EEEN20060 Communication Systems

Physical Layer – Part 2

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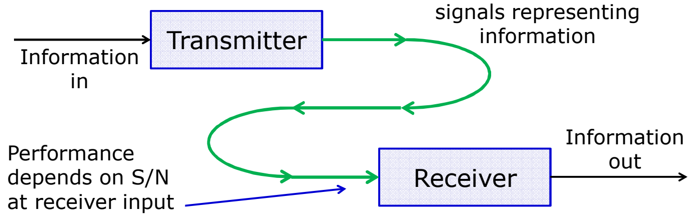
Scoil na hInnealtóireachta Leictrí, Leictreonaí agus Cumarsáide UCD

Physical Layer Basics



- Analogue system – analogue info signal in
  - analogue signals travel on channel
  - output should be close replica of input
- Digital system – info in as stream of bits
  - continuous signals on channel, represent bits
  - output bits should have low prob. error

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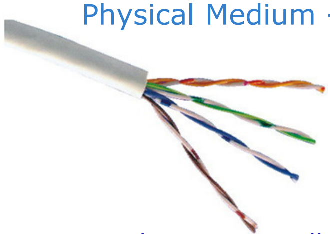
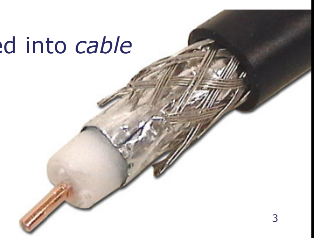
Physical Medium – Wires



- Metal wires – usually copper
  - any conductor will do
  - usually insulated, bundled into *cable*
- Usually need two wires
  - for electrical circuit
  - often *twisted pair*
  - *coaxial* cable for higher frequencies



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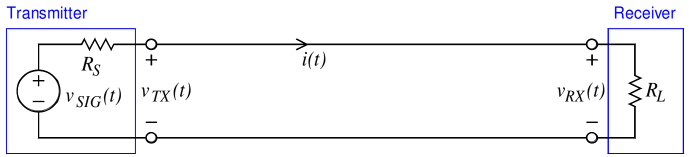
Signals on Wires



- Electrical circuit view - signal could be
  - voltage difference between wires?
  - current flowing along wires?
- Finite propagation velocity (speed of travel)
  - voltage and current not same at all points
  - for typical cables, ~ 2×10^8 m/s
- At 100 Mbit/s, how long is a bit?

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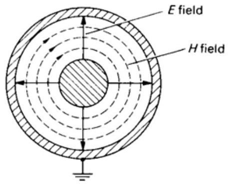
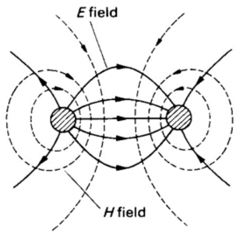
Alternative View





- Electromagnetic view
  - signal travels as electromagnetic wave
  - guided by the conductors of the cable
- Related:
  - current in wire ⇒ magnetic field around it
  - voltage between wires ⇒ electric field

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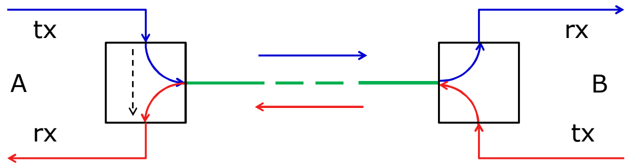
Two-way Communication



- Signals can travel in either direction
  - on one pair of conductors
- Signals can travel in both directions at same time
  - problem is launch and recovery
  - most electronic circuits one-way (e.g. amplifier)
  - need to keep tx signal out of rx
  - clever circuits needed, never quite perfect…

