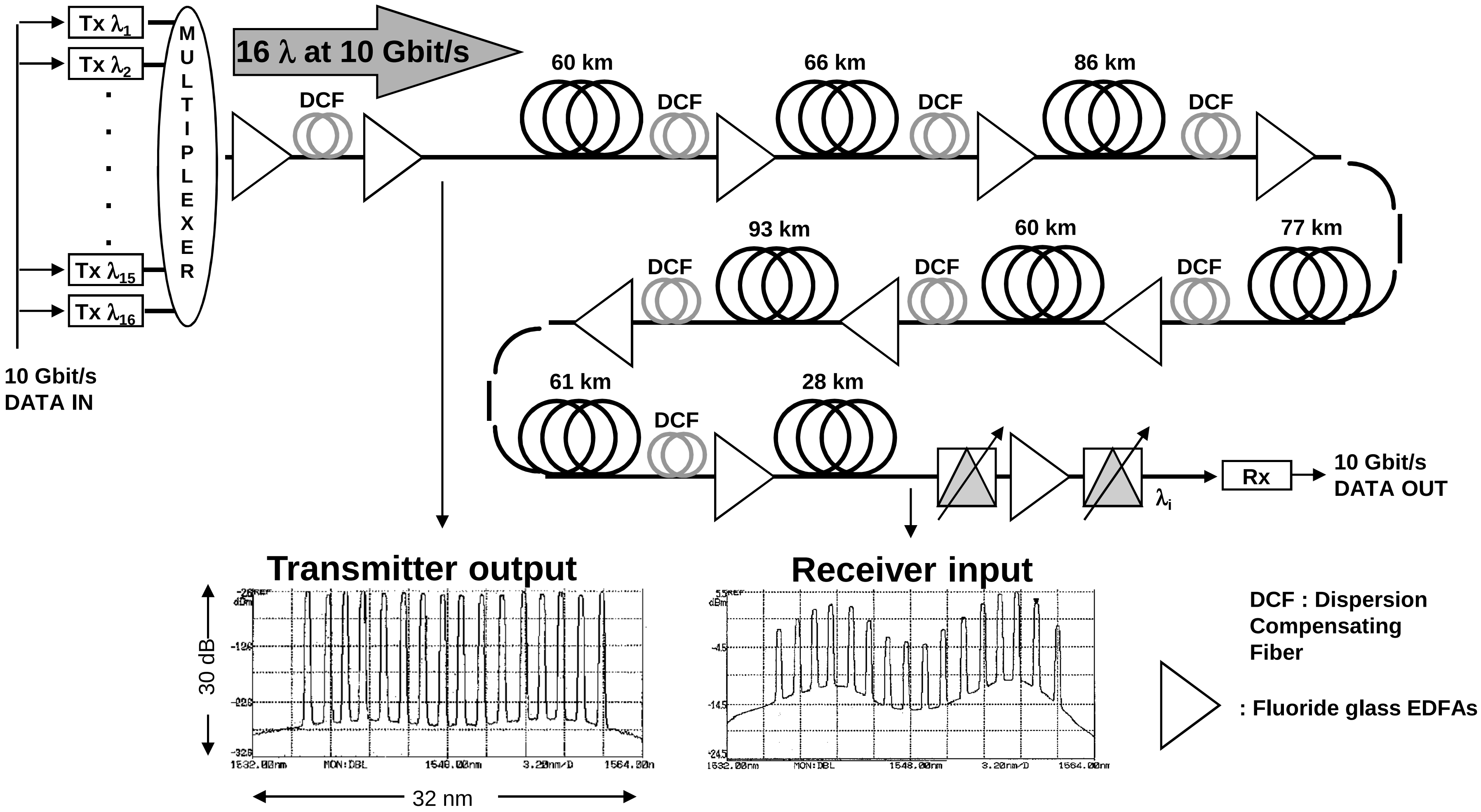
- **Overall input power can vary :**
  - **Non uniform in-line loss between amplifiers**
  - **Variation of the number of channels due to :**
    - Progressive increase of the number of channels (system upgrade)
    - Possible defect of a transmitter electronic board
    - Wavelength routing networks integrating OADM (optical add-drop multiplexing) function

