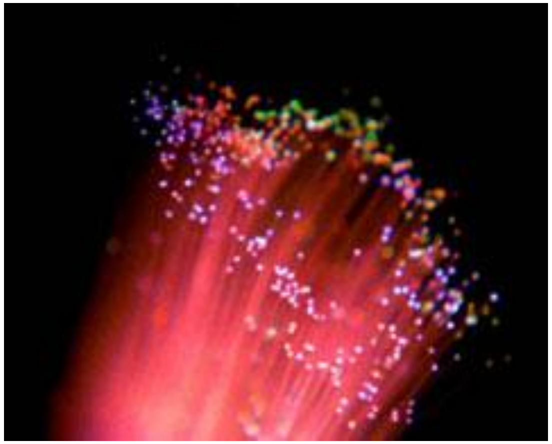
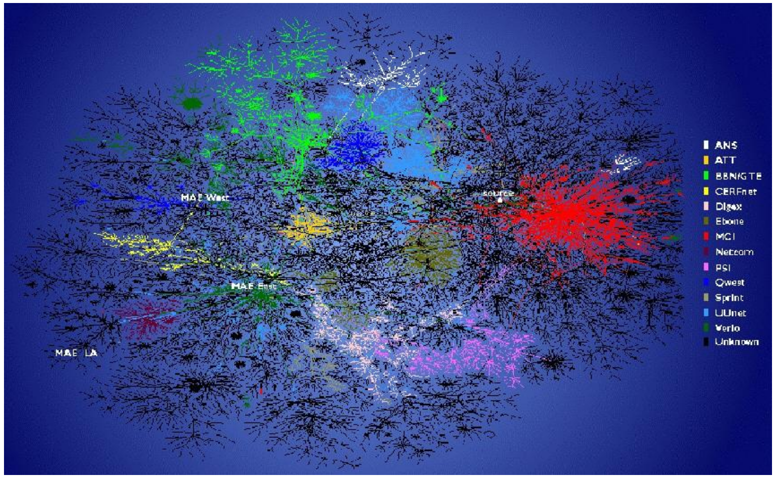
EEE442/6420: Optical Fibre Communication

Components and system design
for optical fiber communications





Course Books

Keiser "Optical fiber communications" McGraw Hill Intnl.
ISBN 0-07-116468-5

"Optical Communication Systems" By G Gowar, Publisher - Prentice Hall

"Optical Fibre Communications" By JM Senior, Publisher – Prentice Hall

Objectives

Understand design and operation of fibre optic systems

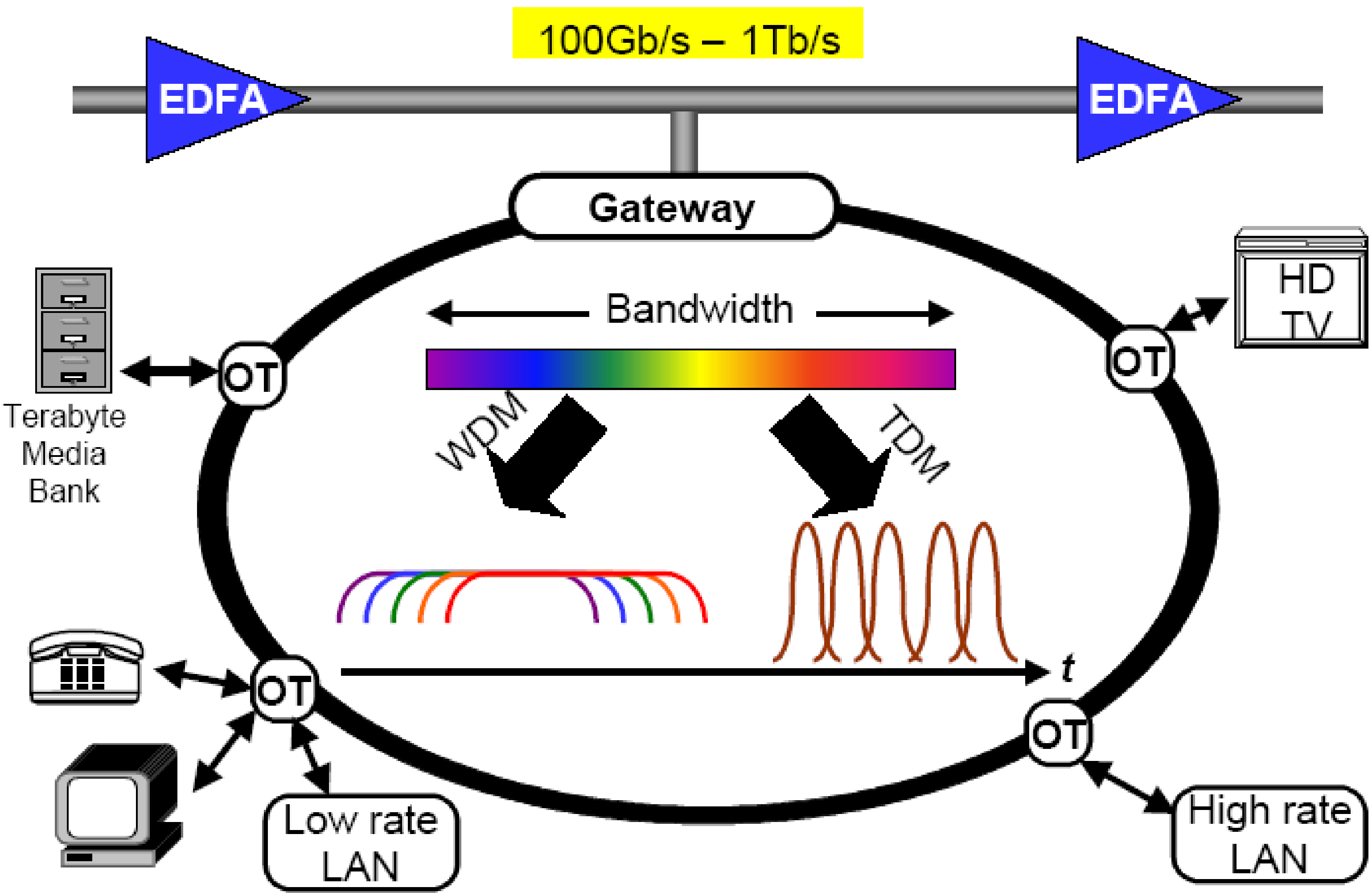
Understand parameters of optical fibres

Understand Optical networks

Why Optical Communications?

- Optical Fibre is the backbone of modern communication networks
  - Voice (SONET/Telephony)
  - Video (TV) over Hybrid Fiber Coaxial (HFC)
  - Fiber Twisted Pair for Digital Subscriber Loops (DSL)
  - Multimedia (Voice, Data and Video) over DSL or HFC
  - Radio over fibre

Introduction



Why Optical Communications?

- Lowest attenuation → attenuation in the optical fibre (at 1.3 μm and 1.55 μm bands) is much smaller than electrical attenuation in any cable at useful modulation frequencies
  - Much greater distances are possible without repeaters
  - This attenuation is independent of bit rate
- Highest Bandwidth (broadband) → high-speed
  - Single Mode Fibre (SMF) offers the lowest dispersion → highest bandwidth → rich content
- Upgradability: Optical communication system can be upgraded to higher bandwidth, more wavelengths by replacing only the transmitters and receivers
- Low Cost for fibre

Evolution of optical communication

Modulating light to transmit information

Smoke signals / fires / lanterns / heliographs / mirrors

- Slow “digital” encoding, simple intensity modulation
- Very trivial messages (“All clear”, “Send help”)
- More of a broadcast than a dedicated channel

