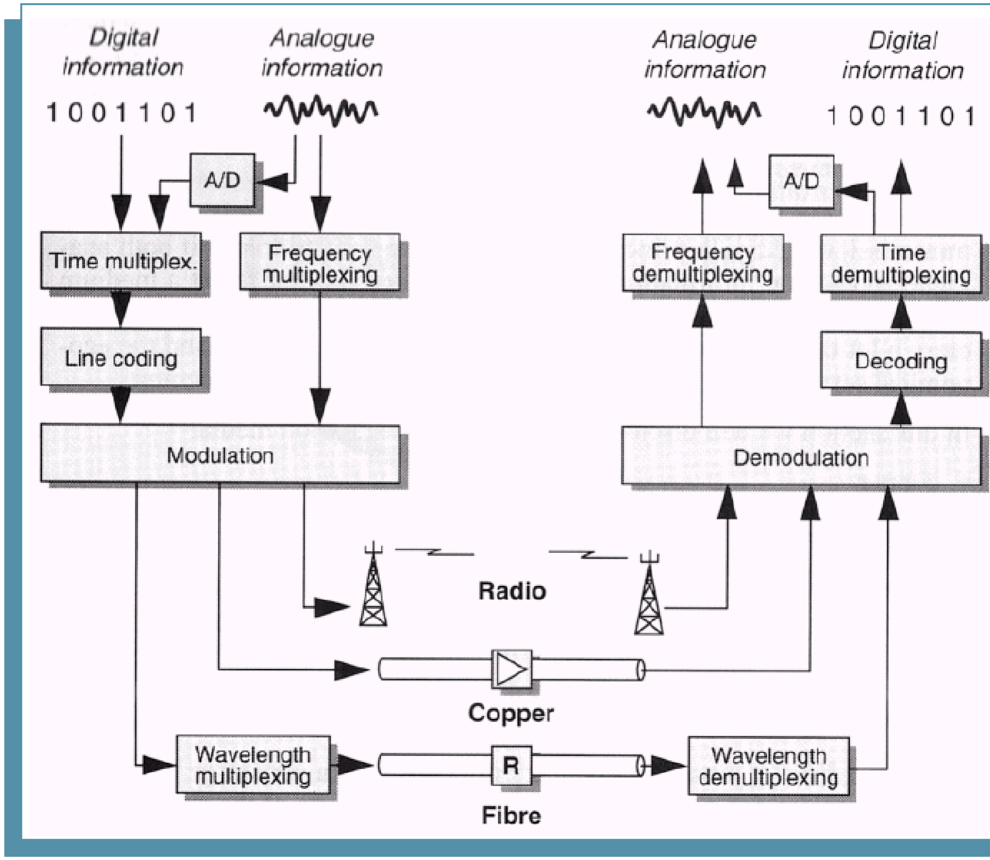
S-72.245 Transmission Methods in Telecommunication Systems (4 cr)

Transmission Channels

Agenda today

- Characterizing channels
  - linearity
  - non-linearity
  - time-variability
- Measuring channels
- Overview to some channels
  - wired channels
    - coaxial cables
    - twisted cables
  - wireless cellular channel
    - large-scale path loss
    - small scale modeling, e.g
      - delay spread
      - coherence bandwidth
      - Doppler spread



Analog and digital transmission in various channels [8]

Communication channels and medium

- A **physical medium** is an inherent part of a communications system
  - Wires (copper, optical fibers) , wireless radio spectra
- Communications systems include **electronic or optical devices** that are part of the transmission path followed by a signal
  - Equalizers, amplifiers, signal conditioners (regenerators)
  - Medium determines **only part** of channels behavior. The other part is determined how transmitter and receiver are connected to the medium
  - Therefore, by telecommunication channel we refer to the **combined** end-to-end physical medium and attached devices
- Often term "**filter**" refers to a channel, especially in the context of a specific mathematical model for the channel. This is due to the fact that all telecommunication channels can be modeled as filters. Their parameters can be
  - deterministic
  - random
  - time variable
  - linear/non-linear

Guided and unguided medium

- Medium convoys message by electromagnetic waves
  - wireless/wired (medium)
  - baseband/carrier wave (transmission band)
  - digital/analog (message format)
- In free space information propagates at v=c/$\sqrt{\varepsilon}, \lambda = v / f_0$
- <u>Wireless</u>: easy deployment, radio spectra sets capacity limit. Attenuation as function of distance *d* follows $d^{n(f)}$ *n(f)*=2..5 (cellular ch.)

$$A_{wireless} = n(f)\log_{10} d\,[\text{dB}] \quad \text{(omni-directional radiation)}$$

- Wired: more capacity by setting extra wires (may be complicated, costly, time consuming). Attenuation as function of frequency follows $10^{k(f)d}$, where *k(f)* is the attenuation parameter, yelding

$$A_{wired} = k(f)d\,[\text{dB}]$$

- Therefore, in general, wireless systems may maintain signal energy longer that wired systems. However, actual received power depends greatly on transmission parameters

Selecting the medium/media

- What is **amount of traffic** to be distributed?
- What is the **cost** we can afford?
- What is the **interference** environment?
- Is mechanical **robustness** adequate?
- Point-to-point or **networking** usage?
- Capability to transfer **power** (for instance for repeaters)?
- Often the first selection is done between
  - Wired
  - Wireless
- Often one can consider if **digital** or **analog** message is to be transmitted
  - analog PSTN takes 300-3400 kHz
  - digital PCM takes 64 kbit/s
  - digital, encoded GSM speech only 13 kbit/s
  - what is the adequate compression level?

Channels parameters

- Characterized by
  - attenuation $[\mathrm{dB/km}]$, transfer function
  - impedance $[\Omega]$, matching
  - bandwidth $[\mathrm{Hz}]$, data rate
- Transmission **impairments** change channel's effective properties
  - system internal/external **interference**
    - cross-talk - leakage power $[\mathrm{dB}]$ from other users
    - channel may introduce inter-symbolic interference (ISI)
    - channel may absorb interference from other sources
    - wideband noise $[\mathrm{W/Hz}]$
  - **distortion**, linear (uncompensated transfer function)/nonlinear (non-linearity in circuit elements)
- Channel parameters are a function of frequency, transmission length, temperature ...