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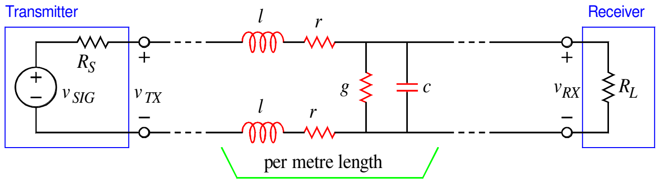
Cable Characteristics



		example Cat 5
Each conductor has		
– resistance	r	~90 mΩ/m
– inductance	l	~500 nH/m
Between conductors		
– capacitance	c	~55 pF/m
– leakage conductance	g	<1 pS/m

- So some signal power lost – attenuation
  - varies with frequency

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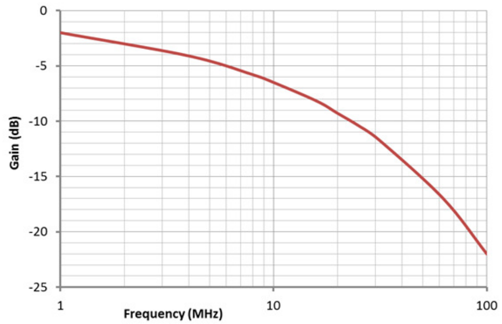
Attenuation Example

100 m length of Cat5 cable

decibel used to express power ratio



$$\text{Gain (dB)} = 10\log_{10}\left(\frac{P_{out}}{P_{in}}\right)$$

- Attenuation or loss = 1/gain
  - more attenuation at higher frequency
  - at 8.5 MHz, 25% of tx power arrives at rx
  - at 85 MHz, 1% of tx power arrives at rx

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deciBel ?

	3 dB	6 dB	10 dB	20 dB
Power ratio	2	4	10	100
Voltage ratio	1.414	2	3.16	10

$$\text{ratio (dB)} = 10\log_{10}\left(\frac{P_1}{P_2}\right)$$

- Logarithmic unit, to express power ratio
  - originally used in telephone system design
- Bel = common log of power ratio
  - unit too large, so use deci-Bel instead (dB)
- Often also used for voltage or current ratio…
  - for same resistance, power ∝ voltage^2 …

$$\text{ratio (dB)} = 10\log_{10}\left(\frac{{V_1}^2}{{V_2}^2}\right) = 20\log_{10}\left(\frac{V_1}{V_2}\right)$$

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deciBel Calculations

TX → RX: cable attenuation 0.8 dB/km, length 200 km

- attenuation 0.8 dB/km means gain -0.8 dB/km
- The hard way: -0.8 dB is ratio 0.832
  - signal scaled by factor 0.832 for every km
  - after *n* km, power reduced by factor 0.832^n
  - after 200 km, factor is $0.832^{200} = 10^{-16}$
- Using dB
  - log ⇒ *raise to power* becomes *multiply*
  - gain -0.8 dB/km, 200 km, total gain -160 dB

$$-160\text{ dB} = 10\log_{10}\left(\frac{P_{RX}}{P_{TX}}\right) \Rightarrow \log_{10}\left(\frac{P_{RX}}{P_{TX}}\right) = -16 \Rightarrow \frac{P_{RX}}{P_{TX}} = 10^{-16}$$

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Analogue Example

- Want to send analogue speech signal
  - from Dublin to Limerick
  - distance ~ 200 km
- Using cable
  - attenuation 0.8 dB/km
  - or gain -0.8 dB/km
  - so total gain 10^{-16}
  - at frequencies in range 300 Hz to 3 kHz
- Receiver needs 10 nW to operate properly (10^{-8} W)
- What power do we need to transmit?
  - most of this will be lost in cable…

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Power in dB

$$\text{power (dBW)} = 10\log_{10}\left(\frac{P}{1\text{ W}}\right)$$

$$\text{power (dBm)} = 10\log_{10}\left(\frac{P}{1\text{ mW}}\right)$$

- deciBel intended for power ratio – relative power
  - often used for absolute power
  - extra letter indicates reference power
- In our example:
  - receive power 10 nW = 10^{-5} mW or -50 dBm
  - required transmit power greater by 160 dB
  - so need +110 dBm, or +80 dBW or 10^8 W
- Realistic transmit power ≤1 W
  - if transmit 1 W, how far can we send the signal?
  - 1 W = +30 dBm, need -50 dBm, so max loss 80 dB
  - so max distance 100 km (on this cable)