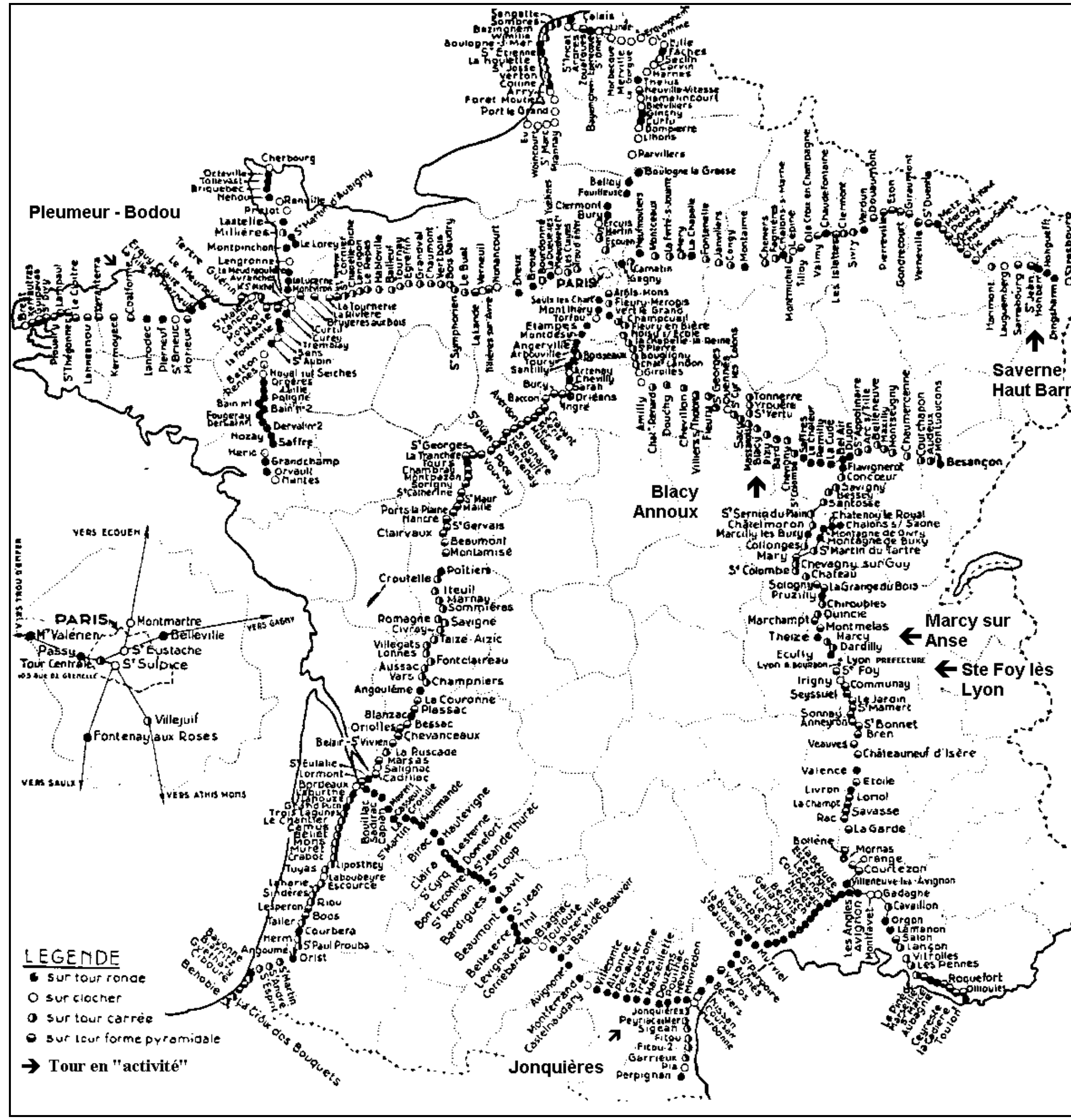
Claude Chappe invents first “optical telegraph”

- Slow “digital” encoding, using shapes
- Sophisticated codes to improve information content
- Reasonably fast and reliable
- Trained humans needed to encode / decode
- Europe’s first telecommunications network

Evolution of optical communication

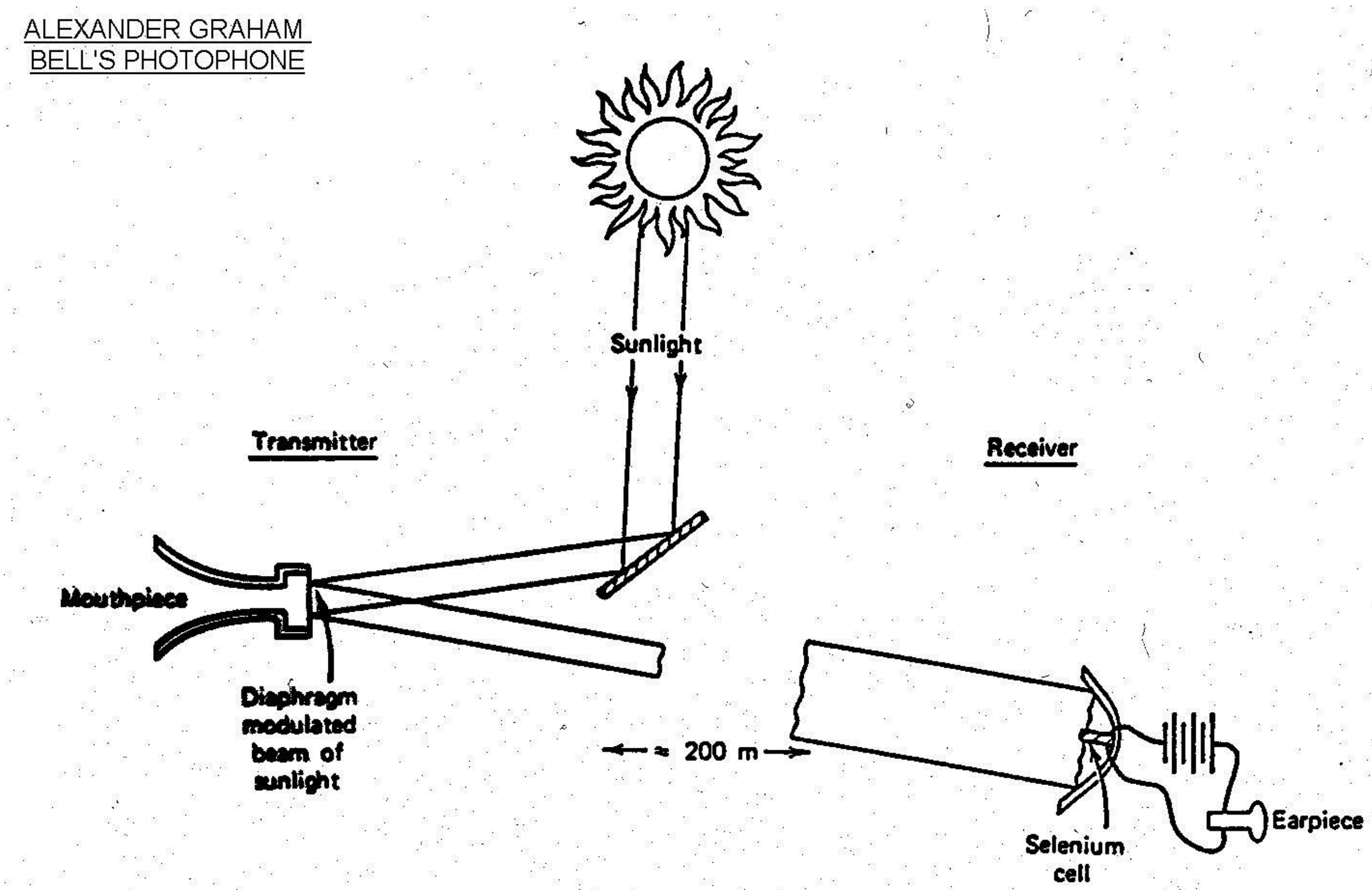
Some of Claude's stations survive to this day ...

These are analogous to today's fibre optic "repeater stations"



A map of Europe's first telecommunications network
Lines established 1793 - 1852

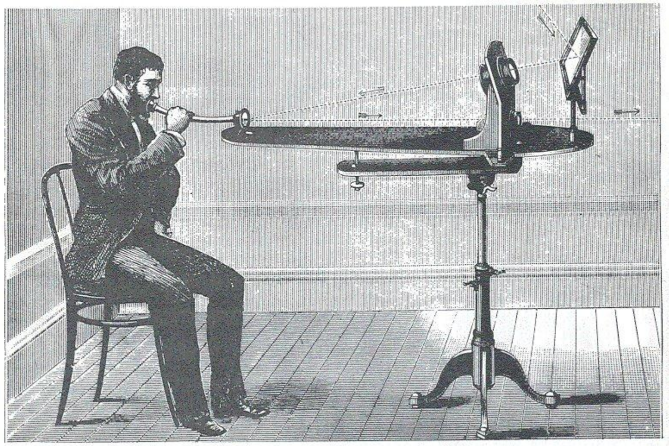
1880 - Bell's Photophone



Sunlight collected and reflected from a silvered diaphragm

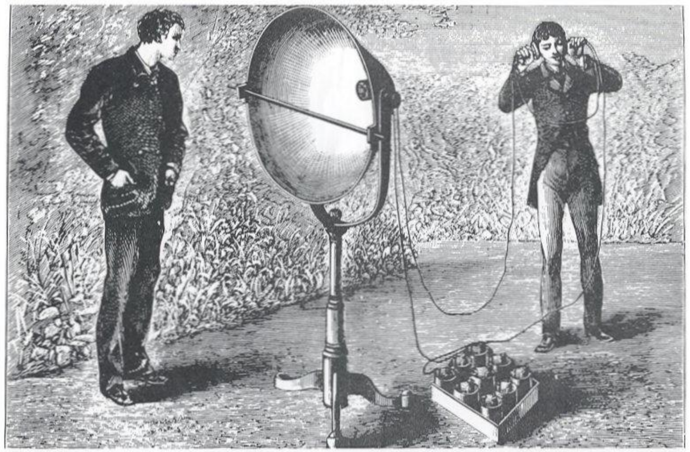
Resistance of selenium cell modulated – change in conductivity results in sound