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

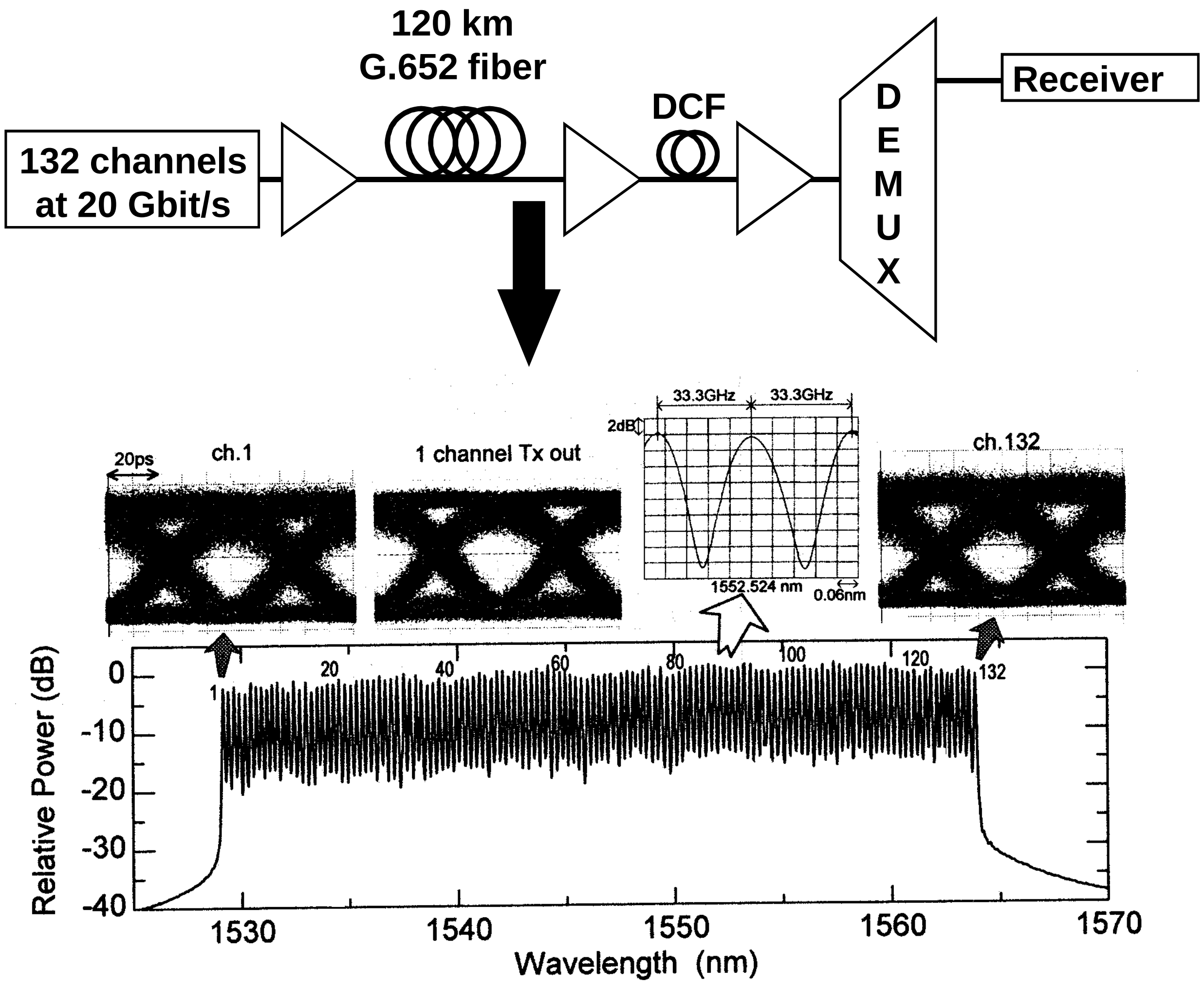


- **Use of wide band fluoride glass amplifiers :**
  - **16 WDM channels, 200 GHz spacing, i.e. 1.6 nm (1533.7 ⇨ 1558.2 nm)**
- **2.5 Gbit/s per channel bit rate :**
  - **Overall capacity of 40 Gbit/s with excellent tolerance to chromatic and polarization dispersions**