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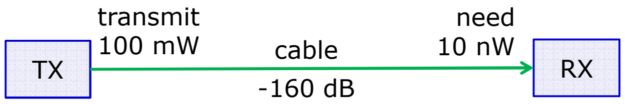
Analogue Example again



- Why does receiver need 10 nW?
  - maybe noise power at receiver is 10 pW
    - some from last few km of cable, more from receiver
  - and we want S/N ratio 1000, or 30 dB
  - note 10 nW in 600 Ω is ~2.5 mV rms
- How do we transmit over long distances?
  - better cable? but always some loss…
    - think of telephone call to Australia…
  - add an amplifier? could compensate for loss…
    - where to put the amplifier?

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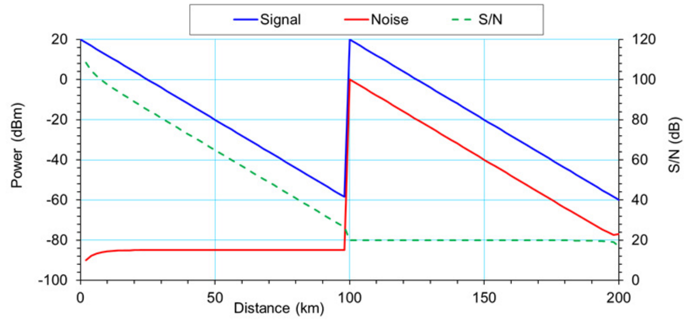
Example with Amplifier



- amplifier added at 100 km point (for example)
  - amplifier gain 80 dB (making up for cable loss)
- amplifier will amplify noise as well as signal…
- amplifier will also generate some noise
  - assume same as example receiver – 10 pW at input

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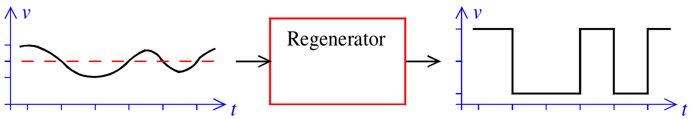
Digital Transmission - Regeneration



- Long-distance transmission
  - don't amplify – *regenerate* along the way
  - receive signal, transmit new signal
  - full amplitude, ~no noise
- Perfect transmission?
  - not quite – always some probability of error
  - regenerator makes decision, just like receiver
    - so some prob. of error at every regenerator…
  - if regenerate early, while S/N still high,
    - can keep probability of error very low

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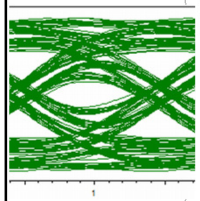
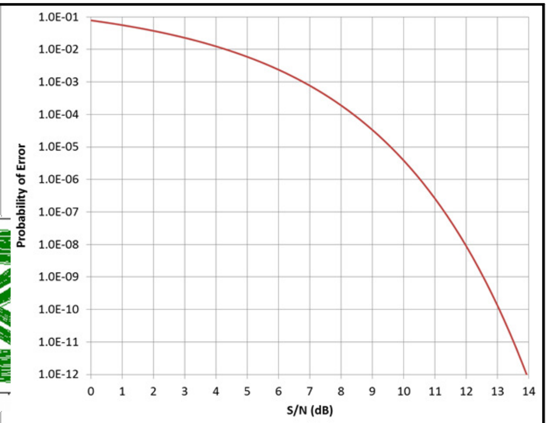
Recall – Decision at Receiver





