1014I – Communication systems and cybersecurity (2025/26)

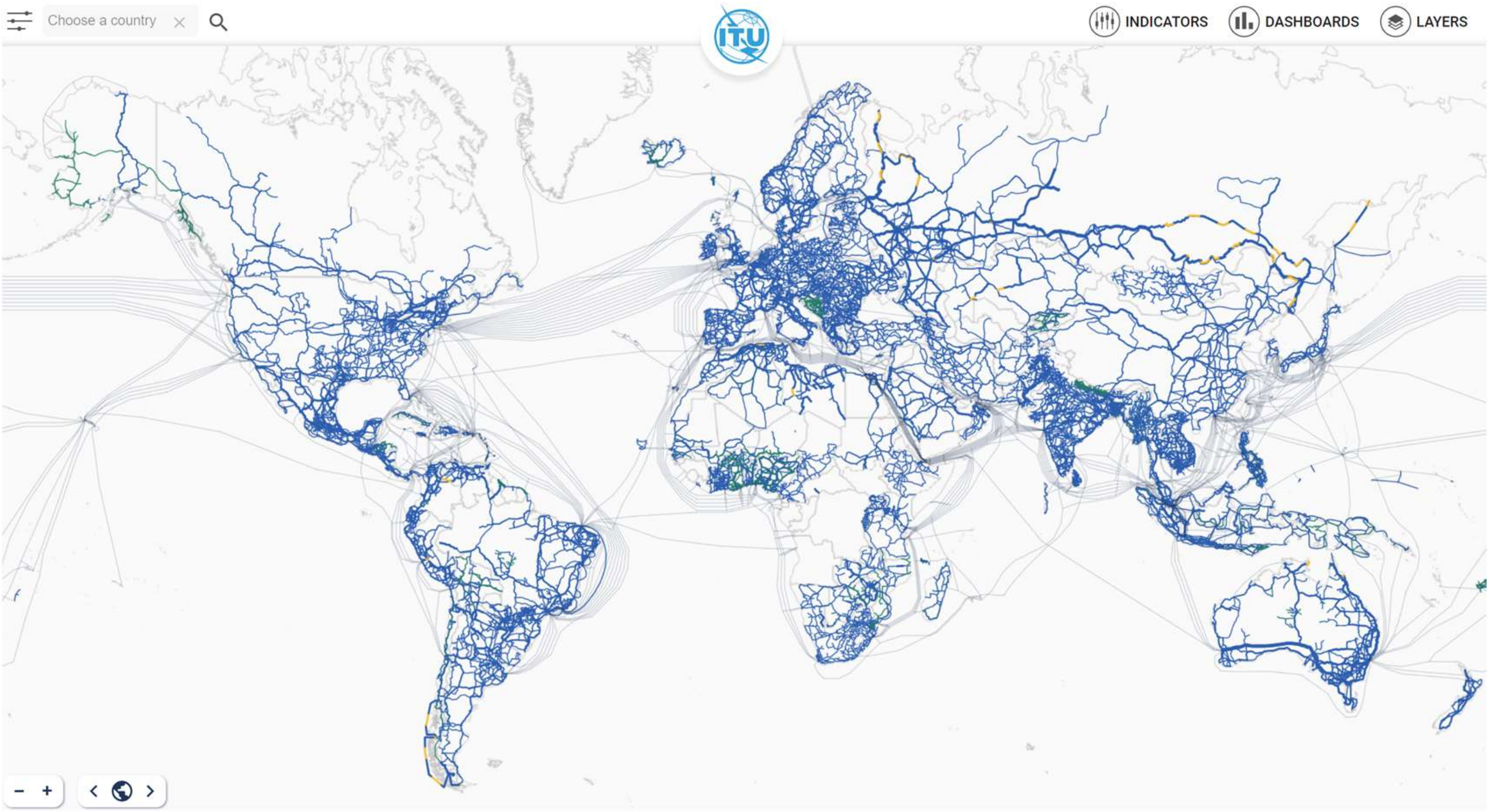
Wired technologies for transport and access networks

Giacomo Bacci
giacomo.bacci@unipi.it

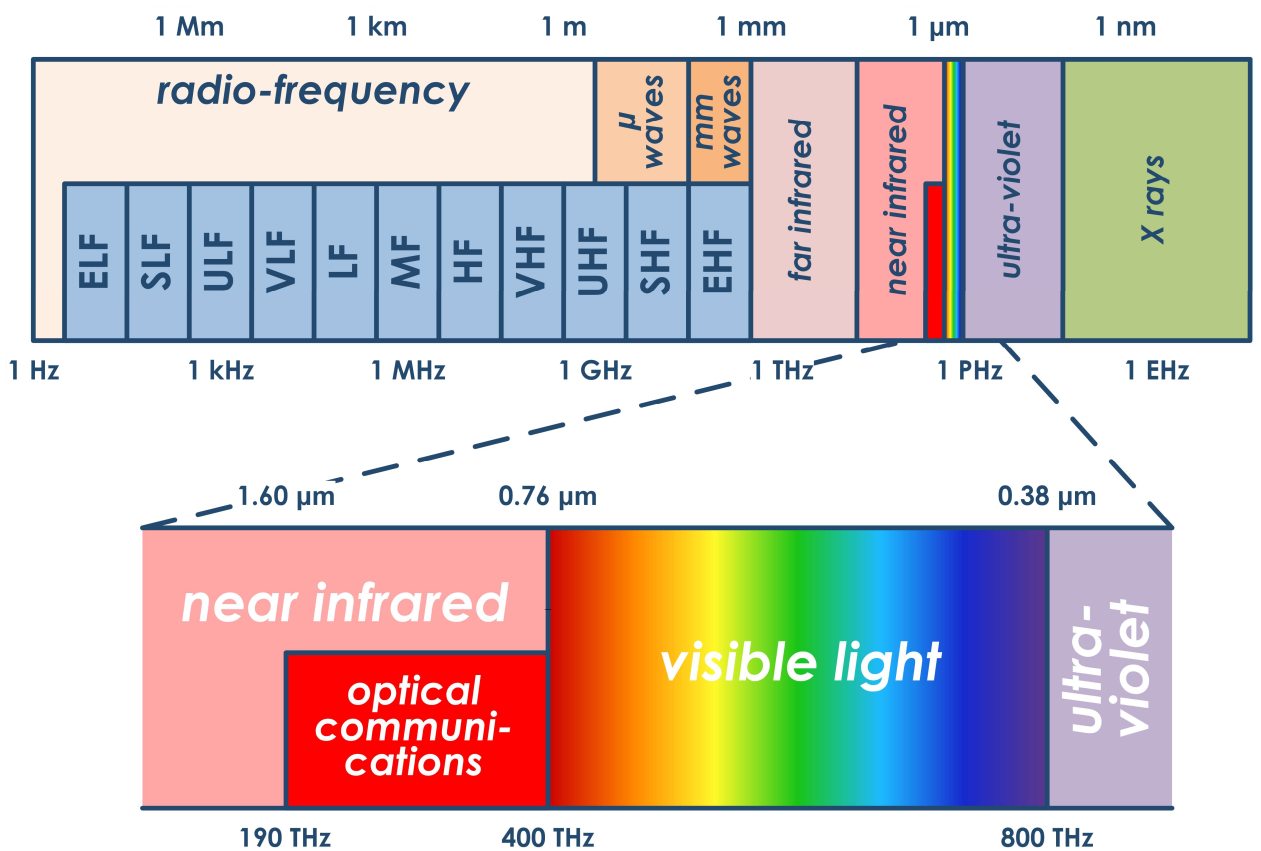
Università di Pisa, Dip. Ingegneria dell'Informazione

Radio vs. optical communications

Map of long-distance Internet backbone fiber cables



Spectrum of electromagnetic radiation



Driving criteria: path loss (1/2)

Radio communications:

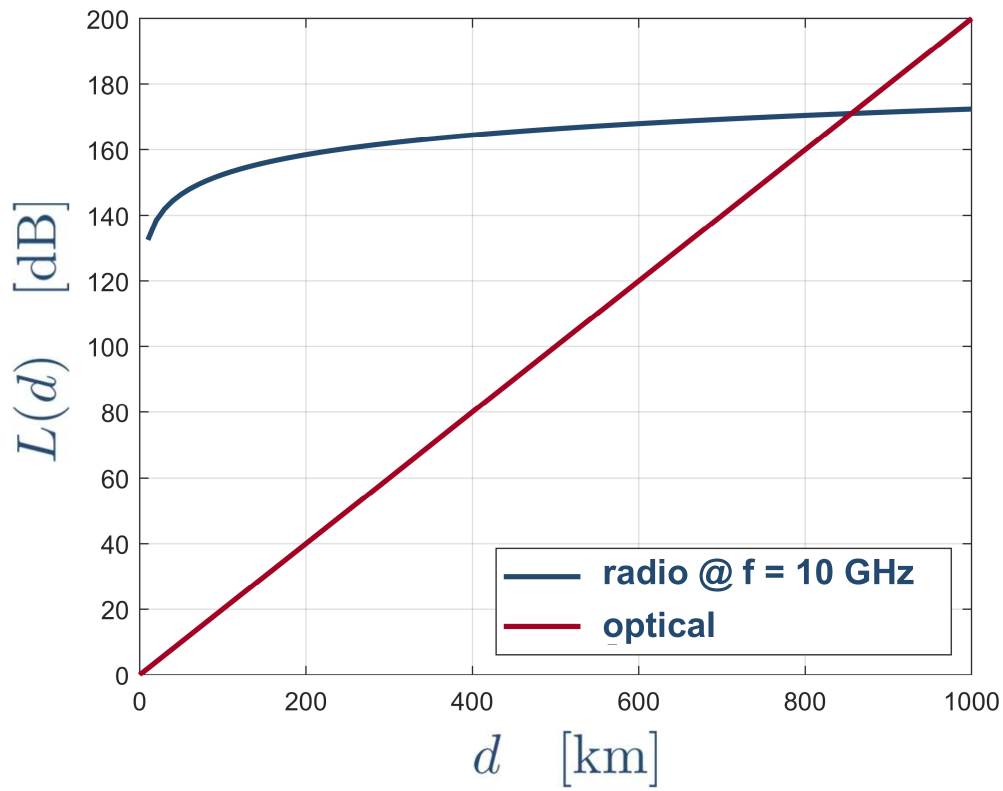
$$L(d) = \left(\frac{4\pi d}{\lambda}\right)^2$$

$$\approx 1.75 \cdot 10^{11} \cdot d^2|_{\mathrm{km}} @ f = 10\,\mathrm{GHz}$$

Optical communications:

$$L(d) = 10^{0.02 d|_{\mathrm{km}}}$$

Driving criteria: path loss (2/2)



Driving criteria: bandwidth

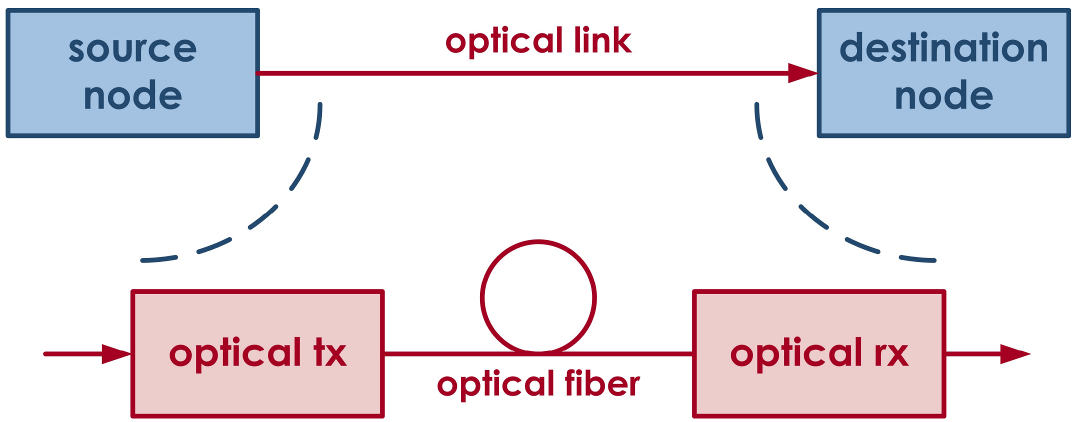
For technological reasons, every bandpass communication has a bandwidth in the order of few percent of the carrier frequency:

$$\eta \triangleq \frac{B}{f_0} \approxeq 5\%$$

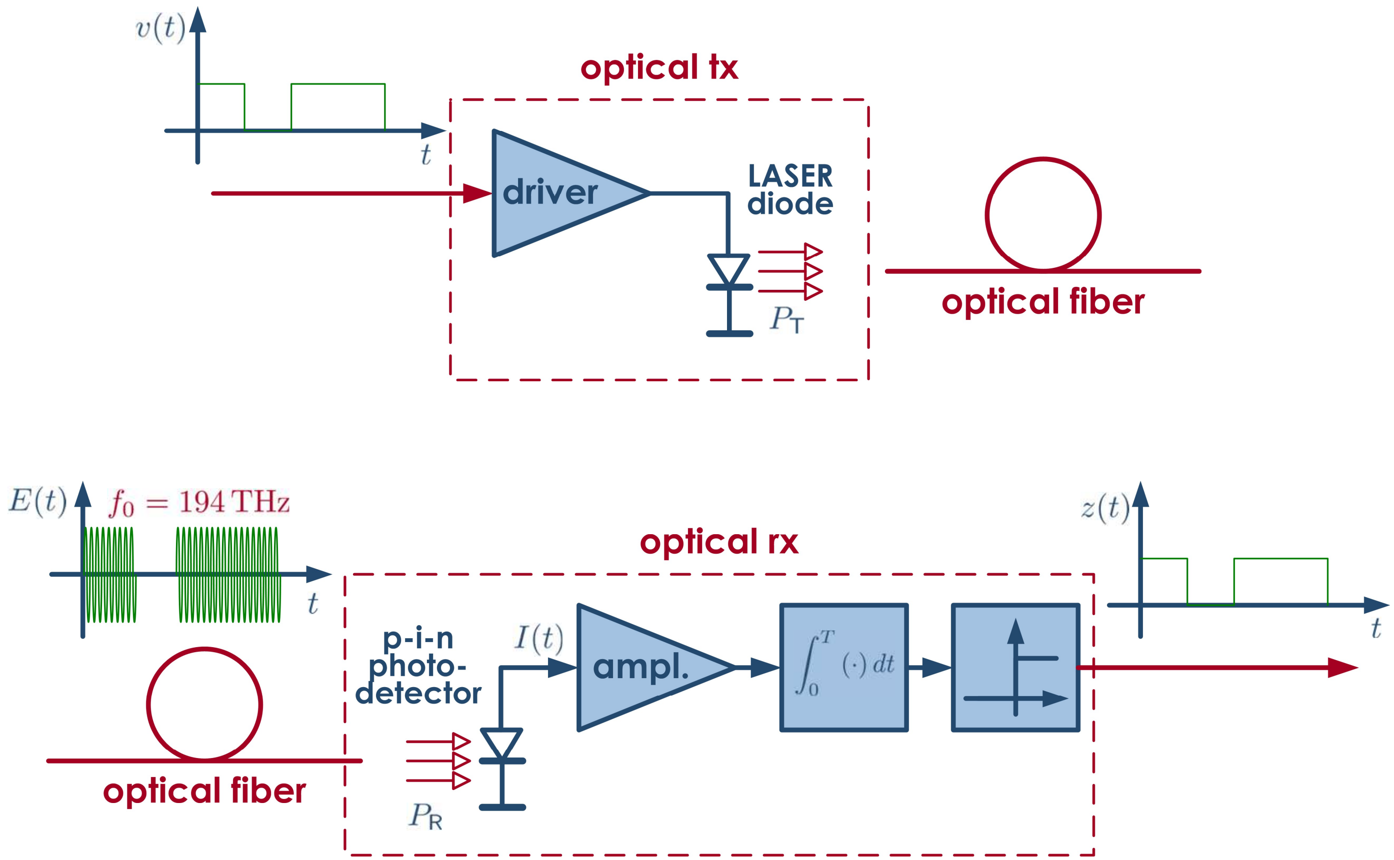
Following the relative-bandwidth rule, the available bandwidth on fibers is roughly 10 THz, four orders of magnitude wider than that of traditional radio communications

Naïve architecture of a fiber-optical link

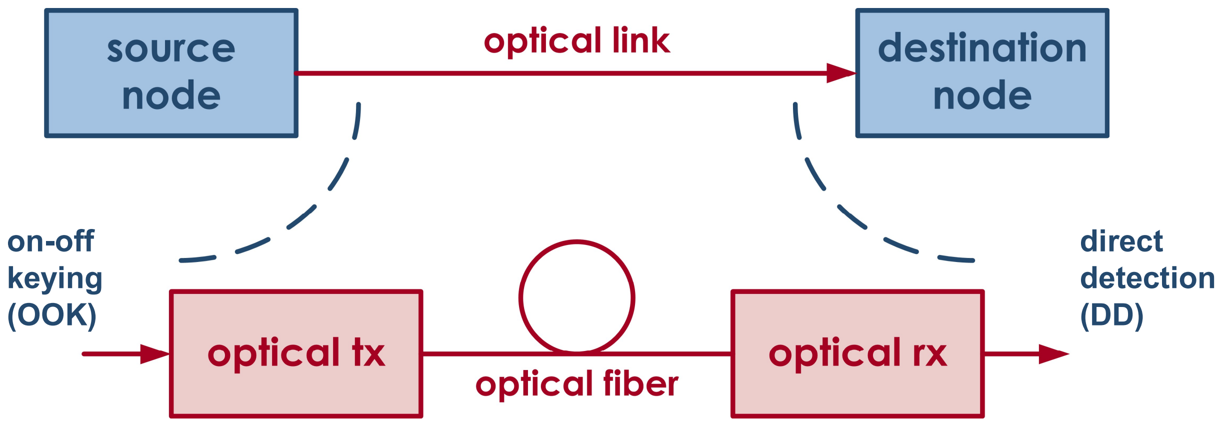
The optical fiber link (1/3)



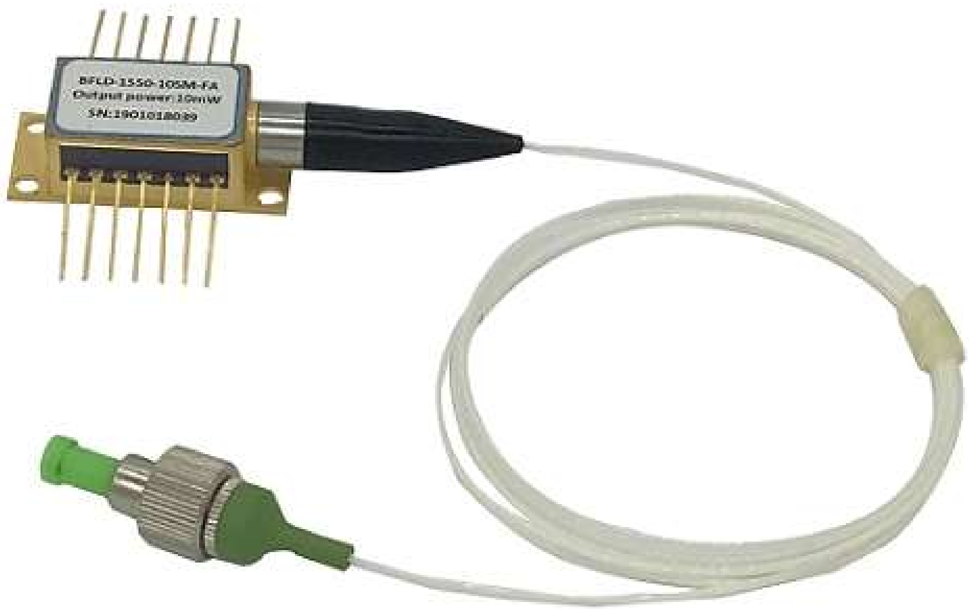
The optical fiber link (2/3)



The optical fiber link (3/3)



An example of an integrated semiconductor LASER

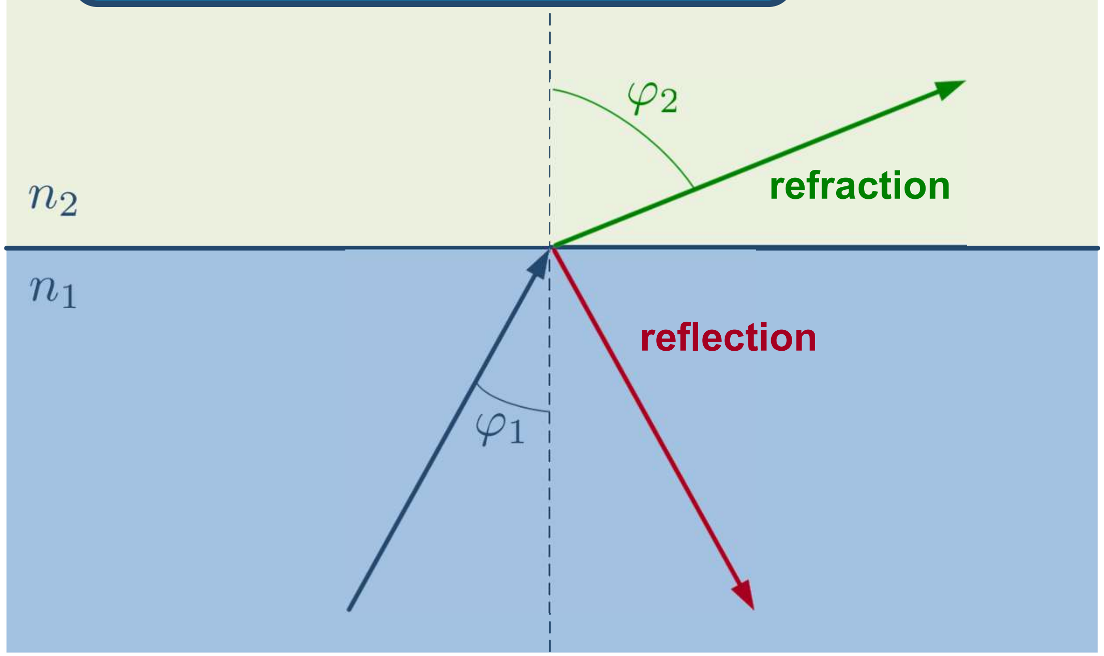


What is an optical fiber?

