Mobile Communications

Part VI- Propagation Characteristics

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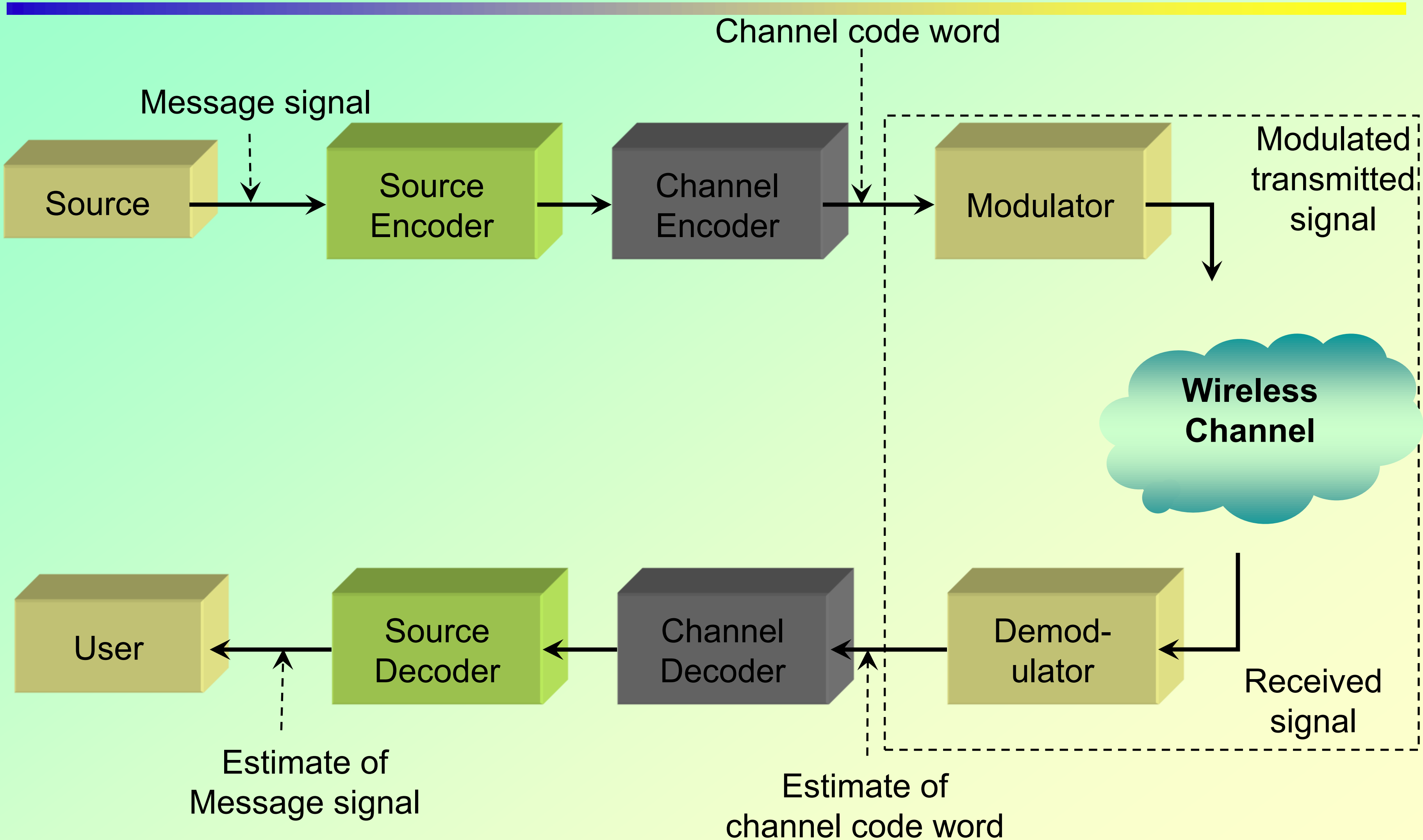
Contents

- Wireless communication systems
- Radiation from antenna
- Signal propagation
- Channel model
- Interference

Wireless Communications System



Basic Questions

Transmitter:

- What will happen if the transmitter
  - changes the transmit power ?
  - changes the frequency ?
  - operates at higher speed ?

Channel:
What will happen if we conduct this experiment in different types of environments?

Desert	Metro	Street	Indoor

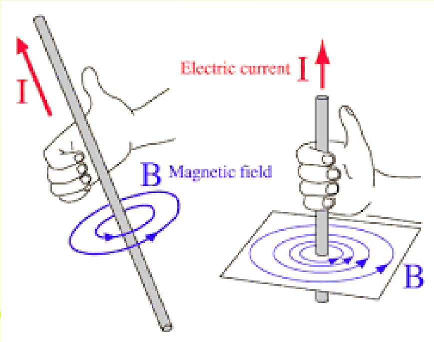
Receiver:

Q- What will happen if the receiver moves?