- same result at regenerator
  - high S/N gives low probability of error

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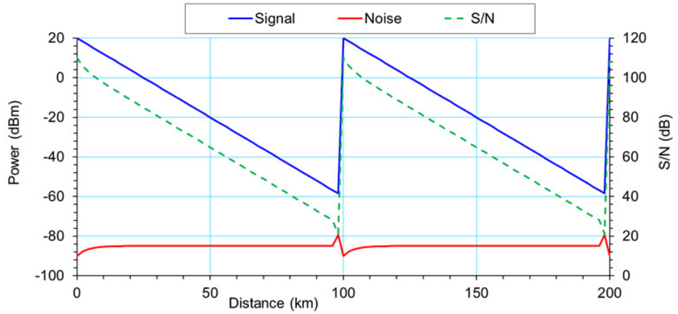
Example – Dublin to Limerick



- Note S/N can improve!
  - regenerator outputs "clean" signal
  - noise at input does not propagate
    - but may cause errors, which do accumulate…

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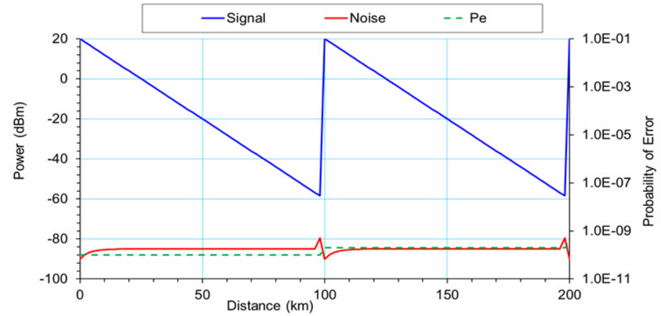
Example – Dublin to Limerick



- Regeneration is key advantage
  - for digital transmission over long distances
  - know in advance what signals could be sent
  - only have to choose between them

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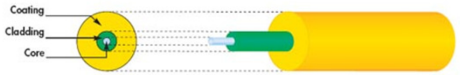
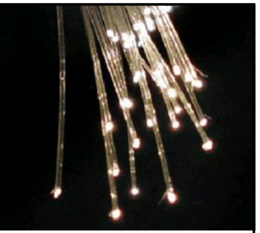
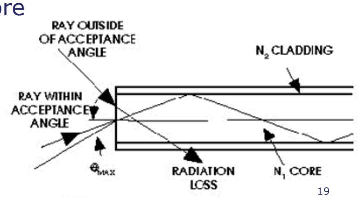
Physical Medium – Optical Fibre





- Strand of very pure glass (core)
  - surrounded by glass of lower refractive index
  - internal reflection at core/cladding boundary
  - light propagates along core
  - electromagnetic wave
    - guided by fibre
- Developed from 1960s
  - Kao & Hockham
  - practical from ~1980



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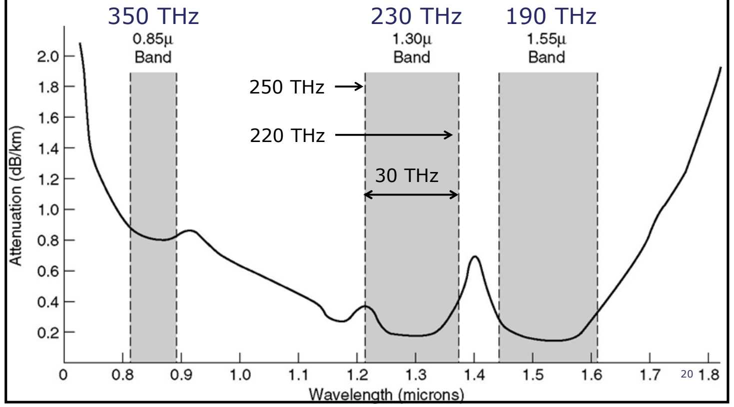
Attenuation on Optical Fibre

image from Tanenbaum

- typical mono-mode fibre
  - core 8 – 10 µm diameter, cladding ~ 120 µm



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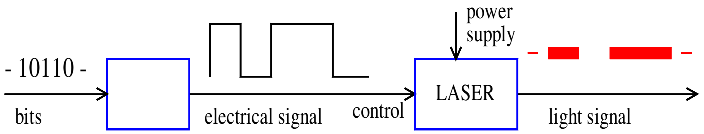
Signals on Optical Fibre