Data rate limits

- Data rate depends on: channel bandwidth, the number of levels in transmitted signal and channel SNR (received signal power)
- For an L level signal with theoretical sinc-pulse signaling transmitted maximum bit rate is (Nyqvist bit rate)

$$r_b = 2B_T \log_2(L)$$

- There is absolute maximum of information capacity that can be transmitted in a channel. This is called as (Shannon's) channel capacity

$$C = B \log_2(1 + SNR)$$

- Example: A transmission channel has the bandwidth $B_T = 1\,\text{MHz}$ and SNR = 63. Find the approproate bit rate and number of signal levels. Solution: Theoretical maximum bit rate is

$$C = B \log_2(1 + SNR) = 10^6 \log_2(64) = \underline{6\,\text{Mbps}}$$

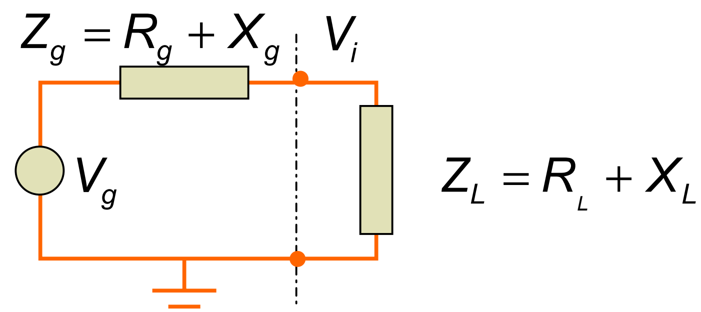
In practise, a smaller bit rate can be achieved. Assume

$$r_b \approx 4\,\text{Mbps} = 2\text{B}_\text{T} \log(L) \Rightarrow \underline{L = 4}$$

Measuring channels

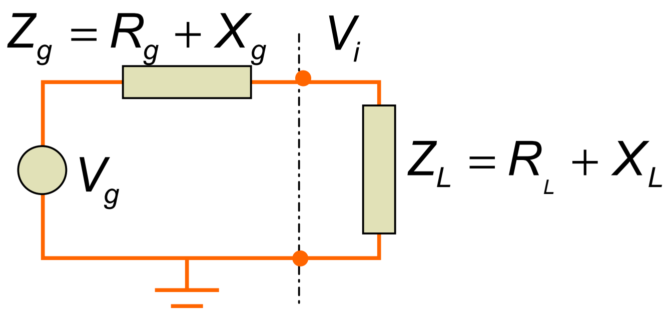
- Parameters of greater interest are transfer function and impedance. **Transfer function** can be measured by
  - launching **white noise** (in the frequency range to be measured) to the channel (frequency response)
  - Launching **impulse to the channel** (theoretical). In practice, short, limited amplitude pulse will do (impulse response)
  - Launching **sweeping tone(s)** to the channel (frequency response)
- **Impedance** can be measured by measuring voltage across the load in the input/output port:

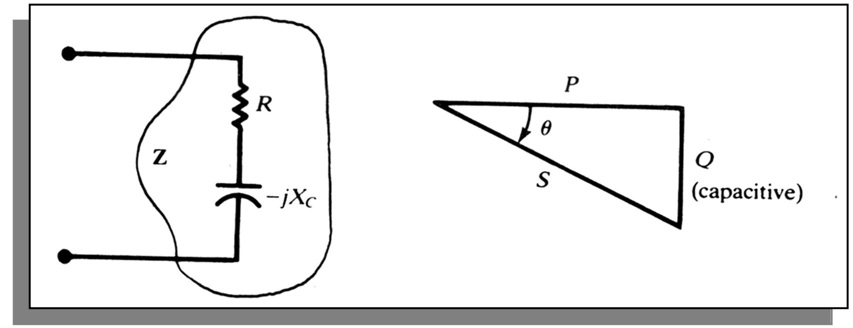
$$\frac{V_g}{V_i} = \frac{Z_g + Z_L}{Z_L} \quad \Rightarrow Z_L = \frac{V_i Z_g}{V_g - V_i}$$



- **Transfer characteristics** of nonlinear channels can be deducted from generated extra frequency components (we will discuss this soon with non-linearity)

Impedance matching



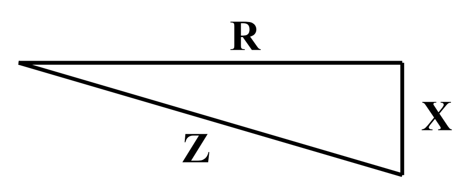


$$\frac{V_g}{V_i} = \frac{Z_g + Z_L}{Z_L}, P_L = V_i I_i \cos\theta$$

Example: a capacitive loading impedance;
What is the respective, optimum generator impedance Z_g?

$$\cos\theta = R_{tot} / Z_{tot} = R_{tot} / \sqrt{R_{tot}^{\ 2} + X_{tot}^2}, X_{tot} = X_g + X_L, R_{tot} = R_L + R_g$$

- Often (as with coaxial cables) channel interfaces must be impedance matched to maximize power transfer and to avoid power reflections
- In applying power to a transmission channel (or a circuit) source and loading impedances must be **complex conjugates** in order to maximize power dissipated in the load
- **Perfect match** means efficiency of 50%
- Setting impedances Z_g and Z_L to fulfill this condition is called **impedance matching**



Impedance triangle

Linear channels [1]

- *Linear channels* have the output that is input signal multiplied by a constant and delayed by a finite delay:

$$y(t)=Kx(t-t_d)$$
$$Y(f)=\mathcal{F}\left[y(t)\right]=\underbrace{K\exp\left(-j\omega t_d\right)}_{H(f)}X(f)$$

  due to the fact that system output is also $Y(f)=H(f)X(f)$
- Therefore, for linear systems $\left|H(f)\right|=\left|K\right|, \arg H(f)=-2\pi f t_d$
- Linear distortion can be
  - amplitude distortion: $\left|H(f)\right|\neq\left|K\right|$
  - delay distortion: $\arg H(f)\neq -2\pi t_d f$
- Solving above gives **phase delay**, defined by

$$t_d(f)=-\arg H(f)/(2\pi f)$$

- In **distortionless channel** *all Fourier-components retain their relative phase positions while propagating in channel*

Nonlinear channels[1]