Vintage table lamp from the ’70s

Reflection and refraction

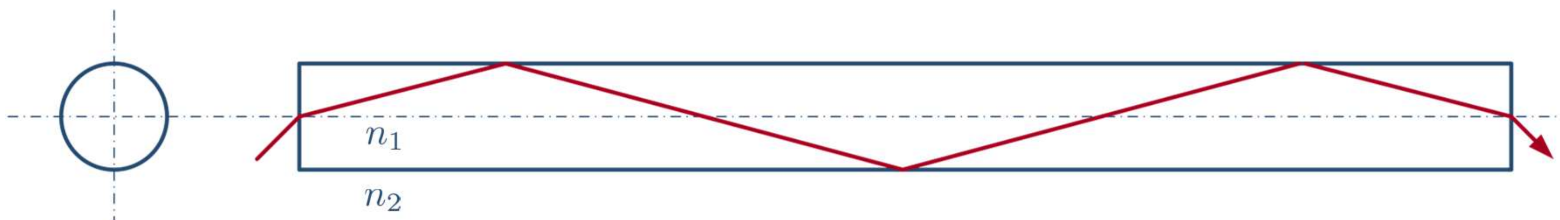
$$n_1 \sin \varphi_1 = n_2 \sin \varphi_2$$



Critical angle and total internal reflection

As long as the incident angle φ_1 increases, the refracted rays depart more and more from the normal, until we get to $\varphi_2 = \pi/2$:

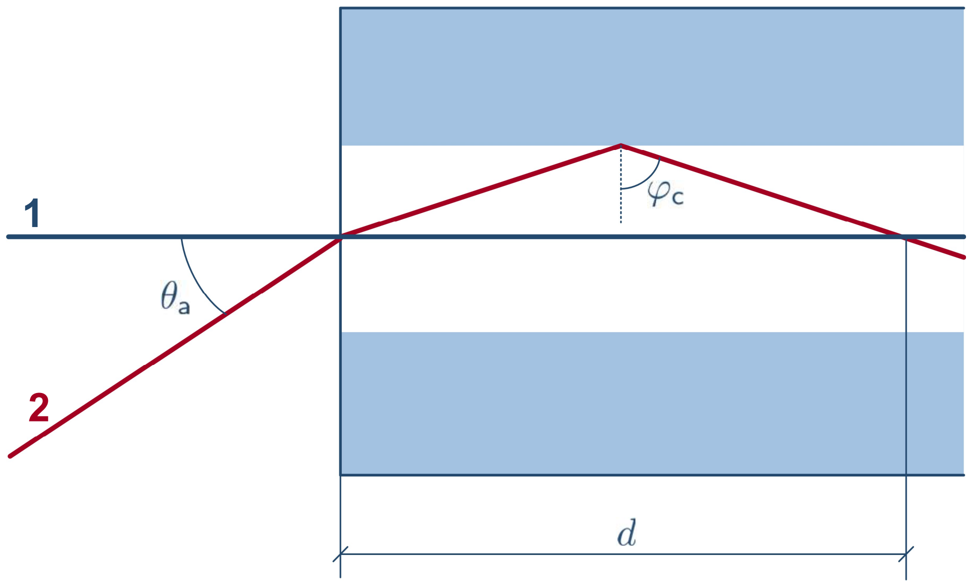
$$\boxed{\varphi_c = \sin^{-1}(n_2/n_1)}$$



total internal reflection

Step-index fibers

Intermodal dispersion of the MM-SI fiber (1/2)



$$\Delta_t = t_2 - t_1 = \frac{d}{v}\left(\frac{1}{\sin\varphi_c} - 1\right) \approx \frac{dn_1}{c}\Delta_n$$

Intermodal dispersion of the MM-SI fiber (2/2)

To limit the pulse broadening, we can impose:

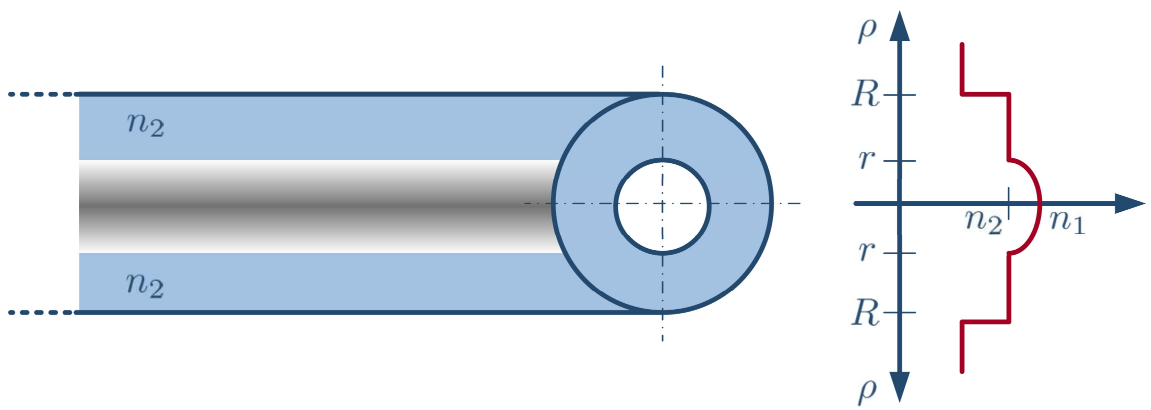
$$\Delta_t \approxeq \frac{dn_1}{c}\Delta_n \leq T = \frac{1}{R_b}$$

The limitation is on the product between the bitrate and the fiber length:

$$R_b \cdot d \leq \frac{c}{\Delta_n n_1}$$

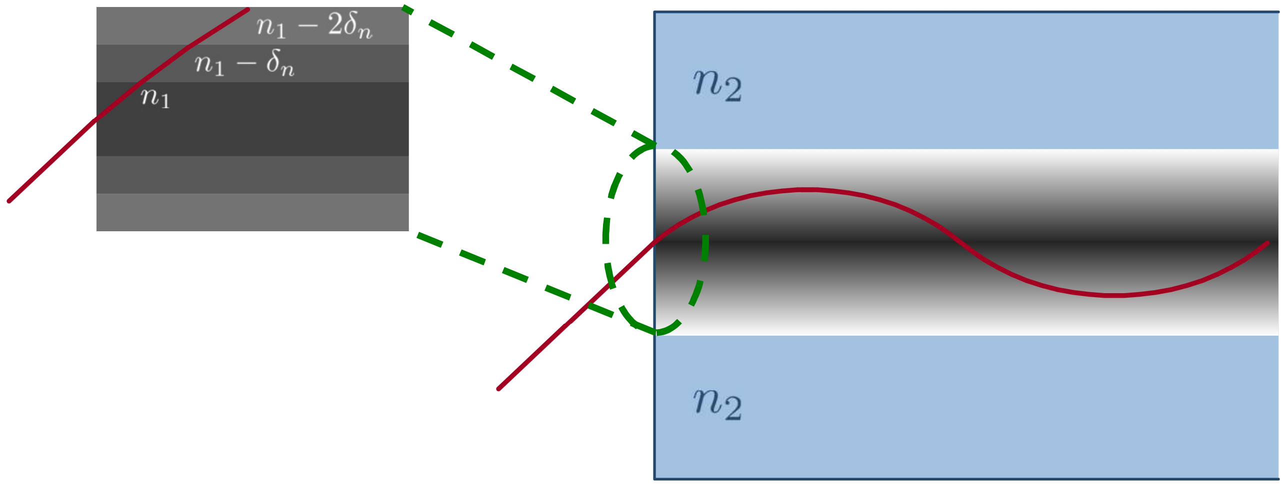
Graded-index fibers

Refraction index

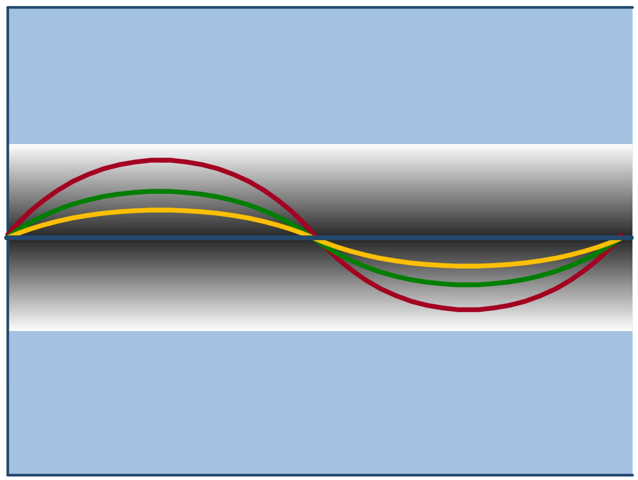


$$n(\rho) = \begin{cases} n_1\sqrt{1-2\Delta_n(\rho/r)^{\beta}}, & |\rho| \le r, \\ n_2, & r \le |\rho| \le R \end{cases}$$

Light path bending in the graded core



Light paths in a parabolic-profile MM-GI fiber



Intermodal dispersion of the MM-GI fiber

The impact of pulse broadening is reduced to

$$\Delta_t \approxeq \frac{dn_1}{8c}\Delta_n^2 \leq T = \frac{1}{R_b}$$

The capacity in terms of the product between bitrate and fiber length is:

$$R_b \cdot d \leq \frac{8c}{\Delta_n^2 n_1}$$

Single-mode SI fibers

From geometrical to electromagnetic optics

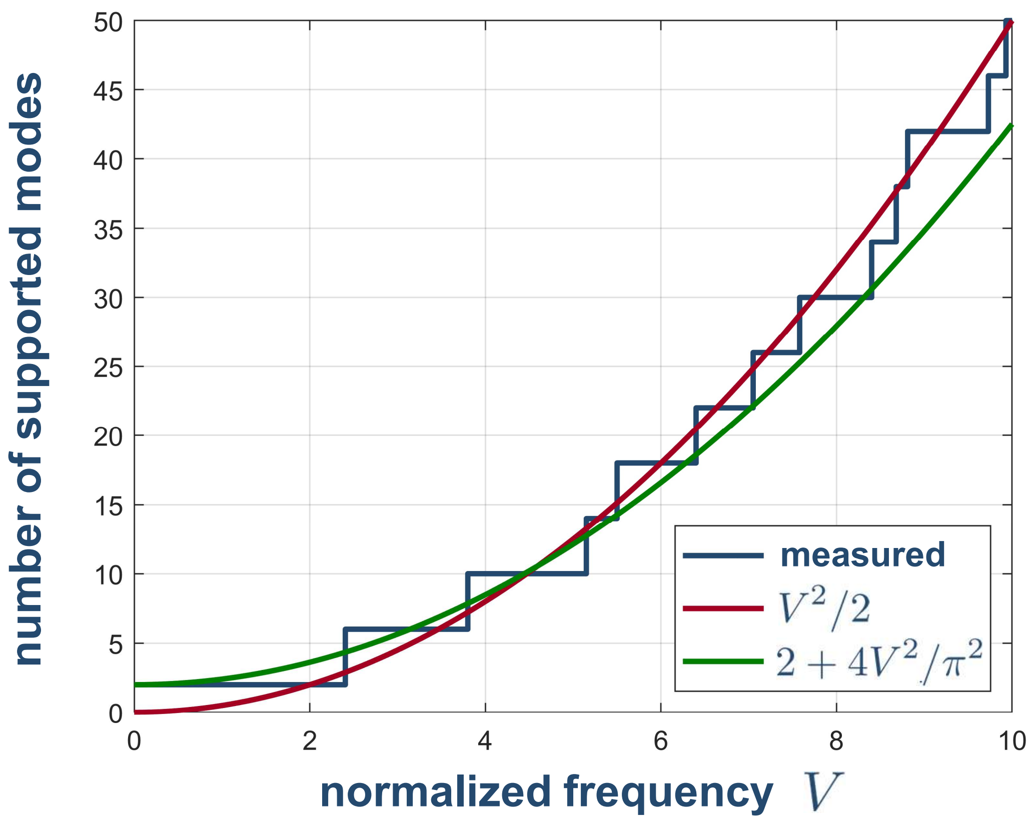
Geometrical analysis is valid as long as $\lambda_0 \ll r$

What happens with a narrow-core fiber, when $\lambda_0 \approxeq r$**?**

The number of supported modes depends on the normalized frequency:

$$V = \underbrace{\frac{2\pi}{\lambda_0}}_{\text{transmission details}} \cdot \underbrace{r \cdot \mathrm{NA}}_{\text{fiber parameters}}$$

Number of propagation modes in an SI fiber



From multi-mode (MM) to single-mode (SM) fibers

Single-mode (SM) fibers can be obtained by ensuring $V \leq 2.405$

With the usual parameters, we get $r = 2\,\mu\mathrm{m}$

This derivation would have not been possible using the geometrical optics, as it violates the hypothesis $\lambda_0 \ll r$

Intramodal dispersion

Can SM fibers guarantee infinite bitrates?

Of course, the absence of MM dispersion does not provide infinite bitrates, due to the presence of intersymbol interference (ISI)

Due to glass properties, which show a refractive coefficient $n(f)$, when applying data modulation the LASER produces a wave which is not monochromatic

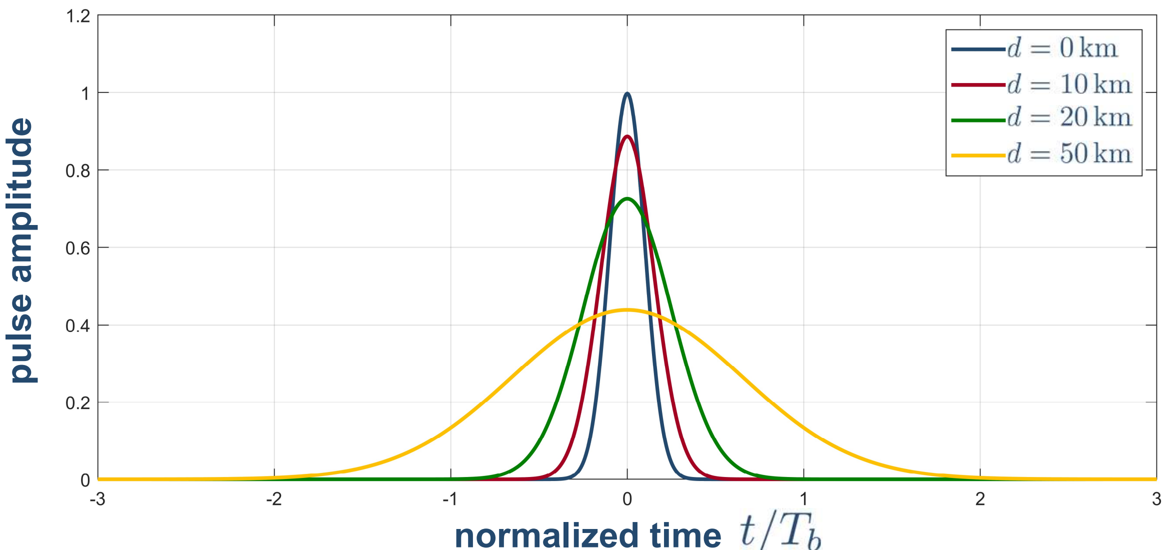
Chromatic dispersion

Pulse broadening due to intramodal dispersion

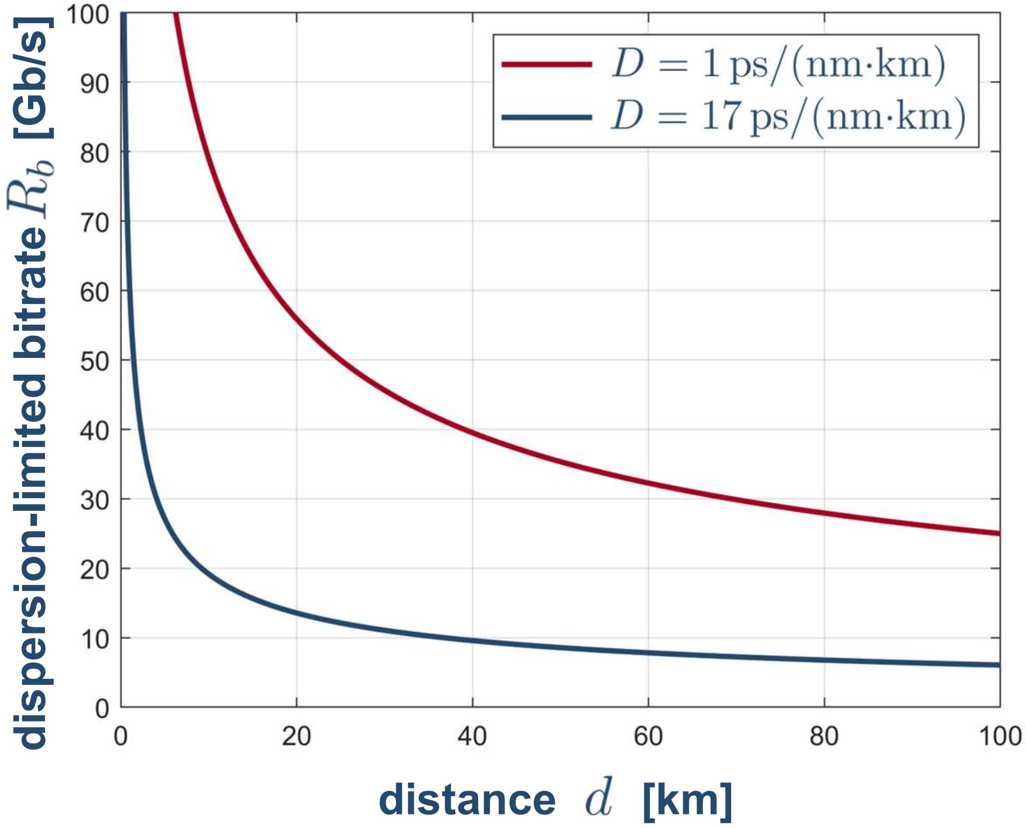
The differential phase distortion induced by chromatic dispertion provides a certain pulse broadening, equal to

$$\Delta_t \approx d \cdot \Delta\lambda \cdot |D|$$

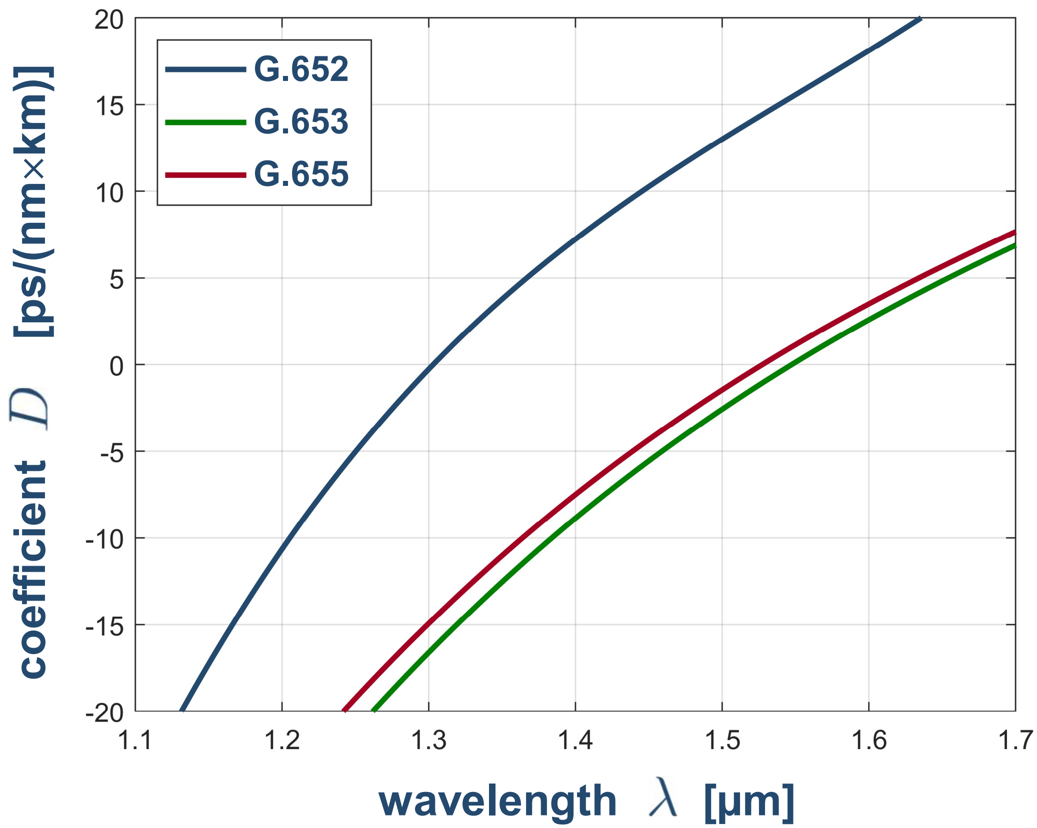
where D is the dispersion coefficient of the fiber



Dispersion-limited bitrate on the SM fiber



Variation of the material dispersion coefficient



Fiber attenuation

Why 1.55-μm fibers?