Transmission System



The photophone of Bell and Tainter: the transmitter [1881]

200m of air

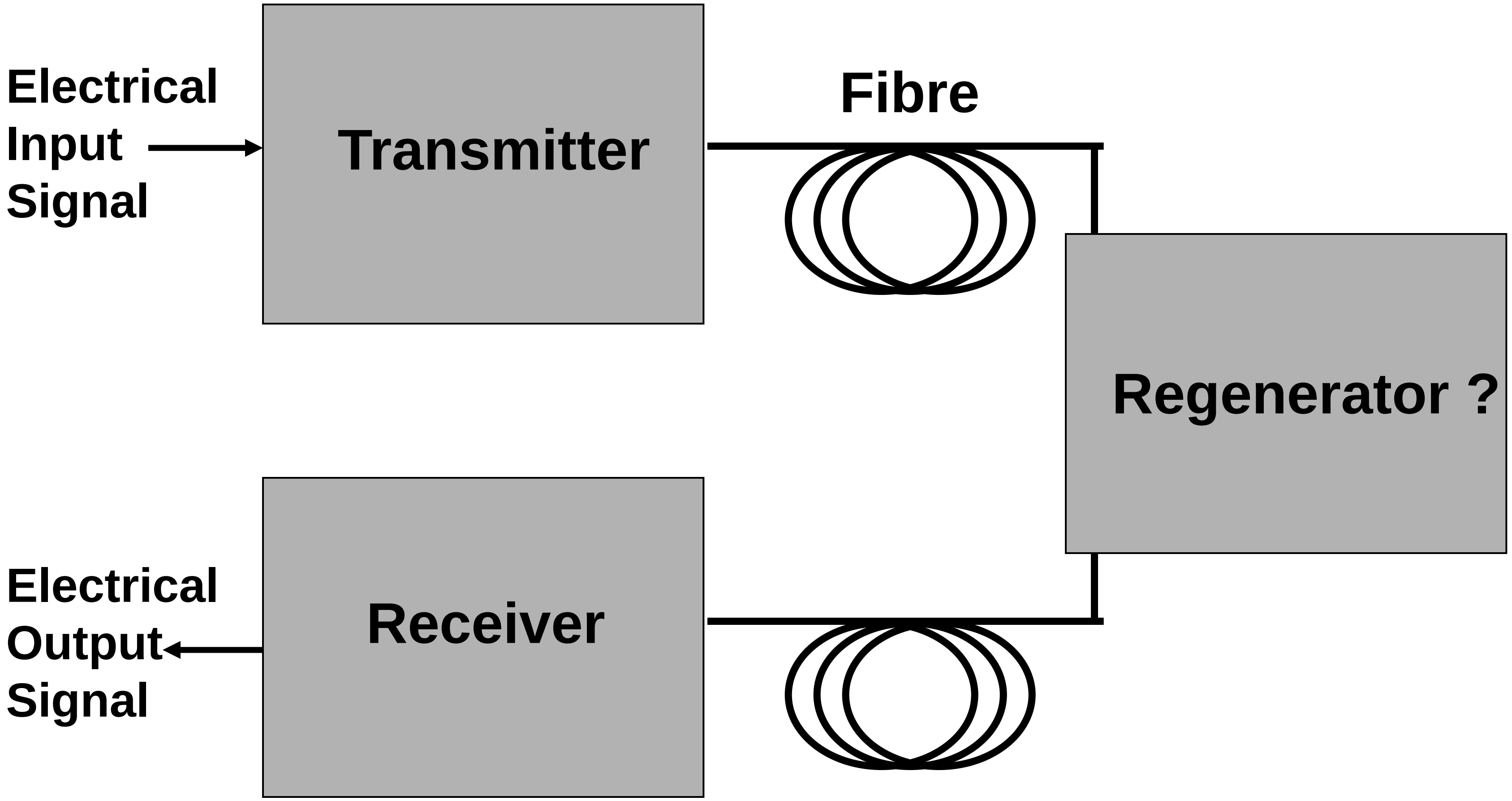


The photophone of Bell and Tainter: the receiver [1881]

Transmitter, Receiver, transmission medium – air

For Fibre Optics – transmission medium is glass (SiO_2)

Optical Fibre System



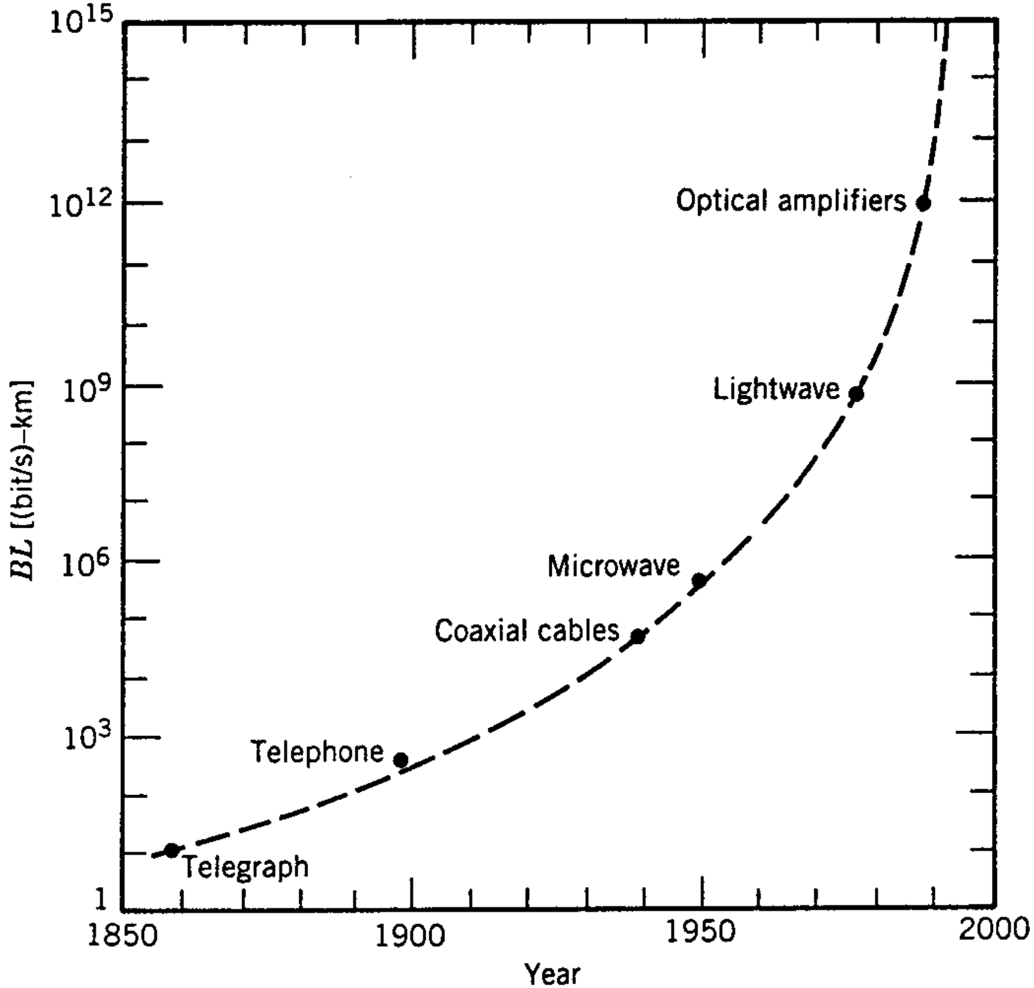
Optical fibres Vs copper cables

- 600 twisted-pair copper cable carries 600 conversations
- 6 coaxial copper cable carries
  2700 conversations
- 30 optical fibre cable carries 28,720 conversations.
- (each conversation assumes 2-way transmission)

