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Optical Transport Tutorial

4 February 2015

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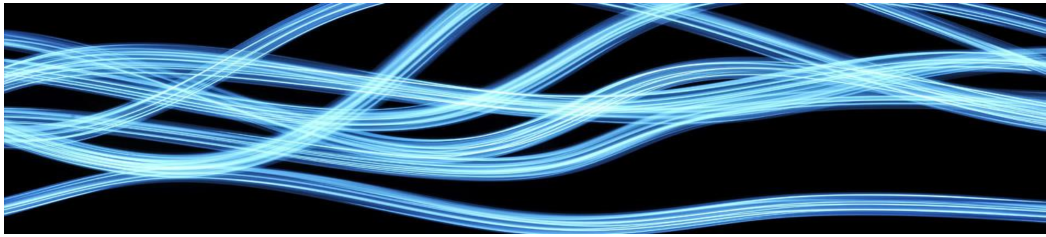
- Wavelength Division Multiplexing (WDM) Basics

Optical Transport Basics

Optical Fiber Transport

- Optical fibers have outstanding features enabling long-haul, high-capacity transport:
  - Low attenuation
  - Huge bandwidth
  - Allow Wavelength Division Multiplexing (WDM)



- However:
  - Attenuation is not equal to zero due to absorption and scattering.
  - Optical pulses are degraded/distorted by:
    - Chromatic dispersion
    - Polarization Mode Dispersion (PMD)
    - Non-linear effects:
      - Self-Phase Modulation (SPM)
      - Cross-Phase Modulation (XPM)
      - Four-Wave Mixing (FWM)
      - Stimulated Rayleigh Scattering (SRS)
      - Stimulated Brillouin Scattering (SBS)
  - Most of these effects are wavelength dependent.

Some Fiber Wavelength-Dependent Effects

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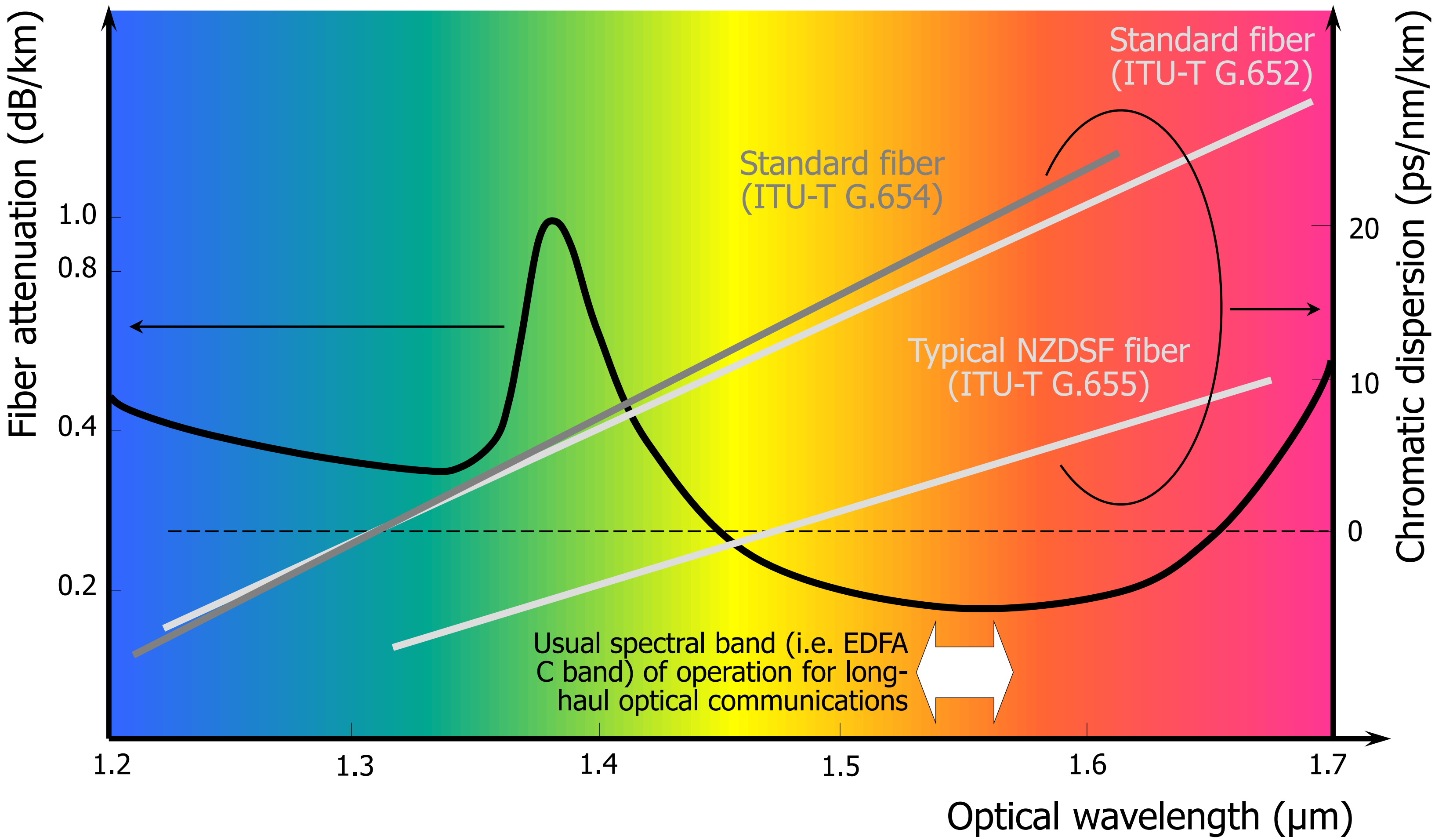
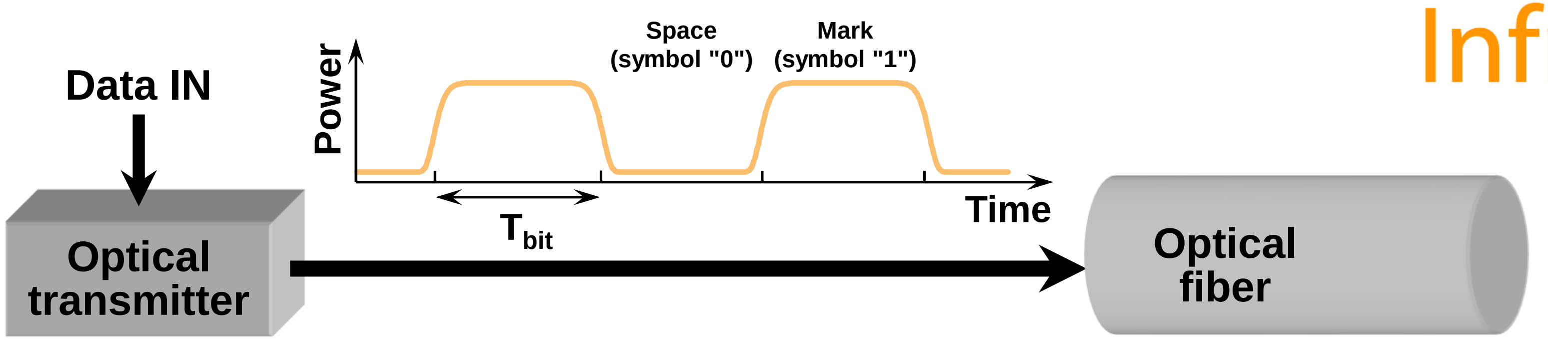