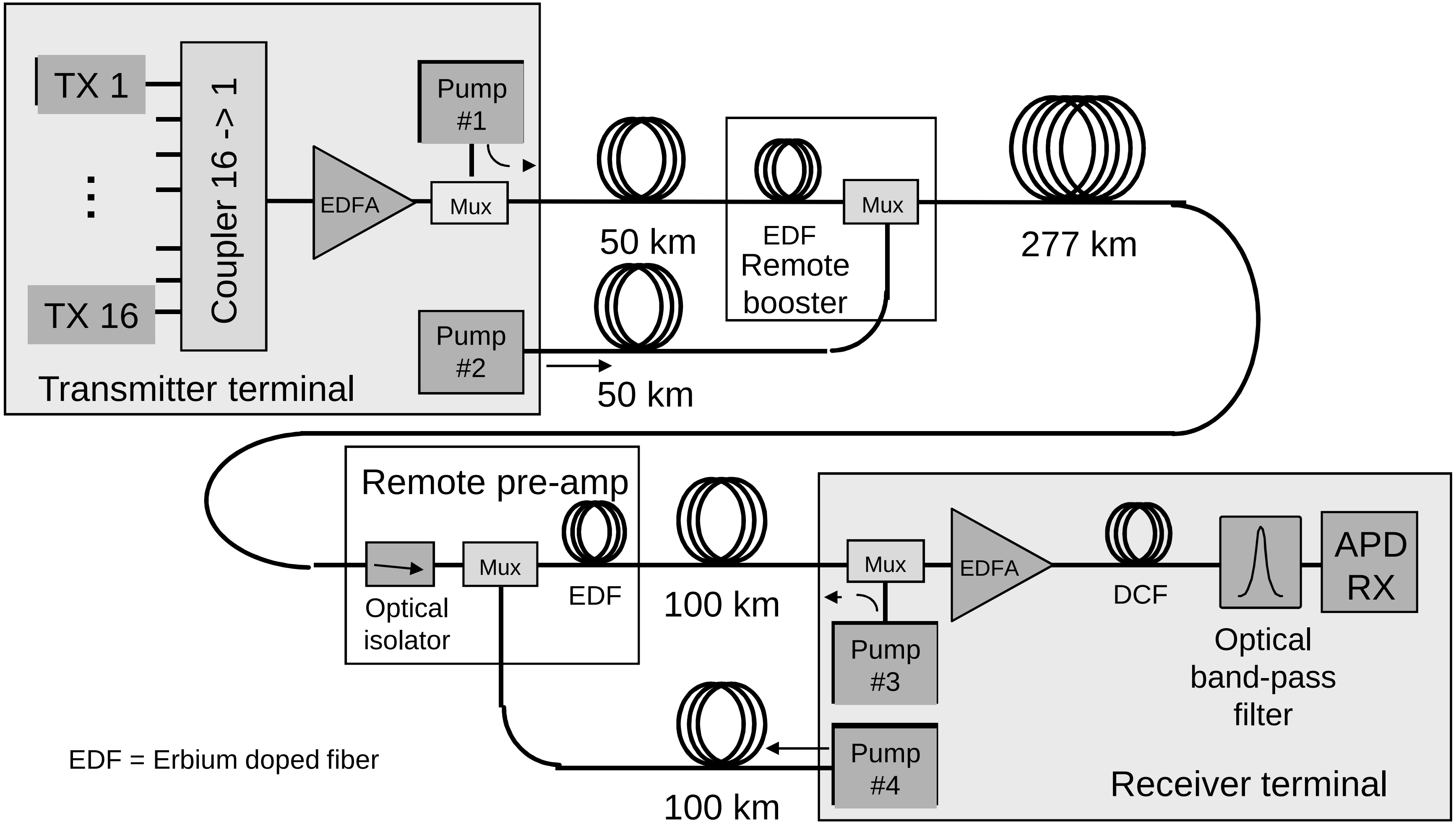
Transmission of 16 channels at 10 Gbit/s over 531 km of standard G.652 fiber



