INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION

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WORKSHOP ON OPTICAL FIBER COMMUNICATION
(24 February - 21 March 1986)

OPTICAL FIBRE SYSTEM DESIGN

presented by

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OPTICAL FIBRE SYSTEM DESIGN

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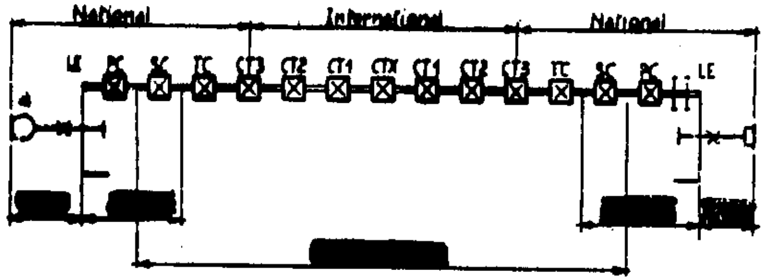
TLC APPLICATIONS OF OPTICAL FIBRES

a) Long distance network

b) Distribution network

c) LAN

Longest connection for transmission and switching.



LE local exchange
PC primary centre

SC secondary centre
TC tertiary centre

CT transit centre

FREQUENCY (Hz)	WAVELENGTH	DESIGNATION
$\sim 10^5$	$\sim 10^3$ m	LW
$\sim 10^7$	~ 10 m	SW
$\sim 10^8$	~ 1 m	VHF
$\sim 10^9$	~ 10 cm	UHF
$\sim 10^{10}$	~ 1 cm	Microwaves
$\sim 10^{11}$	~ 1 mm	Far infrared
$2 \div 7.5 \cdot 10^{14}$	$1.6 \div 0.4$ μm	Near I.R. - Visible
$\sim 10^{15}$	$\lesssim 0.4$ μm	U.V.
$\sim 10^{16}$	~ 10 nm	X Rays
$\sim 10^{18}$	~ 0.1 nm	γ Rays

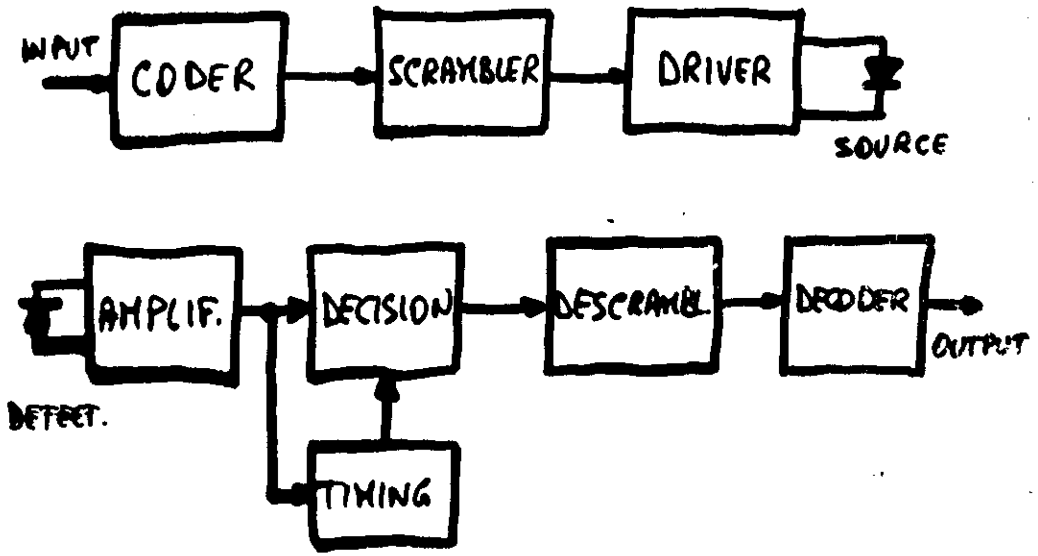
DIGITAL HIERARCHY

1) 2 Mbit/s		1.5 Mbit/s
2) 8 Mbit/s		6 Mbit/s
3) 34 Mbit/s	45 Mbit/s	32 Mbit/s
4) 140 Mbit/s	274 Mbit/s	97 Mbit/s
5) 565 Mbit/s		~400 Mbit/s

WHAT IS PECULIAR OF AN OPTICAL TRANSMISSION SYSTEM

- an E/O converter
  (optical source)
- an optical fibre
  (transmission medium)
- an O/E converter
  (photodetector/optical receiver)

BLOCK DIAGRAM OF A FIBRE-OPTIC TRANSMISSION SYSTEM



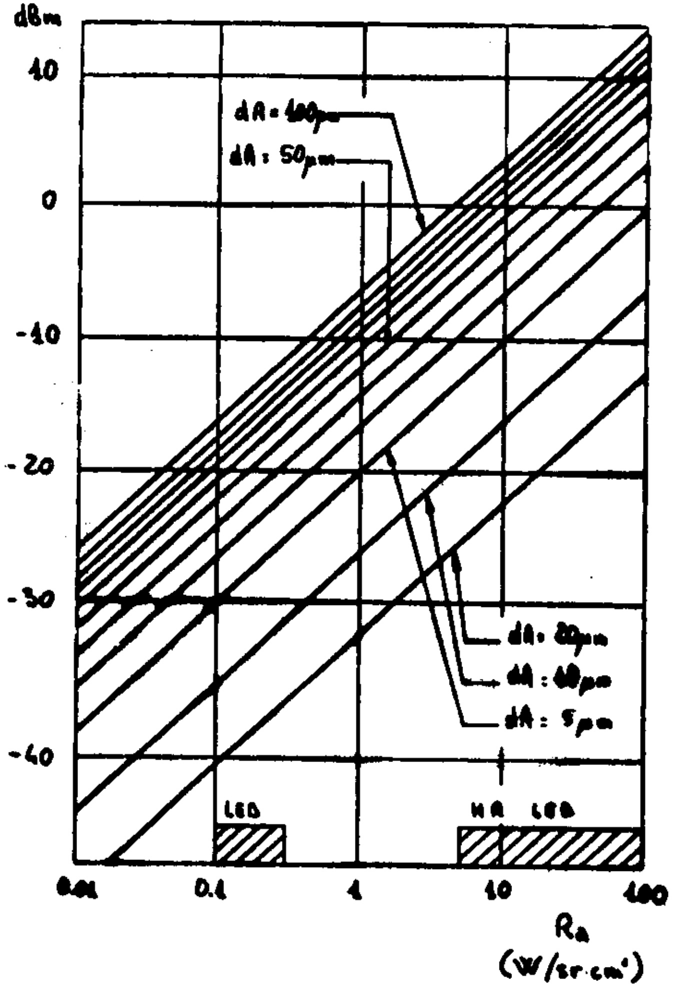
CHARACTERISTICS OF OPTICAL SOURCES

- EMITTED POWER
- INJECTED POWER
- MAXIMUM MODULATION FREQUENCY
- LINEARITY

CARATTERISTICHE DELLE SORGENTI

	LASER		LED	
λ (μm)	0.80-0.88	(1.2) 1.3 (1.5)	0.80-0.90	(1.2) 1.3 (1.5)
MATERIALE	GaAlAs	InGaAsP	GaAlAs, GaAs	InGaAsP
P_{OUT} (mW)	5-20	5-10	1-10	1-10
$P_{IN\ FIBRA}$ (mW)	1-3 (M.M.) 0.4-1 (S.M.)	1-3 (M.M.) 0.4-1 (S.M.)	0.05-0.10	0.02-0.05
Δλ (nm)	1-5	1-5	30-40	80-140
B (MHz)	>500	>500	50	150
VITA (h)	10^5-10^6	10^5-10^6	10^8	10^8

