

Transmission of data

- **Real systems are often distributed**

data source is remote from signal processing

instruments in hazardous or very remote environments, eg satellites, HEP, nuclear reactors,...

but

also applies to much shorter distances - like nearby labs or instruments in the same room

so need to transfer data from source to receiver

and usually send messages (eg. control signals) back

- **need to understand**

practical ways of doing this

issues: power, speed, noise,... other physical constraint

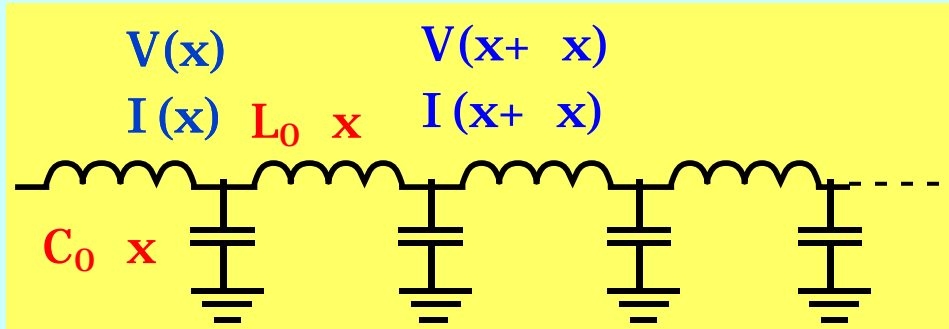
- **methods - a mixture**

electrical, but increasing use of optical fibres,

radio for satellites and space, mobile telephones,...

Electrical transmission lines

- Line with characteristic inductance and capacitance per unit length



An important assumption
 R negligible

- Voltage and current satisfy 2nd order differential equation

$$d^2V/dx^2 = -\omega^2 L_0 C_0 V = -k^2 V \quad \text{ie } k = (\omega^2 L_0 C_0)^{1/2}$$

- Solution

$$V = A e^{jkx} + B e^{-jkx}$$

Inject signal $\sim e^{j\omega t}$ $V = A e^{j(kx + \omega t)} + B e^{-j(kx - \omega t)}$ *two opposite direction waves*

- Speed $v = \omega/k = 1/(\omega L_0 C_0)^{1/2}$

- Impedance $Z_0 = (\omega L_0 / C_0)^{1/2}$

NB real, ie resistive, but defined by L and C

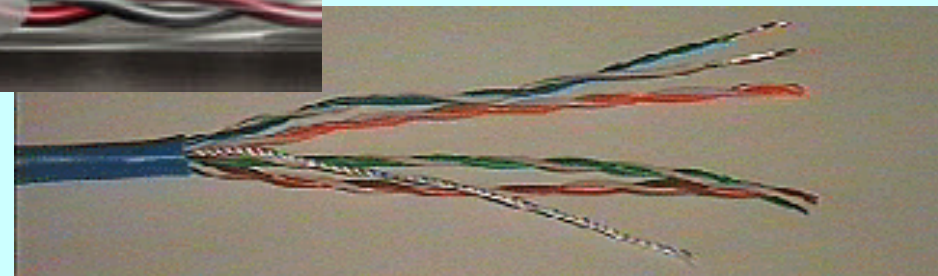
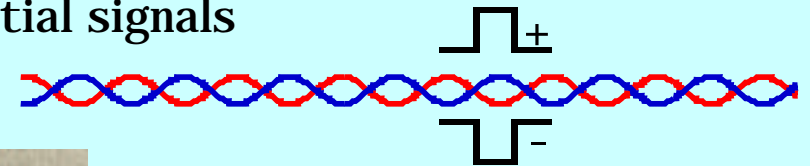
Cables

- Any wire has inductance, capacitance and resistance

so when is it a transmission line?