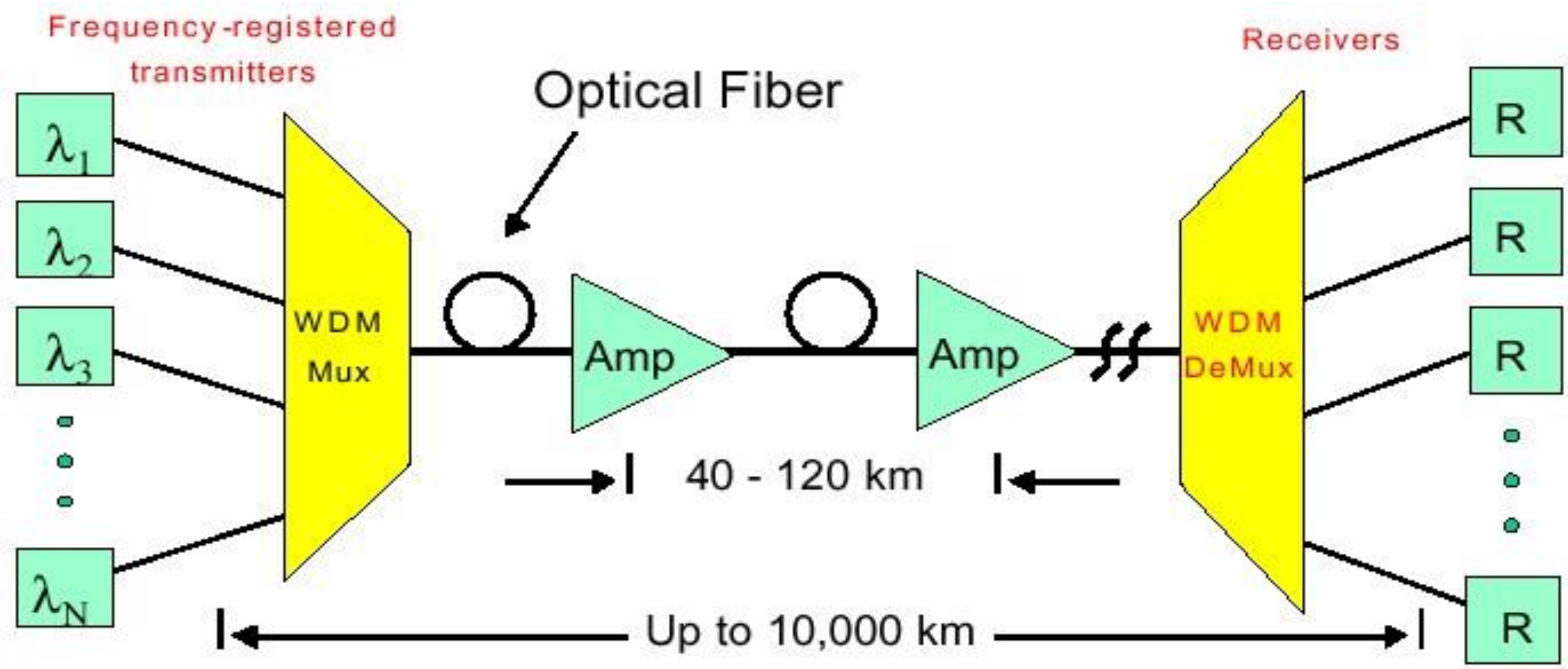
Importance of Optical Fibres in Communications

- Signal Attenuation
  - Silica glass fibres have attenuation less than 0.2 dB/km
    - only need signal repeaters every 30 km or so.
    - This is 5-15 times better than copper cables!
- Electromagnetic Interference
  - Optical Fibres immune to electromagnatic interference (EMI).
    - Can be used in electrically noisy environments
    - good for secure info transmission as no EM radiation leakage.

Bit-rate x Distance Product over time



Optical Fiber System



$\Delta\lambda$ = 25 - 100 GHz
(0.4 or 0.8 nm @ 1500 nm)

Fibre Optic System Design

Design Variables;

System - configuration, signal coding, data rate, BER, multiplexed?, switching requirements,

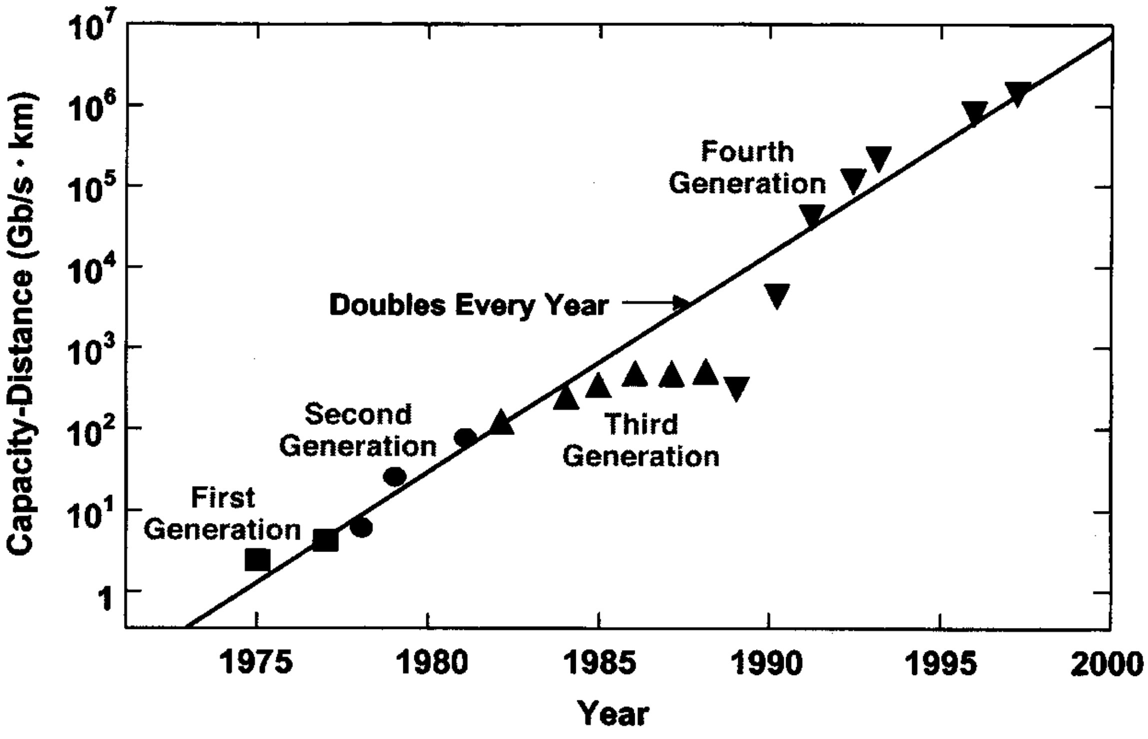
Transmitter – output power, spectral linewidth, response time, wavelength, direct/indirect modulation?

Fibre – type(single/multimode),core diameter, NA, coupling losses between Tx and fibre, attenuation, dispersion, number of splices & couplers, etc.,

Receiver – response time, bandwidth, sensitivity

Regenerators Required – what type?