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

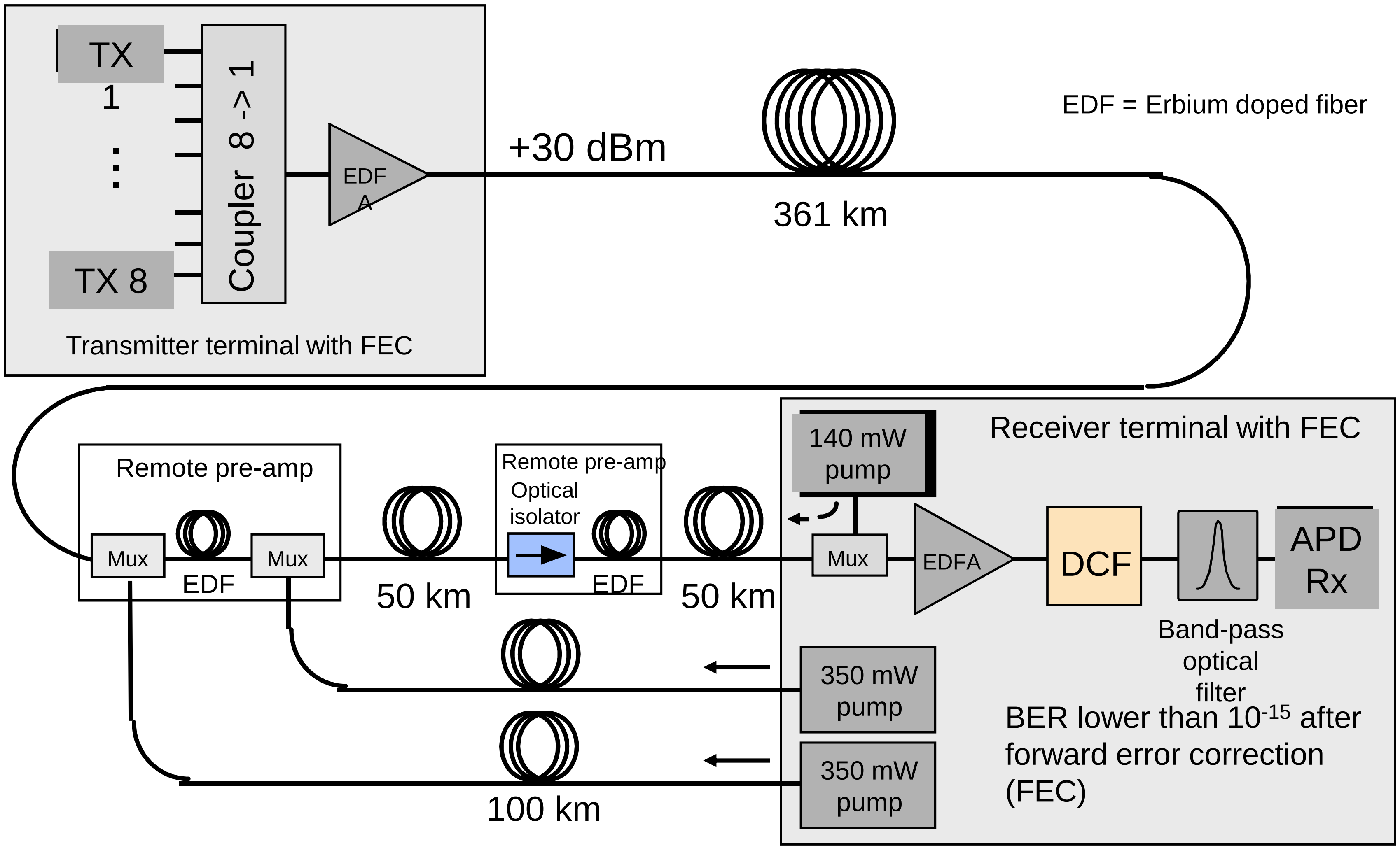


Demonstration of a non-regenerated WDM system of 16 x 2.5 Gbit/s over 427 km



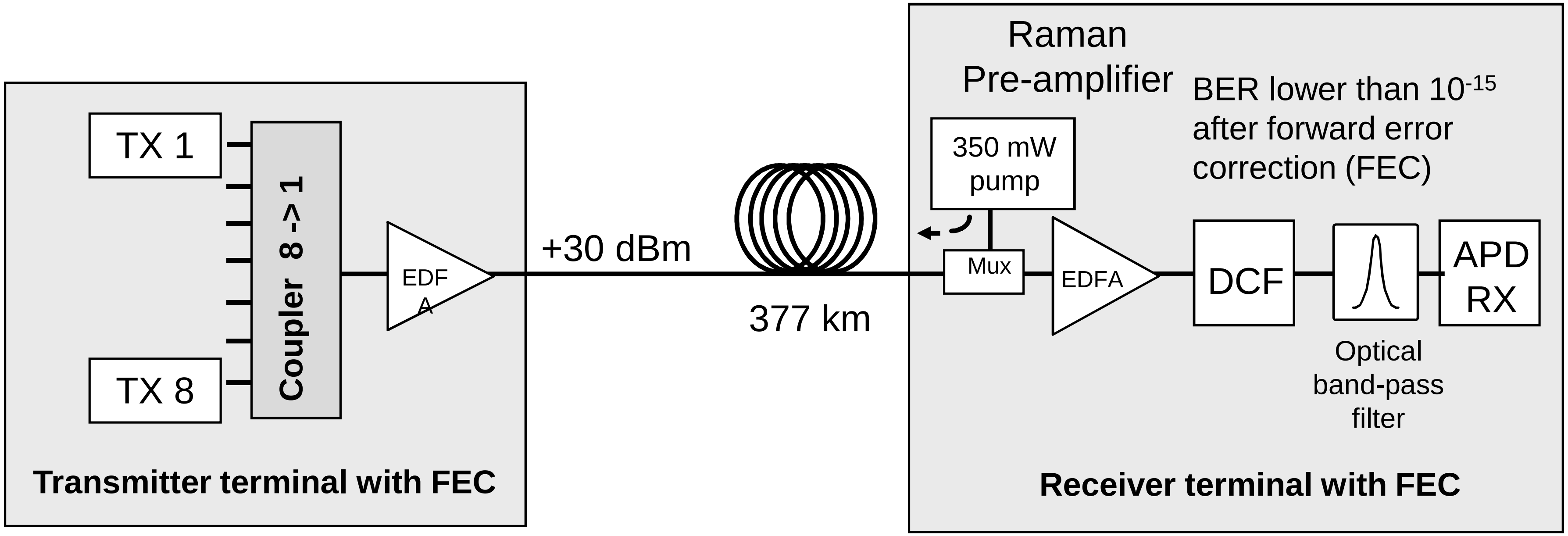
EDF = Erbium doped fiber

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