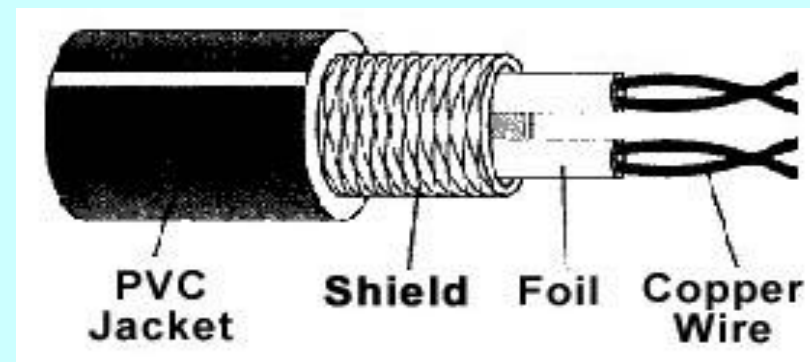
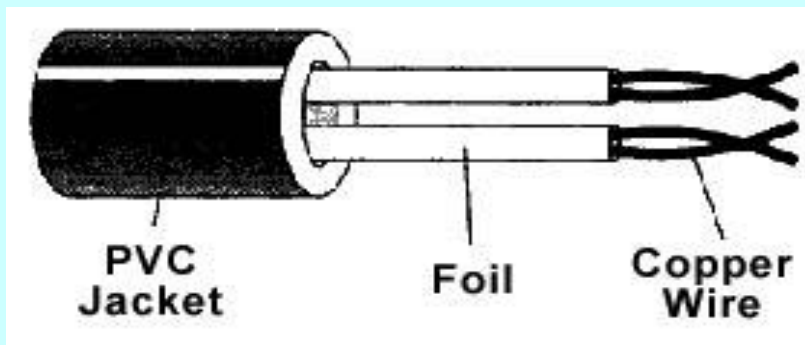
- Twisted pair

simple pair of wires, mainly intended for differential signals



Can also be unshielded...