ACCOPPIAMENTO LED-FIBRA

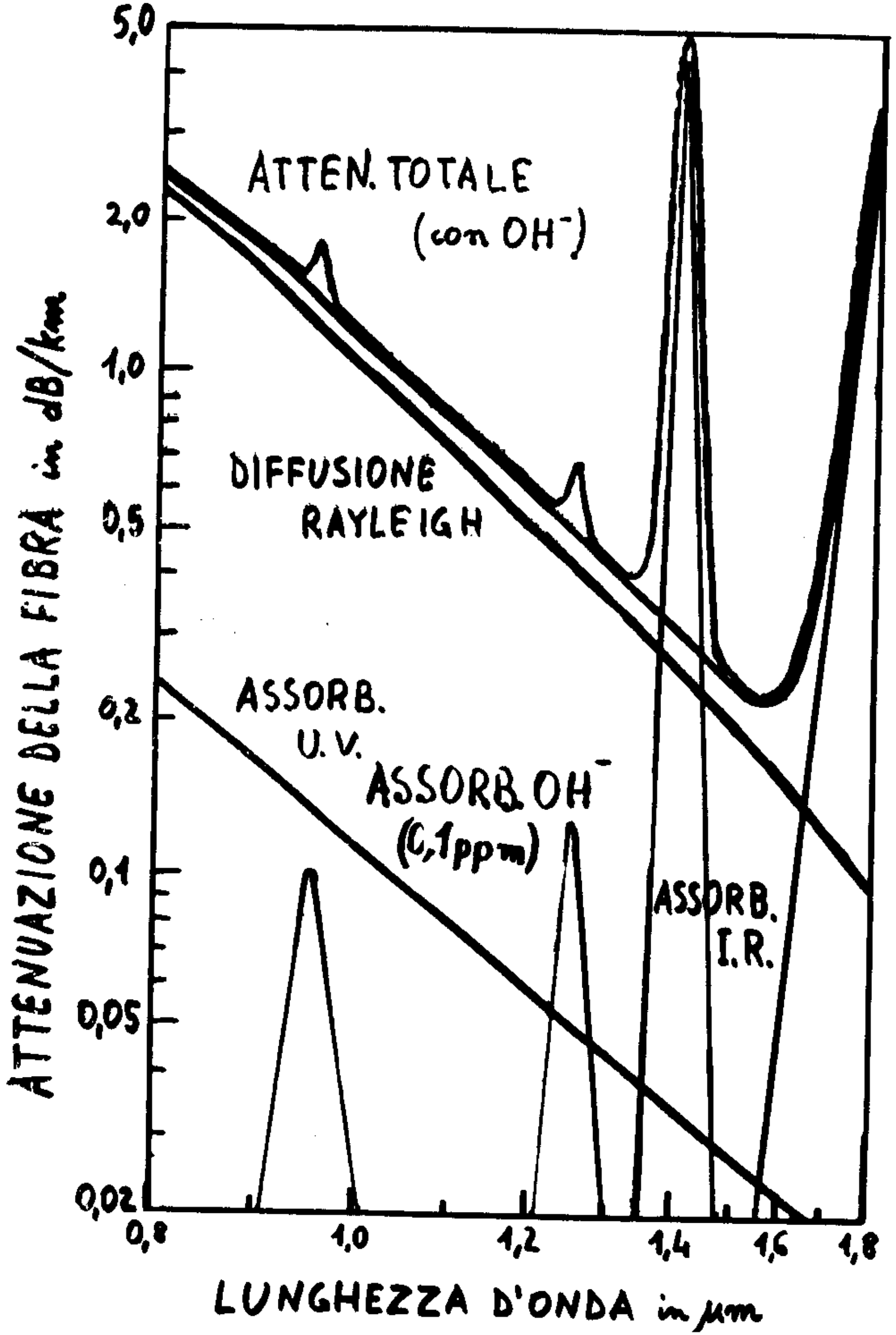


$$\hat{P}_i \simeq R_a \left(\frac{\pi}{2} d A\right)^2$$

$$d = \min(d_f, d_s)$$

CHARACTERISTICS OF OPTICAL FIBRES

- TRANSMISSION LOSS
- BANDWIDTH (DISPERSION)



FIBRE ATTENUATION

λ [μm]	α [dB/km]
0.85	3
1.3	0.7
1.55	0.35

COPPER CABLE ATTENUATION (COAX)

ϕ_i/ϕ_e [mm]	α [dB/km $\sqrt{MHz}$]
0.7/2.9	8.7
1.2/4.4	5.3
2.6/9.5	2.3

BANDWIDTH

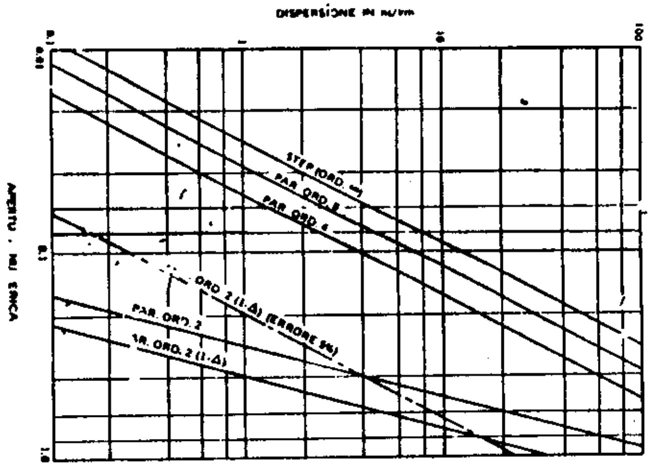
MODAL DISPERSION

$$\tau_m \propto L^x$$

$x = 1$ without mode coupling

$x = 0.5$ with complete mode coupling

- τ_m increases with A
- with mode coupling $h_m(t)$ has gaussian shape



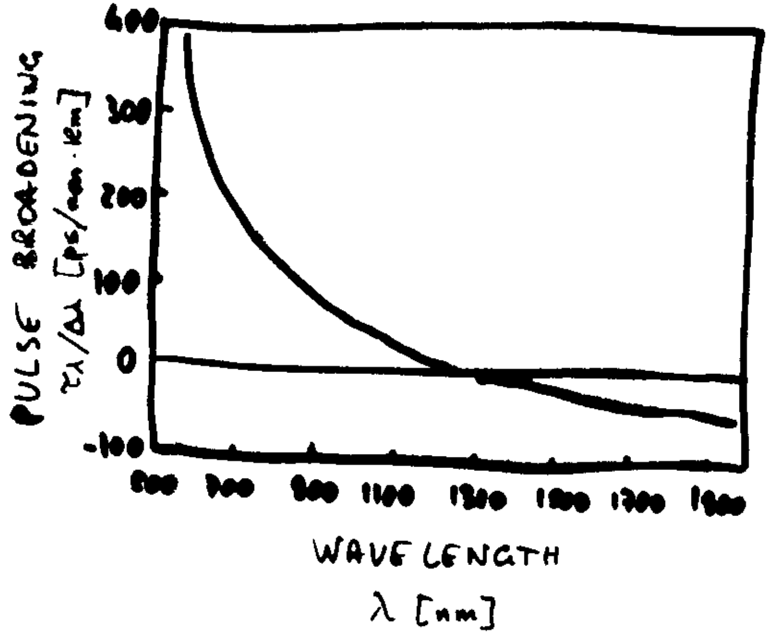
BANDWIDTH

MATERIAL DISPERSION

$$\tau_\lambda \propto \Delta\lambda \cdot L$$

Under proper conditions (linear differential delay versus wavelength all over the spectrum of the optical source) the impulse response has the same shape as the source spectrum. In practical cases the shape is nearly gaussian.