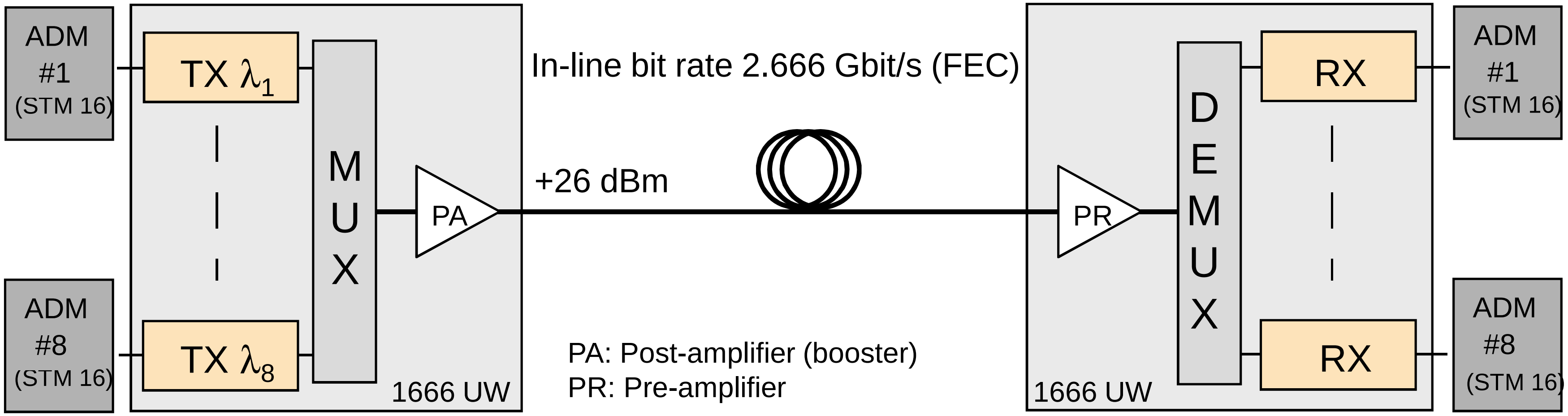


BER lower than 10^{-15} after forward error correction (FEC)

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

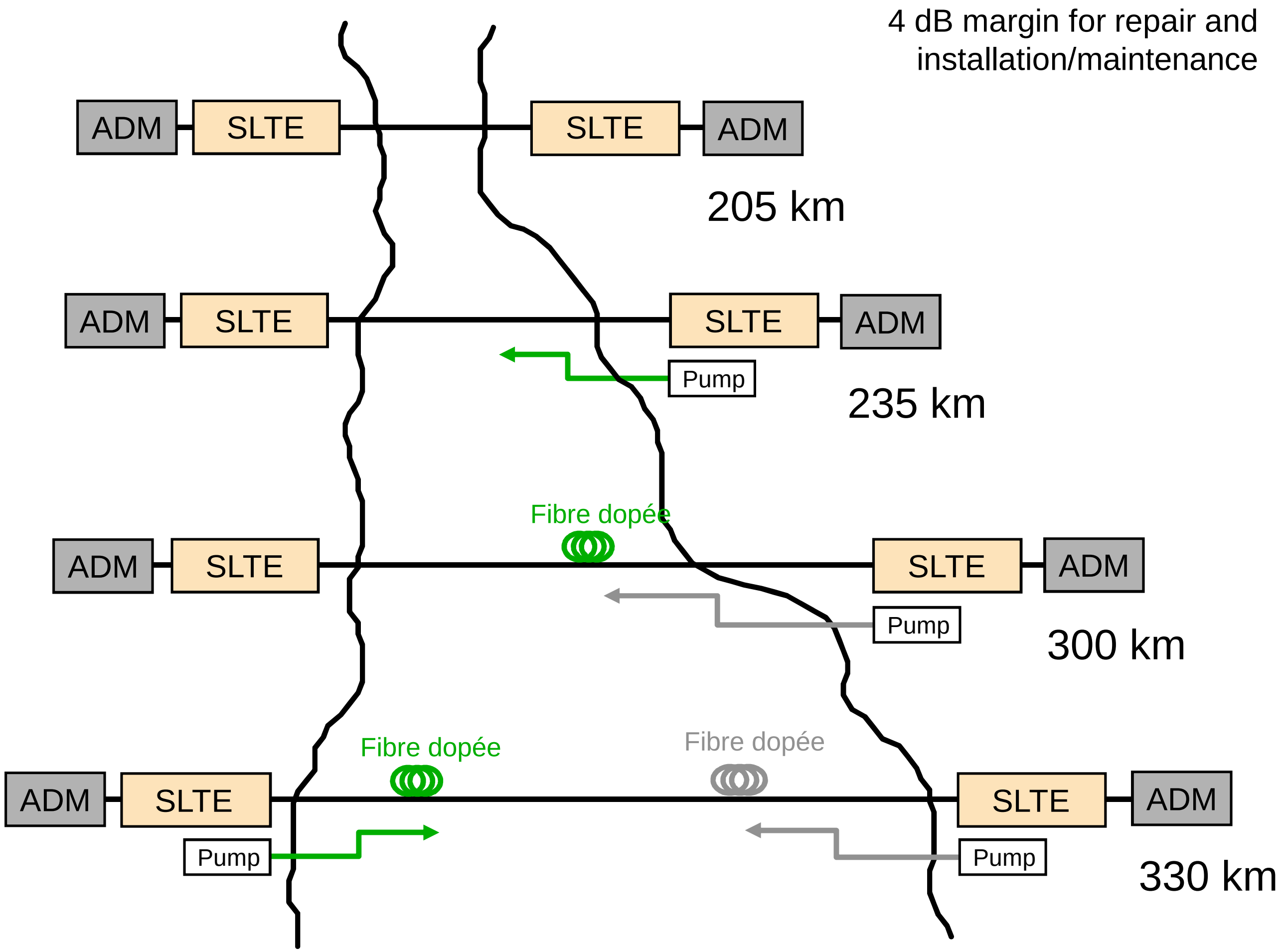
Operational 16 x 2.5 Gbit/s submarine systems