Unlike wireless communications, optical communications experience a different, exponential relation between transmitted and received power:

$$P_{\mathsf{R}}(d) = P_{\mathsf{T}} \cdot e^{-\overline{\alpha} d}$$

$$\boxed{L(d) = 10\overline{\alpha}\log_{10} e \cdot d = \alpha \cdot d \quad [\mathrm{dB}]}$$

Attenuation coefficient of a fiber (1/2)

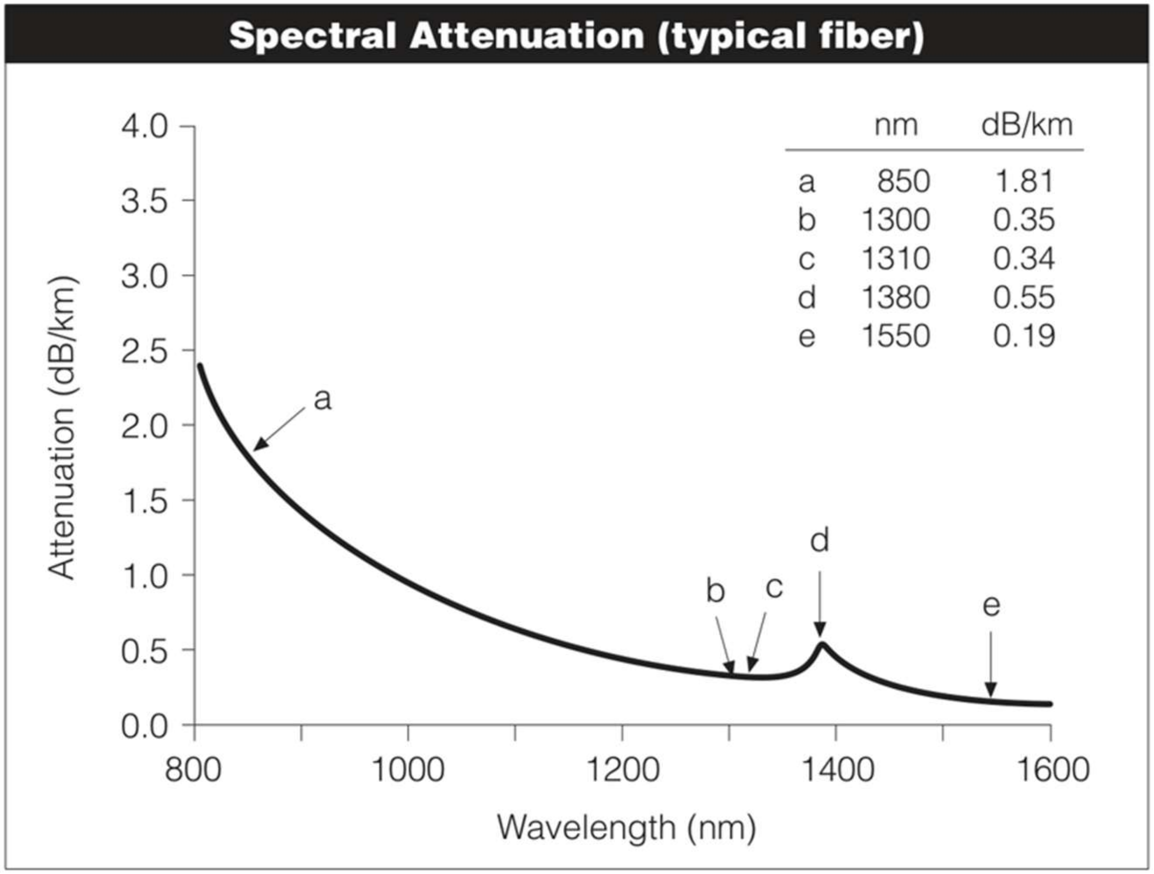
The very first optical experiments (mid-1960s) showed $\alpha \approxeq 1,000\,\mathrm{dB/km}$

Attenuation coefficient of a fiber (2/2)

- very first optical experiments (mid-1960s): $\alpha \approxeq 1,000\,\mathrm{dB/km}$
- outside vapor deposition (OVD) fibers manufactured by Corning (mid-1970s): $\alpha \approxeq 20\,\mathrm{dB/km}\,@\lambda_0 = 0.85\,\mu\mathrm{m}$
- current commercial SM fibers: $\alpha = 0.2\,\mathrm{dB/km}\,@\lambda_0 = 1.55\,\mu\mathrm{m}$
- state-of-the-art fibers: $\alpha = 0.15\,\mathrm{dB/km}\,@\lambda_0 = 1.55\,\mu\mathrm{m}$

Best performance in terms of attenuation are much more important than dispersion issues

Example of the attenuation coefficient



Dispersion-shifted fibers

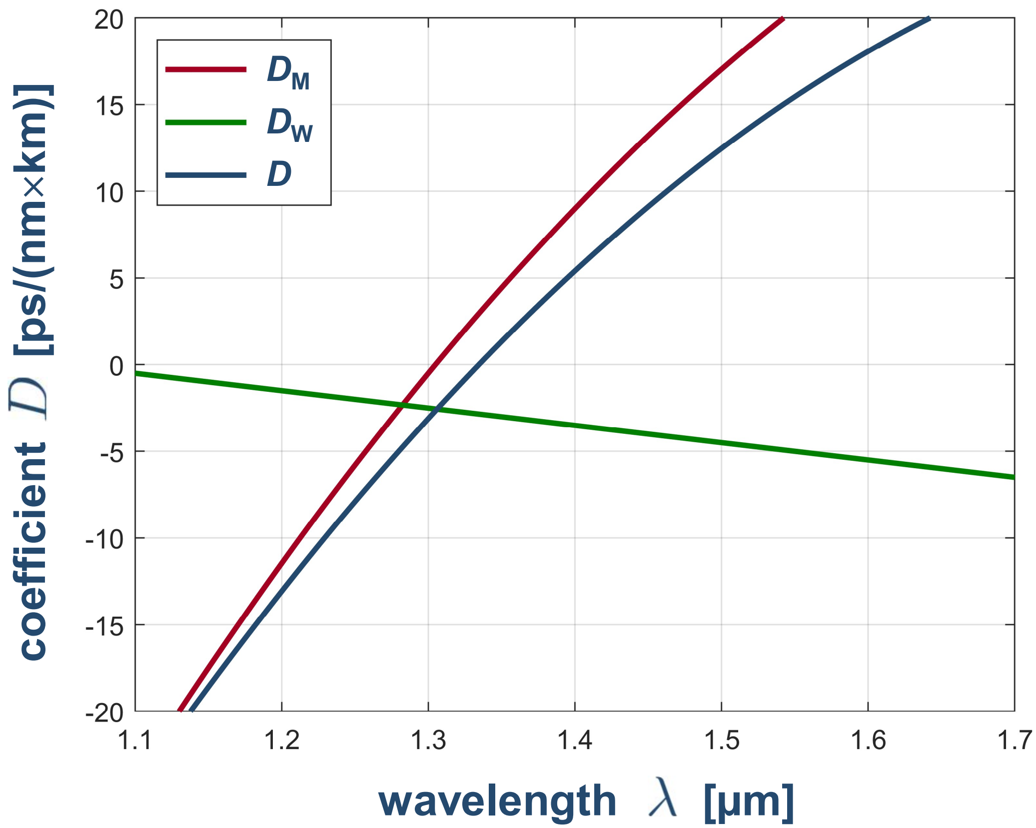
Waveguide dispersion (1/2)

In addition to the chromatic (a.k.a. material) dispersion D_{M}, another (minor, but non-negligible) nuisance to the performance of an SM fiber is the so-called waveguide dispersion (due to the guidance effect) D_{W}

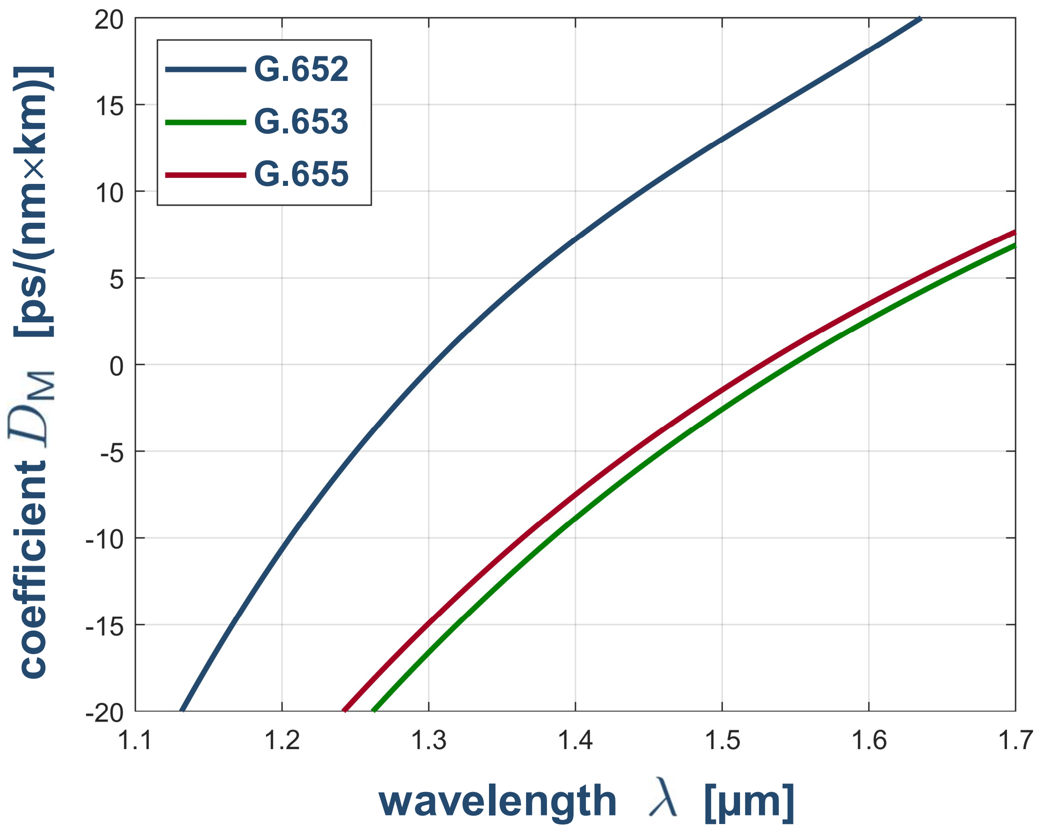
The total (intramodal) dispersion coefficient D is given by

$$\boxed{D = D_{\mathrm{M}} + D_{\mathrm{W}}}$$

Waveguide dispersion (2/2)



Variation of the material dispersion coefficient (revisited)



Types of fibers

- ITU-T G.652: standard SM fiber
- ITU-T G.653: dispersion-shifted (DS) fiber, with $D_{\mathrm{M}} = 0 \,@\lambda_0 = 1.55\,\mu\mathrm{m}$
- ITU-T G.655: non-zero (NZ) DS fiber, with a small residual dispersion to prevent cross-talk phenomena

Optical devices

The optical fiber link (3/3)

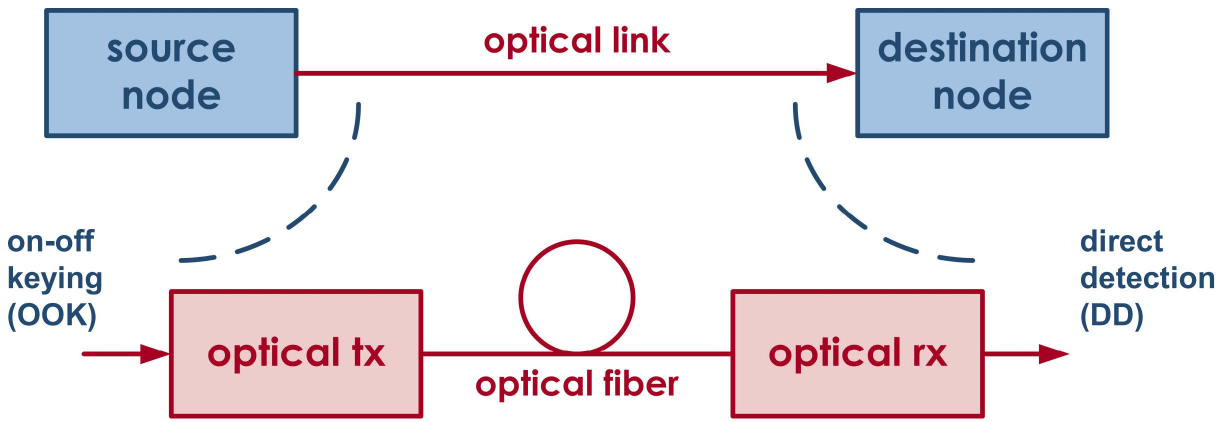
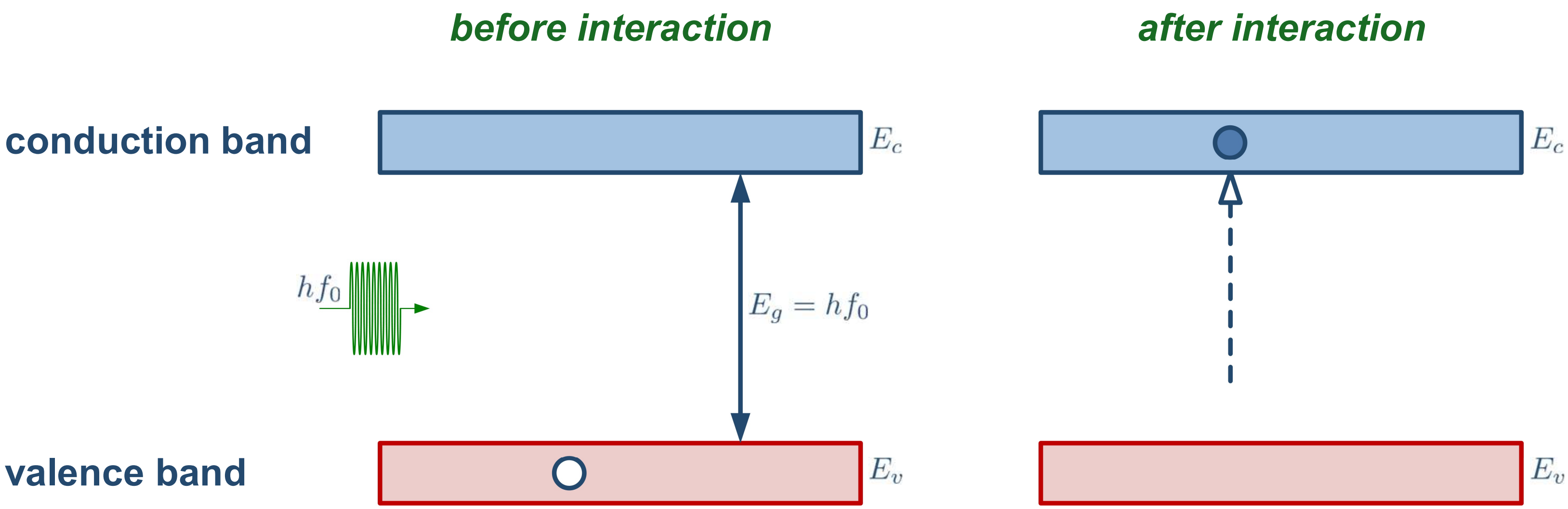


Photo-electric interactions

- Absorption
- Spontaneous emission
- Stimulated emission

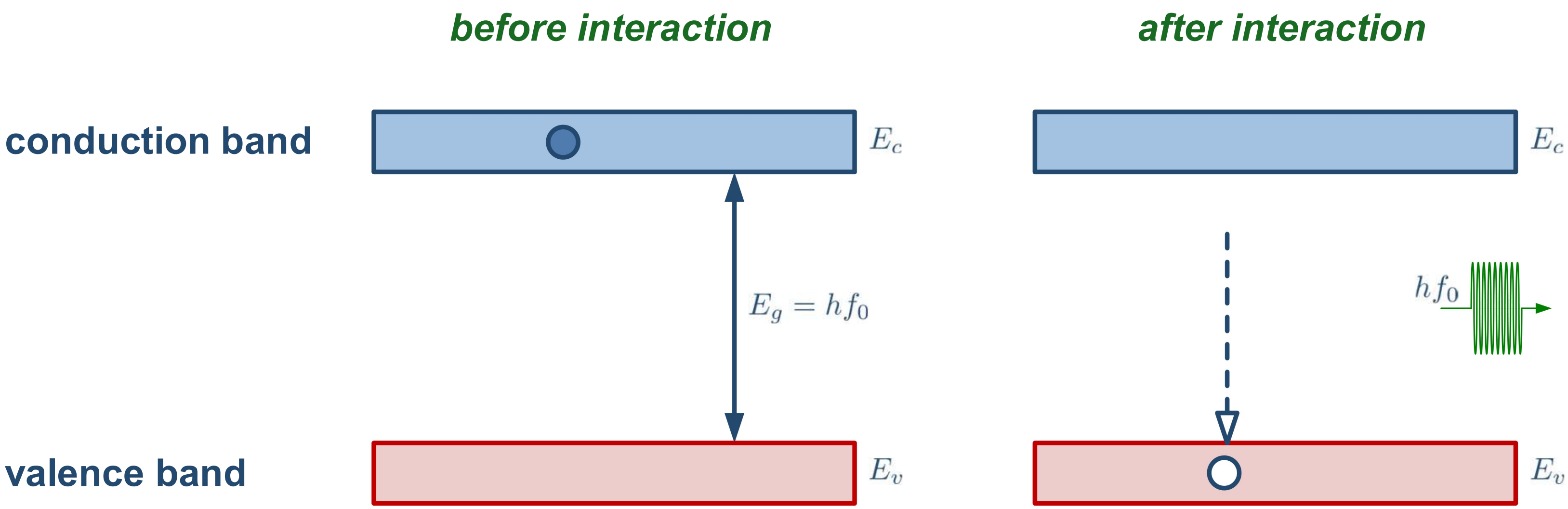
Absorption



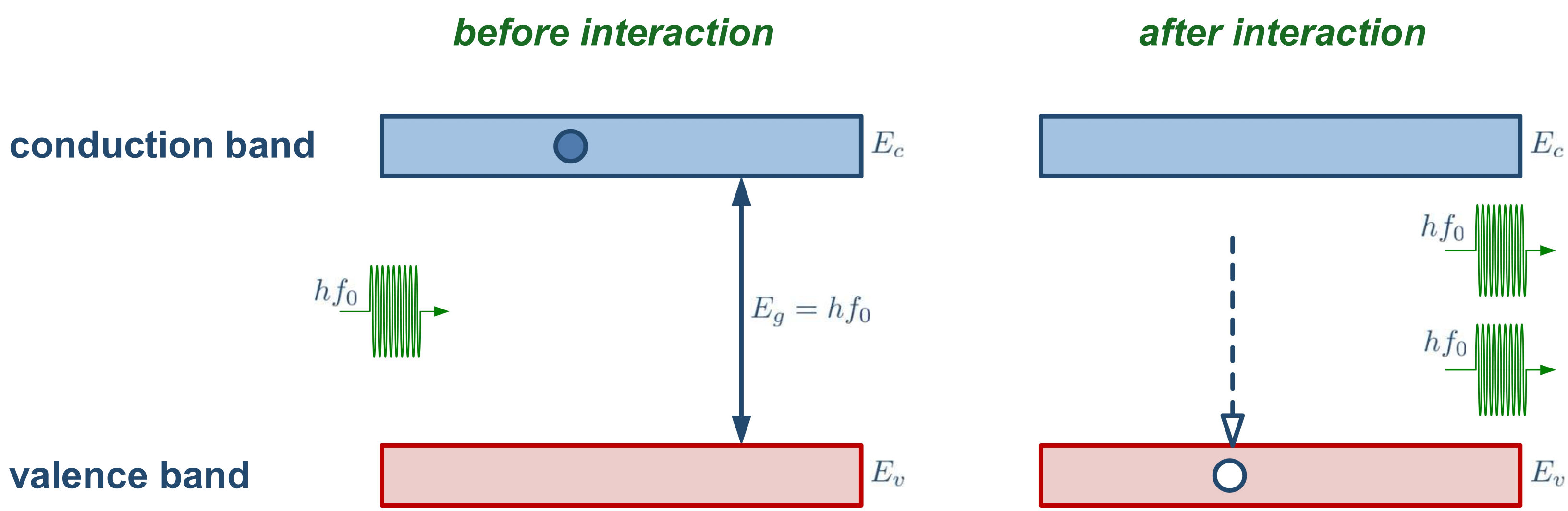
gap energy: $E_g = E_c - E_v$

Dip. Ingegneria dell'Informazione
University of Pisa, Pisa, Italy

Spontaneous emission



Stimulated emission

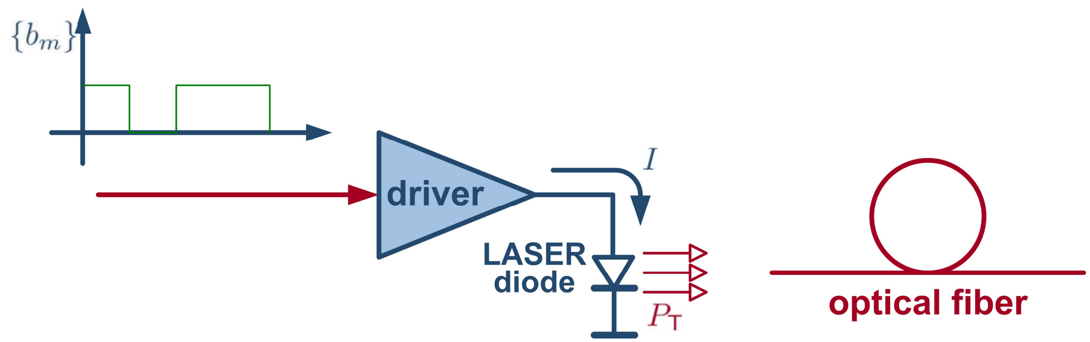


The two photons are clones: same frequency and same momentum

LASERs

Communication systems (25/26) M.Sc. Communications Eng.