- System non-linearity means that its transfer characteristic is nonlinear
- For non-linear channels output is $y(t) = a_1 x(t) + a_2 x^2(t) + a_3 x^3(t) +$
  Assume sinusoidal input $x(t) = \cos\omega_0 t$, then

$$y(t) = \left(\frac{a_2}{2} + \frac{3a_4}{8}...\right) + \left(a_1 + \frac{3a_3}{4}...\right)\cos\omega_0 t + + \left(\frac{a_2}{2} + \frac{a_4}{4}...\right)\cos 2\omega_0 t + ...$$

$$y(t) = D_0 + D_1\cos(\omega_0 t) + D_2\cos(2\omega_0 t)...$$

where D_n:s are the <u>distortion coefficients</u>

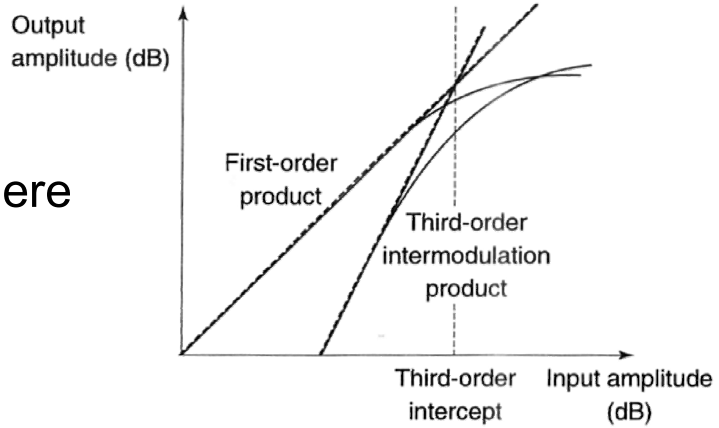
- <u>n:rth-order distortion</u> [%] is determined with respect of the fundamental frequency: $D_n[\%] = (D_n / D_1)x100\%$
- Assume that the input is

$$y(t) = \cos\omega_c t + A\cos(\omega_c + \omega_d)t$$

<u>3rd order intercept</u> [1,p.55] occurs* where

$$A = 4a_1/(3a_3)$$

- This is easy to measure and is used to characterize nonlinear systems

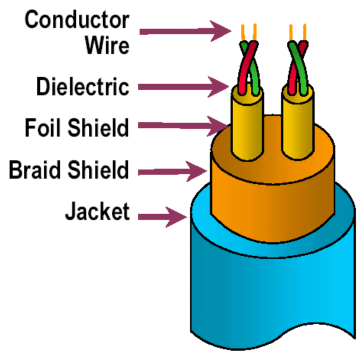


3:rd order intercept [1]

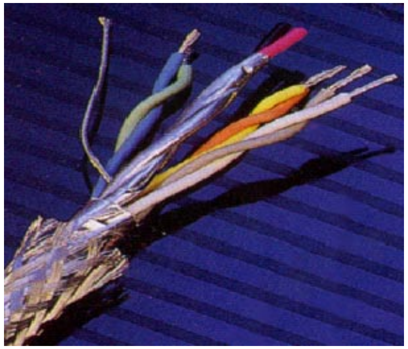
*See the prove in supplementary material (A. Burr: Modulation and Coding)

Wireline channels: Twisted pair

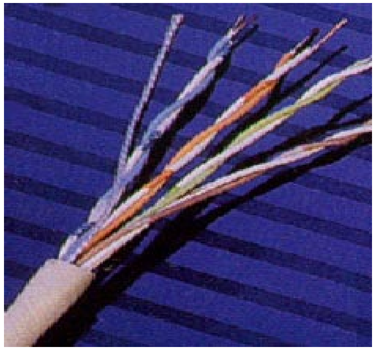
- Comes in two flavors: Shielded (STP) / Unshielded (UTP)



structure



STP-cable



UTP-cable

STP-cable	UTP-cable
•larger attenuation •higher rates •more expensive	•more sensitive to interference •easy to install and work with •example: 10BaseT Ethernet

- Twisting reduces interference, and crosstalk (antenna-behavior)
- Applications
  - Connects **data** and especially **PSTN local loop** analog links (Intra-building telephone from wiring closet to desktop)
  - In old installations, **loading coils** added to improve quality in 3 kHz band, resulting more attenuation at higher frequencies (ADSL)
  - **STP** used especially in **high-speed transmission** as in token ring-networks

Twisted pair - UTP categories in LANs

- **Category 1**: mainly used to **carry voice** (telephone wiring prior to 1980). Not certified to carry data of any type.
- **Category 2**: used to carry data at rates up to 4Mbps. Popular for older Token-passing ring LANs using **4Mbps** specs (IEEE 802.5). Rated bandwidth 1 MHz.
- **Category 3**: known as voice grade. Used primarily in older **Ethernet 10base-T LANs** (IEEE 802.3). Certified to carry **10Mbps** data. 16Mhz. 3-4 twists/feet.
- **Category 4**: primarily used for token-based or 10Base-T. 20MHz.
- **Category 5**: most popular Ethernet cabling category. Capable of carrying data at rates up to **100 Mbps** (**Fast Ethernet,** IEEE 802.3u) and used for 100 base-T and 10base-T networks. Rated to **100 MHz**. 3-4 twists/inch.

Unshielded and shielded twisted pairs attenuation compared

- Electronic Industries Association has specified in EIA-568-A twisted pairs for different applications.