MATERIAL DISPERSION



Under the hypothesis of power linearity in the behaviour of optical fibre, the following relationship is valid:

$$h(t) = h_\lambda(t) * h_m(t)$$

$$\tau^2 = \tau_\lambda^2 + \tau_m^2$$

$$\tau_\lambda \propto \Delta\lambda \cdot L$$

$$\tau_m \propto L^x \qquad x < 1$$

The cut-off frequency of the optical fibre is related to the dispersion characteristics in the following way:

$$f_{m,\lambda} \simeq \frac{0.44}{\tau_{m,\lambda}}$$

$$\boxed{f_c = \frac{1}{\sqrt{\frac{L^{2x}}{f_m^2} + \frac{L^2}{f_\lambda^2}}}}$$

From the above, the <u>transfer function</u> of the fibre can be derived:

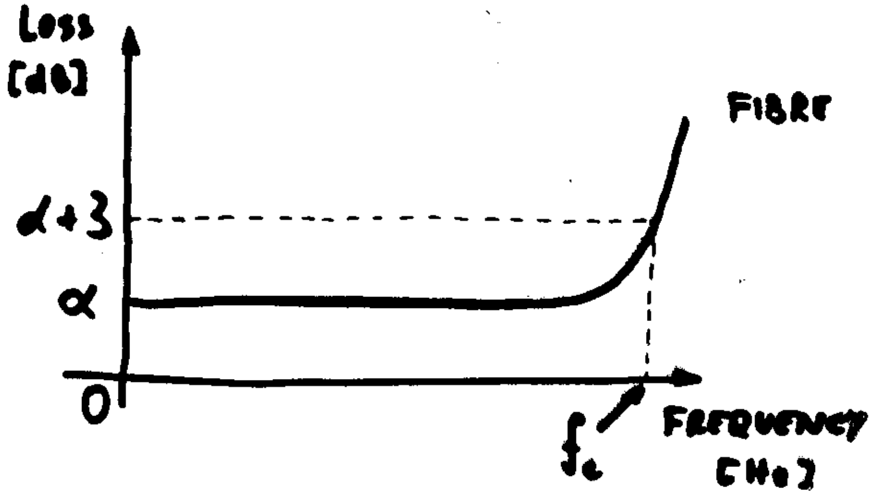
$$H_F(f) = e^{-\alpha L} e^{-\ln 2 \cdot \left(\frac{f}{f_c}\right)^2} \quad \text{FIBRE}$$

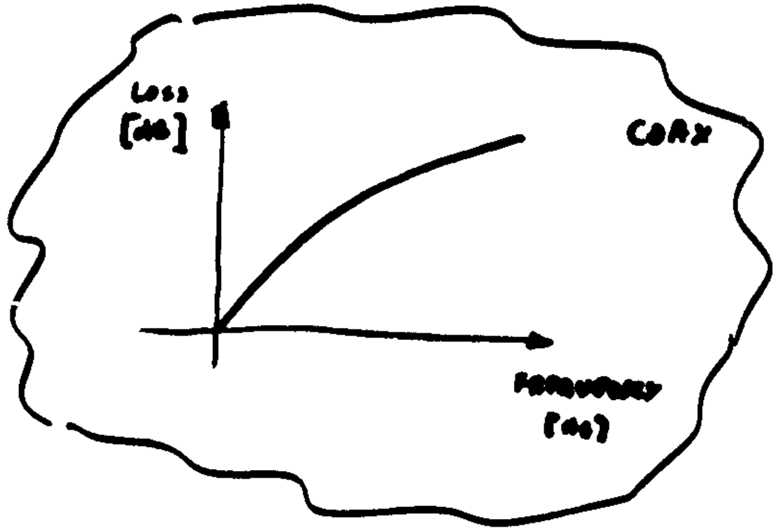
α = Fibre loss

f_c = 3 dB cut-off frequency

$$\boxed{H_c(f) = e^{-\alpha L \sqrt{f}} \quad \text{COAX}}$$

In a pictorial representation, the two transfer functions are as follows:





CHARACTERISTICS OF PHOTODETECTORS

- NOISE
- BANDWIDTH

CARATTERISTICHE DEI RIVELATORI

	PIN		APD	
λ (μm)	0.8 - 0.9	1 - 1.3 (1.6)	0.8 - 0.9	1 - 1.5 (1.6)
G	1	1	100	10
$\Re$ (A/W)	0.4 - 0.6	0.4 - 0.7	0.4 - 0.5	0.4 - 0.6
FATT. RUM.	–	–	4 @ $G=100$	10 @ $G=10$
V_{op} (V)	10 - 50	5 - 30	100 - 300	30 - 50
$C_{[illegible]}$ (pF)	1 - 3	0.2 - 2	1 - 3	1 - 2
MATERIALE	Si	InGaAs	Si	Ge (InGaAs)