Optical Transmitter and Transport



- Optical communications were based till 2010 only on digital binary signals:
  - Series of On/Off power-modulated pulses generated by an optical transmitter and launched into the optical fiber
  - Most common modulation format: NRZ (Non Return to Zero) On/Off keying

- The optical signal leaves the optical transmitter at full strength but as it travels many kilometers down the fiber, it falls victim to the absorption, dispersion, distortion and scattering effects.

➔ Regeneration or amplification is needed.

Regeneration

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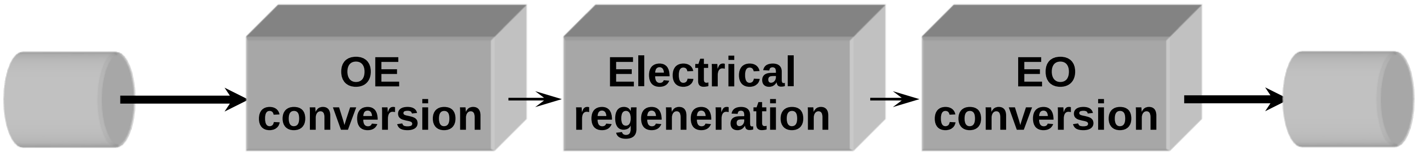
- Regeneration required when the signal has been degraded to the extent that it is difficult to determine accurately whether any bit is a one or a zero.

- Regeneration process based on Optical-Electrical-Optical (OEO) conversion:
  - Conversion of the incoming optical signal to an electrical signal (OE conversion)
  - Regeneration of the electrical signal with high-speed electronics
  - Conversion back to an optical signal for transmission of a cleaned-up version of the original optical signal along the next span (EO conversion)



  - Per wavelength process: one regenerator per wavelength

Digital Pulse Patterns And Eye Diagrams (For NRZ Signals)

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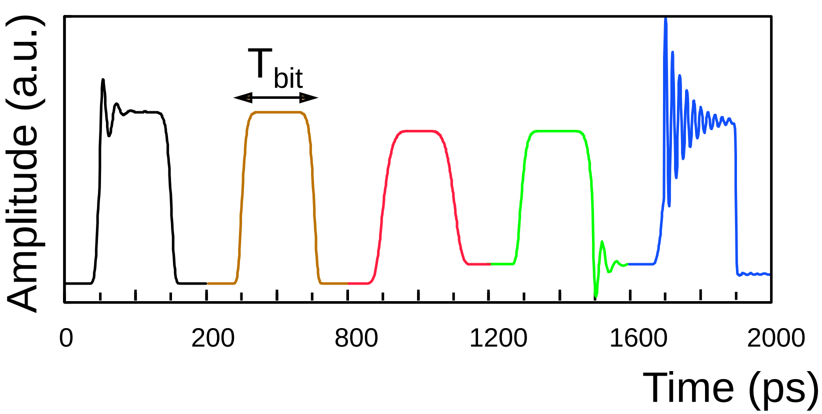
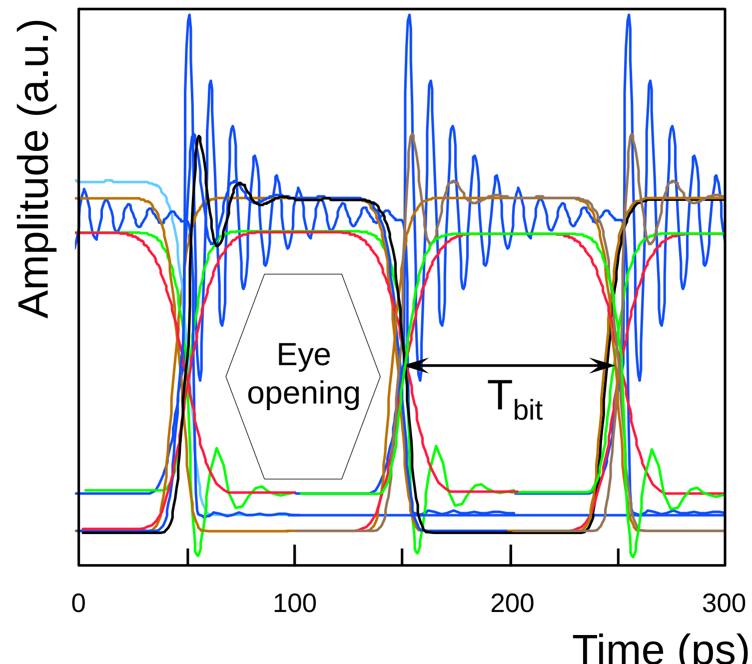
- Eye diagram: oscilloscope display in which a digital data signal from a receiver is repetitively sampled and applied to the vertical input, while the data rate (clock signal) is used to trigger the horizontal sweep.

Synchronization by
the 10-Gbit/s data frame:
➔ Pulse pattern



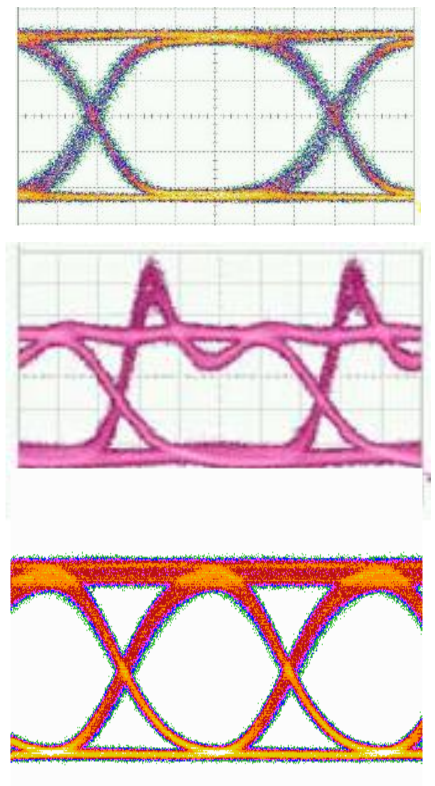
Synchronization by
the 10-Gbit/s clock signal:
➔ Eye diagram