Evolution of Fibre Optic Systems



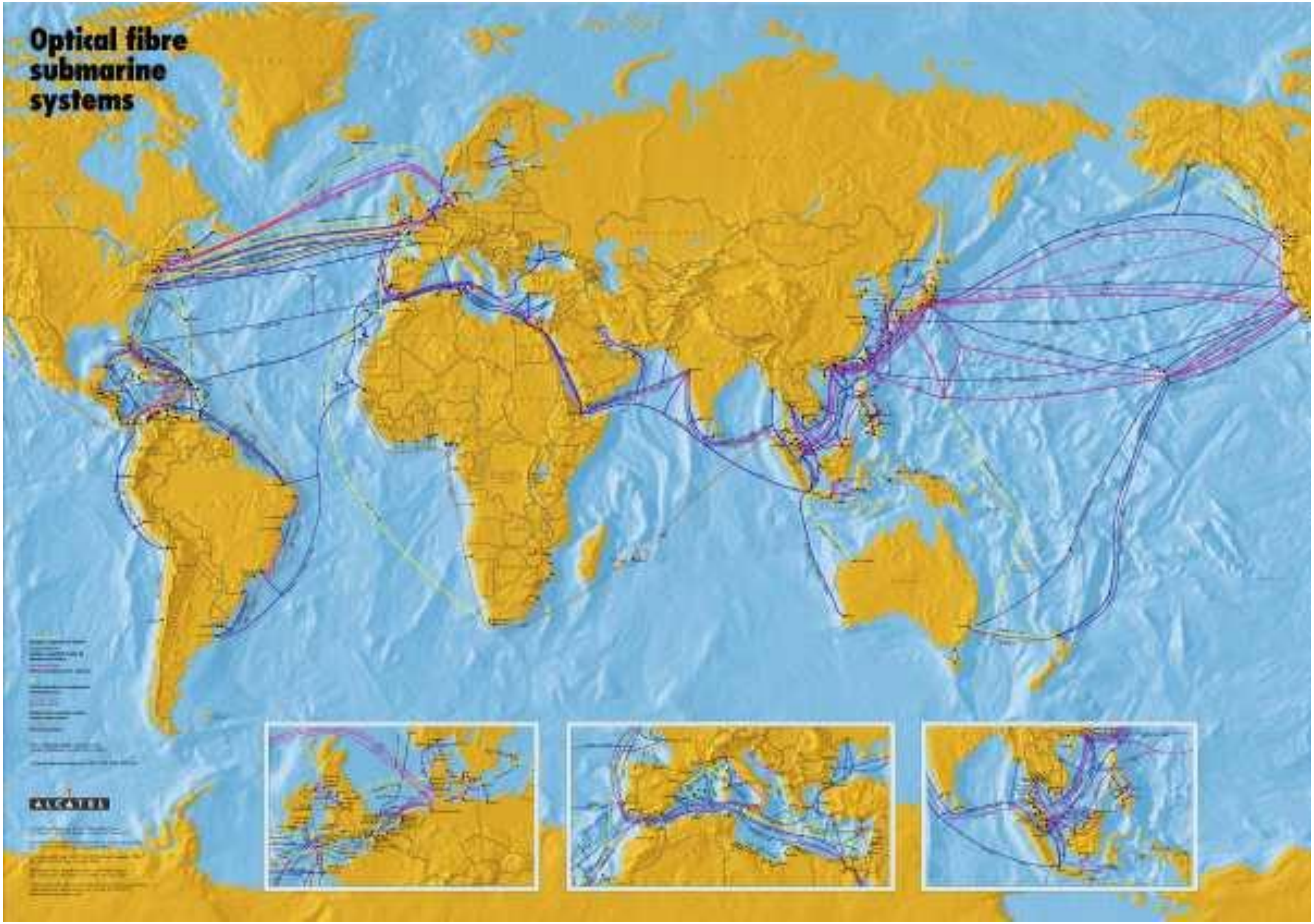
1^{st} G – 0.8um 45Mb/s over 10km

2^{nd} G – 1.3um 1/7Gb/s over 50km

3^{rd} G – 1.55um
2.5 Gb/s over~100km

4^{th} G – optical amplification and WDM – Submarine system – Global network 250,00km capacity of 2.56 Tb/s

Submarine Systems



Quantum nature of Light

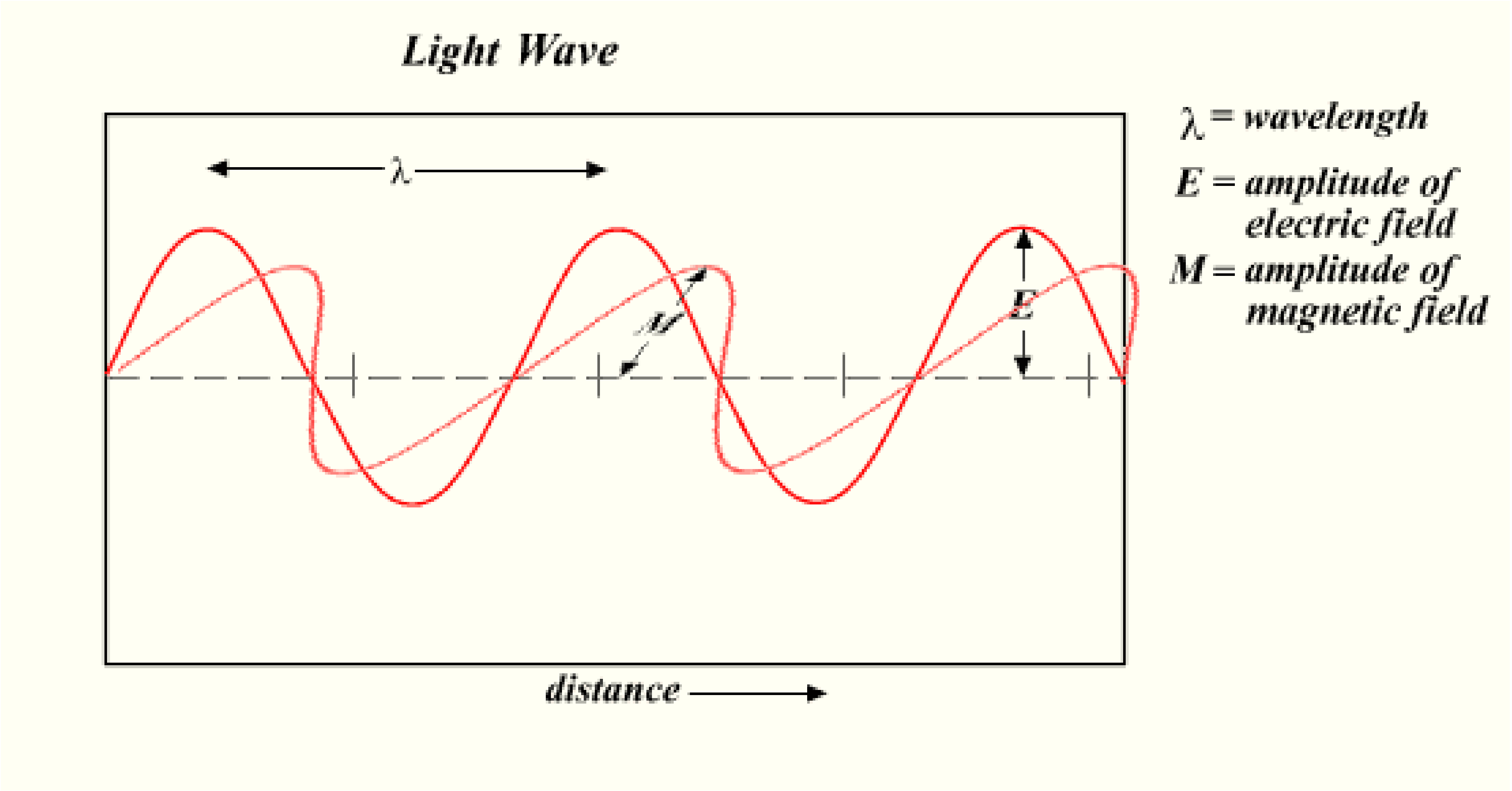
- In dealing with the interaction of light and matter (dispersion, absorption) neither particle nor wave theory are appropriate.
- Instead Quantum theory is used – light energy is emitted or absorbed as photons or quanta.
- Photons have zero mass
- Photon energy E depends on the frequency v
- $E = hv$

where h = Planck’s constant = 6.625×10^{-34} J.s

The frequency $v = c/\lambda$,

where c = speed of light 3×10^{8} m/s and λ = wavelength

Light as an EM wave



Maxwell's Equations

E – electric field
H – magnetic field
D – electric flux density
B – magnetic flux density

$\nabla \times \mathbf{E} = -\delta \mathbf{B} / \delta t$ (1)

$\nabla \times \mathbf{H} = \delta \mathbf{D} / \delta t$ (2)

$\nabla \bullet D = 0$ (3)

$\nabla \bullet B = 0$ (4)

ε - dielectric permittivity
μ - **magnetic permeability**

$\mathbf{D} = \varepsilon_0 \mathbf{E}$ (5)

$\mathbf{B} = \mu_0 \mathbf{H}$ (6)

Equations governing behaviour of E – obtained by eliminating B

Maxwell's Equations 2

Take Curl of both sides of (1)

$$\nabla \mathrm{x}\ (\nabla\ \mathrm{x}\ \mathbf{E}) \quad = \quad -\nabla\ \mathrm{x}\ (\delta \mathbf{B}\ /\ \delta t) \qquad (7)$$

$$= \quad -(\delta\ /\ \delta t)\ (\nabla\ \mathrm{x}\ \mathbf{B}) \qquad (8)$$

Substitute (5) and (6) into (2)

$$\nabla\ \mathrm{x}\ \mathbf{B} \quad = \quad -\nabla\ \mathrm{x}\ (\delta \mathbf{B}\ /\ \delta t) \qquad (9)$$

$$= \quad \boldsymbol{\varepsilon}_{\mathbf{0}}\mu_0\ (\delta \mathbf{E}\ /\ \delta t) \qquad (10)$$