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

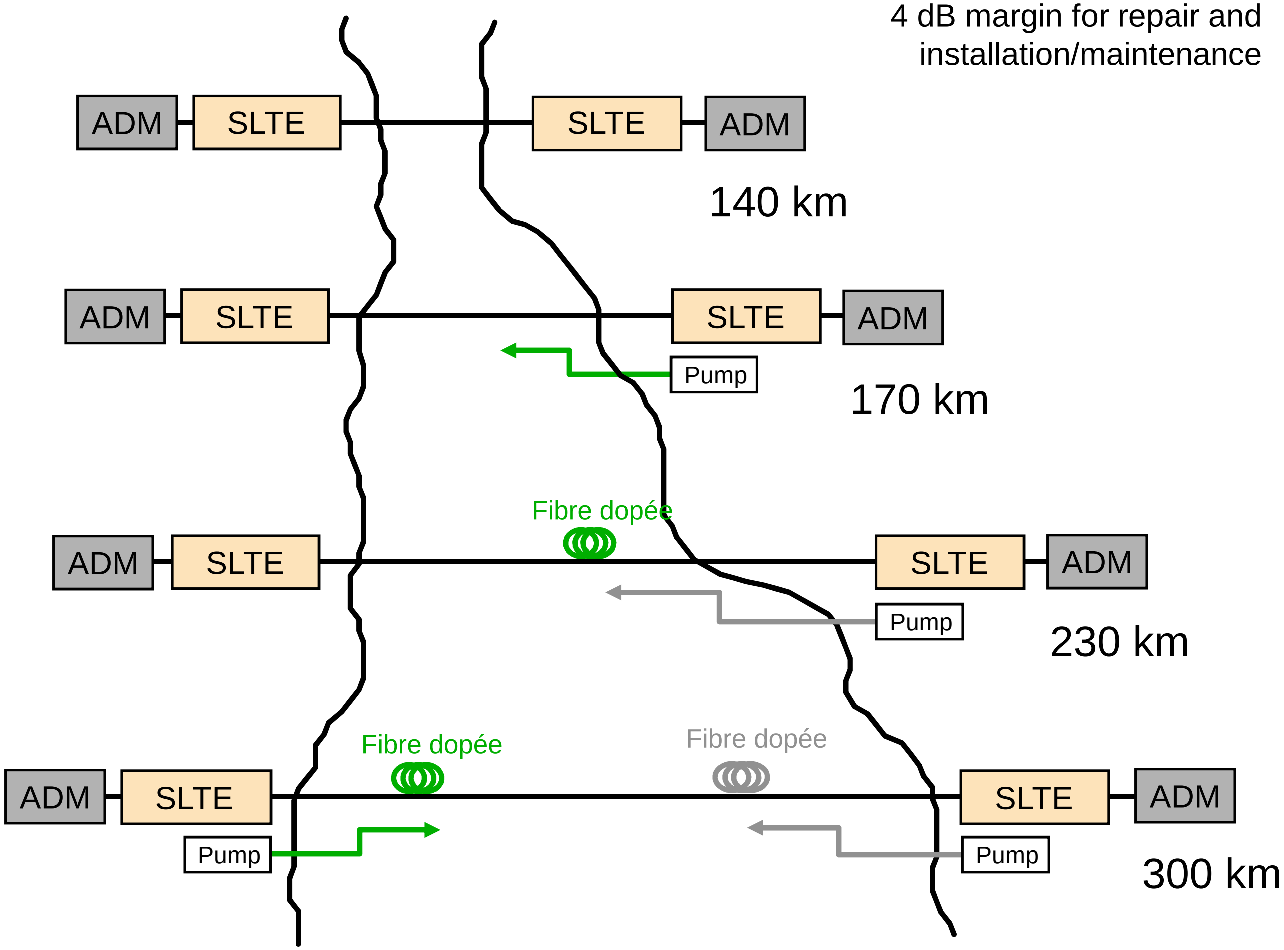
4 dB margin for repair and installation/maintenance

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

- **ITU-T recommandations**
  - G series « Systems and transmission supports, systems and digital networks »
- **Correspondance with CEI classes**

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

WDM system standardization
Allocation of central frequencies

- **Since October 1998, the alloocation of central frequencies of WDM channels is defined by the G.692 ITU-T recommandation :**

  - **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 λ = 1550 nm)

    - Dense WDM (DWDM) : 50 GHz spacing (around 0.4 nm at λ = 1550 nm)

    Currently under study :