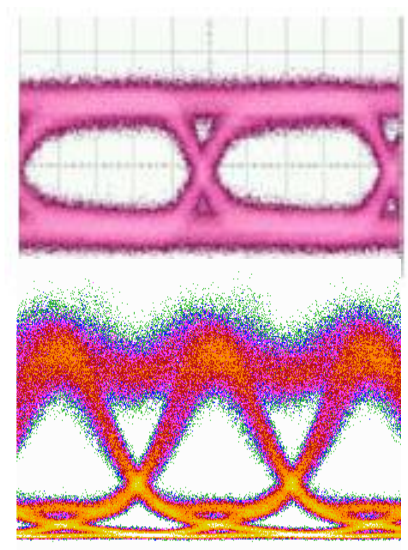
Digital Pulse Patterns
And Eye Diagrams (For NRZ Signals)

- Examples of eye diagrams for NRZ (Non Return to Zero) On/Off keying modulation format

On the transmit side

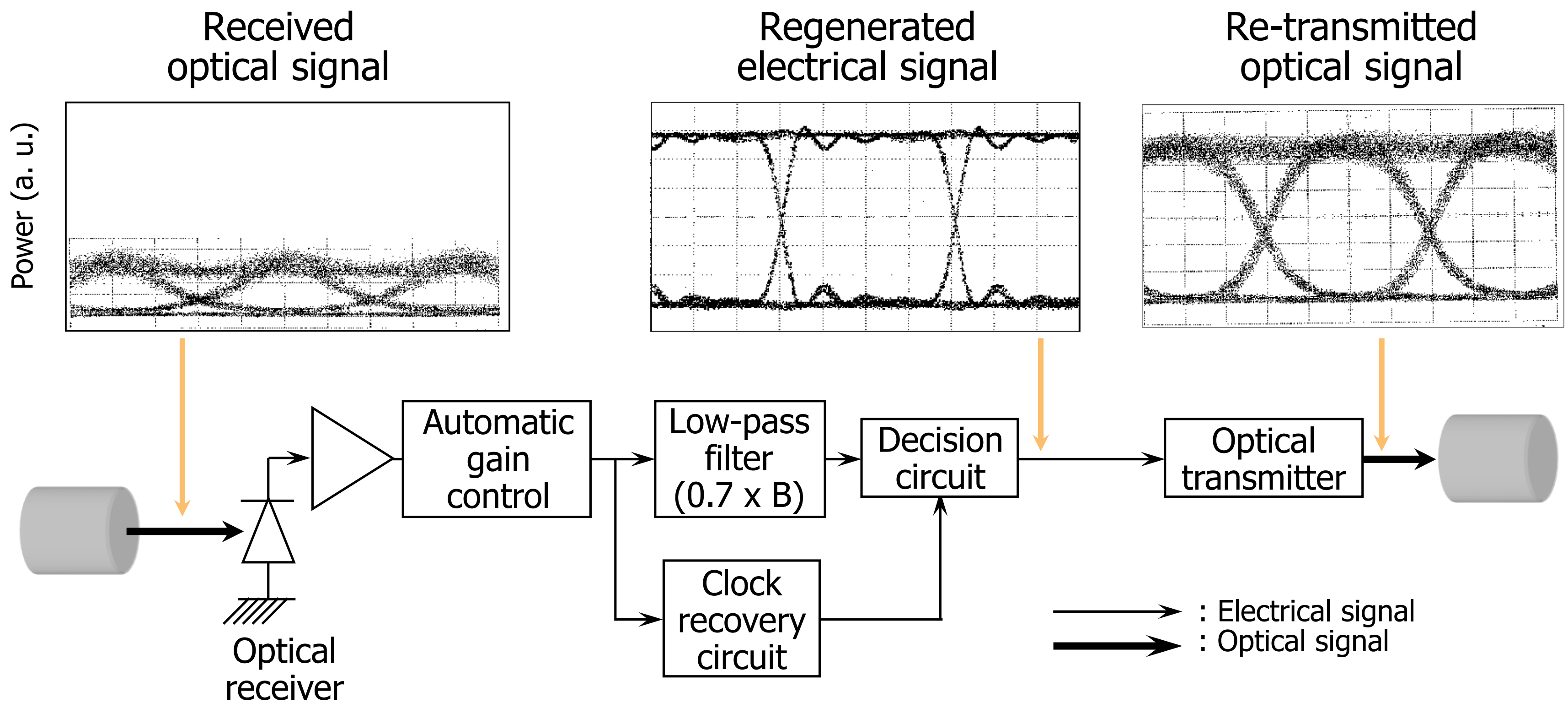


After fiber propagation



Regeneration Principle (Direct Detection for NRZ Signals)

- A closer look at regeneration process (for on/off power-modulated pulses):



Regeneration Features

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- Advantage:
  - Full 3R regeneration:
    - Re-synchronization
    - Re-shaping
    - Re-transmitting
  - Accurate signal supervision and performance monitoring

- Disadvantages:
  - Bit rate specific
  - Low reliability
  - Expensive (on a per wavelength basis)
  - Long time to market and low service velocity when new channels are added
  - Single-channel operation:
    - One regenerating function required per WDM optical channels

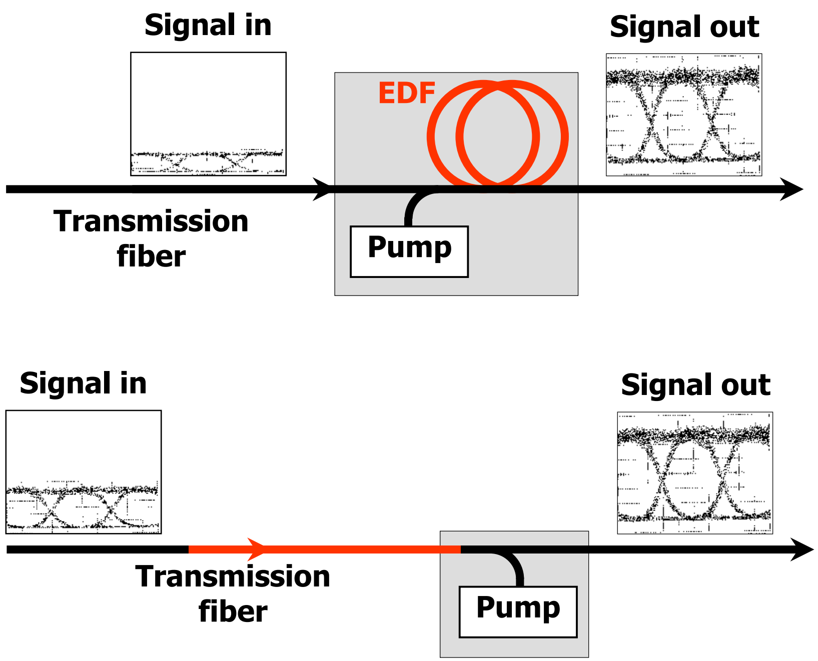
    ➔ Prohibitive capital expenditures

    ➔ Prohibitive operational costs (footprint, power…)