Maxwell's Equations 3

Use vector identity

∇x (∇ x **E) =** ∇**(**∇ • **E) -** ∇^2 **E** (11)

And in Cartesian Coordinates $\nabla \bullet \mathbf{E} = 0$ (12)

Giving

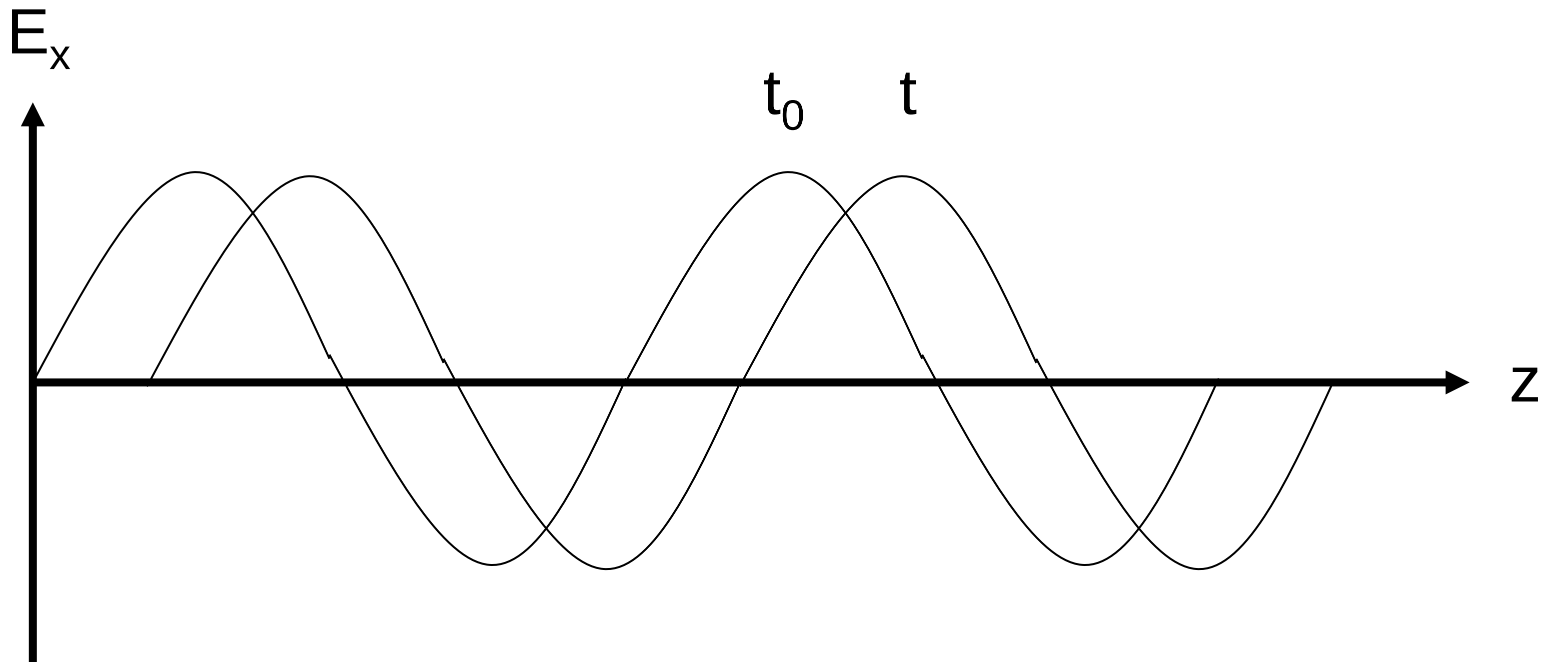
$\nabla^2 \mathbf{E} - \boldsymbol{\varepsilon}_\mathbf{0}\mu_0 (\delta^2\mathbf{E} / \delta t^2) = 0$ (13)

Say E depends on one spatial coordinate (y) then;

$\delta^2\mathbf{E}_y / \delta x^2 - \boldsymbol{\varepsilon}_\mathbf{0}\mu_0 (\delta^2\mathbf{E}_y / \delta t^2) = 0$ (14)

- one-dimensional wave equation

Electromagnetic Waves - Monochromatic



ω- circular (radian) Frequency

$$e_x = E_x\, e^{\,j(\omega t - kz)}$$

k- propagation constant

Electric field vector

Electric field amplitude at z

Phase Velocity

An observer travels to maintain constant phase

$$\omega t - kz = \text{constant}$$

Observer travels with *phase* velocity

$$v_{phase} = dz/dt = \omega/k$$

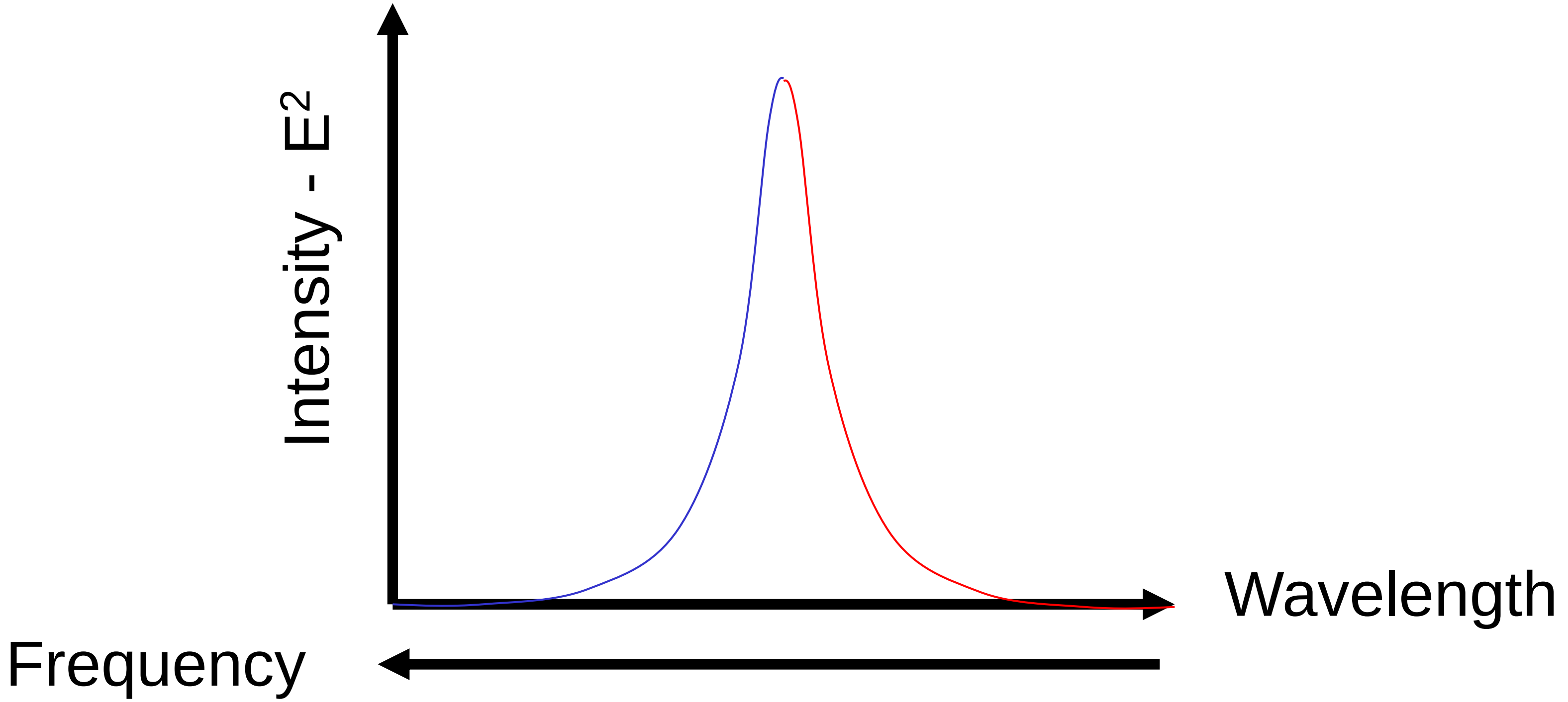
$k = 2\,\pi\,/\,\lambda$, in a medium (i.e. not vacuum) replace k with $\beta = nk$