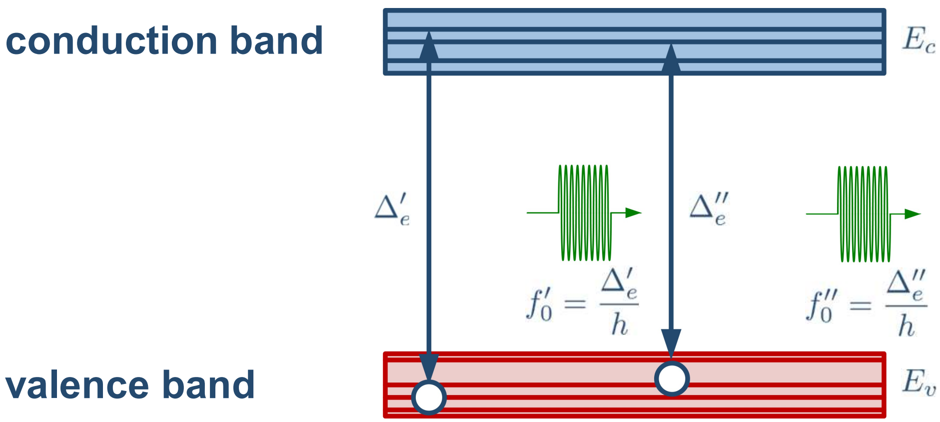
What is a LASER?



- **GaAs:** **gallium arsenide**
- **InGaAs:** **ternary**
- **InGaAsP:** **quaternary**

Light amplification via spontaneous emission

In a **semiconductor**, there are many adjacent levels that form continuous-like bands:



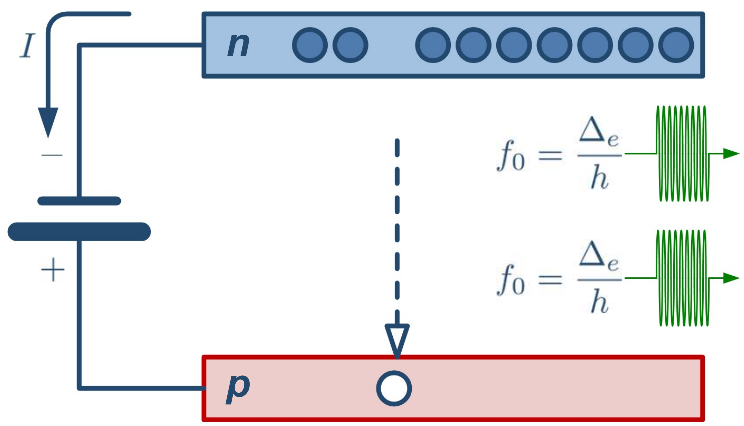
Since photons can have a different frequency and/or phase, the spectrum is **not monochromatic**, and hence **unsuitable** for optical applications

Spontaneous emission is typically used by light emitting diodes (LEDs)

Communication systems (25/26) M.Sc. Communications Eng.

Light amplification via stimulated emission

The (high) drive current leads to a large population of excited electrons:

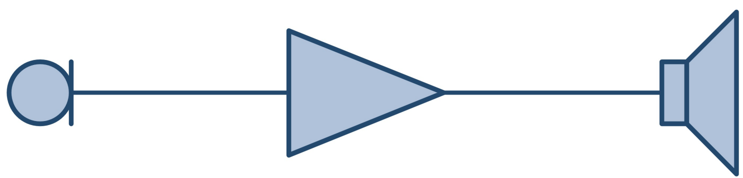


In the *p-n* junction, the stimulated radiation prevails on the spontaneous one, yielding the desired inversion of population

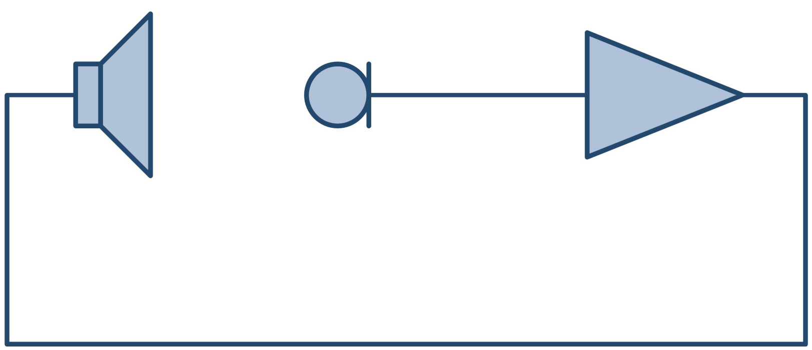
Clone photons provide a coherent emission

Amplifier vs. generator (1/2)

Acoustic domain:



if there is **no** input, the output is **null**

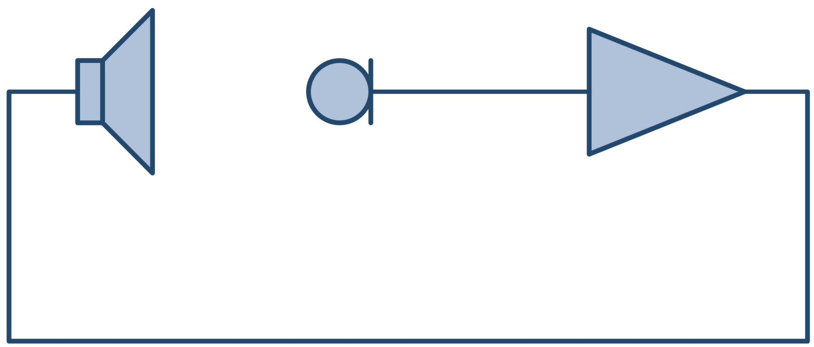


to generate a signal, we can exploit the **Larsen effect**

Dip. Ingegneria dell'Informazione
University of Pisa, Pisa, Italy

Amplifier vs. generator (2/2)

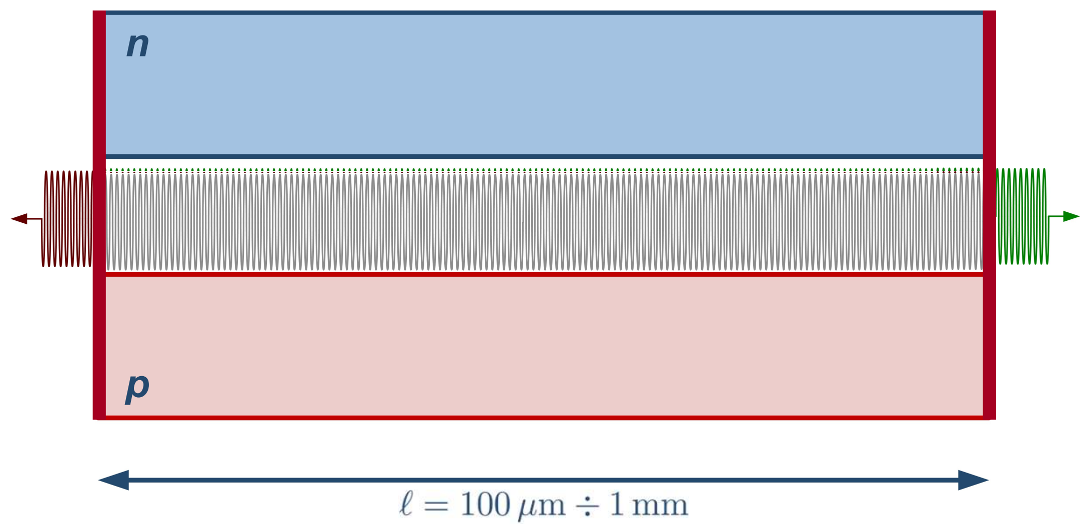
In general, we need to introduce a positive feedback:



In optics, this is obtained by exploiting the
light amplification by stimulated emission of radiation (LASER)

The Fabry-Pérot LASER (1/3)

How can we introduce a positive feedback in the *p-n* junction?



partially reflecting mirrors

This is the Fabry-Pérot LASER

Communication systems (25/26) M.Sc. Communications Eng.

The Fabry-Pérot LASER (2/3)

When propagating back and forth through the junction, the electrical field undergoes a phase rotation

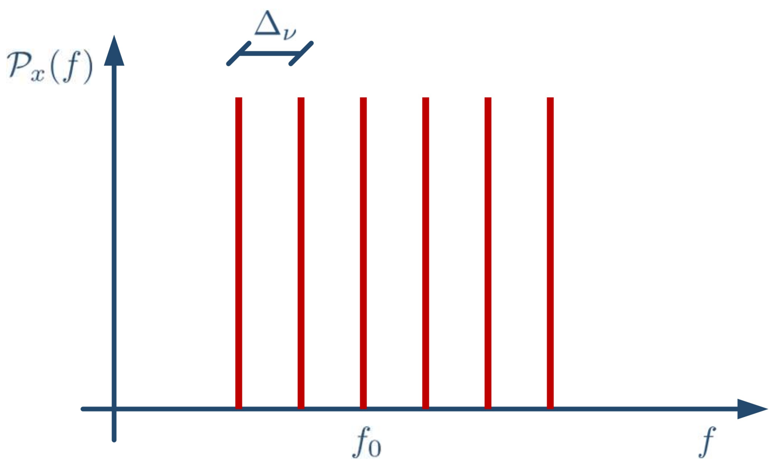
$$2\beta\ell = 2 \cdot \frac{2\pi n}{\lambda_0}\ell$$

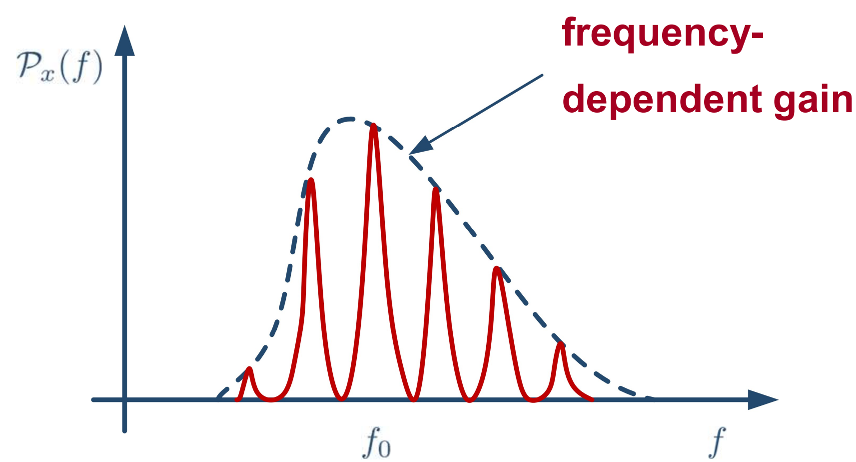
refraction index of the semiconductor, $n = 3 \div 4$

The trigger condition for a coherent amplification is

$$2\beta\ell = 2\pi m, \quad m \in \mathbb{N}^+ \qquad \Rightarrow \qquad f_m = m\Delta_\nu, \quad \Delta_\nu \triangleq \frac{c}{2n\ell}$$

The Fabry-Pérot LASER (3/3)

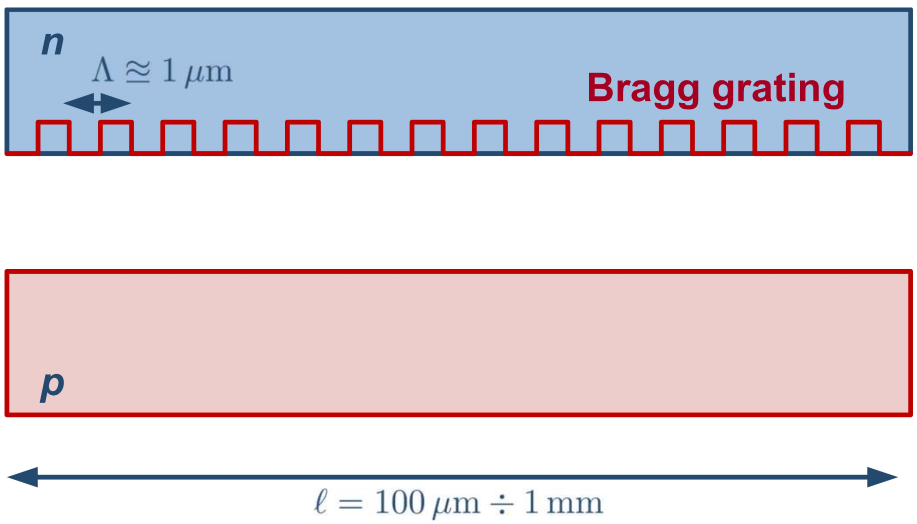


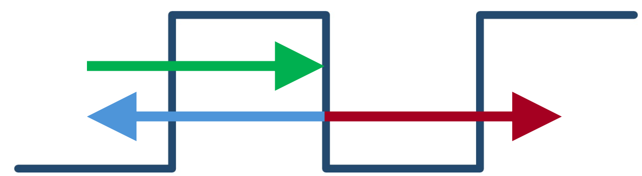


The Fabry-Pérot LASER has a significant dispersion, which highly limits maximum achievable bitrates

The distributed feedback (DFB) LASER (1/2)

To improve the features of fiber communications, we can introduce a distributed feedback (DFB):



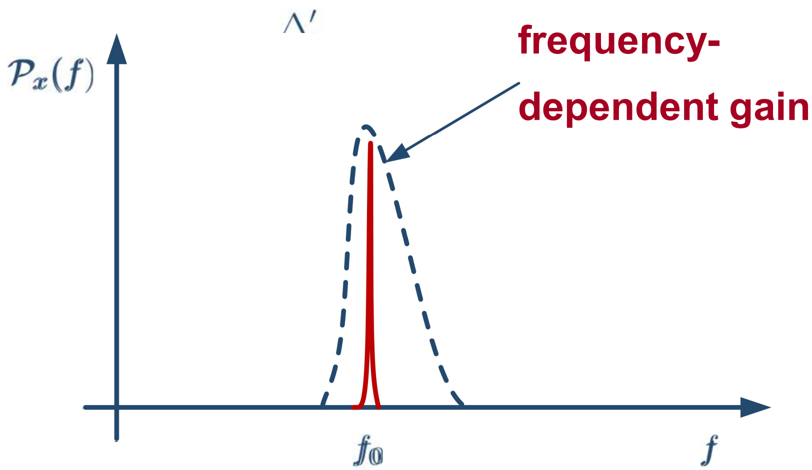


The distributed feedback (DFB) LASER (2/2)

Now we have constructive interaction (i.e., positive optical reaction) when

$$f_m = m \cdot \frac{c}{2n\Lambda} \triangleq m\Delta'_\nu$$

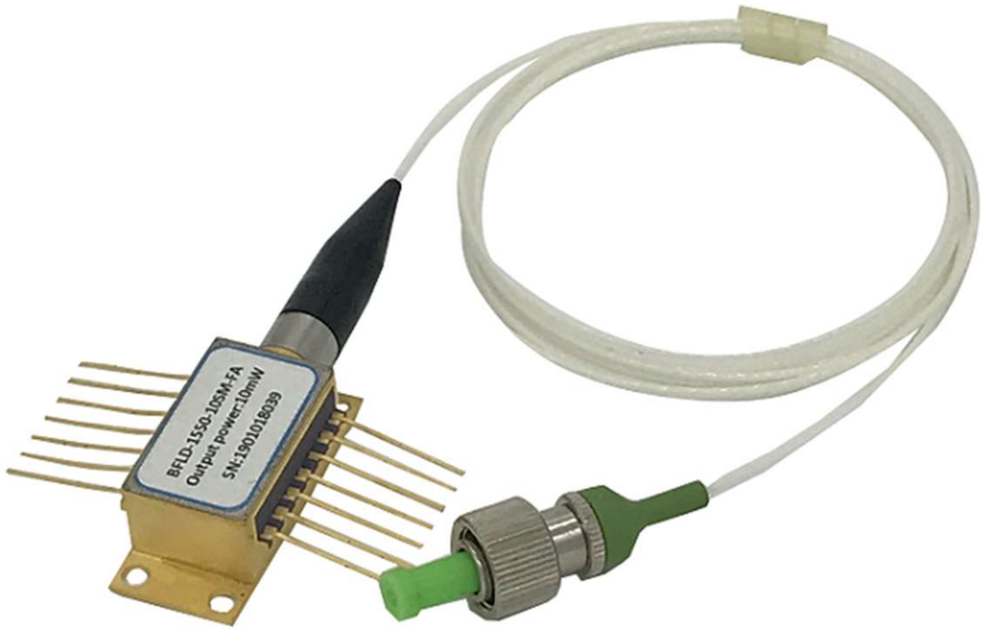
$$\boxed{\Lambda \ll \ell \quad \Rightarrow \quad \Delta'_\nu \gg \Delta_\nu}$$



Monochromatic LASER:

- **GaAs:** **0.85 μm**
- **InGaAsP:** **1.3 ÷ 1.55 μm (tunable)**

An example of a commercial LASER

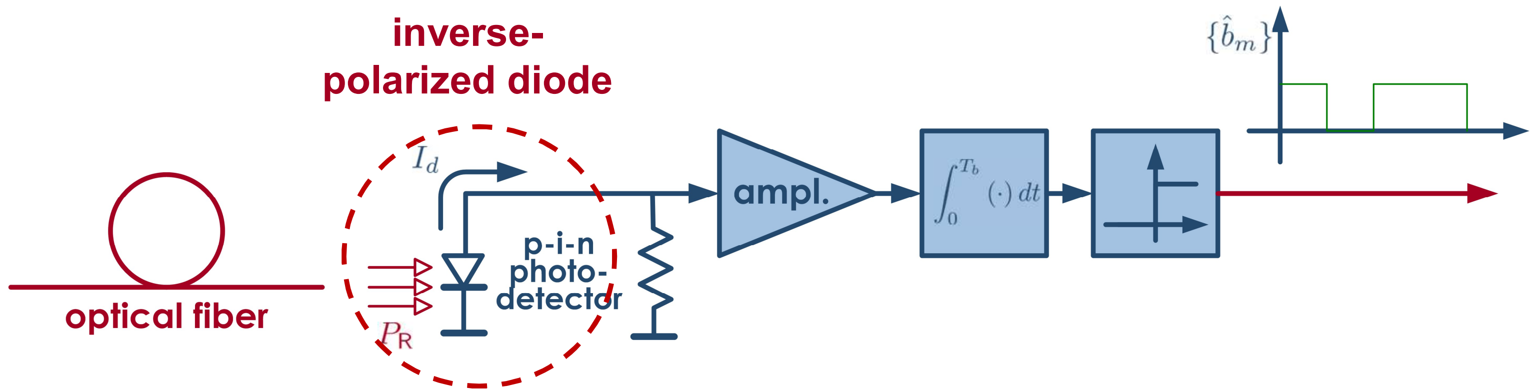


$$P_\mathsf{T} \approx 10\,\mathrm{mW}$$

$$\frac{P_\mathsf{T}}{hf_0} \approx 7.8 \cdot 10^{16}$$ **photons/s**

Photodetectors

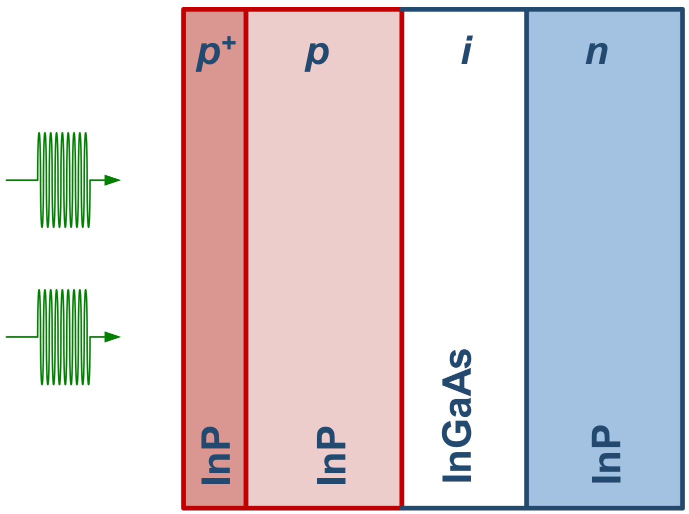
What is a photodetector?