PHOTO DETECTORS

QUANTUM NOISE

$$\overline{i_q^2} = 2q\, I(t)\, b\, G^2 F_a$$

DARK CURRENT

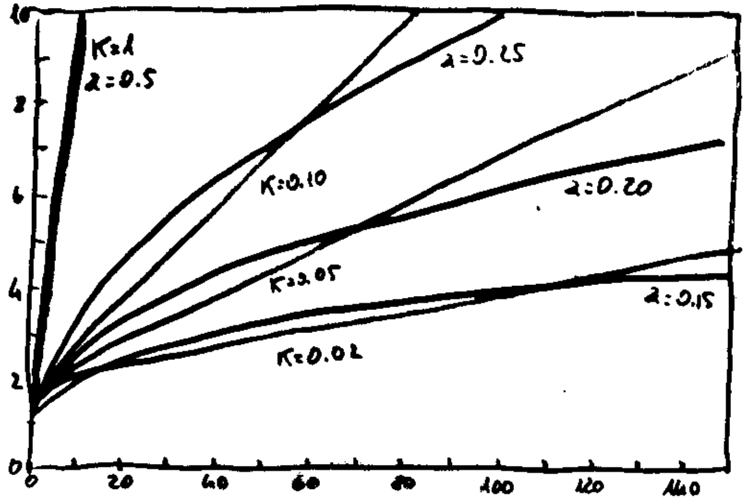
$$\overline{i_s^2} = 2q I_s b$$

$$\overline{i_b^2} = 2q I_b G^2 F_a$$

NOISE FIGURE

$$F_a = G\left[1-(1-k)\frac{(G-1)^2}{G^2}\right] \simeq G^{2a}$$

Fattore di rumore del processo di valanga

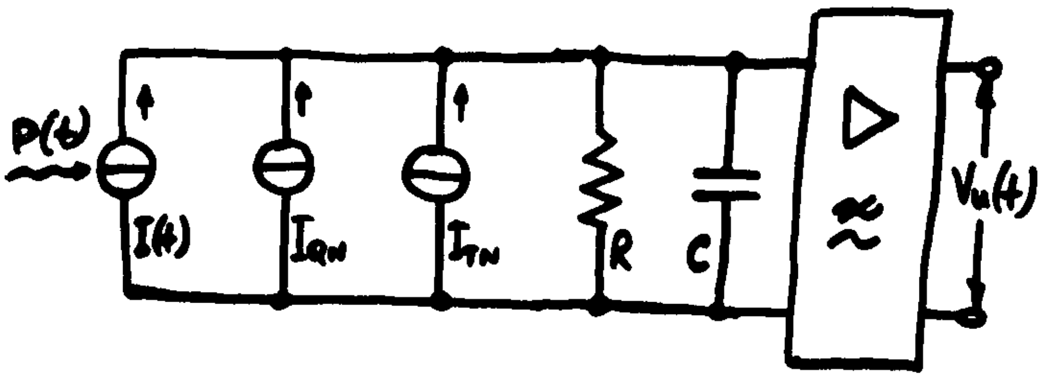


Guadagno di valanga G

— Valore esatto

— Curva approssimante

PHOTODETECTOR EQUIVALENT CIRCUIT



$$I(t) = \rho\, G\, P(t)$$

$$I_{QN} = \sqrt{2 q B \rho P(t)}\; G^{(1+a)}$$

$$I_{TN} = \sqrt{\frac{4kTBF}{R}}$$

$q = 1.6 \cdot 10^{-19}\, C$

$k = 1.38 \cdot 10^{-23}\, J/°K$

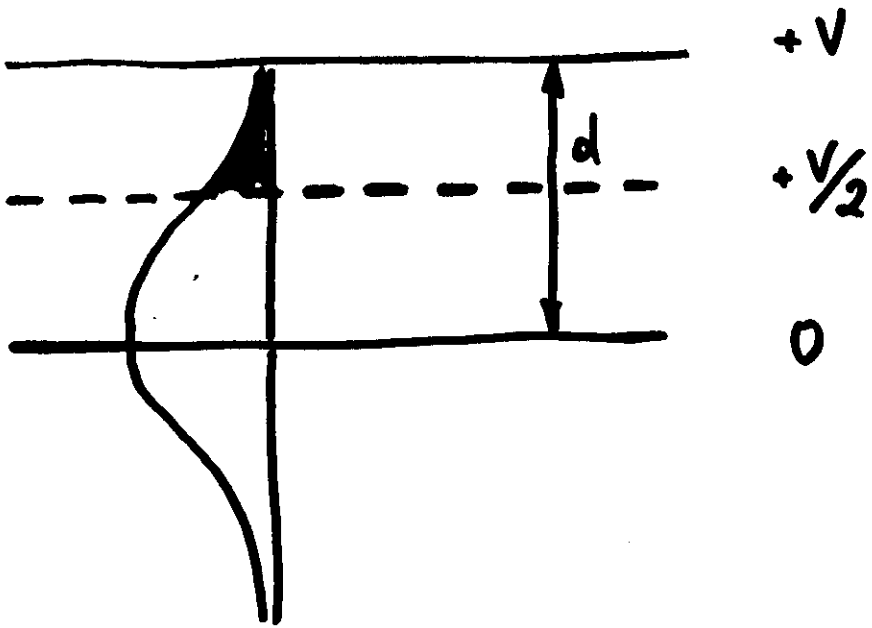
$T = 293°K$

In the design of the receiver and for evaluating the repeater spacing we must take account of:

- thermal noise (gaussian)
- quantum noise (filtered Poisson)
- avalanche noise (G is random variable)
- intersymbol interference (I.S.I.)

If I.S.I. is negligible, the probability distribution of all the noises can be considered gaussian.

ERROR PROBABILITY IN PRESENCE OF GAUSSIAN NOISE



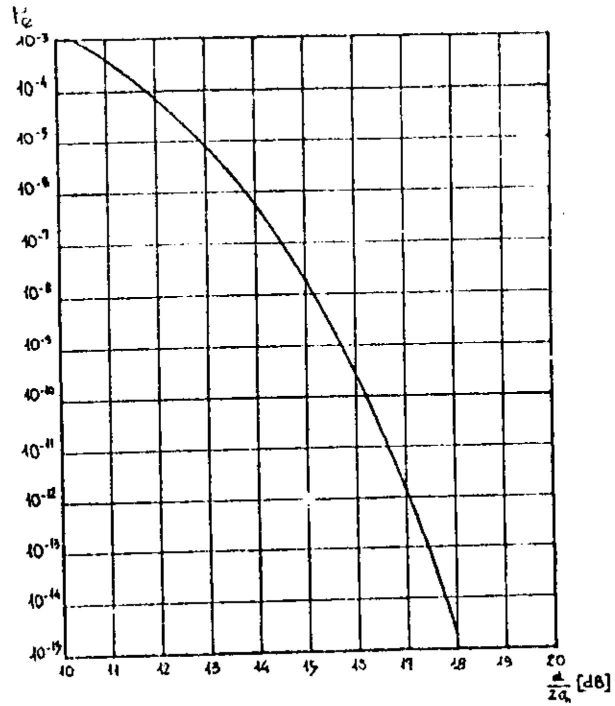


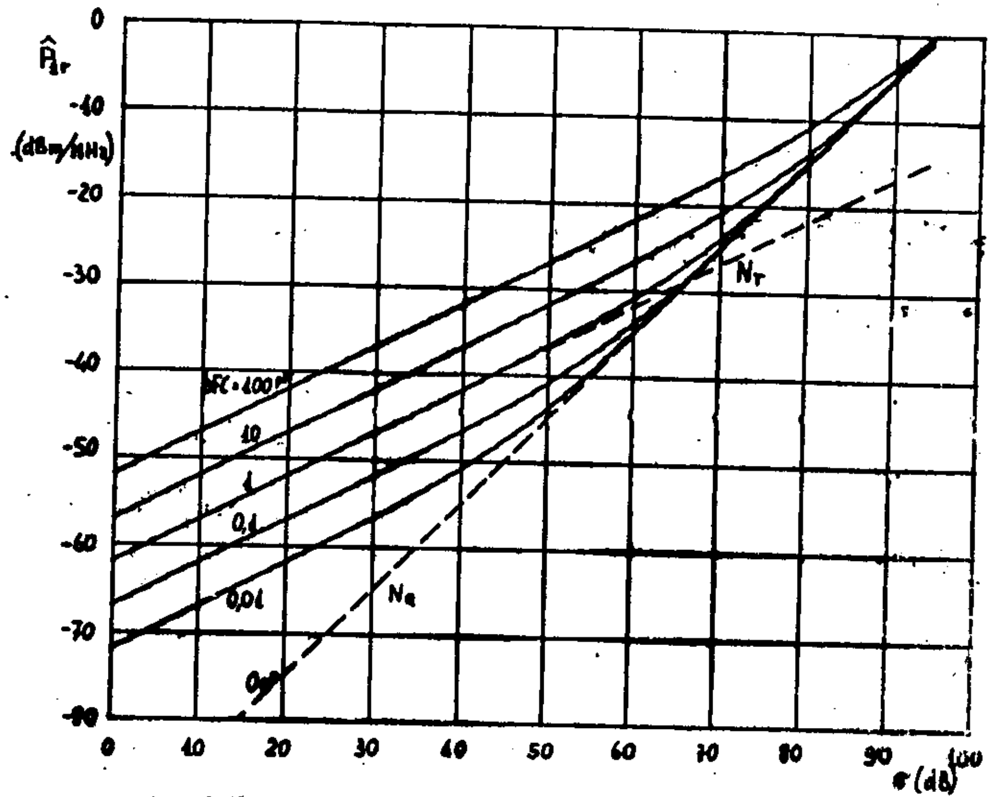
Fig. 4.5 - Andamento della probabilità d'errore in funzione del rapporto $d/2\sigma_n$.