or shielded



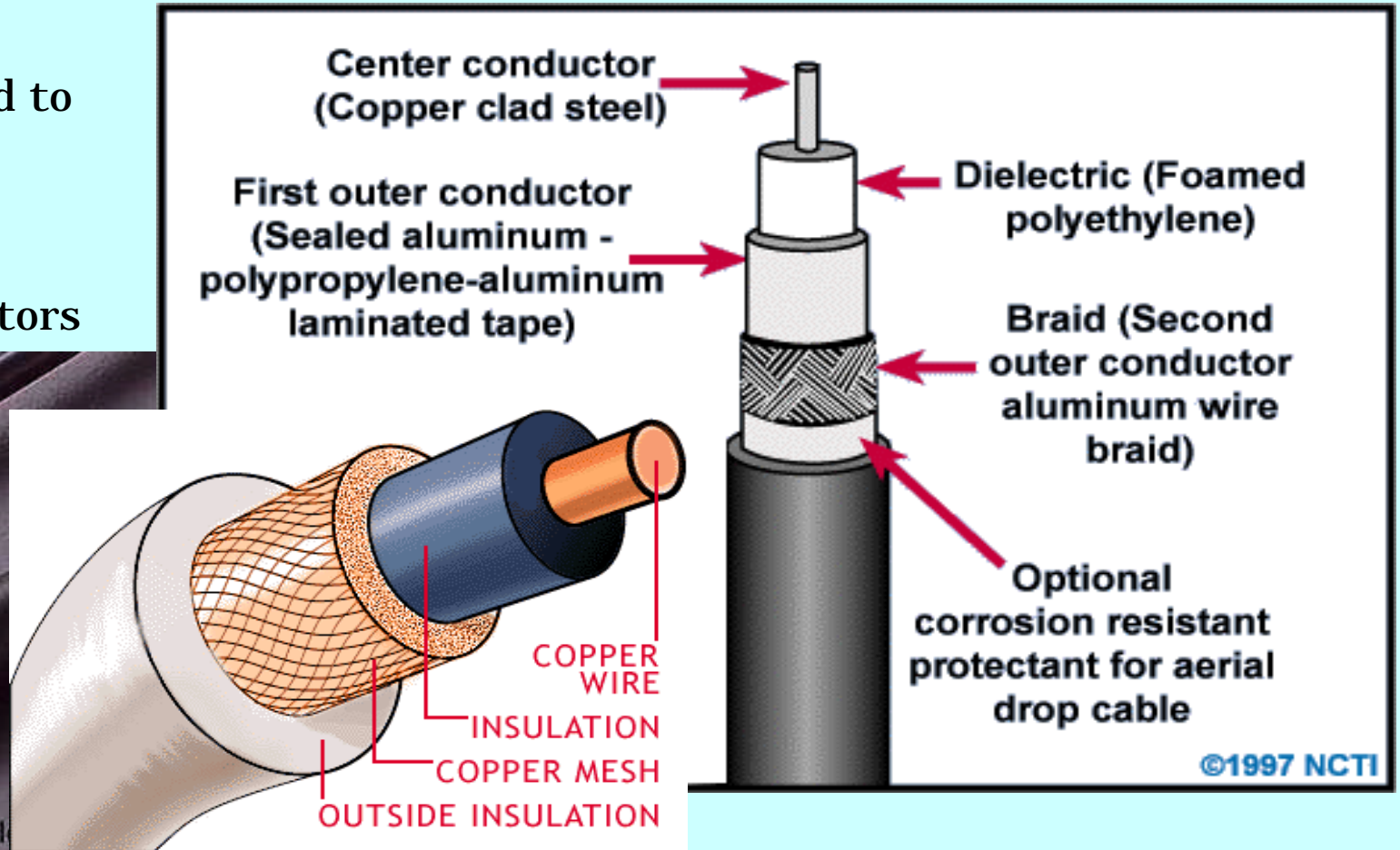
Coaxial cable

central copper core radius r_1 , with plastic dielectric, braided metal shield in cylindrical geometry radius r_2

$$C_0 = 2\pi\epsilon_0 / \ln(r_2/r_1) \quad L_0 = (\mu_0/2\pi) \ln(r_2/r_1) \quad \text{see lecture 1 notes}$$

•Design

Cu braid connected to ground provides electrical shield
use special connectors



Coaxial cable properties

from G. Knoll	see also	http://www.colemancable.com/fstechnical.htm				
	RG- 58	RG- 178	RG- 8	RG- 11	RG- 62	
typical dielectric	Polyethylene	Teflon	Polyethylene	Gas injected polyethylene	Foamed Fluorinated Ethylene Propylene	
outer diameter	5.0	1.8	10.3	10.3	6.1	mm
v/c	0.659	0.694	0.659	0.659	0.840	
Z₀	50	50	52	75	93	Ω
C₀	100.1	95.1	96.8	67.3	44.3	pF/m
<i>calculated data</i>						
L₀	0.25	0.24	0.26	0.38	0.38	μH/m
dielectric constant	2.30	2.08	2.30	2.30	1.42	
inner diameter	1.4	0.5	2.8	1.5	1.0	mm
C₀	101.2	96.1	97.3	67.5	42.7	pF/m
R_{core} [$\rho_{Cu}=17.2n\Omega.m$]	2.8	18.7	0.7	2.3	5.9	mΩ /m
RC (1m)	0.28	1.78	0.07	0.15	0.26	ps
RC (100m)	2.8	17.8	0.7	1.5	2.6	ns

- TV antenna cables typically have 75 Ω, although look similar to these
- Twin lead portable TV cables Z ~ 300