In a medium $v_{phase} = c\,/n$

(n= phase index, c = speed of light in vacuum

Modulation or Envelope of Wave

- We have a speed for an EM wave…..
- At what speed does the information travel?
- In dispersive media (all except vacuum) different wavelengths may travel at different velocities



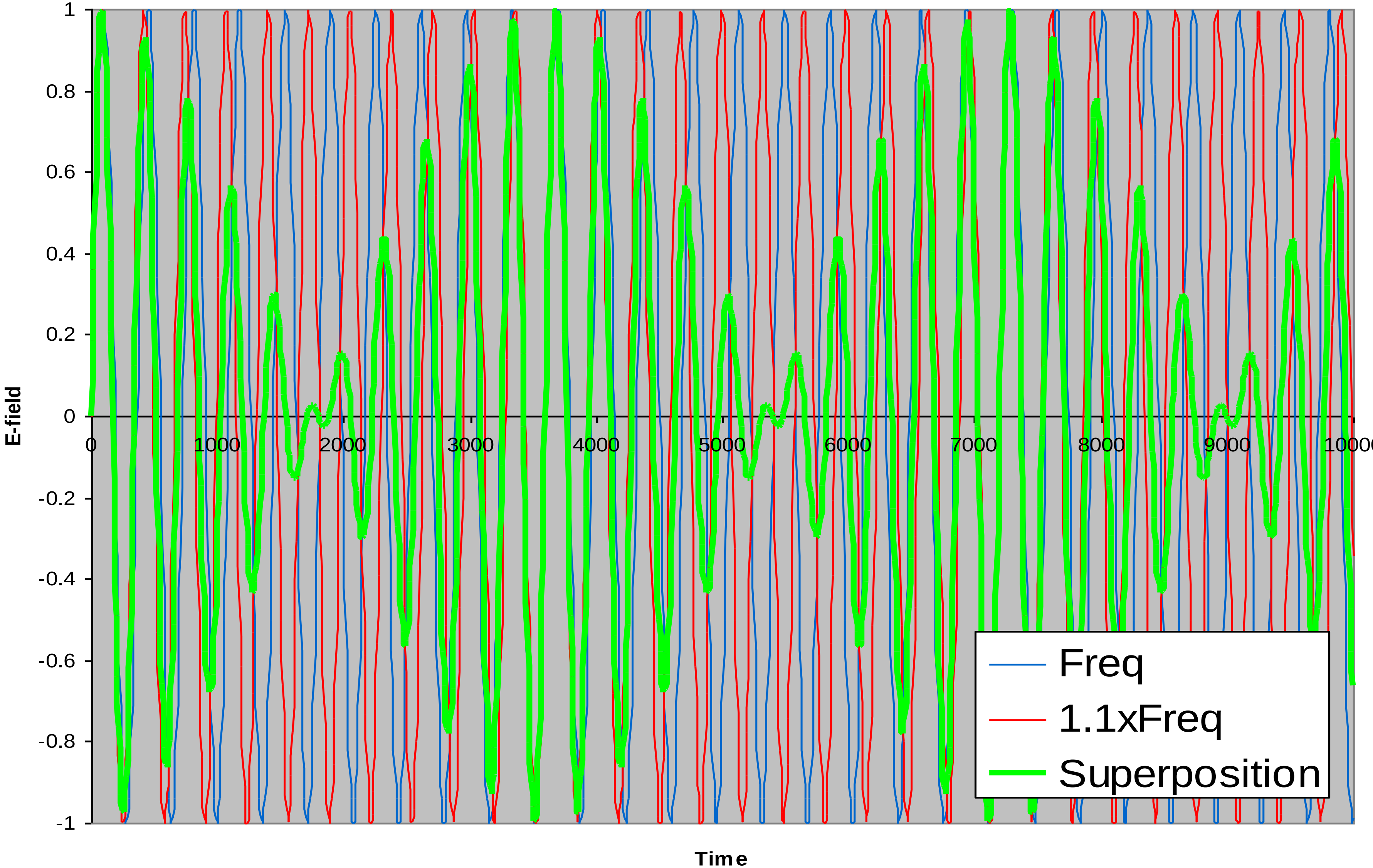
WAVE PACKETS

A **wave packet** is a short "burst" or "envelope" of wave action that travels as a unit.

A wave packet can be analyzed into, or can be synthesized from, an infinite set of component sinusoidal of different wavenumbers, with phases and amplitudes such that they interfere constructively only over a small region of space, and destructively elsewhere.

The wave packet's envelope may remain constant (no dispersion) or it may change (dispersion) while propagating

Wave Packets



Check wikipedia for animated version!