The <u>error probability</u> P_e is function of the signal-to-noise ratio at the decision point.

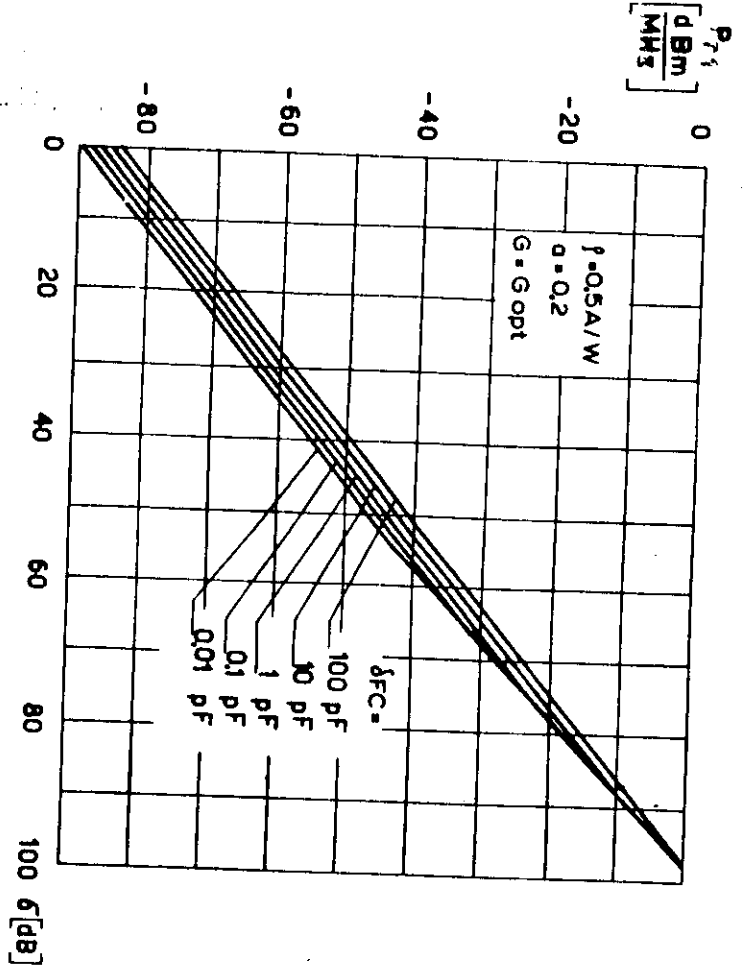
$$\text{Signal} = 2 \rho G P_m$$

$$\text{Noise} = \left(2 q \rho P_m G^{2(1+a)} + \frac{4KTF}{R} \right) B$$

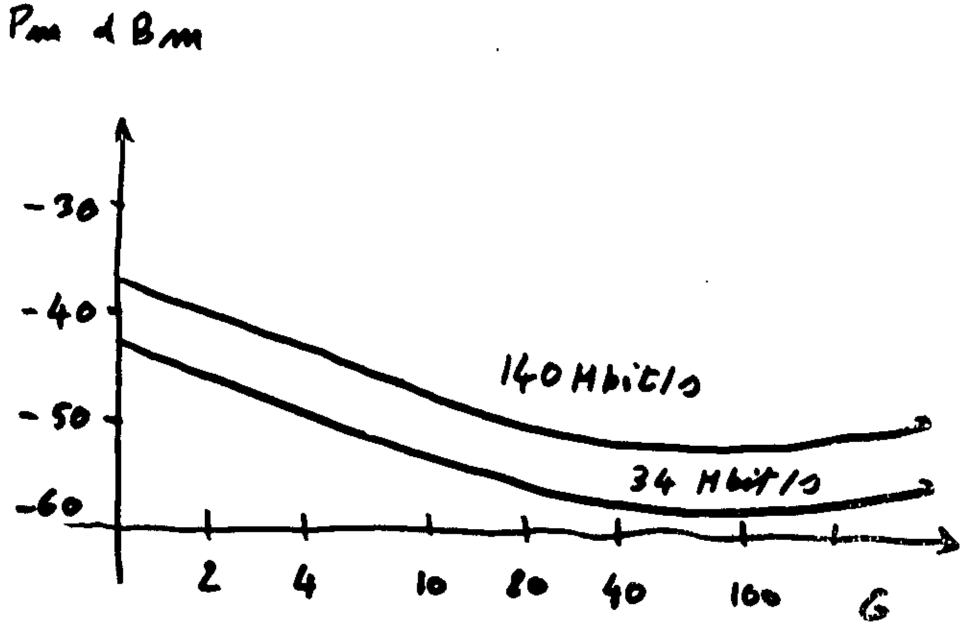
$$\frac{S}{N} = \frac{\ell_1 G P}{\left[\ell_2 B P G^{2(1+a)} + \ell_3 B \right]^{1/2}}$$



POTENZA OTTICA PER UNITÀ DI BANDA ALL'INGRESSO DI UN FOTORIVELATORE p-i-n IN FUNZIONE DEL RAPPORTO SEGNALE DI PICCO / RUMORE σ IN USCITA



ρ=0,5A/W
a=0,2
G=Gopt
δFC=
100 pF
10 pF
1 pF
0,1 pF
0,01 pF
dBm/MHz
100 G[dB]