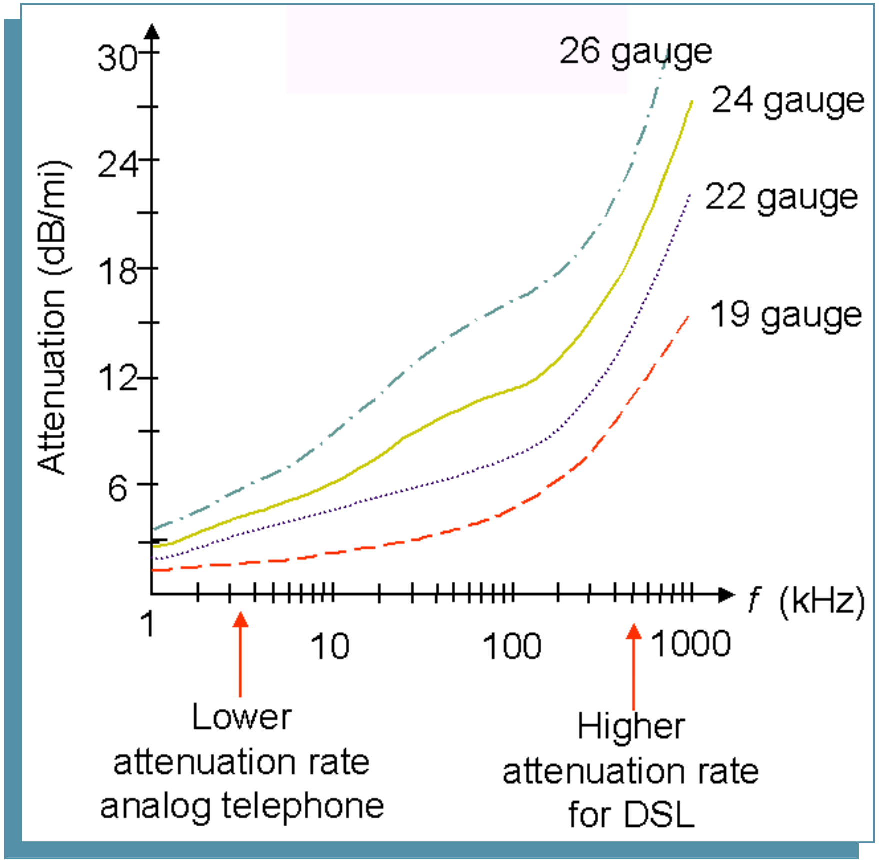
	Attenuation (dB per 100 m)			Near-end crosstalk (dB)		
Frequency (MHz)	Category 3 UTP	Category 5 UTP	150 Ω STP	Category 3 UTP	Category 5 UTP	150 Ω STP
1	2.6	2.0	1.1	41	62	58
4	5.6	4.1	2.2	32	53	58
16	13.1	8.2	4.4	23	44	50.4
25	—	10.4	6.2	—	32	47.5
100	—	22.0	12.3	—	—	38.5
300	—	—	21.4	—	—	31.3

Twisted pair - application examples [6]

- Comes in different wire thickness,
  e.g. 0.016 inch (24 gauge)
- The longer the cable, the smaller the bandwidth

Standard	Data Rate	Distance
DS-1	1.544 Mbps	18,000 feet, 5.5 km
DS-2	6.312 Mbps	12,000 feet, 3.7 km
1/4 STS-1	12.960 Mbps	4500 feet, 1.4 km
1/2 STS-1	25.920 Mbps	3000 feet, 0.9 km
STS-1	51.840 Mbps	1000 feet, 300 m

Data rates & distances for 24-gauge twisted pair



Twisted cable attenuations

DS-1,DS2: Digital Signal 1,2
Synchronous Digital Hierarchy (SDH) levels
STS-1: Synchronous Transport Signal level-1,
Synchronous Optical Network's (SONET) physical level signal

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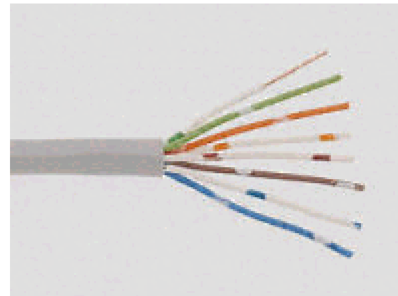


Quick Tip
Click on the picture or this icon to see a better quality image of this product

Sold in reels of 100m

	type	reel length	reel wt (kg)	stock no.	price per reel 1-6	price per reel 7-14
Order	4 pair	100m	3·0	203-6001	€53.50	€51.50

The unshielded twisted pair category 3 data cable for use in data networks and structured wiring systems. The cable have 1/0·52mm (24 a.w.g.) solid copper conductors insulated with PVC twisted into pairs and covered with an overall PVC sheath. The cable meet the requirements of IEEE802.31 10 base T.

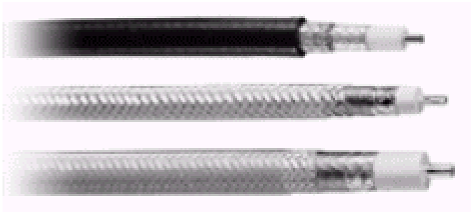
	4 pair
Overall dia. mm	4·9
Equivalents :	
BICC	H9614

technical specification

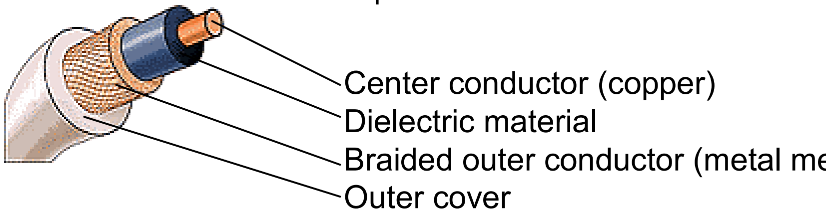
Impedance	95Ω (10MHz)
Attenuation (per 100m)	9·0dB (10MHz)

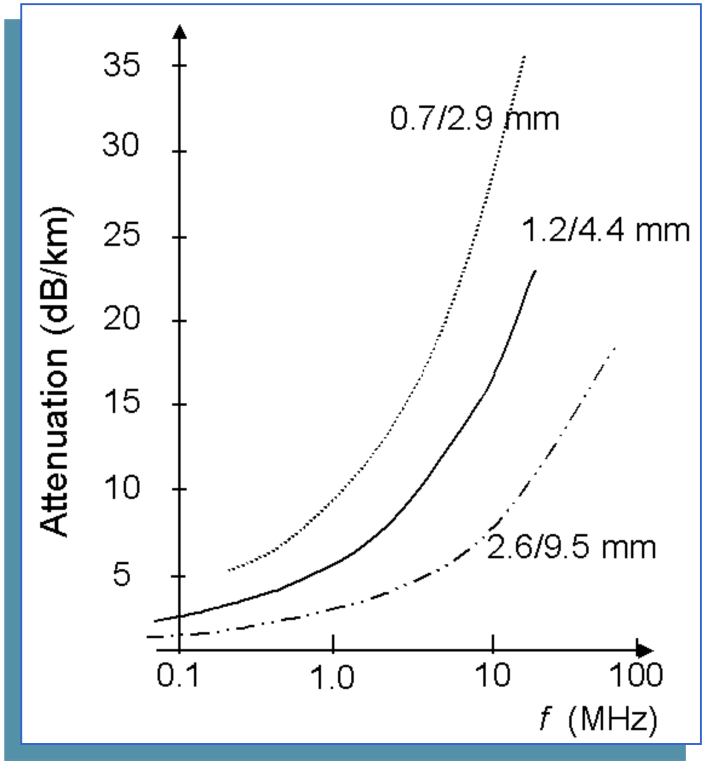
Wireline channels: Coaxial cables

- Mechanics
  - Cylindrical braided outer conductor surrounds insulated inner wire conductor
- Properties
  - Well shielded structure -> immunity to external noise
  - High bandwidth, up to Ghz-range (distance/model)
- Applications
  - CATV (Cable TV networks)
  - Ethernet LANs
  - Earlier a backbone of PSTN