When $P_{\mathrm{R}} = 0$, dark currents have negligible values (in the order of nA)

The p-i-n semiconductor junction

The photodetector makes use of a p-i-n diode, in which the central layer is an intrinsic (i.e., not doped) one:



Photoelectric effect

Ideally, every photon is absorbed by one electron:

detection current

$$\eta \, \frac{P_\mathsf{R}}{h f_0} = \frac{I_d}{q}$$

elementary charge

We can thus compute the detection current:

responsivity [A/W]

$$I_d = \eta \, \frac{q}{h f_0} P_\mathsf{R}$$

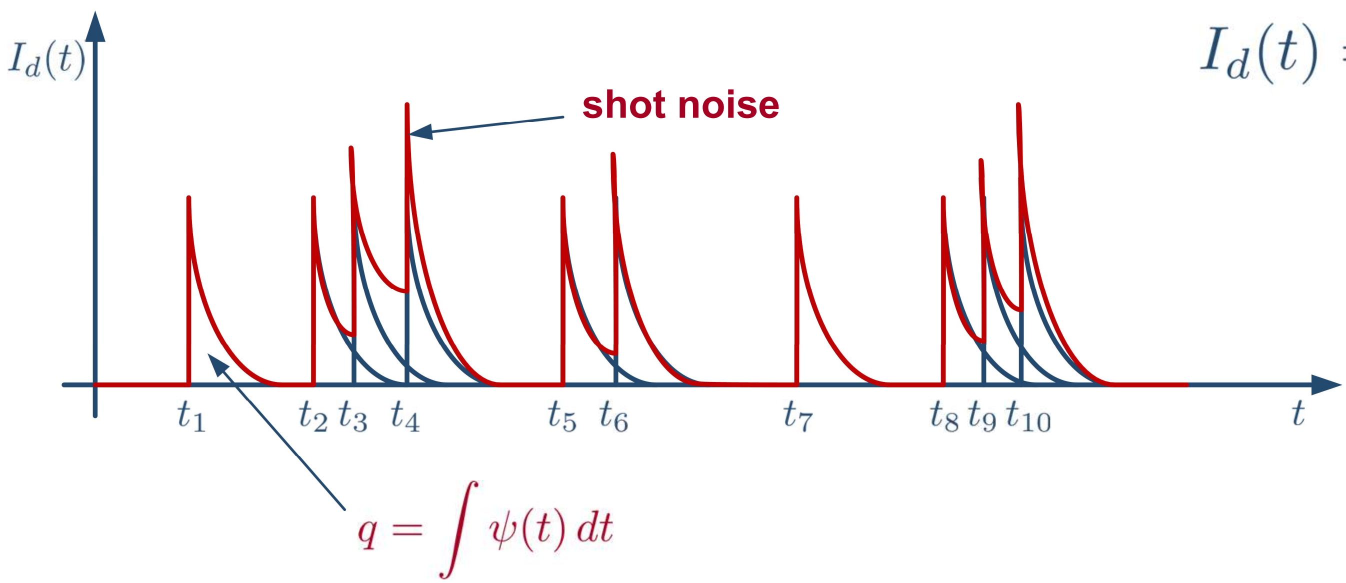
quantum efficiency

$$\eta < 1 \; (\eta = 0.7 \div 0.8)$$

Link performance

The Campbell theorem (1/2)

In the practice, the (macroscopic) detection current is composed by a combination of elementary contributes, due to the absorption of a single photon:



$$I_d(t) = \sum_k \psi(t - t_k)$$

Poisson-distributed, with intensity μ

The Campbell theorem (2/2)

Since the received current is a filtered Poisson-distributed process, we can derive the following relationships:

number of observed electrons

$$\Pr\{N_T = k\} = e^{-\mu T_b} \cdot \frac{(\mu T_b)^k}{k!}, \quad k \geq 0$$

$$I_d = \mathrm{E}\{I_d(t)\} = \mu \cdot q \quad \Rightarrow \quad \mu = \frac{I_d}{q} = \eta \frac{P_\mathrm{R}}{h f_0}$$

Quantum limit (1/3)

To measure the BER performance, let us use the law of total probability:

$$
\begin{aligned}
\mathrm{P}(E) &= \Pr\{E|b_m = 0\}\Pr\{b_m = 0\} + \Pr\{E|b_m = 1\}\Pr\{b_m = 1\} \\
&= \frac{1}{2}\underbrace{\Pr\{E|b_m = 0\}}_{\Downarrow \atop 0} + \frac{1}{2}\Pr\{E|b_m = 1\}
\end{aligned}
$$

$$\Pr\{E|b_m = 1\} = \Pr\{N_T = 0\} = e^{-\mu T_b}$$

Quantum limit (2/3)

$$\mathrm{P}(E) = \frac{1}{2}e^{-\mu T_b} = \frac{1}{2}e^{-2N_b}, \quad N_b \triangleq \frac{1}{2}\frac{\eta T_b 2P_{\mathrm{R}}}{hf_0}$$

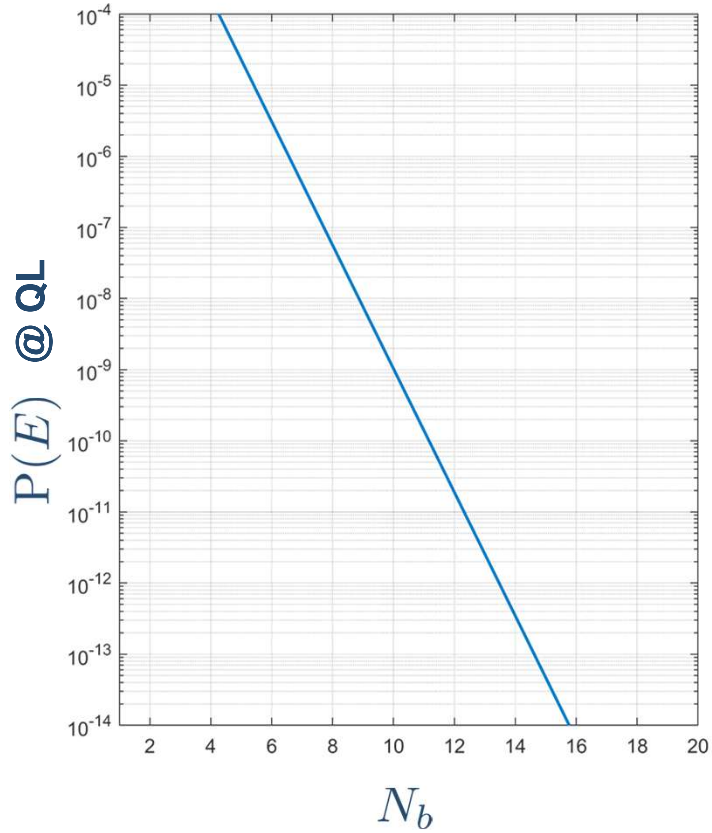
average number of photons per bit

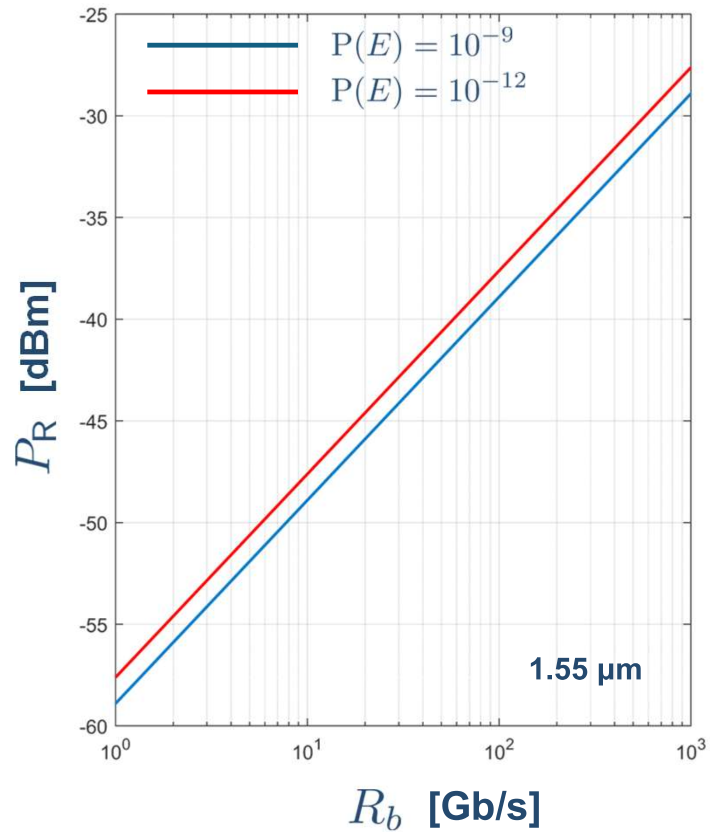
When η=1, this is called quantum limit (QL) and accounts for the maximum achievable (ideal) performance of the DD receiver

$$P_{\mathrm{R}} = N_b h f_0 R_b = -\frac{1}{2}\ln\left\{2\mathrm{P}(E)\right\} h f_0 R_b$$

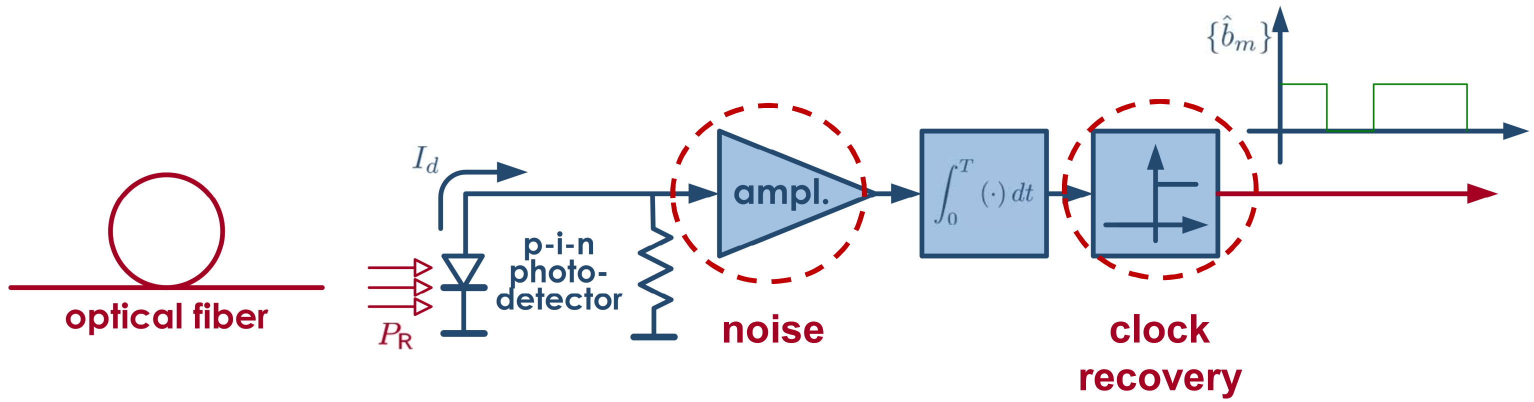
sensitivity of the receiver

Quantum limit (3/3)





Impact of noise and clock recovery

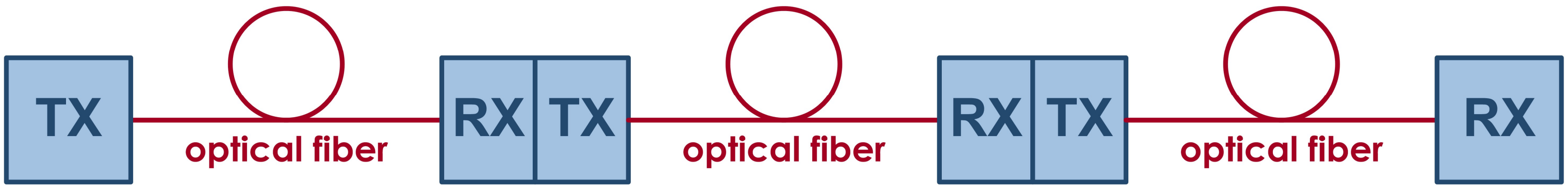


A way to improve the performance is to resort to coherent receivers

Wavelength division multiplexing (WDM)

Communication systems (25/26) M.Sc. Communications Eng.

Regenerative amplifiers



Pros:

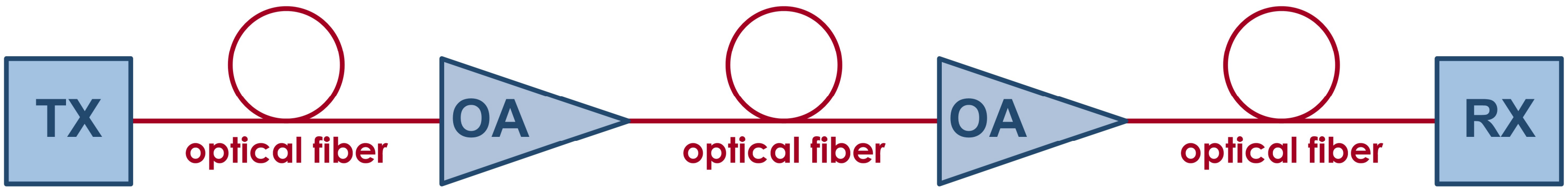
- Better SNR (quality)

Cons:

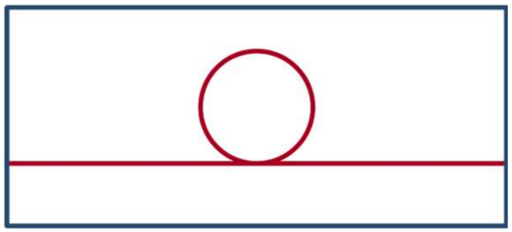
- Too complex and expensive
- Not flexible and future-proof
- Lower duration

Erbium doped fiber amplifier (EDFA) (1/2)

Since the late ’90s, transparent approaches are preferrable:



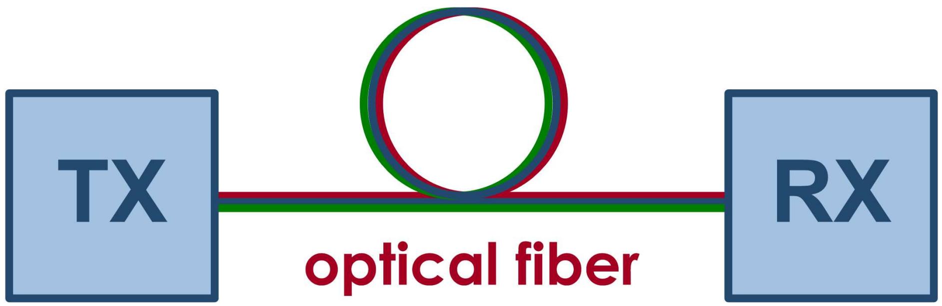
The optical amplification (OA) is performed using Erbium-doped laser amplifiers (EDFAs), special fibers doped with Erbium, a rare-Earth element, that exploit stimulated emission:



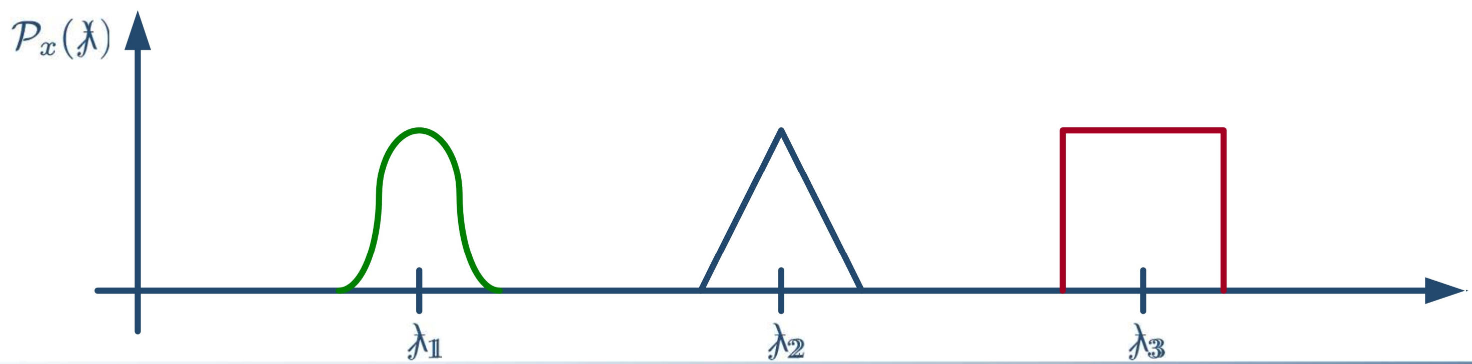
20-m special fiber

An example of a commercial EDFA

What is WDM?

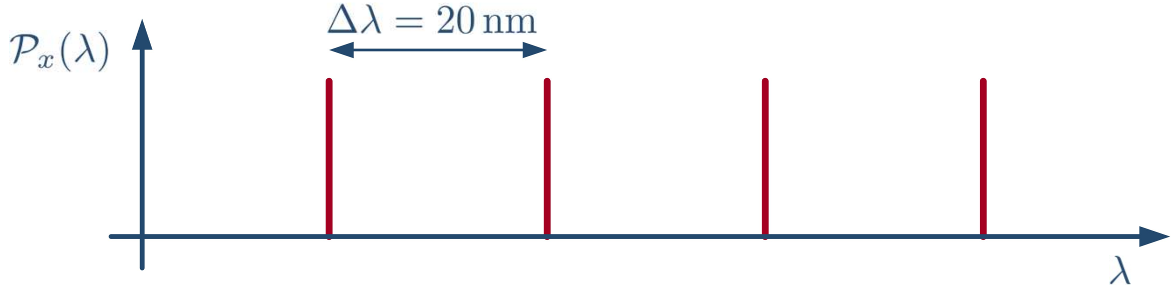


WDM is exactly FDM, done on an optical fiber:



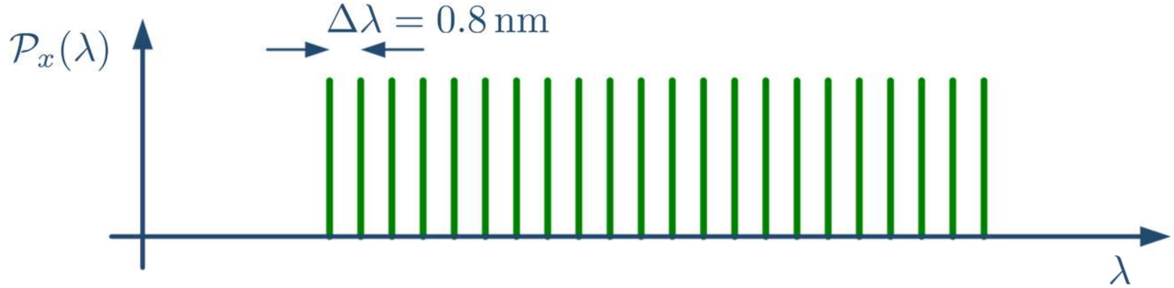
Coarse vs. dense WDM

Coarse WDM (CWDM):



$$\Delta f \approx \frac{f_0}{\lambda_0}\Delta\lambda \approx 2.5\,\mathrm{THz}$$

Dense WDM (DWDM):



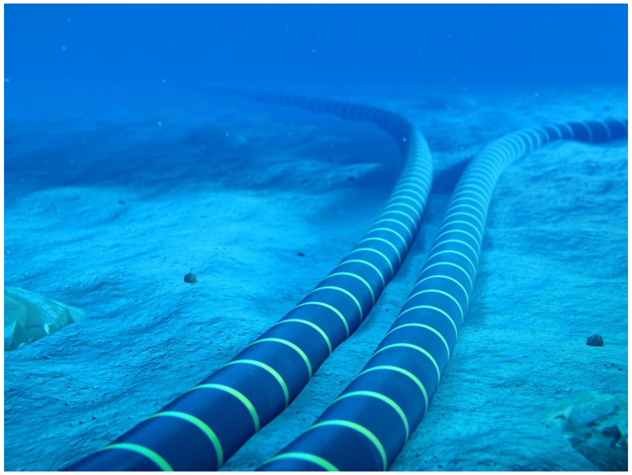
$$\Delta f \approx \frac{f_0}{\lambda_0}\Delta\lambda \approx 100\,\mathrm{GHz}$$

Access vs. transport

Communication systems (25/26) M.Sc. Communications Eng.