    ➔ Scales up linearly with the number of optical wavelengths transported in the fiber

Optical Amplification

- Optical amplification required when the signal is simply an attenuated version of the original signal
- Optical amplification process based on the way atoms and molecules in the fiber react when excited with a high-power optical pump
- Two basic options:
  - Optical amplification occurs in a specific coil of fiber placed in intermediate optical repeating sites (which is the case in Erbium-Doped Fiber Amplifiers – EDFAs)
  - Optical amplification occurs in the transmission fiber itself (such as in Raman amplifiers)



- Optical amplifiers can handle multiple wavelengths.

Optical Amplification Features

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- Advantages:
  - Bit rate and protocol agnostic
  - Reliable (no high-speed electronics)
  - Single- and multi-channel operation
  - High service velocity when new channels are added
  - Cost effective:
    - A single amplifier can amplify virtually any channel count (the cost does not scale up linearly with the number of optical wavelengths transported in the fiber).
    - Low capital and operational expenditures

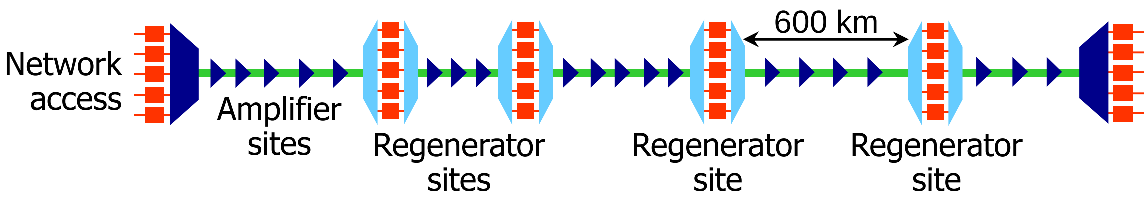
- Disadvantage:
  - Optical amplification comes at the expense of noise added to the signal(s).
  - No full 3R regeneration:
    - Only power amplification is carried out

    ➔ Accumulation of optical noise and pulses distortion until optical-electrical conversion is performed

    ➔ Careful end-to-end design of the whole system for high global performance

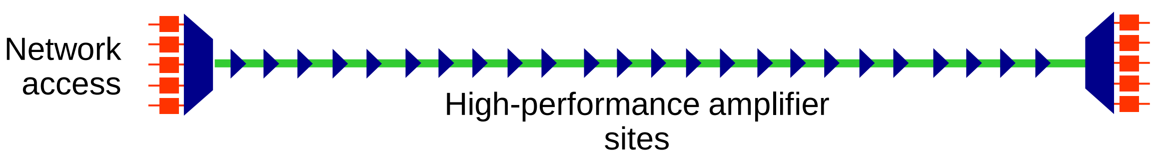
Regeneration Versus Amplification

- Conventional WDM point-to-point solution with limited reach



  - Regenerating or back-to-back transponders (■) for each wavelength:
    - Price, size, and power consumption issues
    - Need of in-field intervention for adding new wavelengths

- Ultra long-reach WDM solution



  - No regenerating site:
    - Decrease in price, size, and power consumption
    - Fast end-to-end capacity upgrade

Assessment of Optical Communication Quality Bit Error Rate and Q Factor

Assessment of Optical Communication Quality

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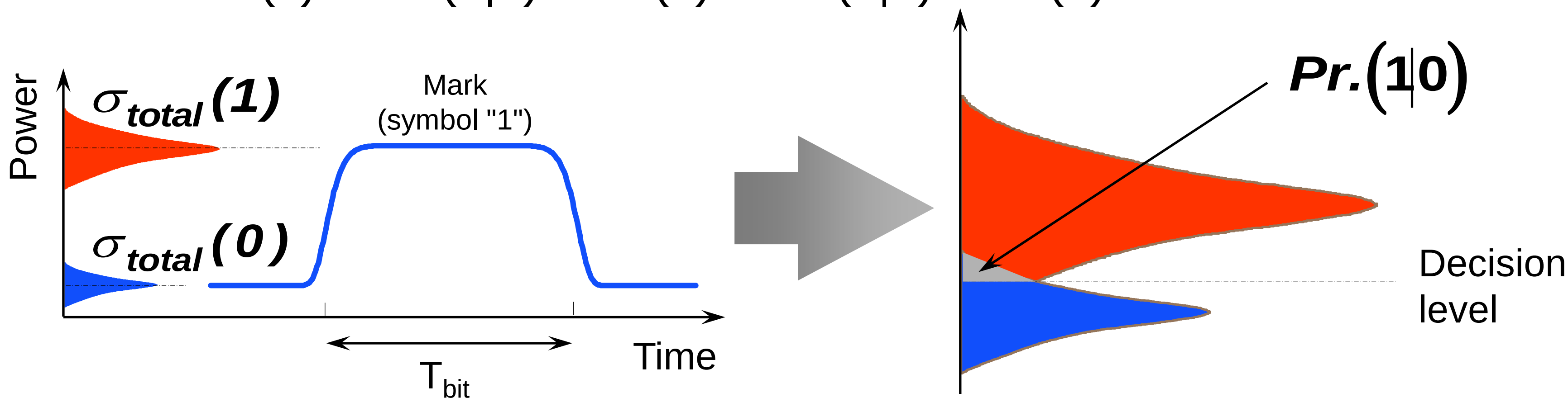
- Ultimate performance criterion: Bit Error Rate (BER)
  - Typical requirements are BER lower than 1×10^{-12} or 1×10^{-15} at End-Of-Life (EOL) conditions (maximal capacity transported, all span losses increased by span margin – typically 2 or 3 dB in multi-span links).
  - BER lower than 1×10^{-12} or 1×10^{-15} is the BER delivered to the operators' customers or at the interface between two network domains. This is the BER after error detection and correction performed in the receive interface.
  - Channel coding schemes, such as redundant Forward Error Correction codes, enable error detection and correction performed at the egress point.
  - The stronger the coding gain offered by the FEC, the higher the BER before correction can be (e.g. up to 1.9×10^{-2} with 2015 generation soft-decision FEC).