Termination and Matching

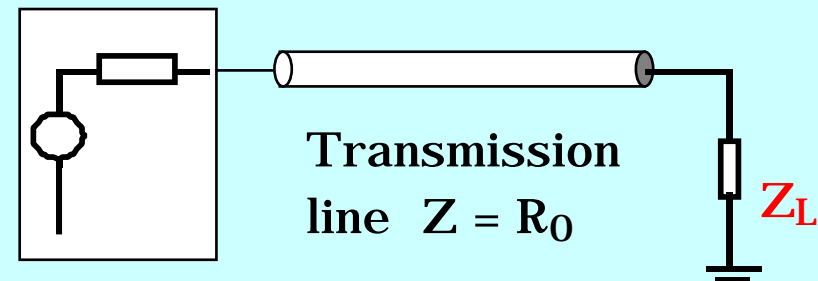
- **boundary conditions at termination**

$$I_{\text{inc}} + I_{\text{ref}} = I_L \quad \& \quad V_{\text{inc}} + V_{\text{ref}} = V_L$$

apply them (NB $V_{\text{ref}} = -I_{\text{ref}}Z_0$)

$$V_{\text{ref}}/V_{\text{inc}} = (Z_L - Z_0)/(Z_L + Z_0)$$

$$V_L/V_{\text{inc}} = 2Z_L/(Z_L + Z_0)$$



- **open circuit termination $Z_L = \infty$**

$$V_{\text{ref}}/V_{\text{inc}} = +1 \quad V_L/V_{\text{inc}} = 2 \quad \text{reflected signal} = \text{incident signal}$$

- **short circuit termination $Z_L = 0$**

$$V_{\text{ref}}/V_{\text{inc}} = -1 \quad V_L/V_{\text{inc}} = 0 \quad \text{inverted fully reflected signal}$$

- **matched termination $Z_L = Z_0$**

$$V_{\text{ref}}/V_{\text{inc}} = 0 \quad V_L/V_{\text{inc}} = 1 \quad \text{100\% transmission to load}$$

- **improper termination usually causes unwanted effects**

but can sometimes make use of reflection

eg short circuit termination + step pulse = square pulse with width = $2t$

- **why don't we always match terminate?**

To match or not? (i)

- Impedance matching is a general question, not only for transmission lines

- Match if

 - to transfer maximum power to load (source must be capable)

 - eg audio speakers

 - minimise reflections from load

 - very important in audio, fast (high frequency) systems, to avoid ringing or multiple pulses (eg in counting systems)

 - fast pulses

 - pulse properties can contain important information

 - usually don't want to change

 - sometimes we wish to do this with "too fast" signals - "spoiling"

- Usually match by choosing impedances, adding voltage buffers

 - transformer matching is another method if this is impractical

- The same physics is encountered in other areas

 - eg optical coatings, gel in ultrasound scans, optical grease,...

To match or not (ii)

- Don't match if

- High impedance source with small current signals - typical of many sensors

- photodiode, or other sensors must drive high impedance load

- short cables are required to avoid difficulties

- Weak voltage source, where drawing power from source would affect result

- eg bridge circuits

- require to change properties of fast pulse

- eg pulse widening for ease of detection

- electronics with limited drive capabilities

- eg logic circuits, many are designed to drive other logic, not long lines

- CMOS circuits, even with follower, are an example

- If you get this wrong, often end up with new time constants in the system

- or prevent system from working at all, eg diode with low R load

Coaxial cable limits

- **Transmission speed and bandwidth limiting**

all cables have finite resistance

remarkably small - see table for calculated values

for long cables, RC time constant per unit length becomes noticeable

therefore expect delay, attenuation and finite rise time in fast pulses

- **When is a cable a transmission line?**

not reasonable to assume transmission line behaviour unless length of line is at least
~ 1/8 wavelength

- **Other forms of transmission line**

in high speed circuits, tracks must be laid out carefully using knowledge of the characteristics of the boards to control delays, rise times and signal velocities

eg parallel tracks,...