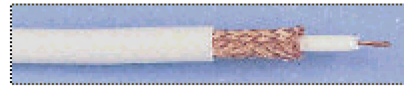


practical structures





BT2003 Cable



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Click on the picture or this icon to see a better quality image of this product

Sold in reels

	reel length	reel wt (kg)	stock no.	price per reel 1-4	5-9
Order	100m	9·5	806-921	€131.00	€125.00
Order	500m	45	806-937	€655.00	€625.00

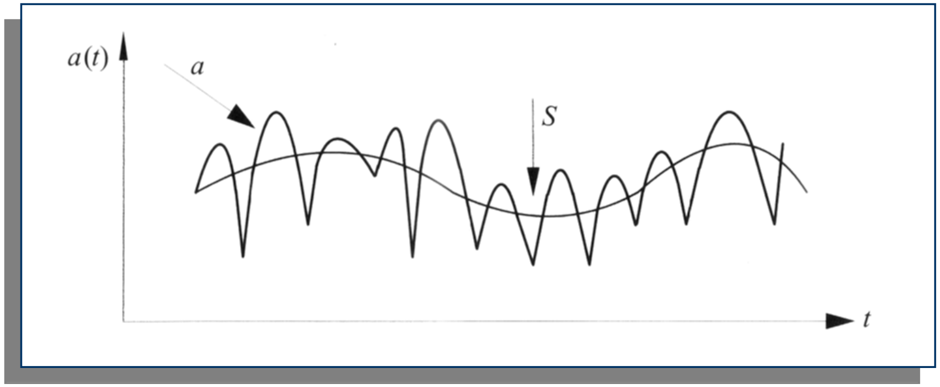
not available by timed delivery options.

A single plain copper wire inner conductor with polyethylene dielectric. The cable has a double braid shield and is oversheathed in white PVC.
BNC connector/cable group H.

technical specification

Inner conductor dia.	0·3mm^2 (1/0·61)
Dielectric	Polyethylene
Shield	Double plain copper wire braid
Nominal O.D. (mm)	6·6
Nominal impedance (Ω)	75
Nominal capacitance (pF/m)	65
Velocity of propagation (%)	66
Attenuation @ 5MHz (dB/100m)	2·4

Slow (S) and fast fading (a) in cellular channel



Fluctuation of received power in cellular channel [4]

- Received power fluctuations can be modeled to consist of:
  - **Shadow fading**, *slow rate*, local averaged signal power component has a Gaussian distribution (in dB) (Caused by larger obstacles between TX and RX)

$$p(S) = \frac{1}{\sigma_S \sqrt{2\pi}} \exp\left(-\frac{(S - S_0)^2}{2\sigma_S^2} \right)$$

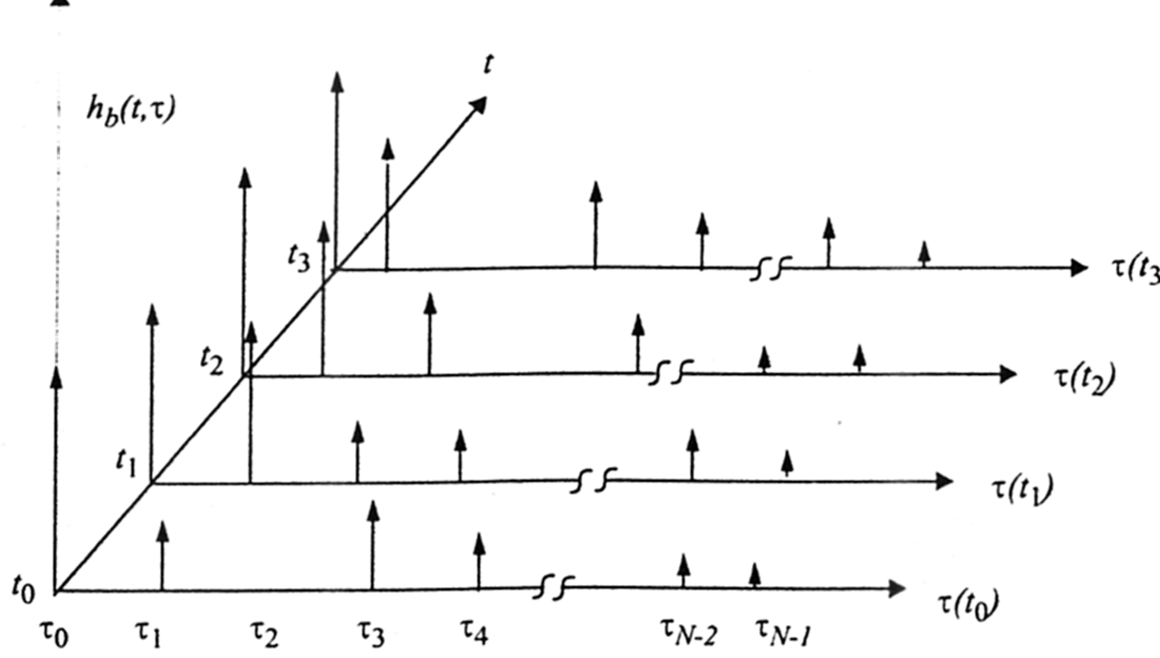
$$S_0 = C / r^{\alpha}, \alpha = 2...5 \text{ (global, average power)}$$

  - **Rayleigh/Rice fading**, *high rate component* due to various sources of multipath. Rayleigh distribution (non-line of sight path) is defined as

$$p(a) = \frac{a}{\sigma^2} \exp\left(-a^2 / 2a^2\right)$$

  - *high rate* **Doppler shifts**

Wideband Channel Impulse Response [7]