Pm dBm
140 Mbit/s
34 Mbit/s
G

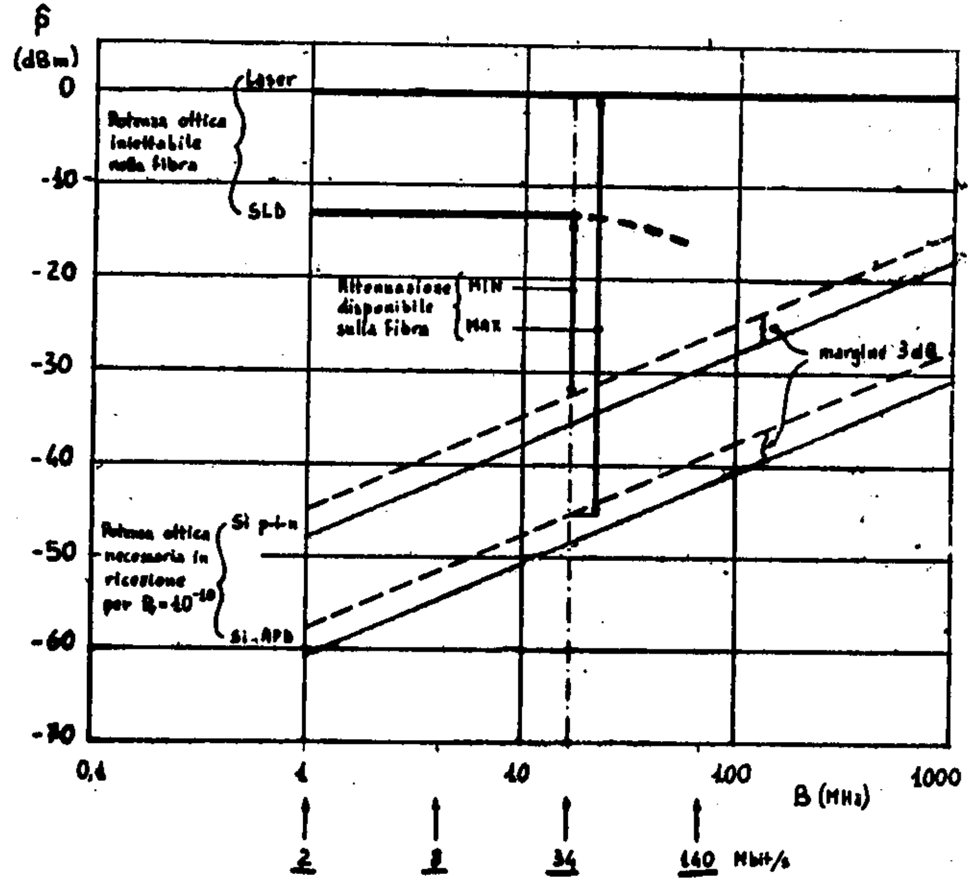
Repeator spacing evaluation

- Without fibre bandwidth limitation

$$P_r = P_t \cdot e^{-2\alpha L}$$

$$\Downarrow$$

$$L = \frac{1}{\alpha}\left[10 \log P_t - 10 \log P_{r0}\right]$$



LIVELLI DI POTENZA OTTICA IN TRASMISSIONE E IN RICEZIONE IN FUNZIONE DELLA BANDA DEL SEGNALE NUMERICO PER $P_e = 10^{-10}$, $d_c = 0{,}5$, $\eta = 0{,}8$, $\alpha = 0{,}25$

Repeater spacing evaluation

- With fibre bandwidth limitation

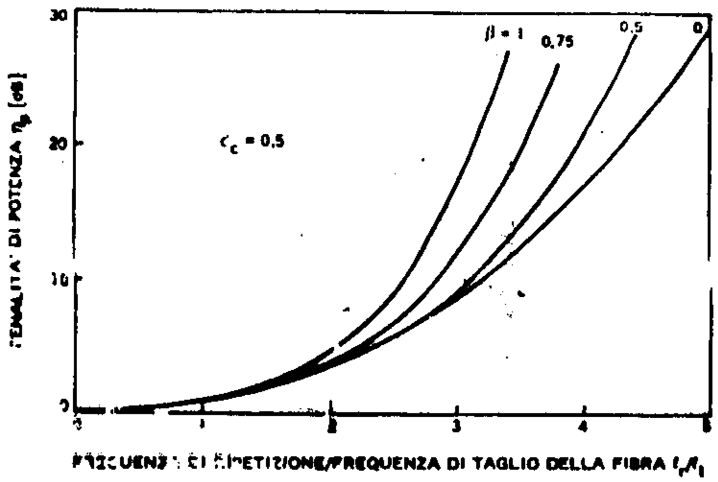
$$\alpha L = 10 \log \frac{P_t}{P_r} = 10 \log \frac{P_t}{P_{r0}} - \underbrace{10 \log \frac{P_r}{P_{r0}}}_{\eta_p}$$

Power penalty η_p

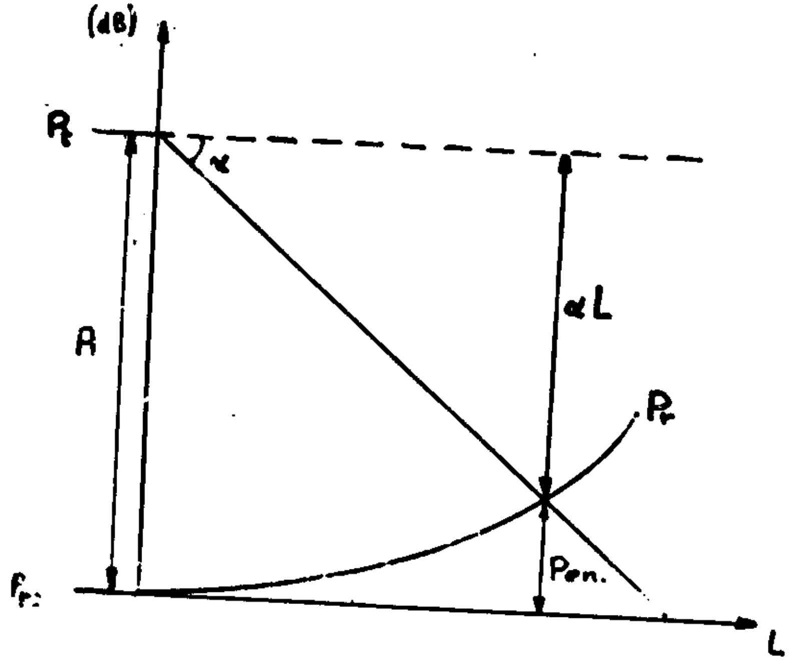
$\Downarrow$ (in dB)

$$P_t - \alpha L = P_{r0} + \eta_p\left(\frac{f_r}{f_t}\right)$$

Both sides of this relationship depend on $L \Rightarrow$ graphic solution



DIMENSIONAMENTO DELLA TRATTA



$$P_t - \alpha L = P_{r0} + P_{en} = P_r$$

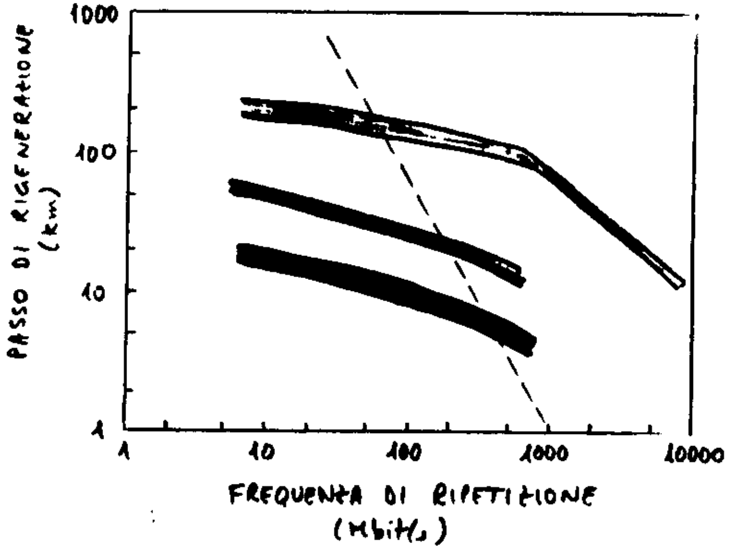
$$P_t - \alpha L = P_{r0} + P_{en} = P_r$$

PASSO DI RIPETIZIONE (Km)

FIBRA		2 Mbit/s	8 Mbit/s	34 Mbit/s	140 Mbit/s	565 Mbit/s
LED + pin	Mf	12.5	—	—	—	—
LED + APD	Mf	—	15.6	—	—	—
LASER + APD	Mf	—	22.9	20.2	13	—
LASER + APD	2ª	—	—	—	44	—
LASER + APD	MM	—	—	—	57	42

RAME	2 Mbit/s	8 Mbit/s	34 Mbit/s	140 Mbit/s	565 Mbit/s
Coppie simm.	~ 2	—	—	—	—
Microcoax 0.7/2.9	—	4	2	—	—
Coax 1.2/4.4	—	—	—	2	—
Coax 2.6/9.5	—	—	—	4.5	1.5

PASSO DI RIGENERAZIONE



Multimodo 1ª fin.
Multimodo 2ª fin.
Monomodo 3ª fin.
Limitazione per dispersione modale

LINE CODING

Line coding is used to shape the spectrum of the signal and to adapt it to the transmission medium characteristics.