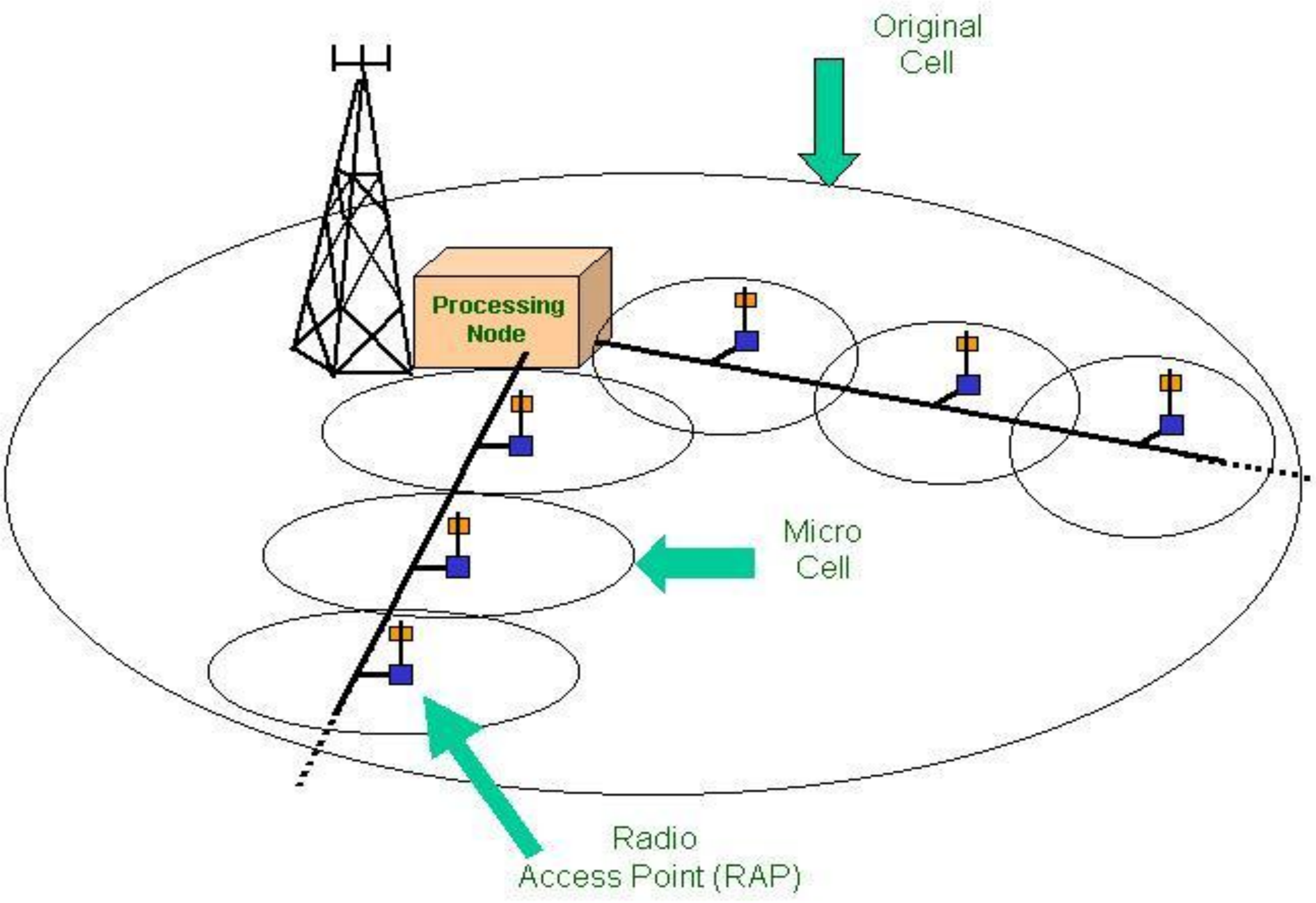
Group Velocity

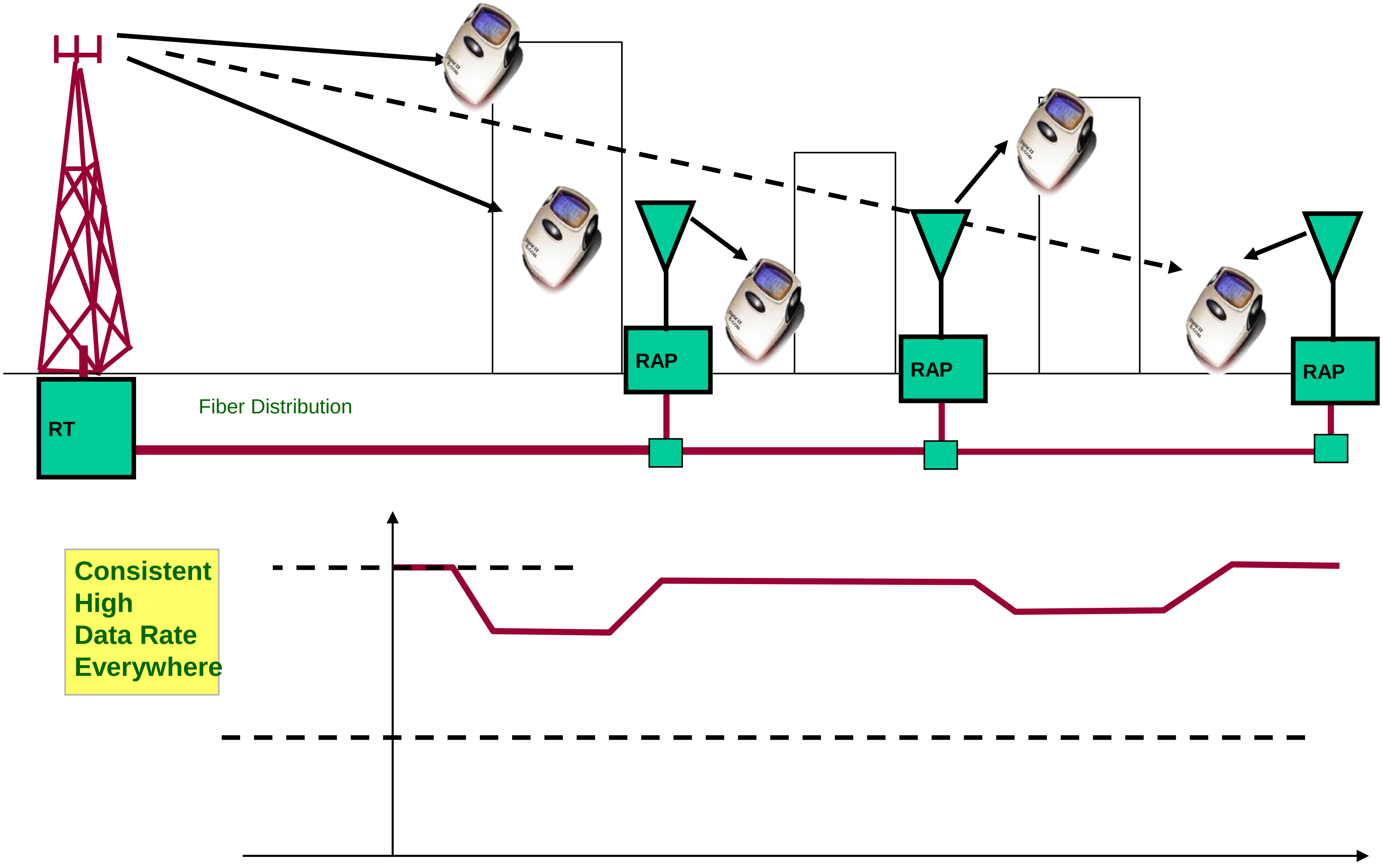
- Speed at which this packet moves is not the phase velocity it is the rate at which the modulation envelope moves – only the phase velocity if n is independent of frequency (wavelength) i.e. $dn/d\lambda = 0$
- Group velocity is speed at which the information or energy travels
- Use the term "group velocity" and group index n_{group}
- $v_{group} = c / n_{group}$
- $n_{group} = n - \lambda(dn/d\lambda)$

Emerging technology – Radio over Fiber (ROF) for Wireless Systems

Radio signals are transmitted along an optical fibre network and signal is transmitted into the free-space to give wireless access and mobility. Gives unique challenges.

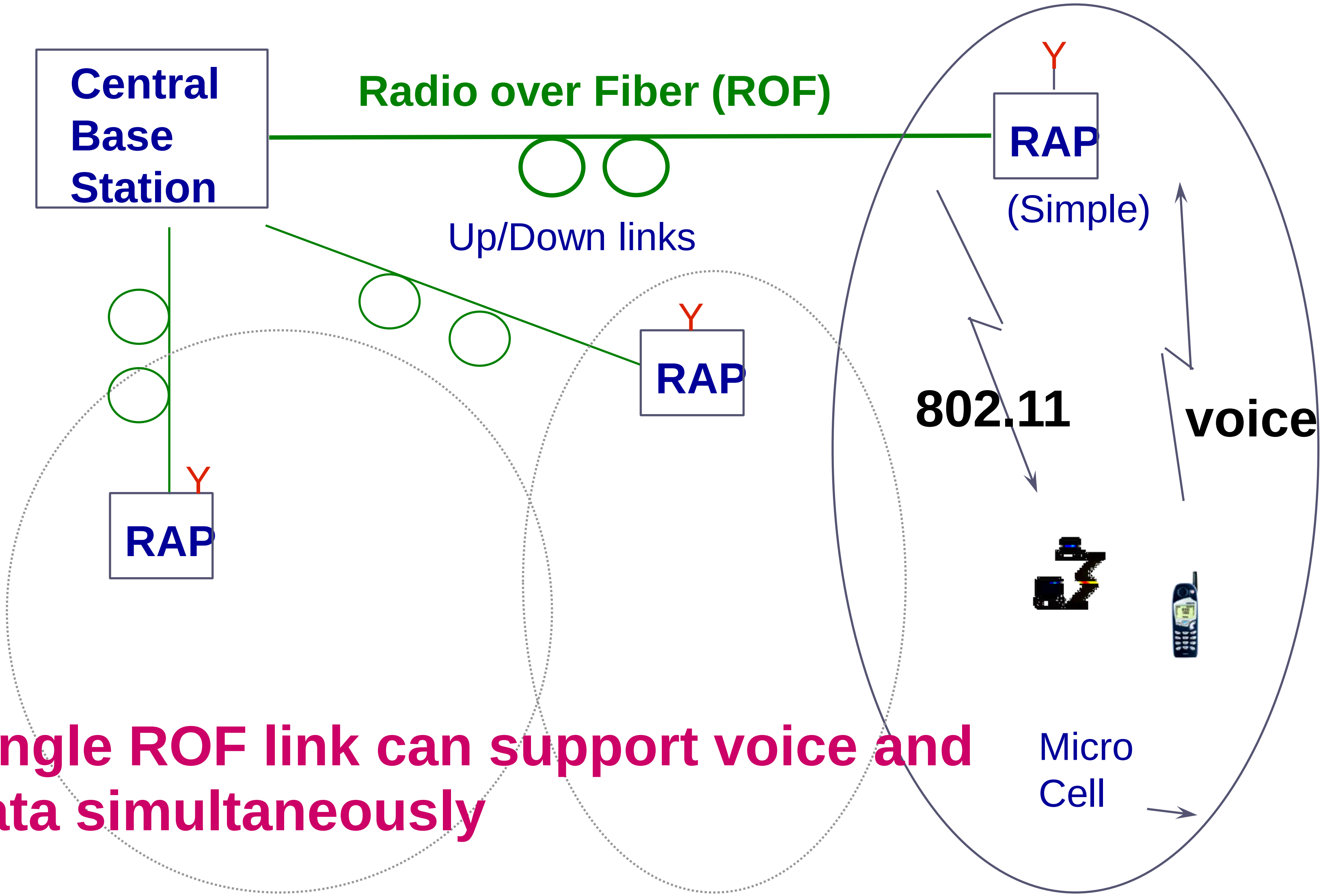
The Technology





Dramatic Increase in Capacity !!

Multi Standard Fiber-Wireless



Single ROF link can support voice and data simultaneously

Summary - Light Propagation

- Light can be considered as a wave
- Governed by Maxwell's equations
- For monochromatic wave in media can define a phase velocity = c / n_{phase}
- For non-monochromatic light, the wave packet travels with the phase velocity only if n_{phase} is not a function of wavelength.
- This is not the case for silica (glass) so introduce n_{group}
- Group velocity = c / n_{group}