- The time variable channel impulse response is

$$h_b(t,\tau) = \sum_{i=0}^{N-1} a_i(t,\tau)\exp(j2\pi f_c \tau_i(t) + \phi(t,\tau))\delta(\tau - \tau_i(t))$$

- For **time invariant channels** each impulse response is the same or has the same statistics and then

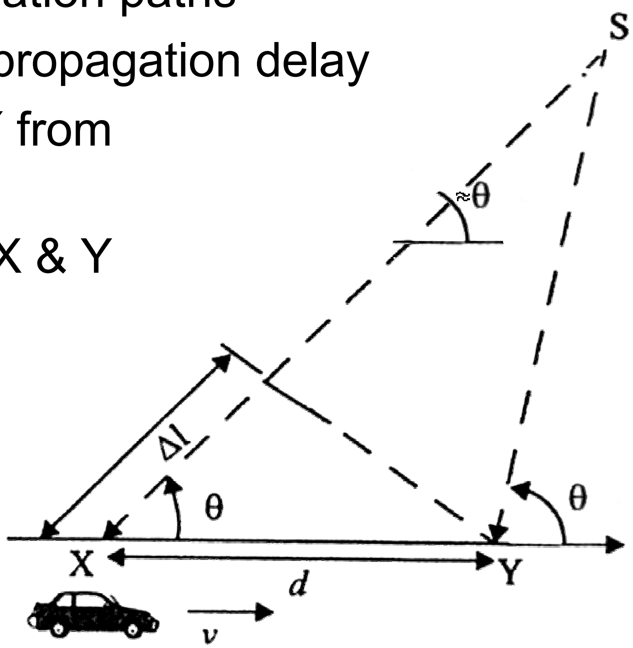
$$h(\tau) = \sum_{i=0}^{N-1} a_i \exp(-j\theta_i)\delta(\tau - \tau_i)$$

Doppler bandwidth

- Multipath created small-scale fading effects
  - rapid changes in **signal strength** due to movement and/or time
  - **random frequency modulation** due to Doppler shifts on different multipath propagation paths
  - **time dispersion** due to multipath propagation delay
- The difference in path lengths to X & Y from source S is $\Delta l = d\cos\theta = v\Delta t\cos\theta$
- The phase change between locations X & Y is then

$$\Delta\phi = \frac{2\pi}{\lambda}\Delta l = \frac{2\pi v\Delta t}{\lambda}\cos\theta$$

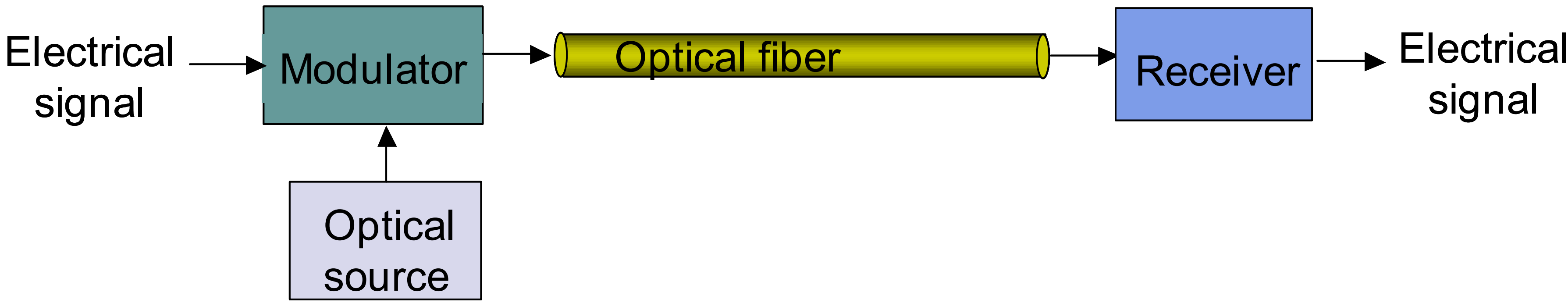
$$f_d = \frac{1}{2\pi}\frac{\Delta\phi}{\Delta t} \overset{*}{=} \frac{v}{\lambda}\cos\theta$$



Doppler effect [7]

*Angular frequency is the derivative of angular phase
see also slides of frequency modulator later

Optical Fiber

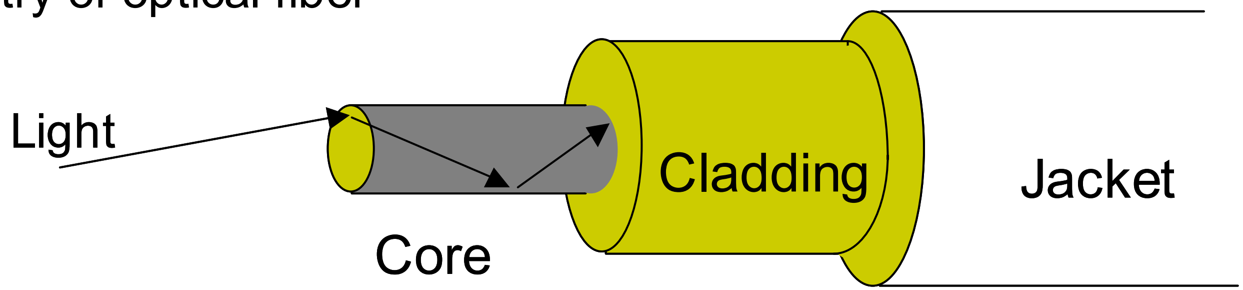


- Light sources (lasers, LEDs) generate pulses of light that are transmitted on optical fiber
  - Very long distances (>1000 km)
  - Very high speeds (>40 Gbps/wavelength)
  - Nearly error-free (BER of 10^{-15})
- Profound influence on network architecture
  - Dominates long distance transmission
  - Distance less of a cost factor in communications
  - Plentiful bandwidth for new services