Access vs. transport networks

vs.



access (last mile)

transport (backbone)

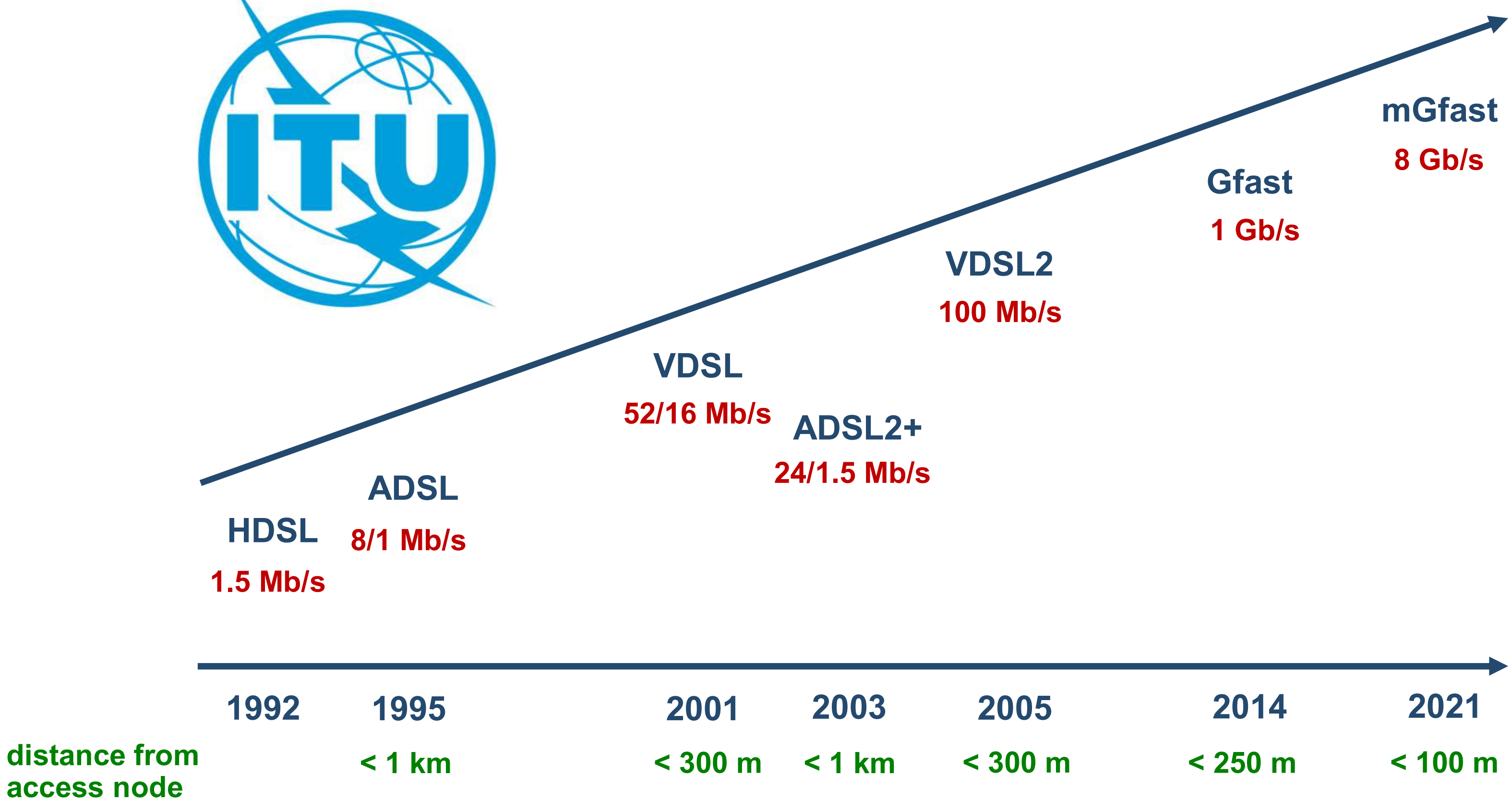
Access technologies

- Wireless communications
- Fixed wireless access (FWA)
- Cable modems
- Satellite communications
- Digital subscriber line (DSL) technologies
- Fiber-based access

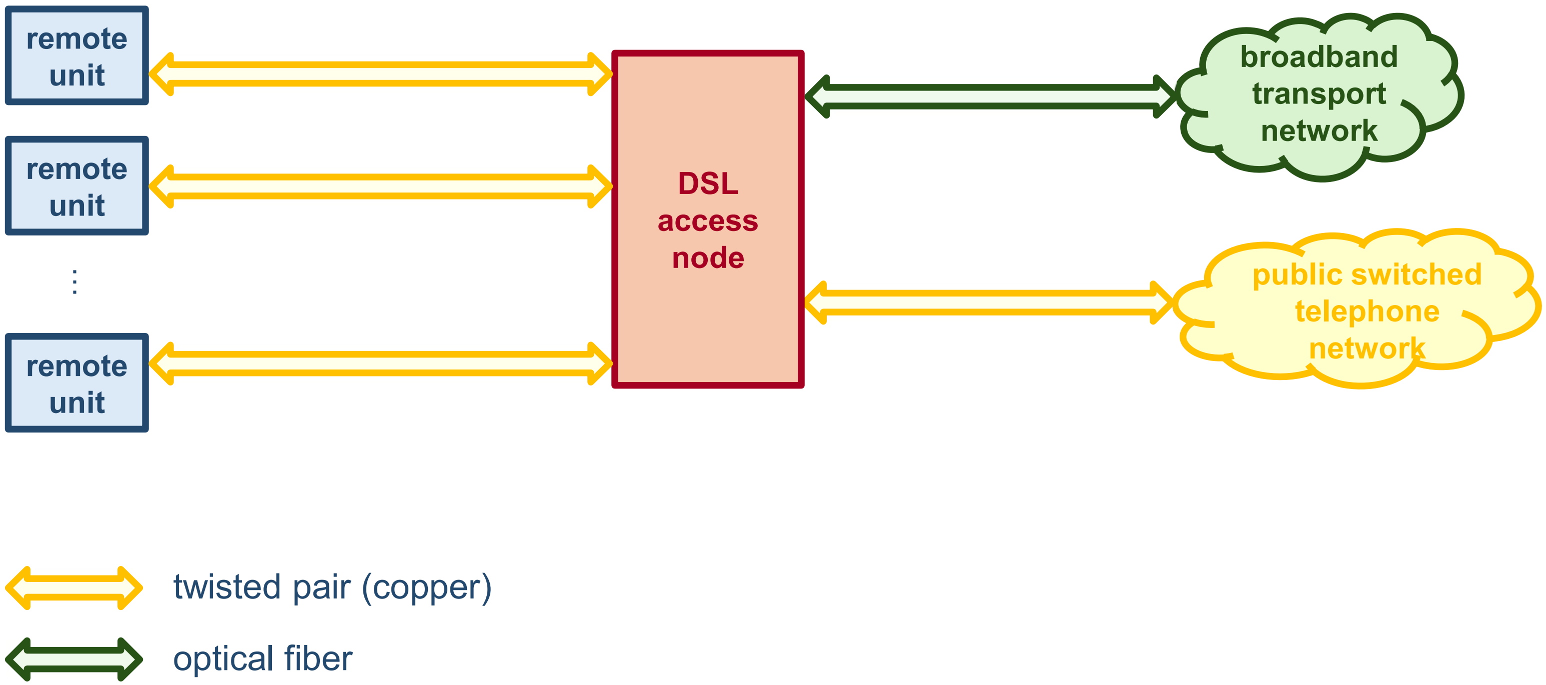
xDSL technologies

Communication systems (25/26) M.Sc. Communications Eng.

xDSL technologies

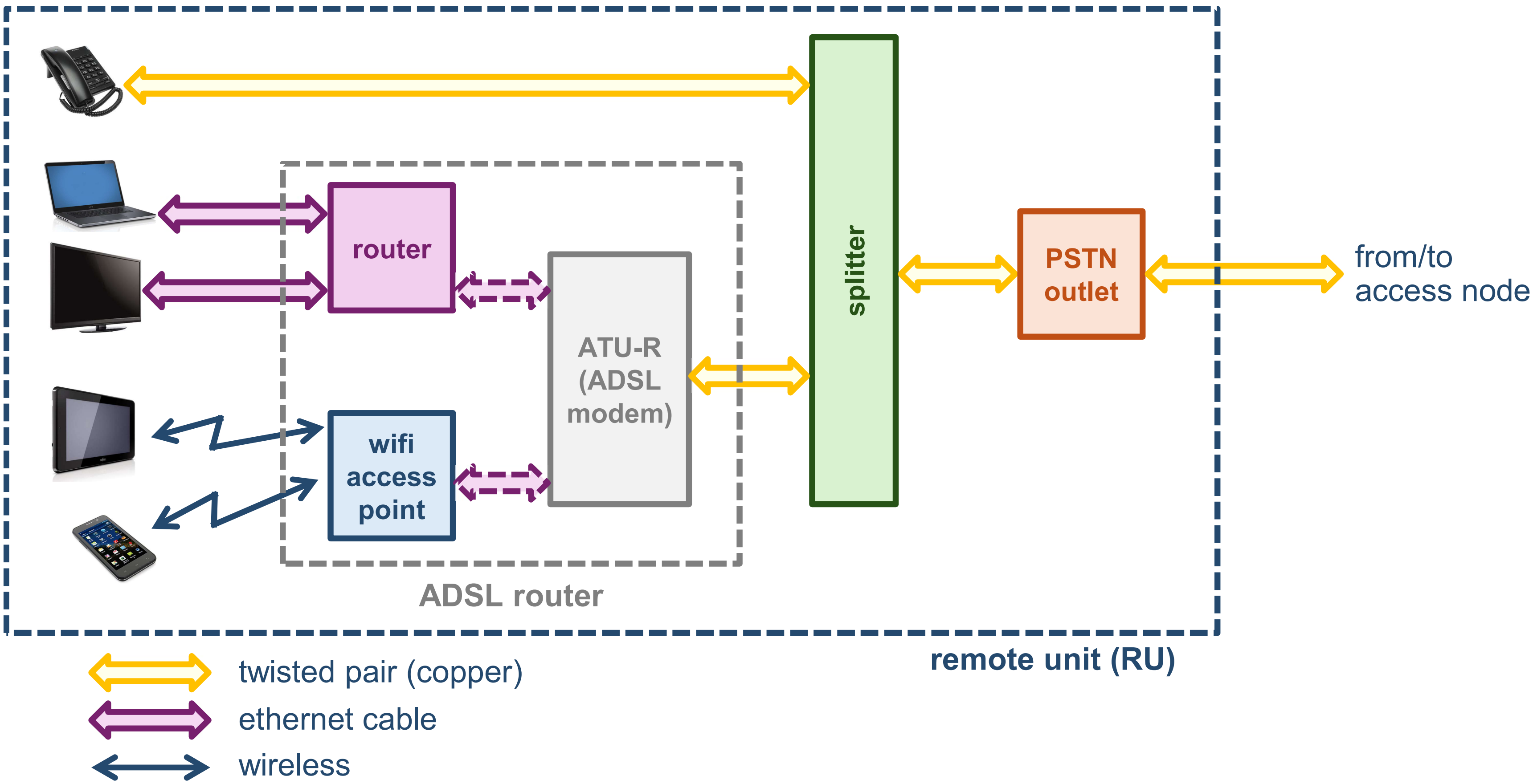


Architecture



Communication systems (25/26) M.Sc. Communications Eng.

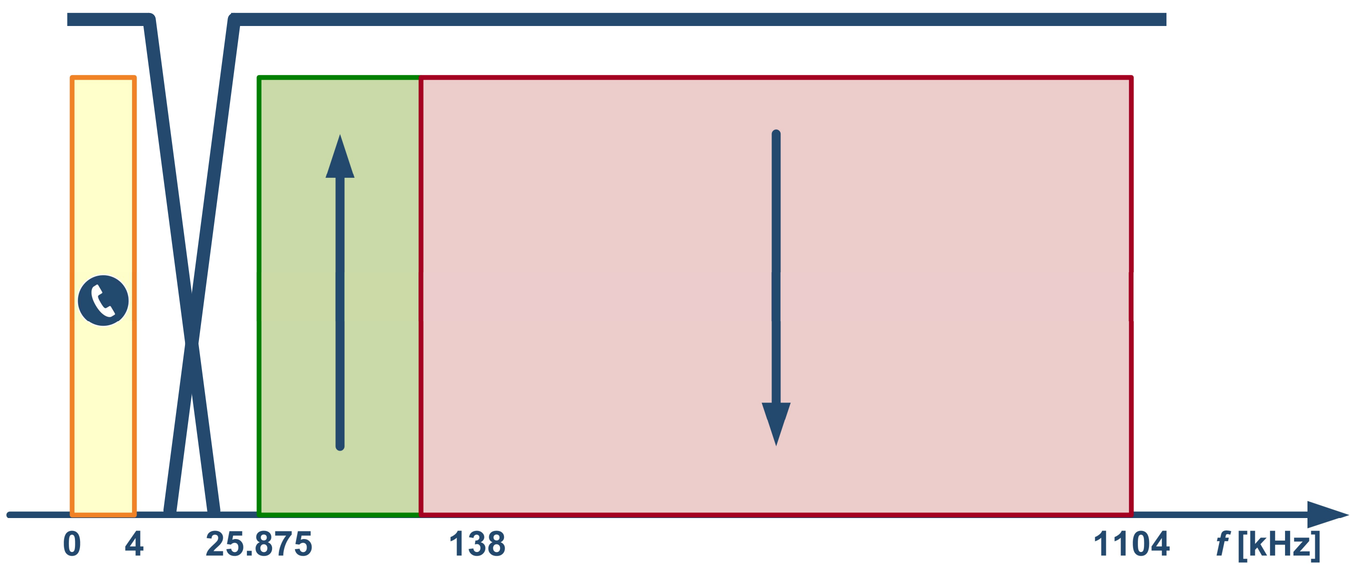
Architecture at end user (1/2)



Communication systems (25/26) M.Sc. Communications Eng.

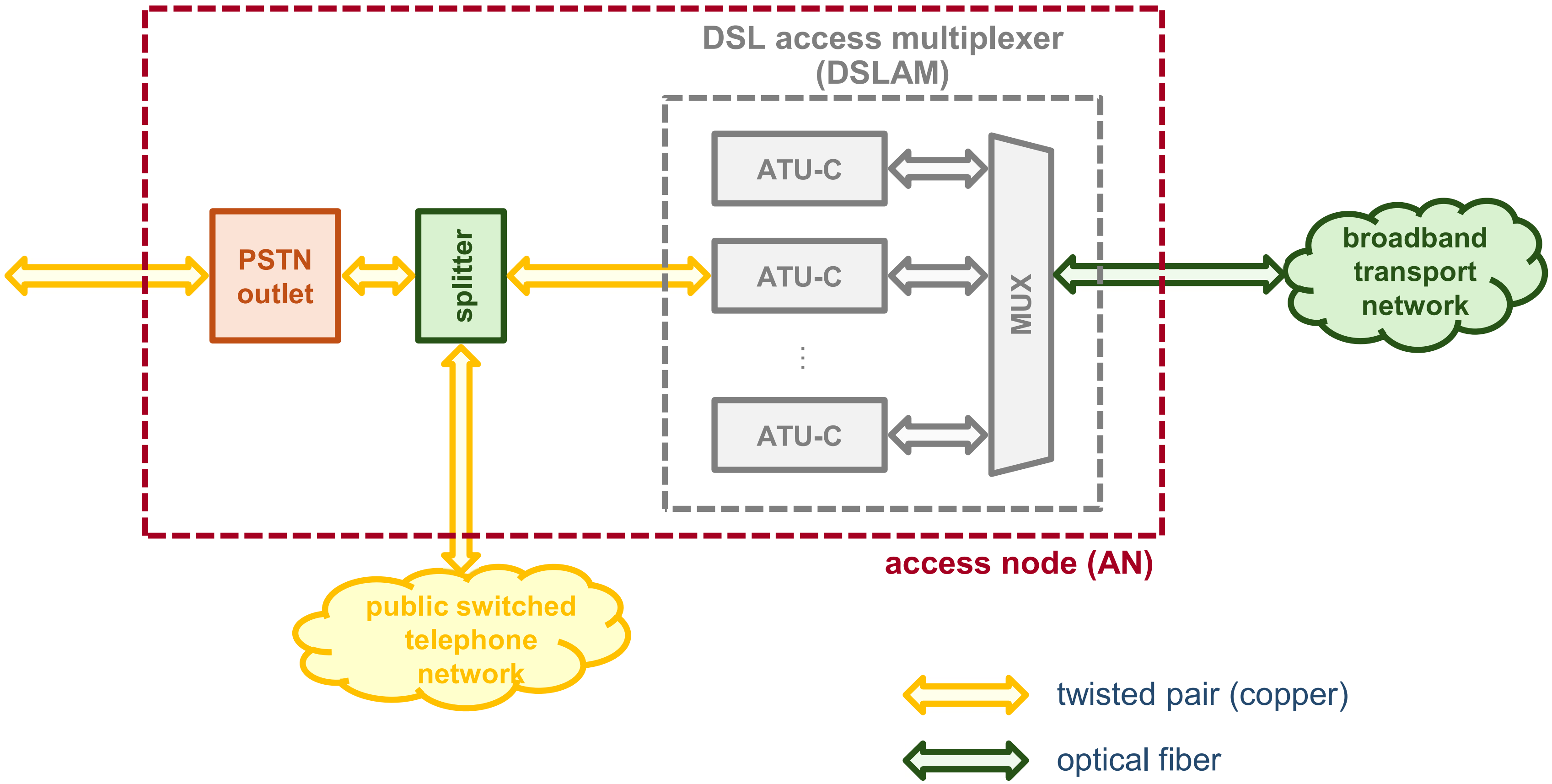
Architecture at end user (2/2)

The splitter is in practice a multiband filter, that separates the band allocated for PSTN services (voice) from the one allocated for data:



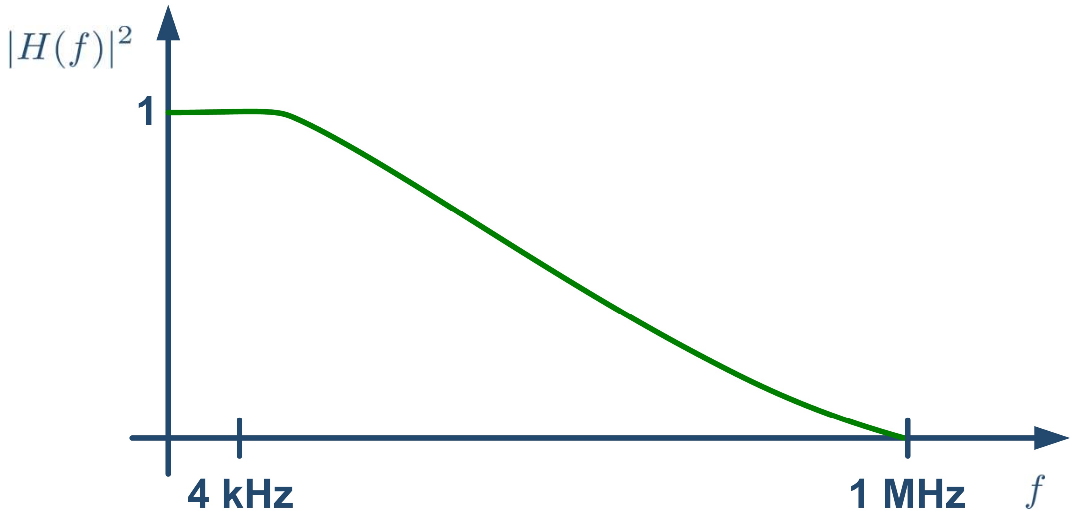
Communication systems (25/26) M.Sc. Communications Eng.