- Cannot send electrical signals
  - only light at suitable frequency or wavelength
- So send a light signal
  - generate using laser (or LED for short distance)
- Need to change the light signal somehow
  - to represent information – *modulation*
- Simple case, binary transmission
  - just switch light on or off

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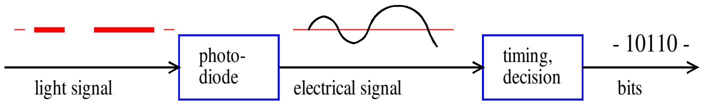
Optical Fibre continued…



- At receiver, convert back to electrical signal
  - then decision: light or no light?
- Main advantages:
  - huge bandwidth available
    - speed limited by electronic circuits each end…
  - low attenuation – good for long distances
  - immune to most interference
- Main disadvantage is cost:
  - cable, installation, electrical/optical conversion

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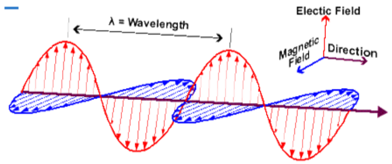
Physical Medium – Space



- Un-guided electromagnetic waves
  - electric and magnetic field
  - propagating together
  - sustaining each other…
- Sometimes at optical frequencies
  - e.g. TV remote control
- More often at radio frequencies
- Wave is modulated to carry information
  - change amplitude, frequency, phase…

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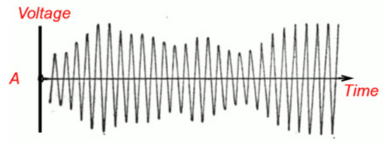
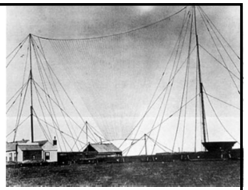
Radio Developments





1887 – radio waves demonstrated, Heinrich Hertz
- predicted in 1864 by James Clerk Maxwell

1894-5 – telegraph signals by radio
- *wireless telegraphy* Oliver Lodge, Guglielmo Marconi
- radio waves switched on/off to carry Morse code

1901 – transatlantic radio transmission, Marconi

1905 – transmit speech, music using radio waves
- *wireless telephony* Reginald Fessenden
- analogue signals, *modulation* of radio wave

1920s – radio broadcasting, transatlantic telephony

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Guglielmo Marconi (1874 – 1937)

- Developed long-distance "wireless" telegraphy
  - technically and commercially
  - Nobel Prize in Physics in 1909 (with K F Braun)
- First commercial trans-Atlantic service 1907
  - Clifden to Nova Scotia

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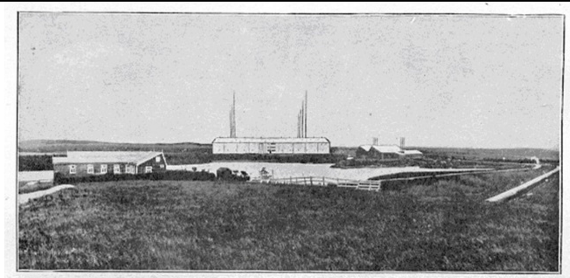
Clifden



[By permission of Marconi's Wireless Telegraph Co., Ltd.

Fig. 20.—View of the Condenser-house and Antenna of Marconi's Transatlantic Radiotelegraphic Station at Clifden, Ireland.