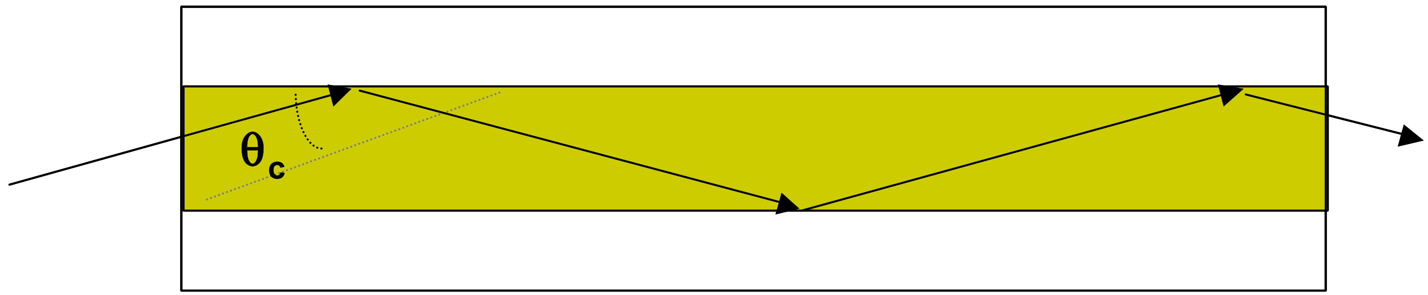
ref [6]

Transmission in Optical Fiber

Geometry of optical fiber



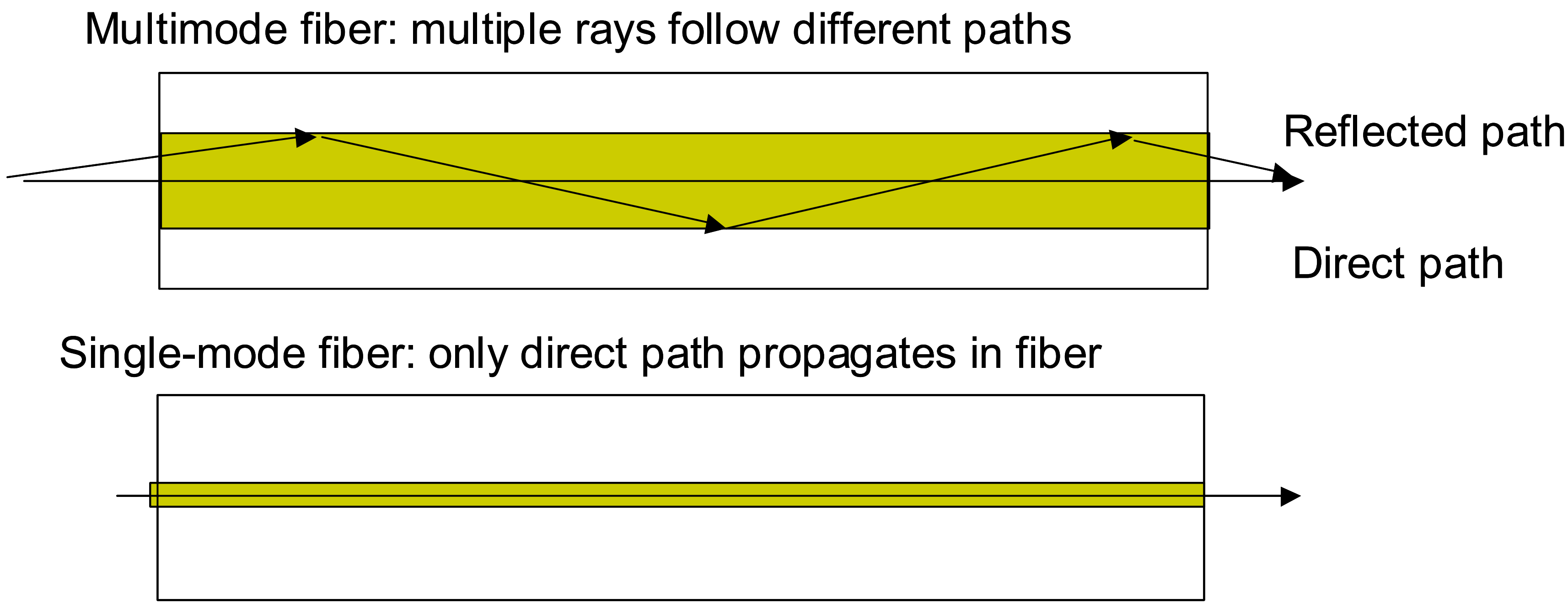
Total Internal Reflection in optical fiber



- Very fine glass cylindrical core surrounded by concentric layer of glass (cladding)
- Core has higher index of refraction than cladding
- Light rays incident at less than critical angle θ_c is completely reflected back into the core

ref [6]

Multimode & Single-mode Fiber



- Multimode: Thicker core, shorter reach
  - Rays on different paths interfere causing dispersion & limiting bit rate
- Single mode: Very thin core supports only one mode (path)
  - More expensive lasers, but achieves very high speeds

ref [6]