Calculation of Bit Error Rate (BER)

- BER is the likelihood of a bit misinterpretation due to noise.
- Assumption:
  - Additive White Gaussian Noises (AWGNs)
  - Bipolar NRZ transmission
- Error probability (likelihood of a bit misinterpretation):
  BER = Pr. (e) = Pr. (0|1) x Pr. (1) + Pr. (1|0) x Pr. (0)



Note: Conditional probability Pr. (1|0) is the probability to detect a symbol "1" while it is the symbol "0" that has been transmitted.

BER and Q Factor

- Issue with BER: The BER measurement for high-performance transmission link can be extremely difficult.
  For example, when requiring a BER of 1×10^{-15}, a minimum measurement time of 27 hours is required at 10G data rate.

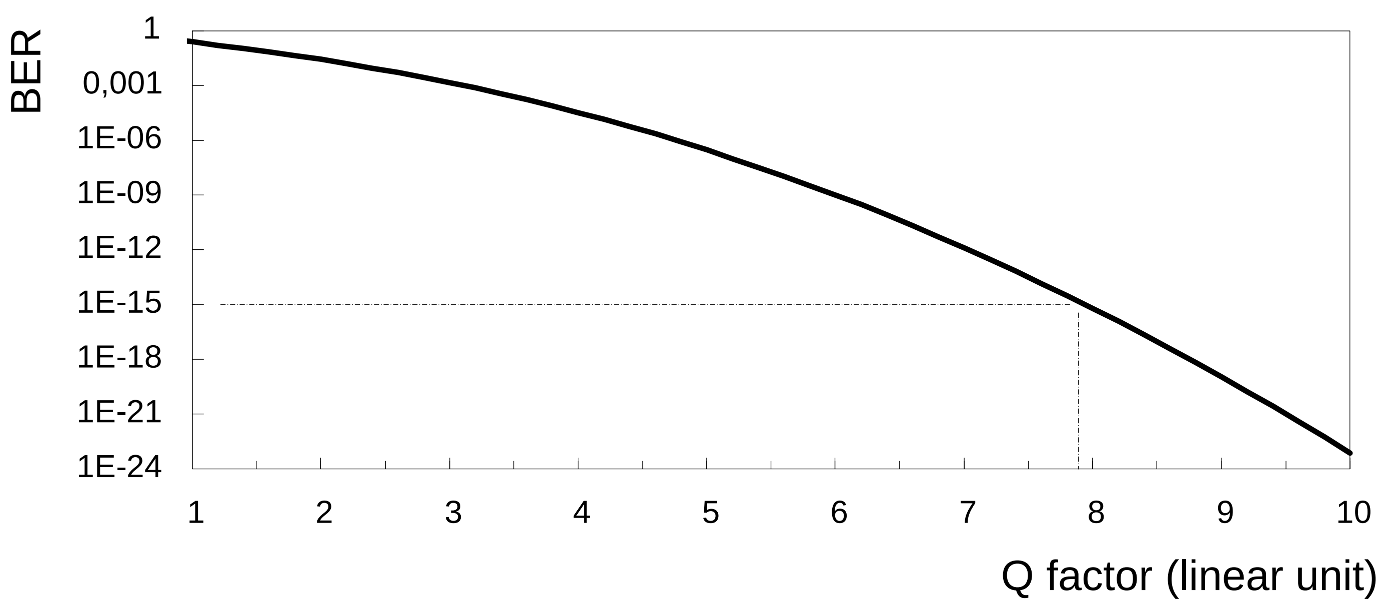
- In these circumstances, Q factor (Quality factor) measurement has become the new quality evaluation parameter.
- Q factor adopts the concept of signal-to-noise ratio in a digital signal and is an evaluation method that assumes a normal noise distribution.
- Q factor can be quickly measured on an oscilloscope screen by looking at the eye diagram.

- There is a direct relationship between BER and Q factor:

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) \approx \frac{1}{\sqrt{2\pi}} \frac{exp\left(-\frac{Q^2}{2}\right)}{Q}$$

Relationship
Between BER and Q Factor

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) \approx \frac{1}{\sqrt{2\pi}} \frac{exp\left(-\frac{Q^2}{2}\right)}{Q}$$



Q Factor

- Q factor adopts the concept of signal-to-noise ratio in a digital signal and is an evaluation method that assumes a normal noise distribution.
- Q factor is defined as:

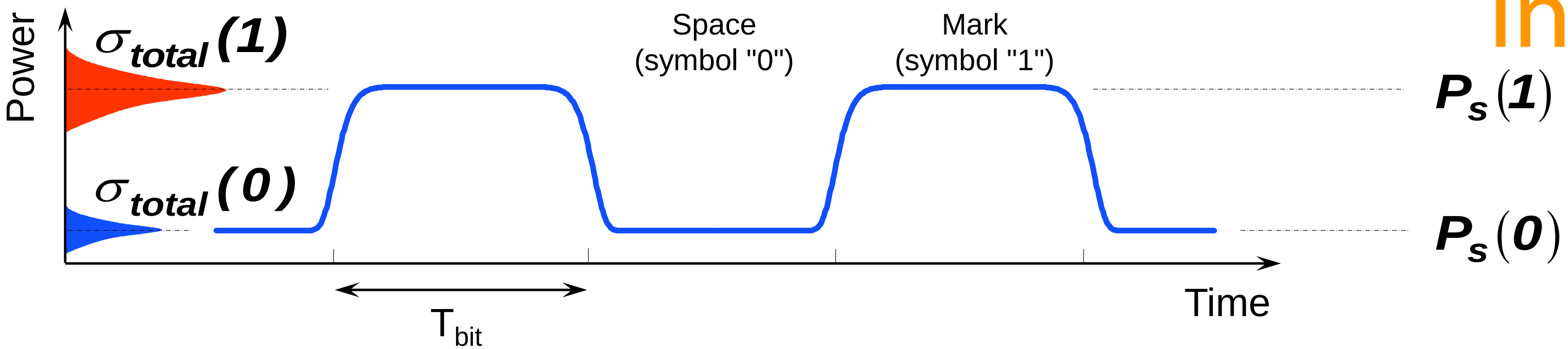
$$Q = \frac{\mu_1 - \mu_0}{\sigma_{total}(1) + \sigma_{total}(0)}$$

where:

- μ_1 and μ_0 correspond to the levels of the transmitted data "1"s and "0"s.
- σ_1 and σ_0 correspond to the standard deviation of the noise on "1"s and "0"s.