- Derrygimla bog, 120 hectare site
  - opened 1907, first message to Nova Scotia
  - tall masts supporting long antenna (aerial) wires
  - 150 permanent staff, 200 seasonal
  - electricity generators, narrow-gauge railway
  - destroyed 1922 – casualty of war

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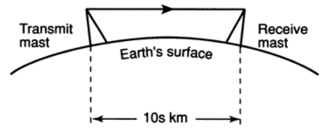
Propagation of Radio Waves



- Applies to all electromagnetic waves
  - propagating in free space (not guided)
- Above 300 MHz…
  - e.g. most modern communication systems
  - assume straight-line propagation, like light
  - called "line of sight" propagation
- On earth, range limited ~10s of km
  - curve of earth, mountains, etc.
    - range depends on terrain, height of antennas…
  - buildings attenuate, flat surfaces reflect…
    - *multi-path* propagation in urban environment

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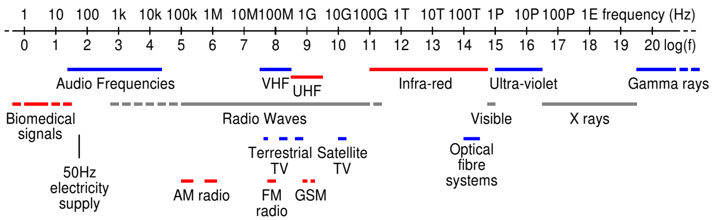
Frequency Spectrum



- Early work at low(ish) frequencies
  - long-wave band – now LF, 30 kHz to 300 kHz
  - medium-wave band – now MF, 300 kHz to 3 MHz
  - short-wave band – now HF, 3 MHz to 30 MHz
  - added VHF, 30 MHz to 300 MHz
  - then UHF, 300 MHz to 3 GHz . . .

Regulation www.comreg.ie

- Radio frequency spectrum is scarce resource
  - every transmission affects everyone
  - waves don't recognise international borders
- Governments control transmissions
  - allocate parts of frequency spectrum to users
    - usually pay annual fee for permission to transmit
    - may re-allocate same frequency in different area
- International agreements
  - different *bands* of frequency assigned to different applications
    - e.g. TV broadcast, mobile phone, air traffic control
  - a few bands left un-regulated – ISM bands
    - anyone can transmit, with some limit on power
    - no guarantee of protection from interference…

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Antenna (Aerial)



- Needed to launch electromagnetic wave
  - transfer from cable into free space
  - also to recover it at receiver
- For efficiency, need large
  - dimensions significant fraction of wavelength
- Can be directional – focus beam one way
  - not always wanted…

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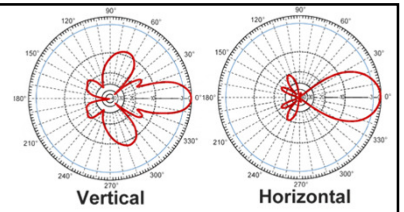
Antenna Properties



- Radiation pattern
- Beamwidth
  - angular width of main beam, to half-power points
- Gain, G (ratio, often in dB, or dBi)
  - improvement in power density, in desired direction
    - relative to hypothetical *isotropic radiator* – uniform pattern
- Aperture or effective aperture, A (m^2)
  - collecting area of antenna
- Reciprocity – antenna properties same for tx or rx
  - so receive antenna has gain, beamwidth
    - although easier to think about when transmitting…

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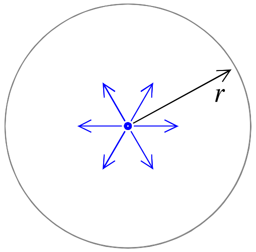
Power Density



- Power per unit area
- For isotropic radiator (hypothetical)
  - transmit power spread uniformly in 3 dimensions
  - imagine illuminating inside surface of sphere…
  - at distance r, surface area $4\pi r^2$
  - so transmit power P_{tx} gives power density (at distance r) $D = \dfrac{P_{tx}}{4\pi r^2}$
- Real antenna, gain G_{tx}
  - power density in desired direction $D = \dfrac{P_{tx} G_{tx}}{4\pi r^2}$
  - increased by gain of antenna
    - at expense of other directions…