Besides line coding allows error performance monitoring, easier timing extraction

Line coding is performed by adding redundancy to the transmitted information.

Redundancy can be added either by increasing the number of transmitted levels or by increasing the transmitted symbol rate.

Apart from one case, the latter is the most suited solution for optical systems.

LINE CODES FOR OPTICAL SYSTEMS

- PARITY CHECK CODES

  m · info bit + n · parity check bit

- BLOCK CODES

  mBnB (n > m)

n even is preferable since code words exist having equal number of 1's and 0's; they are in number of $\binom{n}{n/2}$.

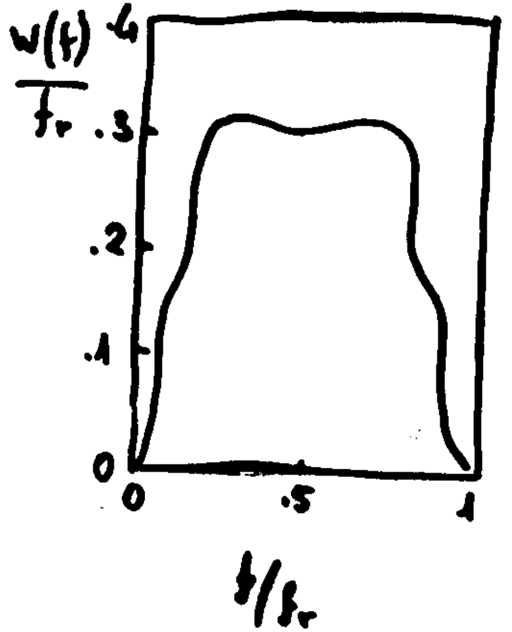
If $\binom{n}{n/2}$ is larger than 2^m a one-to-one relationship can be established between coded and uncoded words. Eg. 6B8B → $\binom{n}{n/2} = \binom{8}{4} = 70 > 2^m = 2^6 = 64$

If this condition is not verified, it is necessary to split the code words into two groups. E.g. 3B4B

INFO WORDS	CODEWORD GROUP 1	D	CODEWORD GROUP 2	D
000	0101	0	0101	0
100	0110	0	0110	0
010	1001	0	1001	0
110	1010	0	1010	0
001	0001	-2	0111	+2
101	0010	-2	1011	+2
011	0100	-2	1101	+2
111	1000	-2	1110	+2

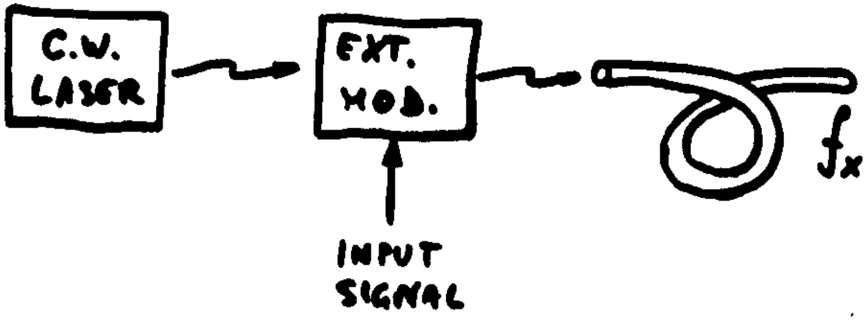
Among the block codes, one of the most utilized is 5B6B. The increase in the line rate is 20%.

Power spectrum of 5B6B code:

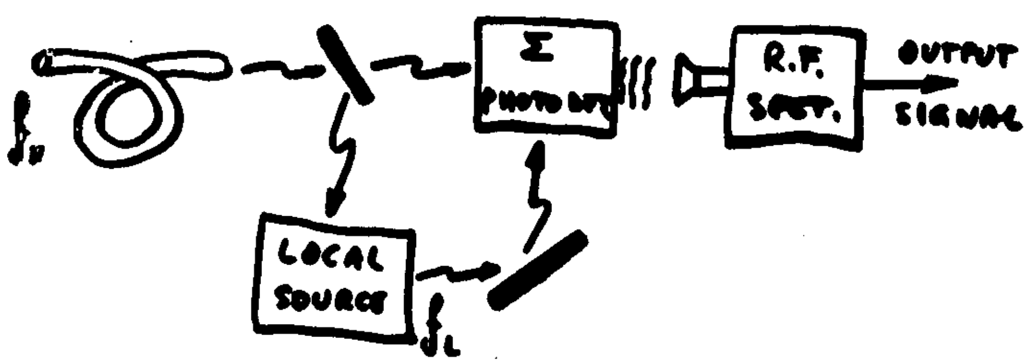


Coherent systems

Transmitter



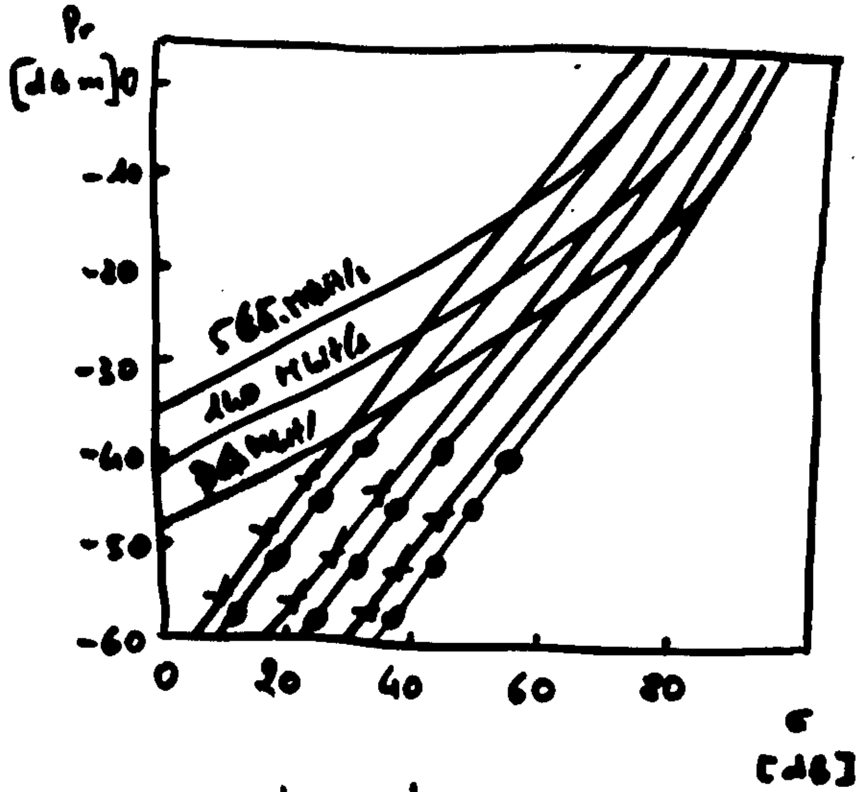
Receiver



$f_x - f_L \simeq 10 \div 5000$ MHz Heterodyne

$f_x - f_L = 0$ Homodyne

Performance of coherent systems



homodyne

heterodyne

direct detection

Coherent systems

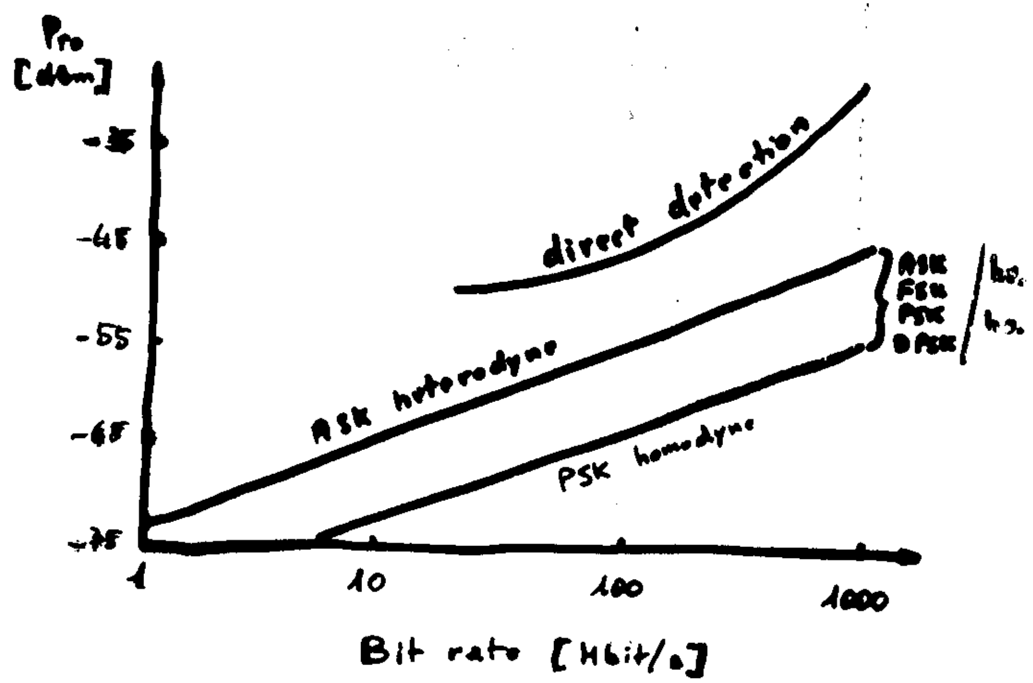
PRO's

- APD noise reduction.
- Gain can be achieved in the conversion process.

CON's

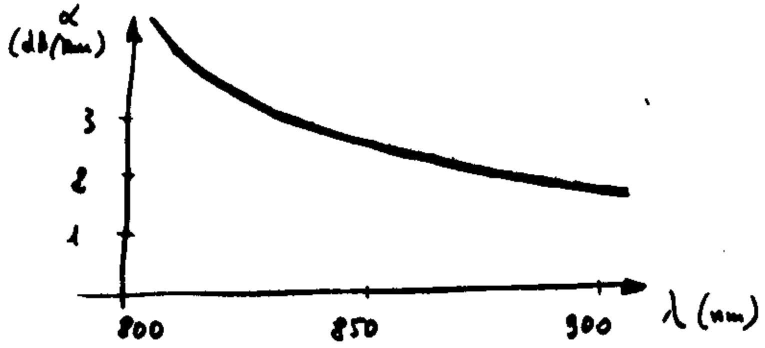
- Local source tracking at the receiving end.
- Transmitter frequency stabilization.
- Summing area design.

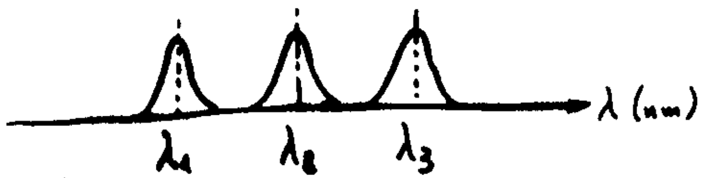
Performance of coherent systems



Multiplazione per Divisione di Lunghezza d'Onda

(W D M)





- Offre la possibilità di trasmettere più segnali indipendenti sulla stessa fibra

- Coesistenza di analogico e numerico

- Adatto per rete locale

- Interferenza tra canali

DEMULTIPLATORE PER WDM

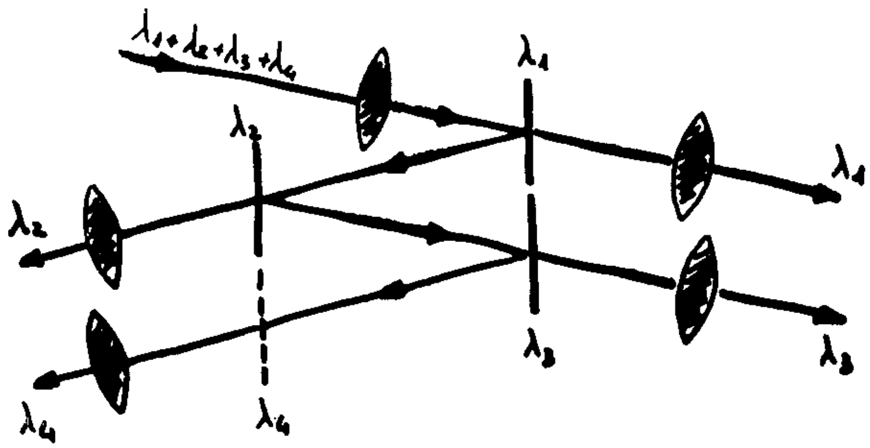
Deviazione dipendente da λ

- Prismi
- Reticoli

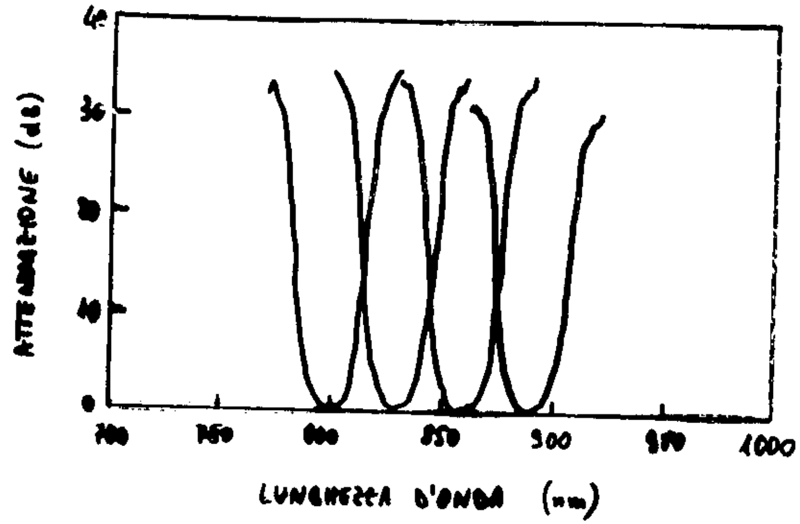
DEMULTIPLATORE PER WDM

Trasmissività dipendente da λ

- Filtri interferenziali



CARATTERISTICHE DI UN DEMULTIPLATORE PER WDM



ATTENUAZIONE D'INSERZIONE	6÷8 dB
ATTENUAZIONE DI TELEDIAFONIA	21÷23 dB
ATTENUAZIONE DI PARADIAFONIA	>38 dB

TRASMISSIONE DI SEGNALI

ANALOGICI (Es. video)