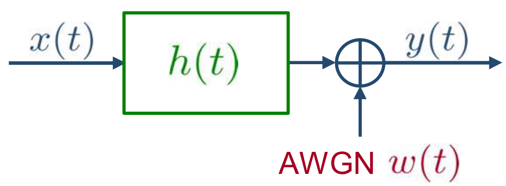
Architecture at access node



Impairments: colored noise and channel selectivity (1/4)

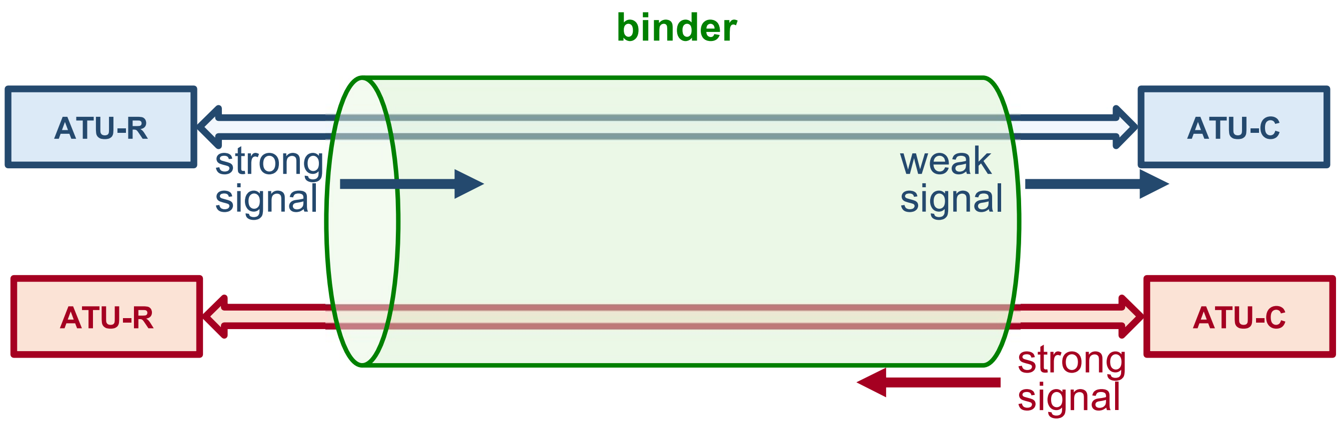
Suppose to use constellations with 10 bits/symbol: in any case, at least 1-MHz bandwidth is needed





Dip. Ingegneria dell'Informazione
University of Pisa, Pisa, Italy

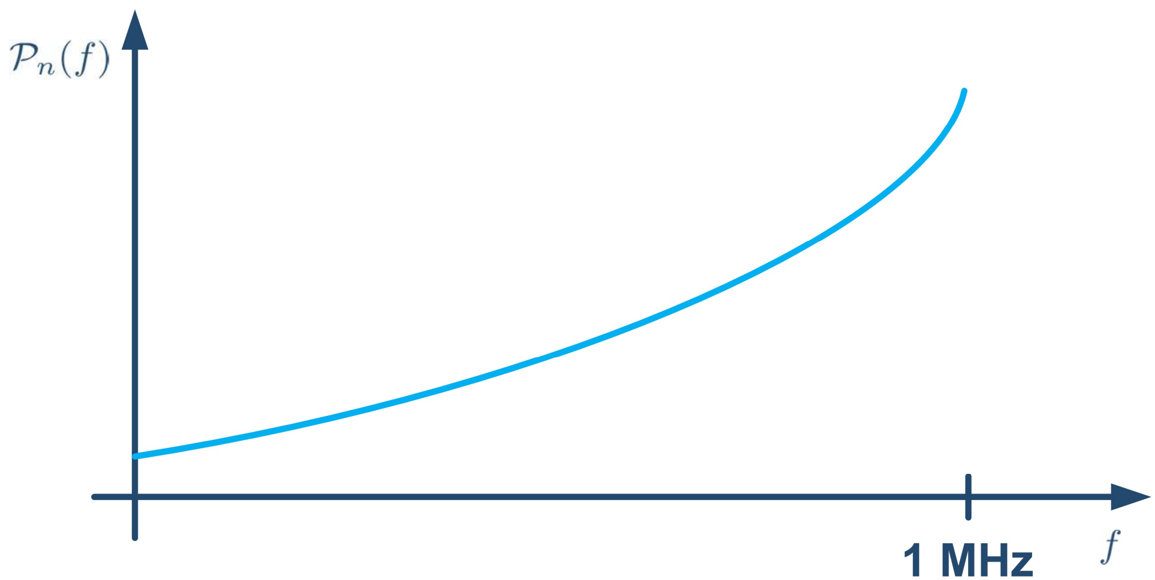
Impairments: colored noise and channel selectivity (2/4)

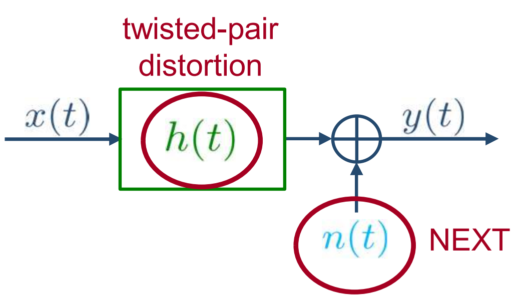


The huge imbalance between the weak upstream signal and the strong downstream signal generates near-end cross-talk (NEXT)

Impairments: colored noise and channel selectivity (3/4)

Due to NEXT, the noise is colored:

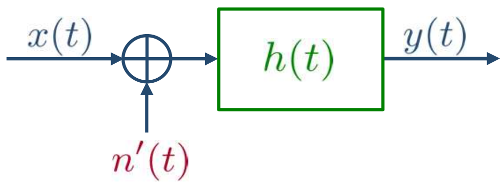




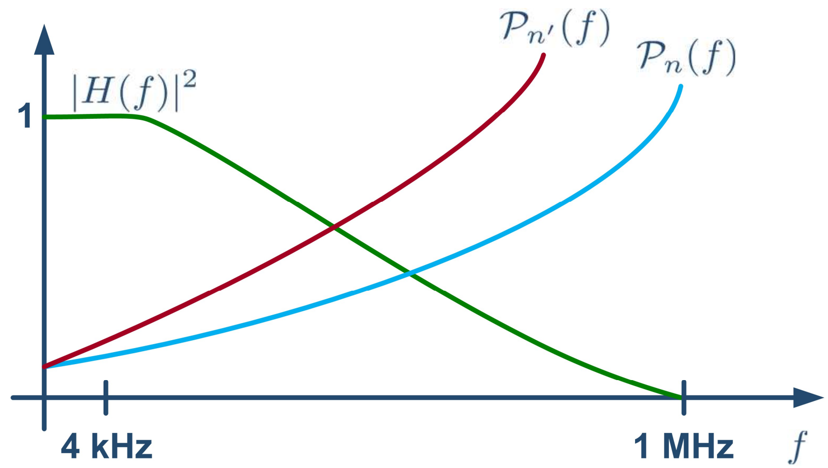
Communication systems (25/26) M.Sc. Communications Eng.

Impairments: colored noise and channel selectivity (4/4)

We can build an equivalent model as follows:

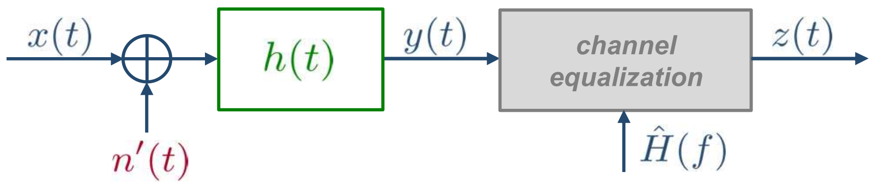


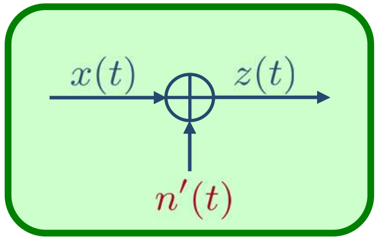
$$\boxed{\mathcal{P}_{n'}(f) = \frac{\mathcal{P}_n(f)}{|H(f)|^2}}$$



Discrete multi-tone (DMT) (1/3)

This formulation is convenient, because we can **isolate** the effect of the twisted pair, by **equalizing** the channel:





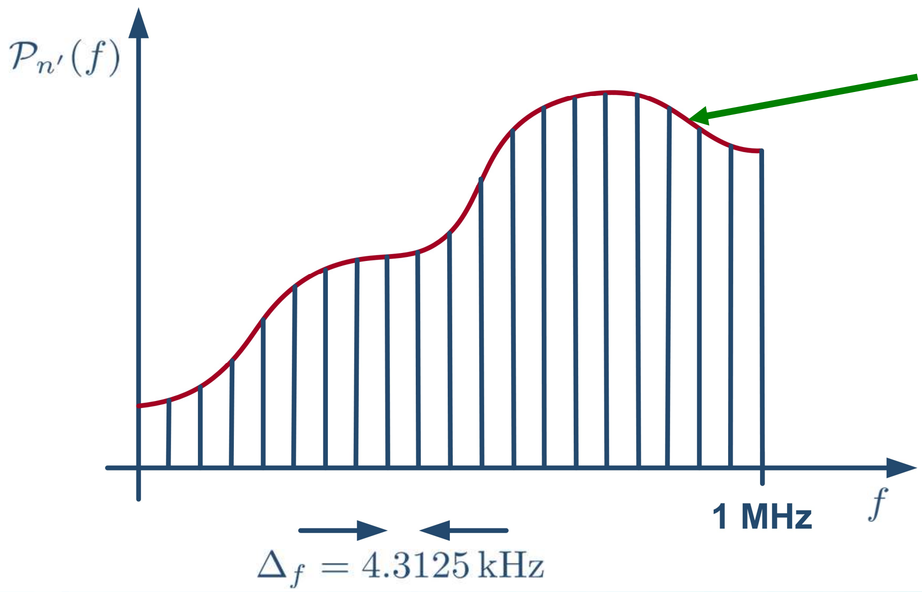
This system bears the **same** Shannon capacity as the original one

However, the Shannon capacity **does depend** on the distortion of the twisted pair, through the equivalent NEXT noise!

Discrete multi-tone (DMT) (2/3)

From the Shannon capacity with AWGN noise $\mathcal{C} = B \cdot \log_2(1+\gamma)$, we need to shift to the paradigm of Shannon capacity with colored noise:

$$\mathcal{C} = \sum_k \mathcal{C}_k = \sum_k \Delta_f \log_2(1+\gamma_k)$$



$$\boxed{\Delta_f = \frac{B}{K}, \quad K = 256}$$

Discrete multi-tone (DMT) (3/3)

The power allocation can be done using a multicarrier technology, called discrete multi-tone (DMT):

$$\gamma_k = \frac{p_k}{\sigma_k^2} \Rightarrow p_k = \alpha\sigma_k^2 \Rightarrow \mathcal{C}_k = \Delta_f \log_2(1+\alpha)\,\forall k$$

Bitrate is adapted on a subcarrier basis (unlike OFDM, in which the same constellation is used on all subcarriers):

$$\boxed{R_{b,k} \leq \mathcal{C}_k}$$

However, equalizing the SNRs per subcarrier does not yield the optimal power allocation:

$$\mathcal{C} = \sum_k \mathcal{C}_k = B \cdot \log_2(1+\alpha)$$

The waterfilling criterion (1/2)

The optimal constrained power allocation is the solution to the problem

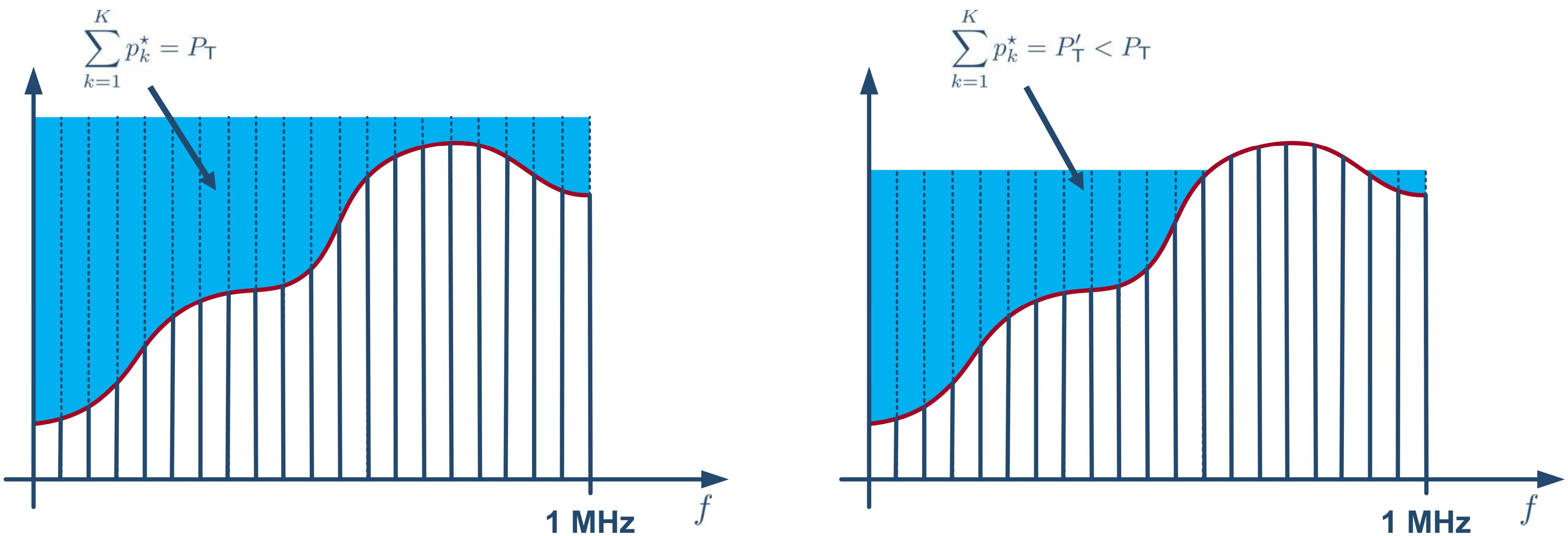
$$\mathbf{p}^\star = [p_1^\star, \ldots, p_K^\star]^T = \arg \max_{\mathbf{p}\in\mathbb{R}^K} \sum_{k=1}^{K} \Delta_f \log_2(1+\gamma_k) \quad \text{s.t.} \sum_{k=1}^{K} p_k \leq P_\mathsf{T}$$

Using the Lagrange multipliers, we find that the optimal powers are such that

$$p_k^\star + \sigma_k^2 = P_\mathsf{T}/K$$

The waterfilling criterion (2/2)

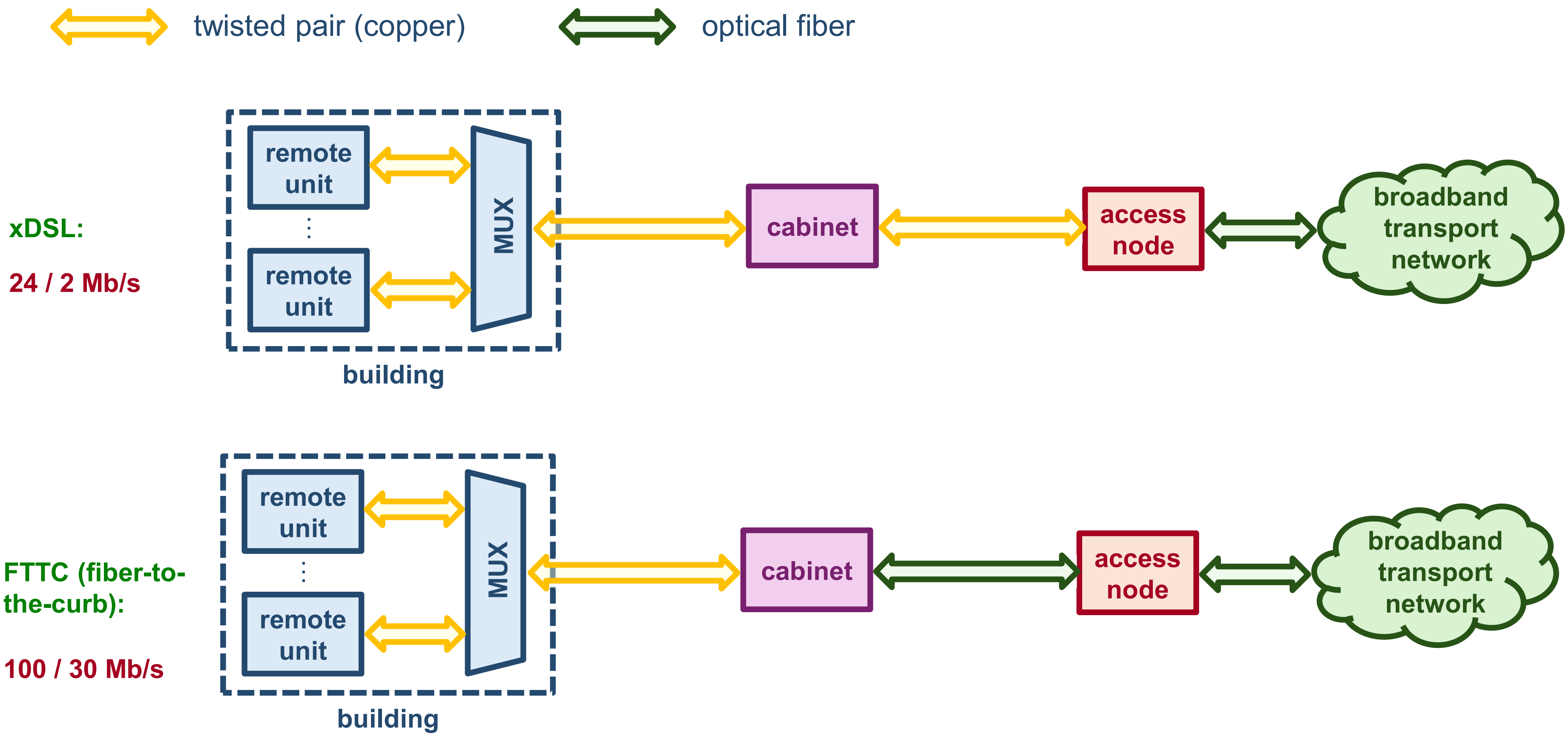
This leads to the water-filling algorithm:



After power allocation, we can perform bit allocation based on $R_{b,k} \leq C_k$ (up to 16k-QAM – 14 bits/symbol, although usually no more than 12 bits/symbol are used)

FTTx technologies

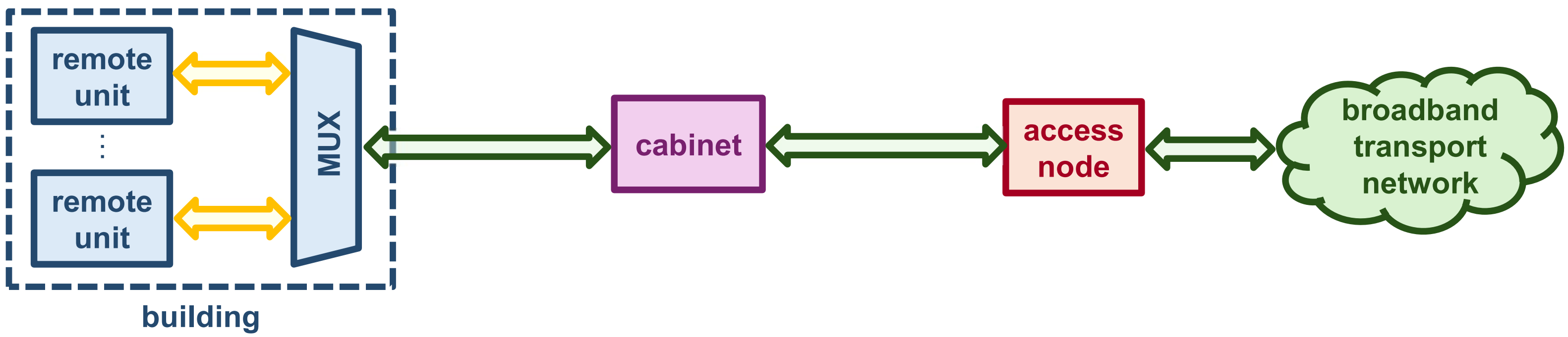
FTTC vs. FTTB vs. FTTH (1/2)