often need measurement to define parameters precisely

ultra high frequencies need waveguides or alternative

Optical fibres

- **Principle: transparent dielectric with $n_0 > n_1$ = lightguide**

usually glass: high silica content, doped with fluorine or oxides

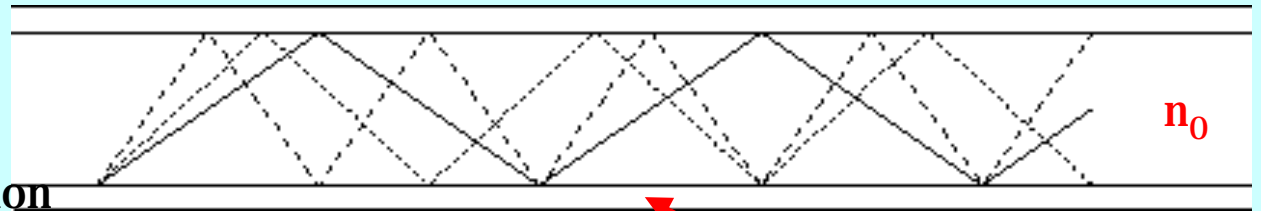
Light propagates by multiple reflections - expect attenuation

$$T \sim R^n$$

- **Cladding - as well as n_1 provides mechanical strength & protection**

limits evanescent radiation from fibre ($\sim e^{-r}$)