- Noise levels (σ_1 and σ_0) can be caused by optical noise impacted symbols "0" and "1" (so impacted by link OSNR performance) but also by other degradations affecting the pulse shapes (distortion, nonlinearities, inter-symbol interferences, bit synchronization problems, etc.).

Calculation of Q Factor



$$Q = \frac{\mu_1 - \mu_0}{\sigma_{total}(1) + \sigma_{total}(0)}$$

with:

$$\mu_1 = MSP_s(1) = MS\frac{2T_{ex}}{1+T_{ex}}P_s$$

$$\mu_0 = MSP_s(0) = MS\frac{2}{1+T_{ex}}P_s$$

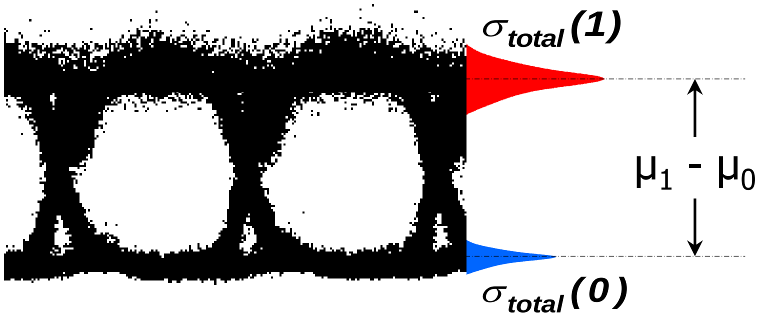
$$\sigma^2_{total}(1) = \left[\Sigma\sigma^2(1)\right]\times B_e$$

$$\sigma^2_{total}(0) = \left[\Sigma\sigma^2(0)\right]\times B_e$$

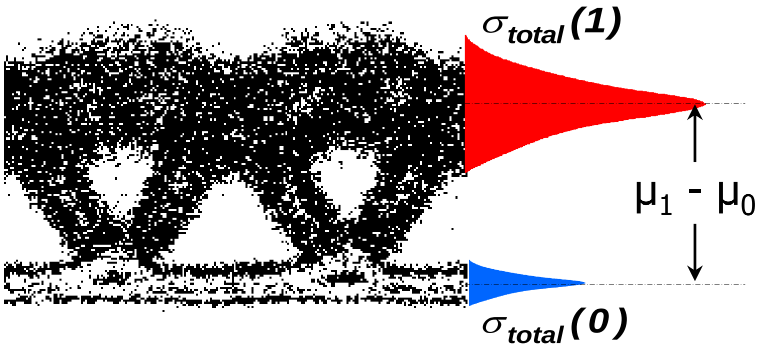
M: Avalanche photodiode factor
S: Photodiode sensitivity
T_{ex}: Transmitter extinction ratio
B_e: Receiver electrical bandwidth

Trace Thickness, OSNR and Q Factor

1. Eye diagram # 1 with optical noise corruption, but no pulse distortion
   - Thicker trace for symbol "1" than for symbol "0" due to optical noise corruption (poor OSNR)
   - Relatively low standard deviation of the noise for both symbols "0" and "1"
   - Not so bad Q factor



2. Eye diagram # 2 with optical noise corruption and pulse distortion
   - Thicker trace for symbol "1" than for symbol "0" due to optical noise corruption (poor OSNR) and pulse distortion
   - Worse Q factor than for eye diagram # 1



➔ Optical Signal-to-Noise Ratio (OSNR) is not the only factor driving Q factor (and BER).

Wavelength Division Multiplexing (WDM) Basics

Wavelength Division Multiplexing

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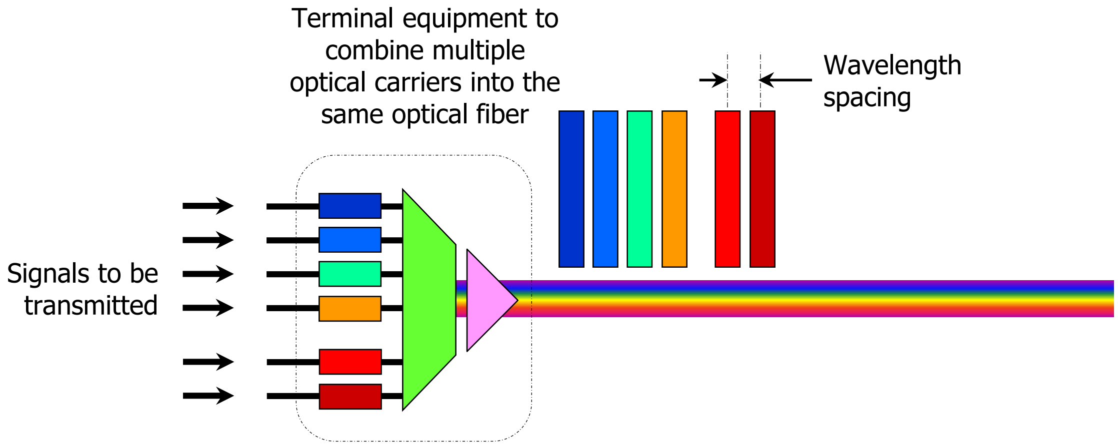
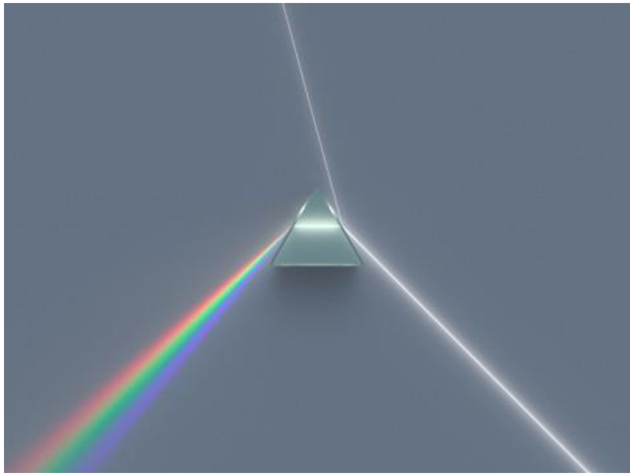
- Wavelength Division Multiplexing (WDM): Combining multiple optical carriers into the same optical fiber for high line capacity
- Optical multiplexing device with single-wavelength input ports and one multi-wavelength output port