Optical Fiber Properties

Advantages

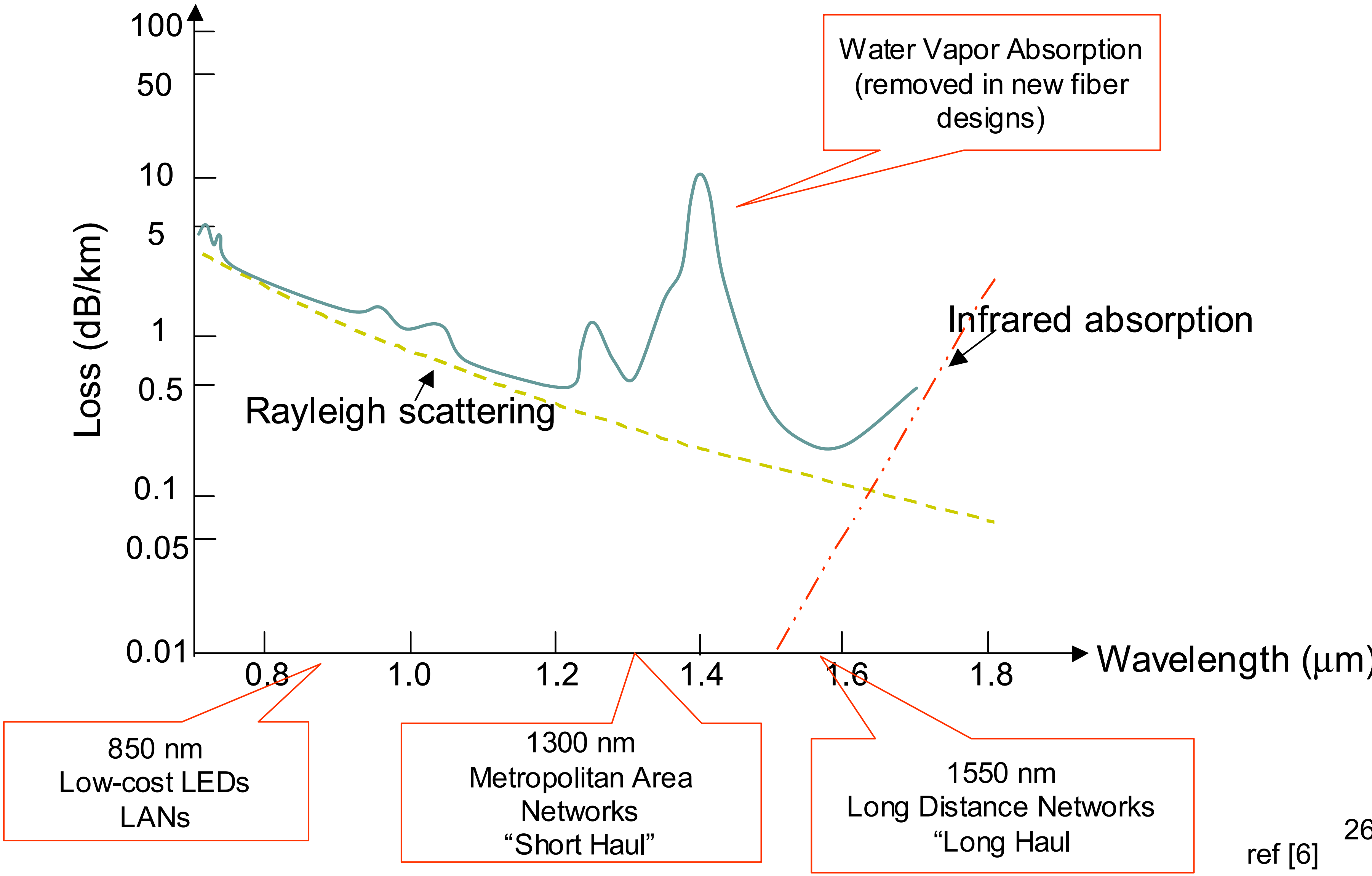
- ***Very low attenuation***
- ***Noise immunity***
- ***Extremely high bandwidth***
- Security: Very difficult to tap without breaking
- No corrosion
- More compact & lighter than copper wire

Disadvantages

- New types of optical signal impairments & dispersion
  - Polarization dependence
  - Wavelength dependence
- Limited bend radius
  - If physical arc of cable too high, light lost or won't reflect
  - Will break
- Difficult to splice
- Mechanical vibration becomes signal noise

ref [6]

Very Low Attenuation



ref [6]

Huge Available Bandwidth

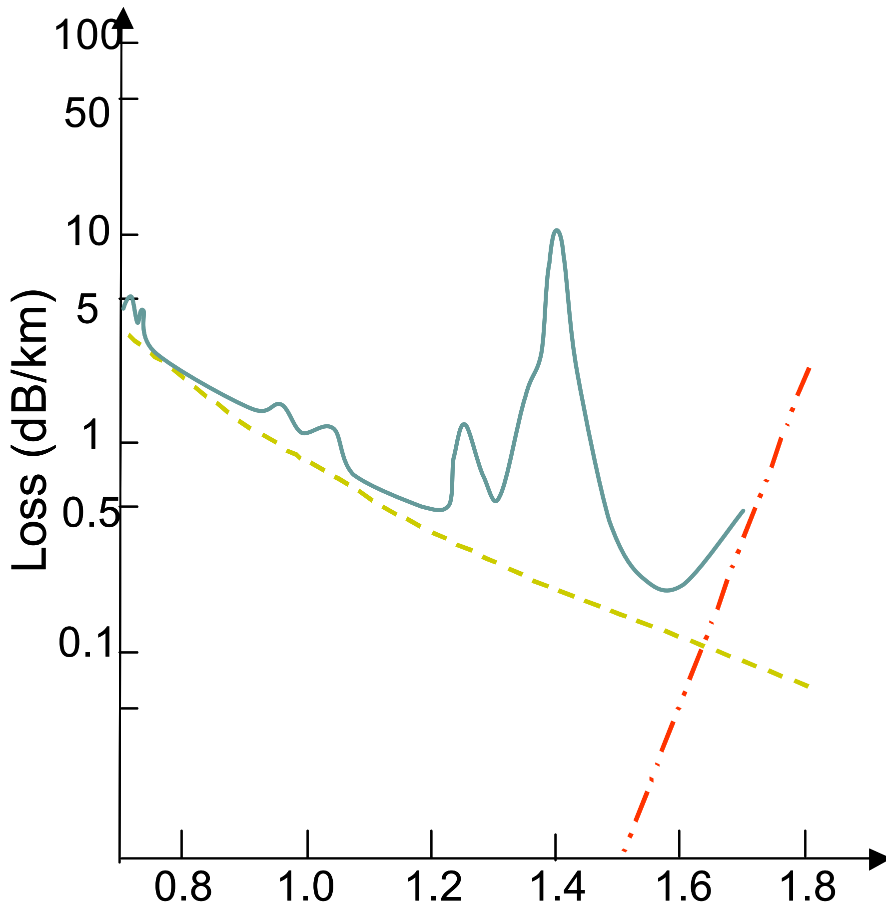
- Optical range from λ_1 to $\lambda_1 + \Delta\lambda$ contains bandwidth

$$B = f_1 - f_2 = \frac{v}{\lambda_1} - \frac{v}{\lambda_1 + \Delta\lambda}$$

$$= \frac{v}{\lambda_1}\left\{\frac{\Delta\lambda / \lambda_1}{1 + \Delta\lambda / \lambda 1}\right\} \approx \frac{v\,\Delta\lambda}{\lambda_1^2}$$

- Example: $\lambda_1 = 1450$ nm $\lambda_1 + \Delta\lambda = 1650$ nm:

$$B = \frac{2(10^8)\text{m/s } 200\text{nm}}{(1450\text{ nm})^2} \approx 19\text{ THz}$$



ref [6]

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