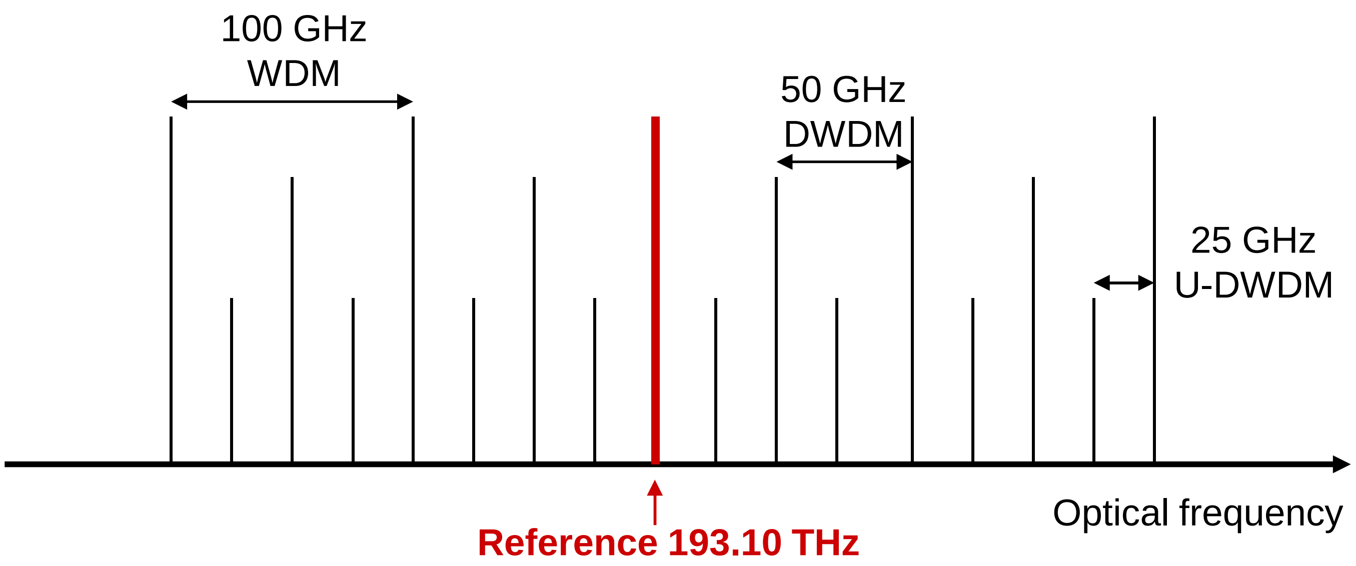
    - Ultra-dense WDM (U-DWDM) : 25 GHz spacing (0.2 nm at λ = 1550 nm)

    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 Δf and wavelength spacing $\Delta\lambda$**

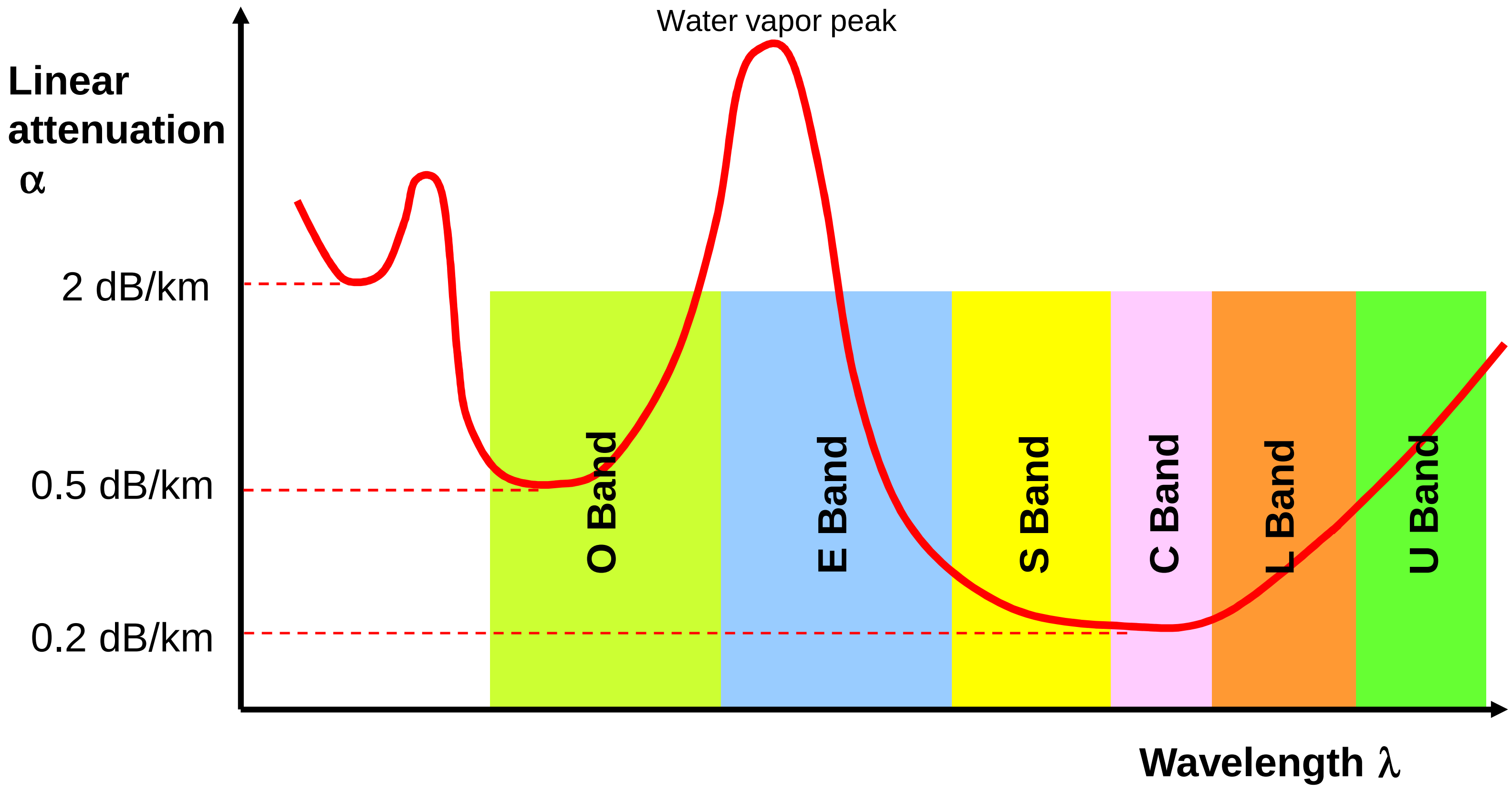
$$\Delta\lambda = \frac{\lambda^2}{c}\Delta f$$