limits spread of velocities down fibre (different routes) - t/L n/c



- **Advantages of fibre**

size, weight and flexibility - typical diameter $\sim 250\mu\text{m}$

electrical isolation - interference immunity, can mix with electrical cable

low transmission loss - as low as 0.2dB/km

security - hard to tap into

- **Cons - (more fragile), connections, need for opto-electronic conversion**

electronic circuits matching speed of fibres \sim multi-Gb/s

Modes

- ray picture inadequate - need to consider wave equations in waveguide

solutions to Maxwell's equations - cylindrical symmetry

$$= (r, \theta) \exp[-j(\omega t - z)] \quad = 2 /$$

eigenvalue solutions for different ω at given z : modes

ie not all rays permitted

- Single and multi-mode fibre

$$NA = \sin \theta_c = n_0 \sin \theta_0 = (n_0^2 - n_1^2)^{1/2}$$

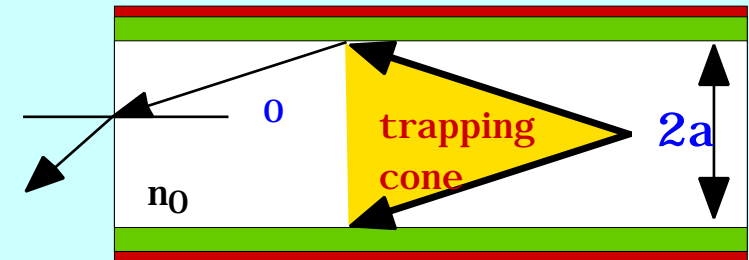
no. modes \sim core area and $(NA)^2$

but find solutions where only single mode propagates

provided $V > 2.405$

- single mode fibre

dominates long distance telecomms



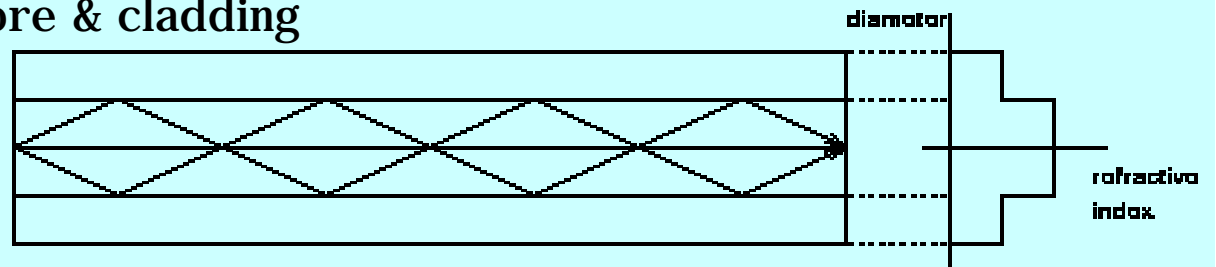
Fibre types

•Step index

uniform ref. index throughout core & cladding

core diameter $\sim 100\text{-}500\mu\text{m}$

multi-mode

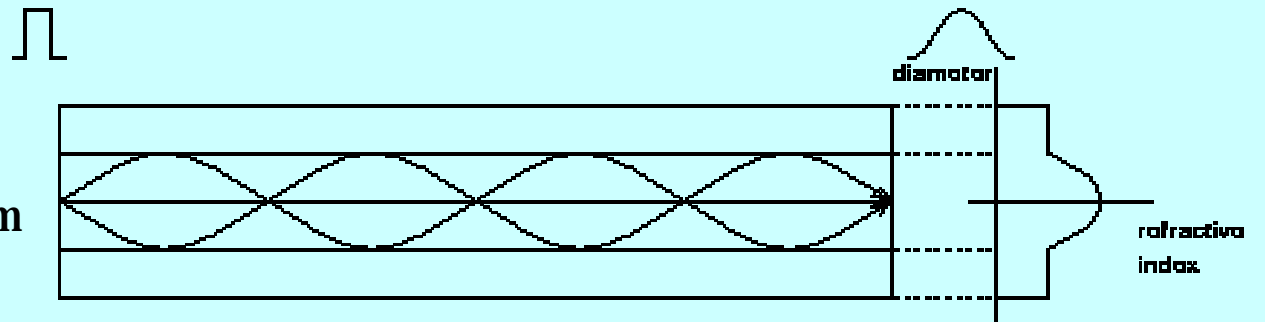


•Graded index

ref index changes with radius

core diameter $50\mu\text{m}$ or $62.5\mu\text{m}$

multi-mode



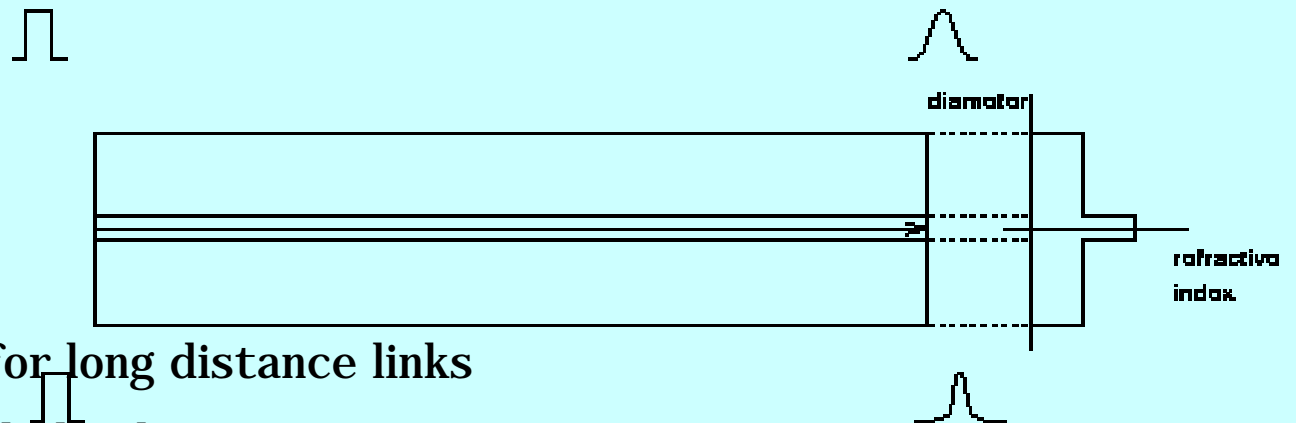
•Single mode

very narrow core $\sim 8\mu\text{m}$

$n \sim 0.35\%$

minimum dispersion so ideal for long distance links

cheaper to produce than graded index



Attenuation in fibres

- **Quality is now so high that attenuation is close to physical limits**

Rayleigh scattering $1.2\mu\text{m}$

glass absorption (GeO_2 , B_2O_3 , SiO_2 band edges at longer wavelengths)