Wavelength Division Multiplexing

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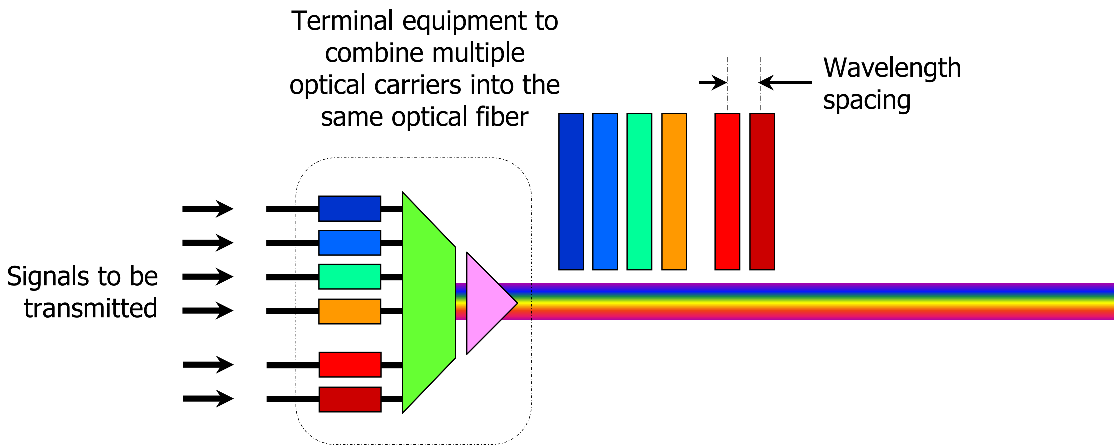

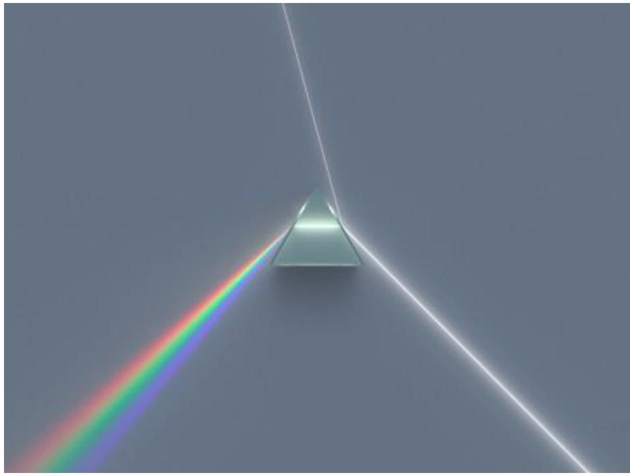

- Each wavelength can carry a data signal at different channel rate, modulation, protocol…
- The wavelength spacing is typically constant across the spectrum and set at 0.4 nm / 50 GHz (for reference, the system optical bandwidth ranges from 35 to 100 nm).

WDM For Fiber Capacity Explosion

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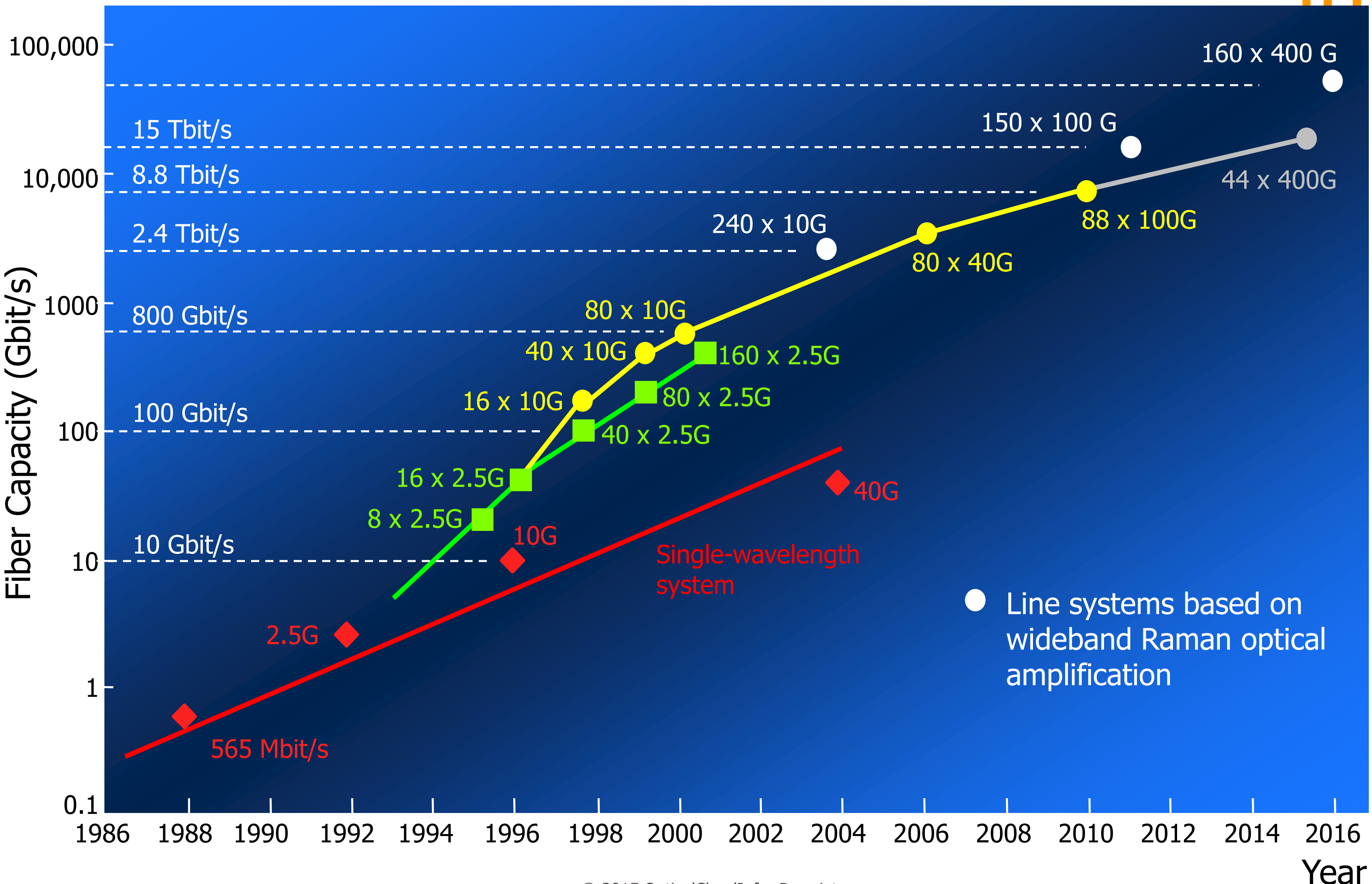