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

- **Representation of spectral bands on the attenuation curve of silica based (SiO_2) fibers**



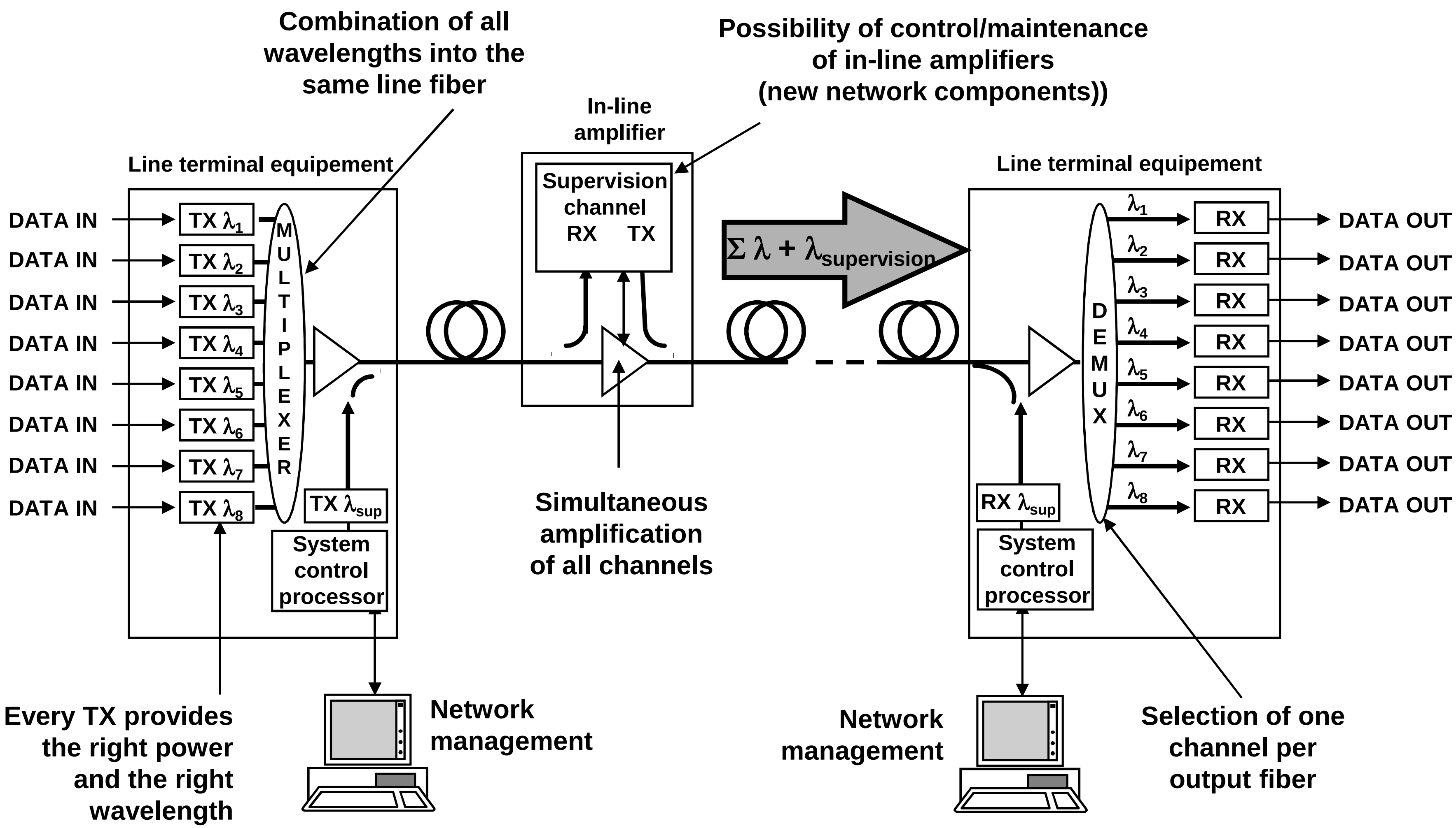
Potential number of channels in the 1.5 µm wavelength range

- **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

- **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