absorption peak $\sim 1.4\mu\text{m}$ (OH- impurity ions)

waveguide imperfections & bending - low level

- **Telecommunications**

$1.3\mu\text{m}$ & $1.55\mu\text{m}$

optical amplifiers $\sim 80\text{km}$

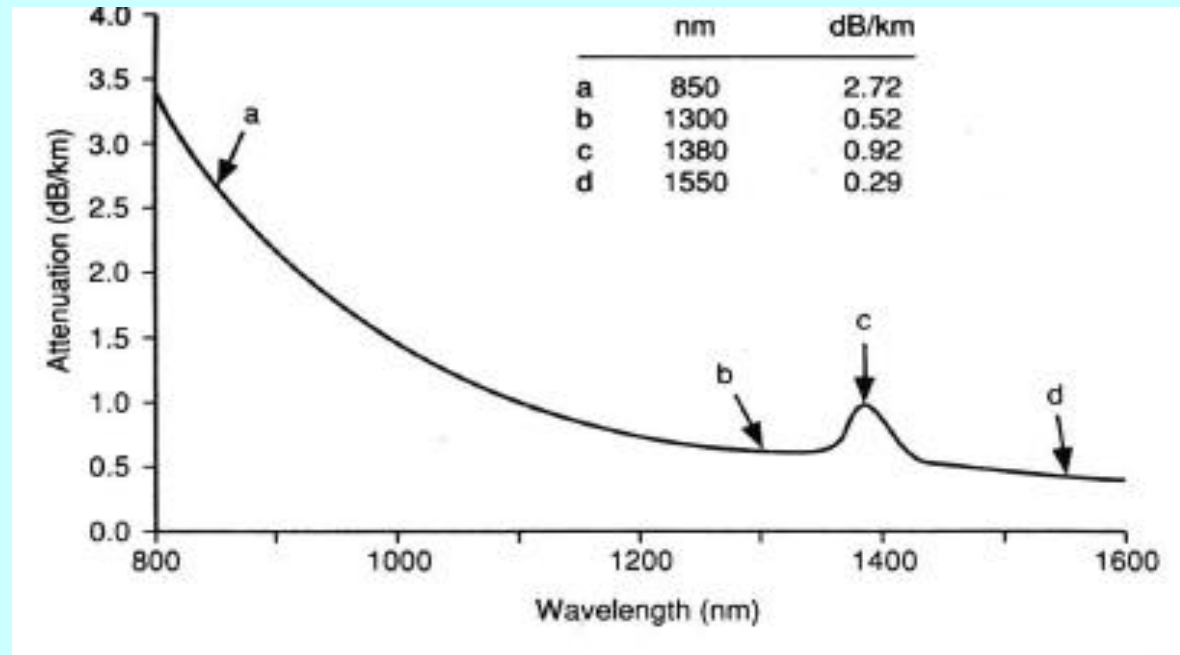
- **Short distance, eg LAN**

$0.85 - 0.9\mu\text{m}$

earlier attenuation minimum

&

availability of optical transmitters



Limits

- **Dispersion- mainly chromatic**

material: dependence of n

waveguide: dependence of c_{fibre}

$$D(\lambda) = S_0 \left[- \frac{\lambda^4}{\lambda_0^3} \right] \text{ ps}/(\text{nm.km})$$

$$S_0 = 0.025 \text{ ps}/(\text{nm}^2.\text{km}) \quad \lambda_0 = 1310\text{nm}$$

- **Analogue vs digital - both kinds of data are transmitted**

Pros

Analogue

Avoid digitisation
circuits/power

Cons

Signal distortion/attenuation
require good linearity

Digital

Transmit 0/1

need complex circuits & power
many bits needed => high speed

telecommunications and computer: digital dominates

cable TV, phone: analogue

- **Bandwidth** constantly striving to increase, eg fibre quality

- **Connectors** typically expensive and care needed to avoid dirt, damage

but fibre is cheap so maximise length before connections