Wavelength Division Multiplexing and Optical Amplification

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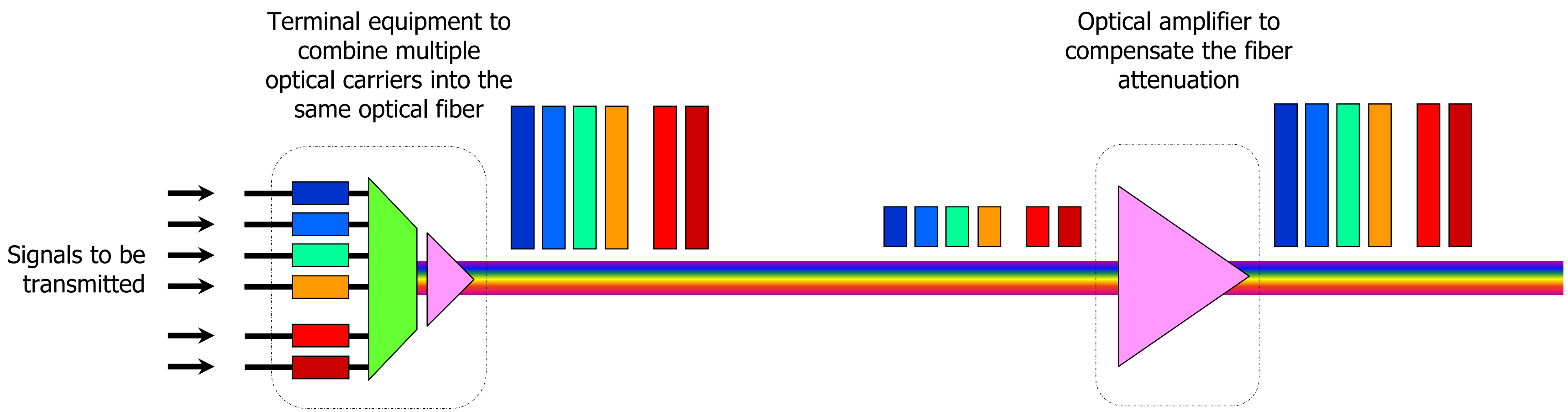
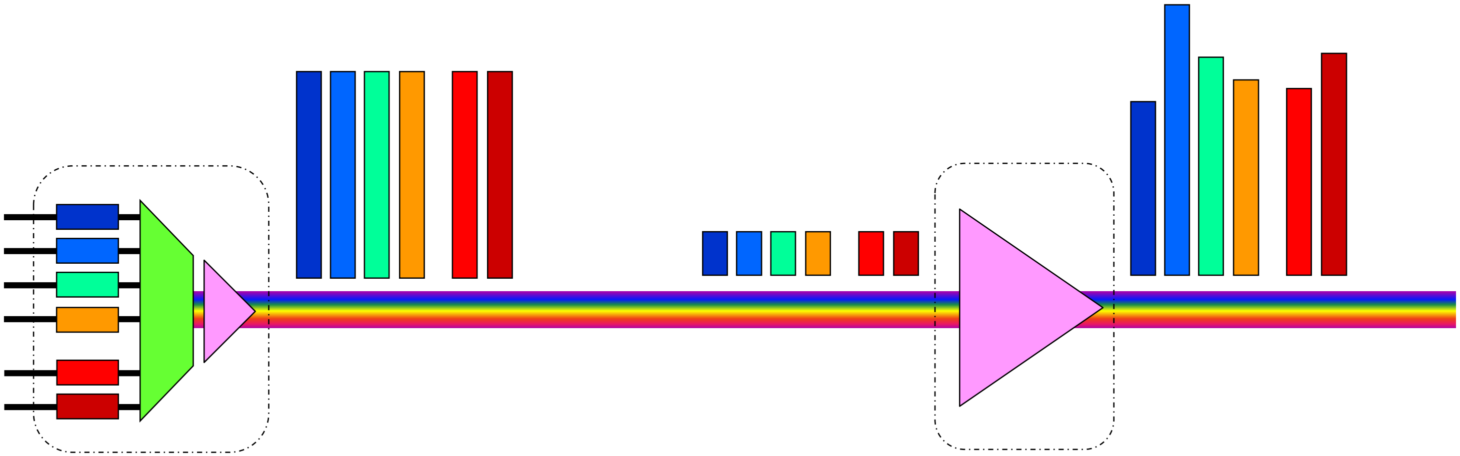
- Wavelength Division Multiplexing (WDM): Combining multiple optical carriers into the same optical fiber for high line capacity
- Optical amplification: Amplifying simultaneously all the wavelengths in the fiber for compensating the fiber attenuation along the optical routes



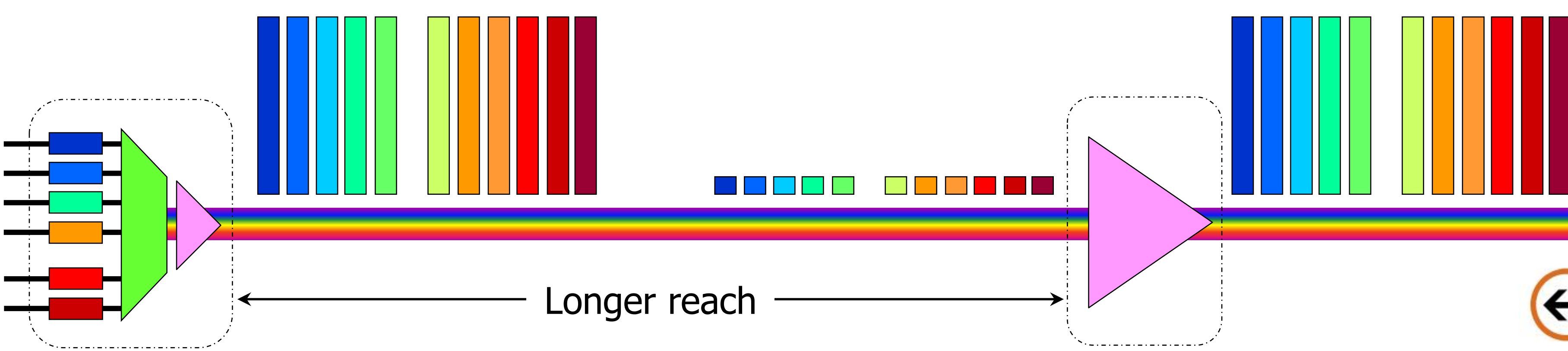
- Main values of optical amplifiers:
  - Common line equipment shared by all the wavelengths
  - Independent on channel rate, modulation, protocol…

Optical Amplification

- EDFA-based optical amplification technology (needs flattening filters)



- Raman optical amplification technology



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Worldwide Web and Cloud