FTTC vs. FTTB vs. FTTH (2/2)

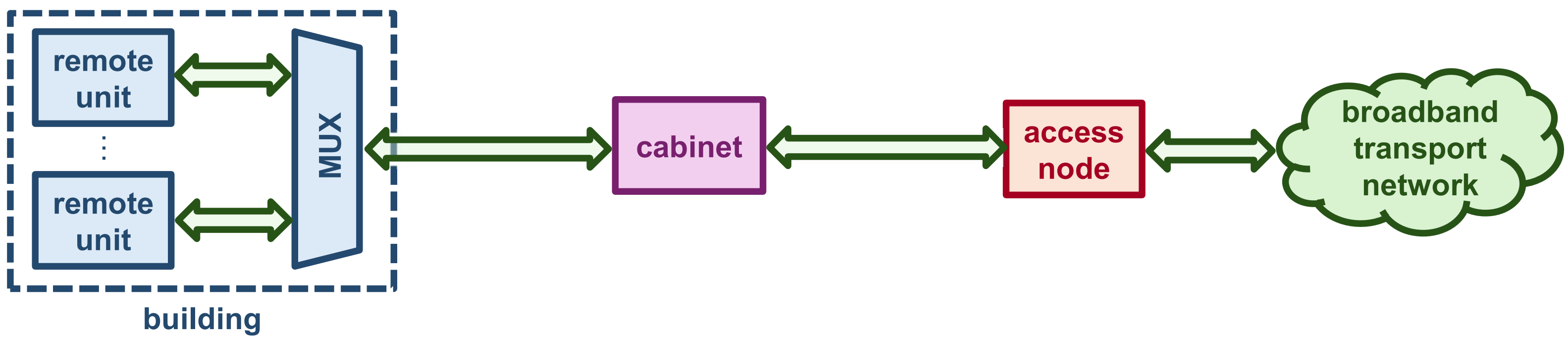
FTTB (fiber-to-the-building):

1 / 0.1 Gb/s



FTTH (fiber-to-the-home):

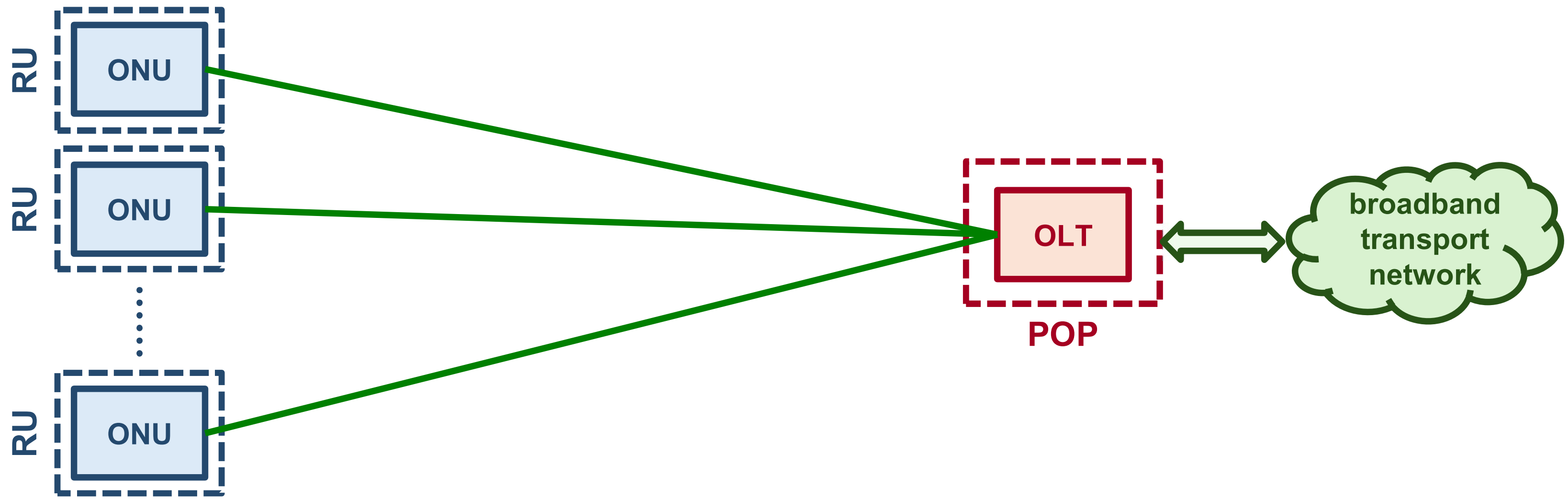
>1 Gb/s



Point-to-point architecture @ FTTH

OLT: optical line termination
ONU: optical network unit

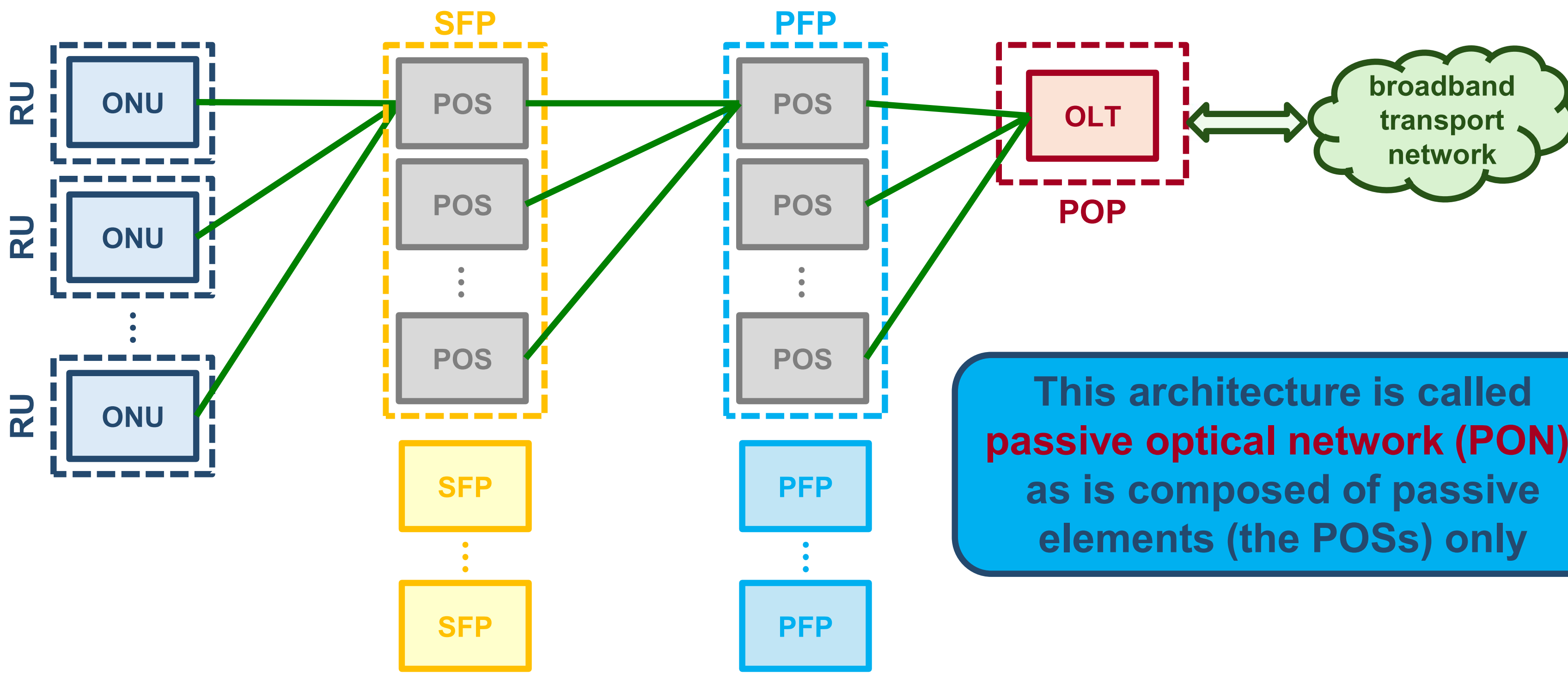
POP: point of presence
RU: remote unit



This architecture, while being future-proof, is extremely expensive

Point-to-multipoint architecture @ FTTH

OLT: optical line termination
ONU: optical network unit
PFP: primary flexibility point
PON: passive optical network
POP: point of presence
POS: passive optical splitter
RU: remote unit
SFP: secondary flexibility point



This architecture is called passive optical network (PON), as is composed of passive elements (the POSs) only

Dip. Ingegneria dell'Informazione
University of Pisa, Pisa, Italy

Elements of a PON

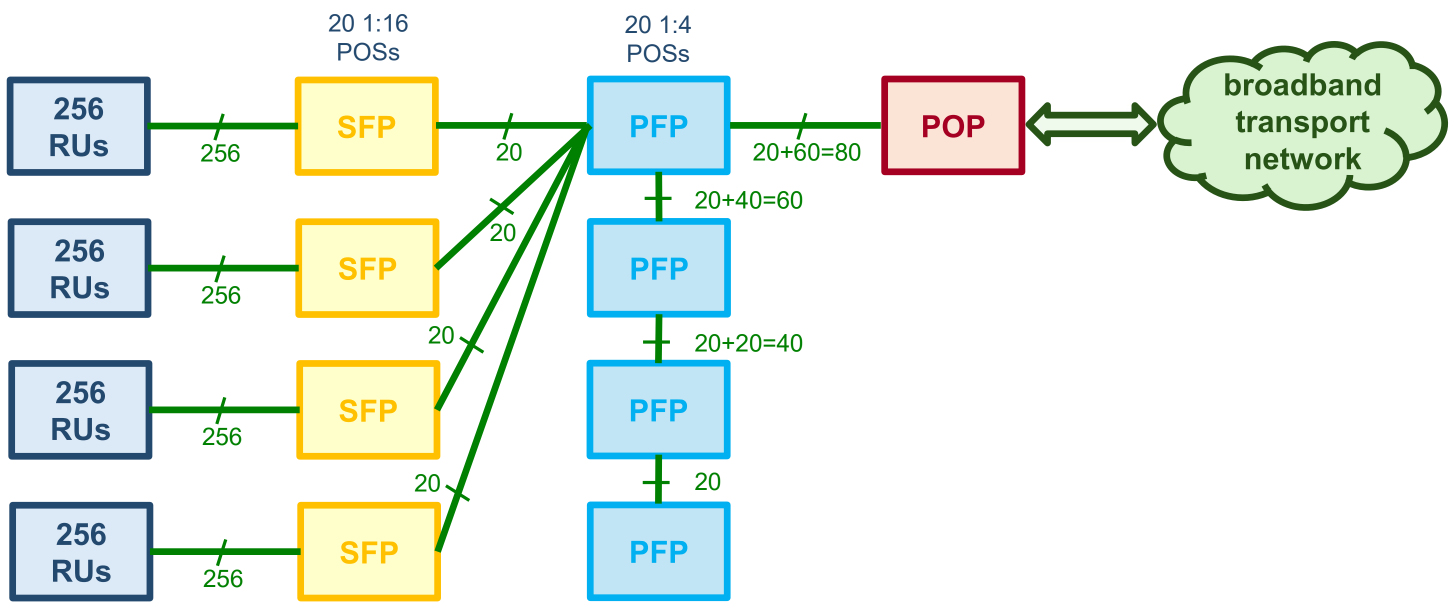
SFP

PFP

POS

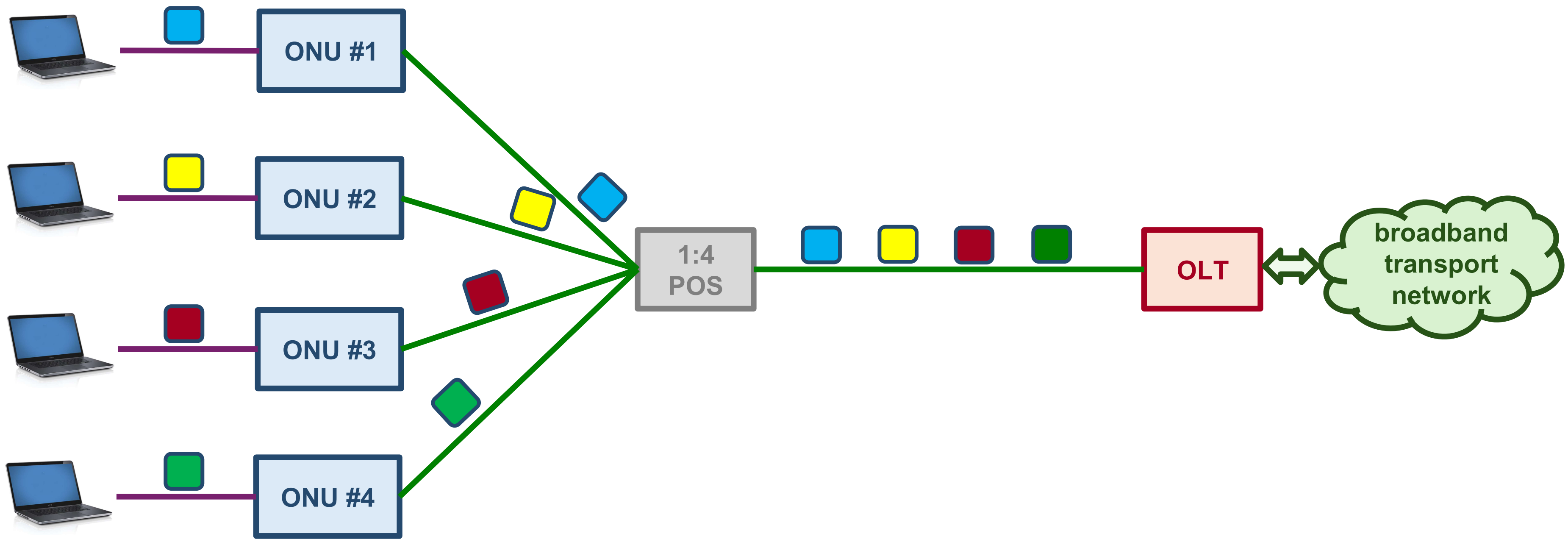
Typical ratios:
- 1:4
- 1:16
- 1:32

Example of a PON deployment



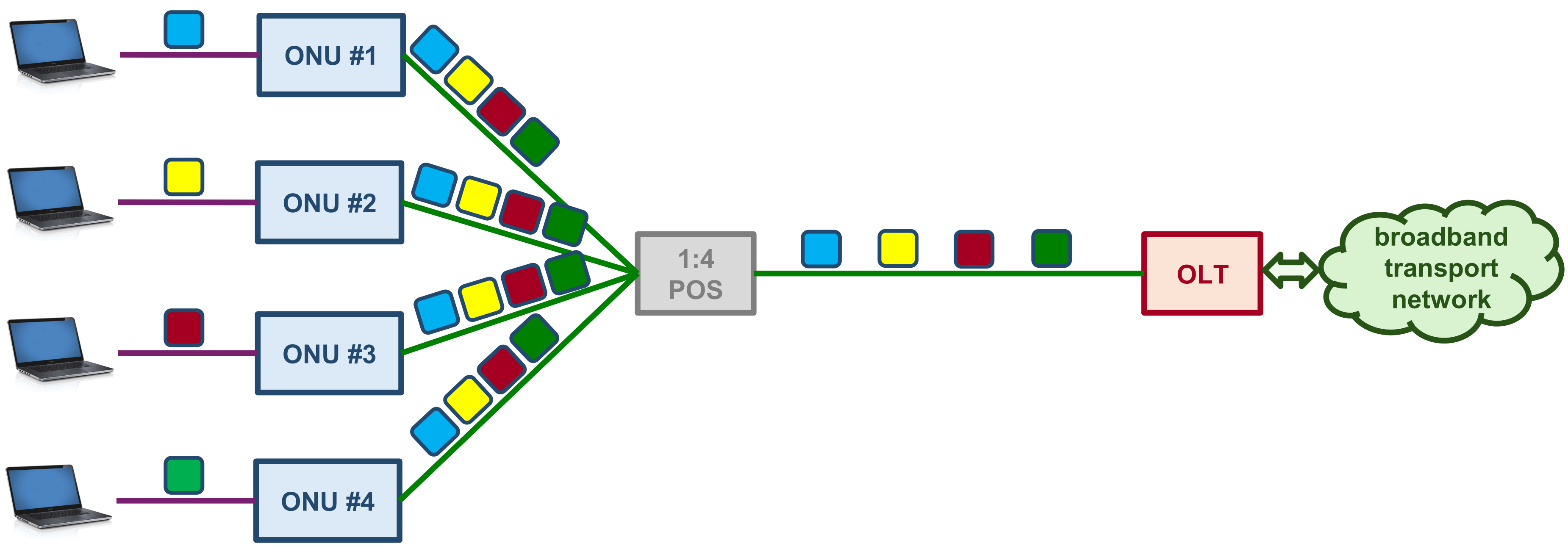
TDM(A) technology (1/2)

Upstream (usually in II window @ 1.3 μm): TDMA

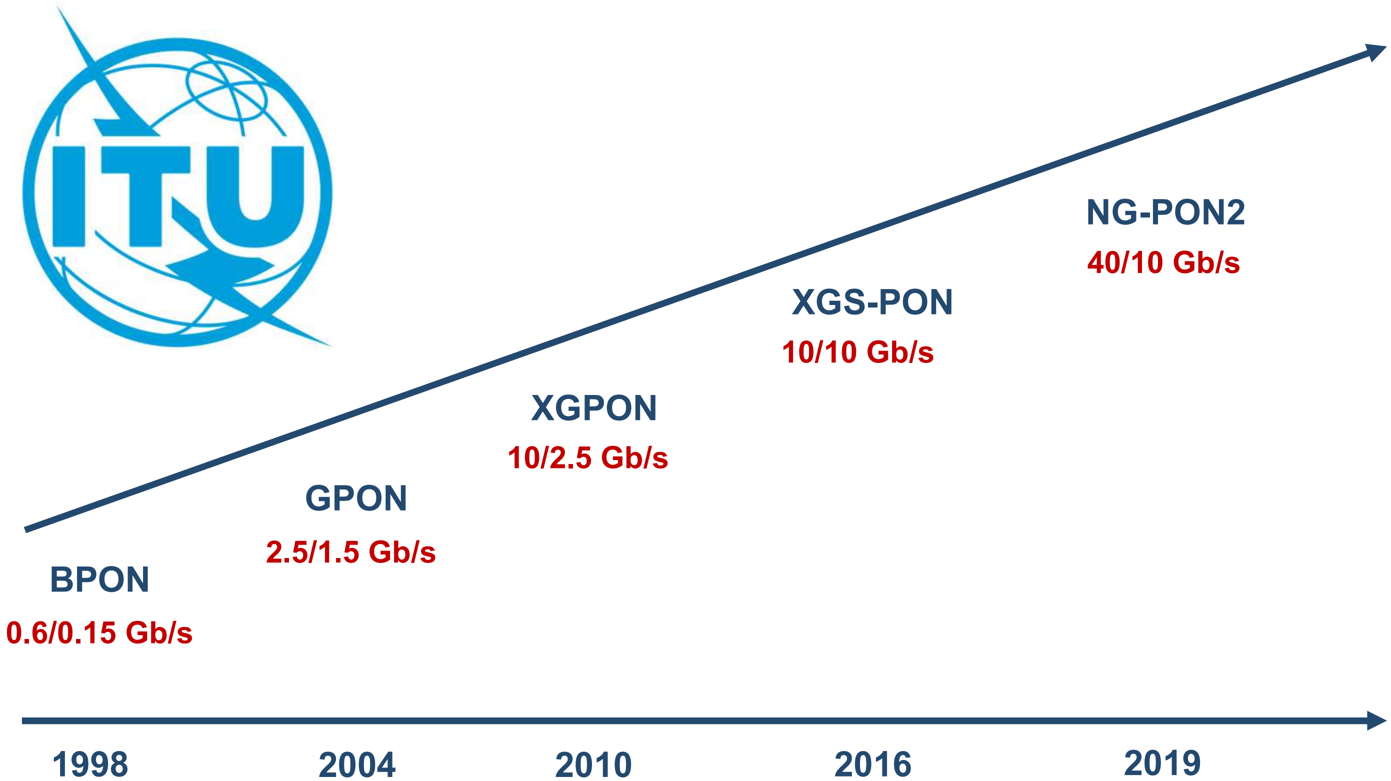


TDM(A) technology (2/2)

Dowstream (usually in III window @ 1.55 μm): TDM



Evolution of PON technologies



Communication systems (25/26) M.Sc. Communications Eng.

Bibliography

[01] M. Luise, *Lecture Notes on Communication Technologies*. Pisa, Italy: Univ. Press, 2023.
[02] G. Keiser, *Optical Fiber Communications*. Singapore: Springer Singapore, 2021.
[03] G. P. Agrawal, *Fiber-Optic Communication Systems*. Hoboken, NJ: J. Wiley & Sons, 4th ed., 2010.