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Received Power

- Power density at receiver $D_{rx} = \dfrac{P_{tx} G_{tx}}{4\pi r^2}$
  - falls with square of distance
- Received power
  - power density at receiver × aperture of receive antenna $P_{rx} = D_{rx} A_{rx}$
  - fundamental equation: $P_{rx} = \dfrac{P_{tx} G_{tx} A_{rx}}{4\pi r^2}$
- Notes on received power:
  - independent of frequency (but G_{tx} might not be)
  - falls as square of distance, in free space
    - no obstructions or reflections…
  - analysis not valid close to transmit antenna

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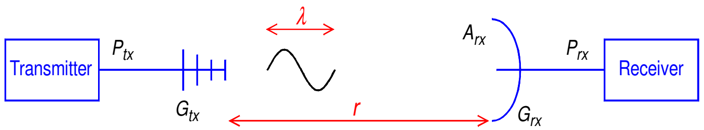
Power Calculation



- Often work with gain of receive antenna
  - related to aperture: $G_{rx} = \dfrac{4\pi A_{rx}}{\lambda^2}$
  - where $\lambda = \frac{c}{f}$ is wavelength in free space
- Then equation becomes: $P_{rx} = \dfrac{P_{tx} G_{tx} G_{rx} \lambda^2}{(4\pi)^2 r^2}$
  - also use $EIRP = P_{tx} G_{tx}$
    - *effective isotropic radiated power*
    - combines transmit power and antenna gain

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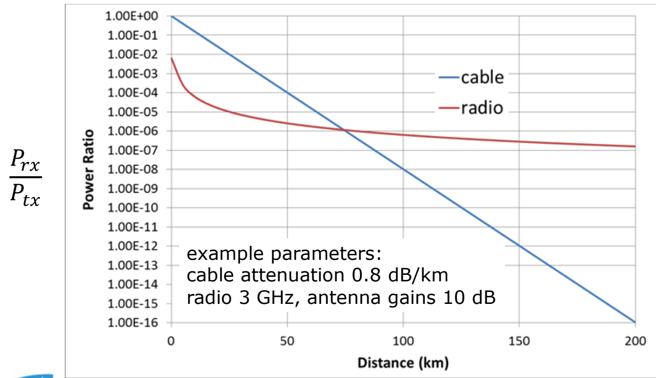
Cable v. Radio example



- radio waves (free space) $\frac{P_{rx}}{P_{tx}} = \frac{G_{tx} G_{rx} \lambda^2}{(4\pi)^2} r^{-2}$
- cable $\frac{P_{rx}}{P_{tx}} = \alpha^r$

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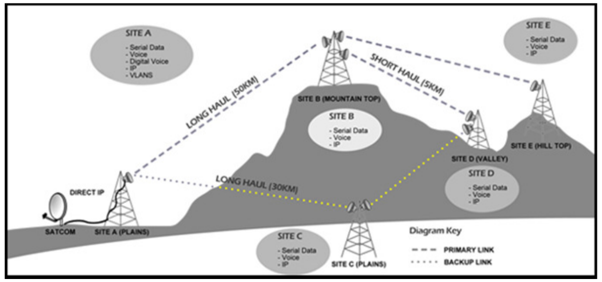
Long-distance Links on Earth



- Use "repeater" along the way (maybe many)
  - often on convenient hill-top…
  - receive, amplify, re-transmit on different freq.
  - Dublin – Cork might use 4 or 5 repeaters…
    - on hills, mountains, high buildings or high masts

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Examples

Satellite Communications

- Repeater in orbit
  - called *transponder*
  - satellite has many transponders, solar power
- Geostationary satellite – altitude 36 000 km
  - orbit synchronised with earth's rotation
  - easy to aim antenna, but very long paths
    - signals severely attenuated, long time delay
  - can cover large fraction of earth's surface
- Low-orbit satellite – 200 to 2000 km
  - moving relative to user on earth
  - but shorter path, stronger signals, less delay

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