Antenna - Concept

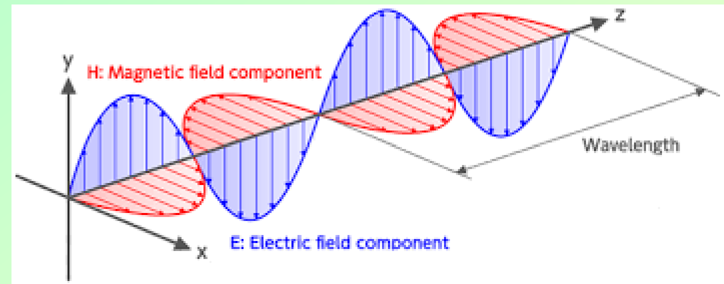
- **Type of antenna**
  - **Omnidirectional**
  - **Sector**
  - **Directional**
- **Aspect of antennas**
  - **Gain/signal spread**
  - **Reciprocity**
  - **Range**
  - **Mounting**

- **Signal is generated by electrons movement (i.e., oscillation) in a piece of metal (wire)**
- **Right-hand rule:**
  - Electrons moving in the direction of thumb is pointed, then a Magnetic field **H (or B)** is produced around the wire in the direction the fingers are pointed.
  - Oscillating current (AC signal) will generated oscillating **H**



Antenna - Concept

- **Speed of electromagnetic waves**



$$c = \frac{1}{\sqrt{\varepsilon_o \mu_o}} \approx 3.0 \times 10^8 \ \mathrm{m/s}$$

Where ε_o = 8.8542 $\times 10^{12}$ C^2s^2/kgm^3 Permittivity of vacuum
μ_o = $4\pi \times 10^{-7}$ $kgm/A^2s^2/kgm^3$ Permeability of vacuum

- **Electromagnetic waves**

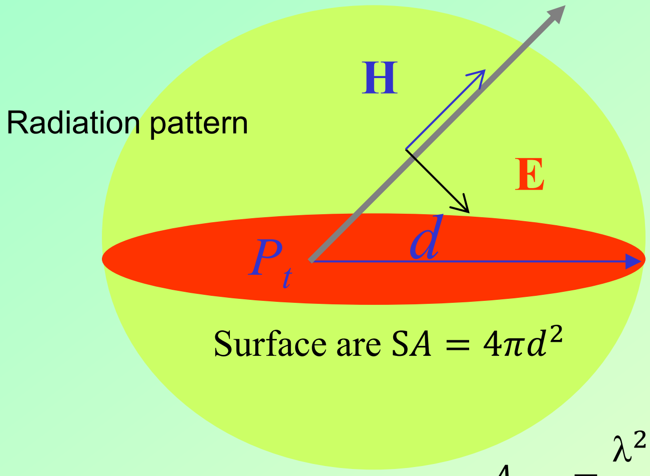
$$E = E_0 \sin(kz - wt); \text{ and } H = H_0 \sin(kz - wt)$$

Where $k = 2\pi/\lambda$

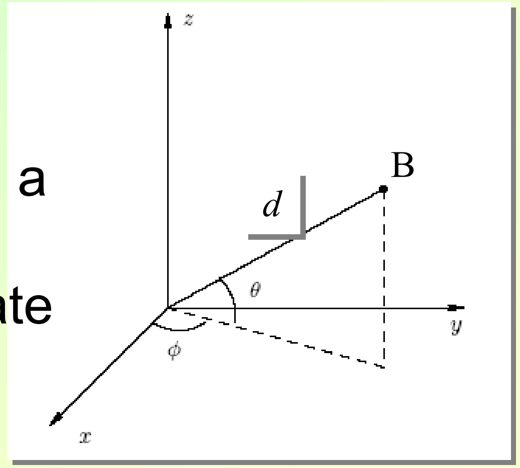
$$E = E_0 \sin[2\pi/\lambda(z - ct)]; \text{ and } H = H_0 \sin 2\pi/\lambda[(z - ct)]$$

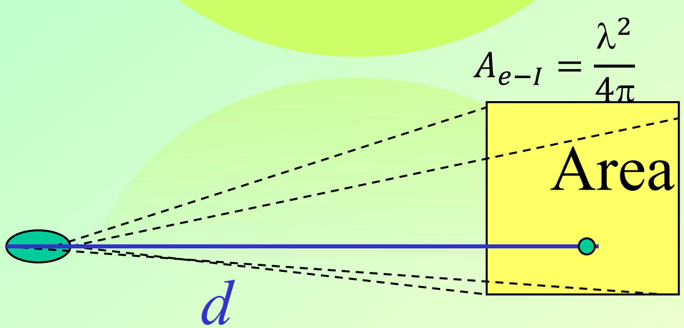
Antenna - Ideal

- Type of antenna: **Omnidirectional; Sector and directional**
- Isotropic antenna: In free space radiates power equally in all direction. Not realizable physically



The EM fields around a transmitting antenna
, i.e., a polar coordinate

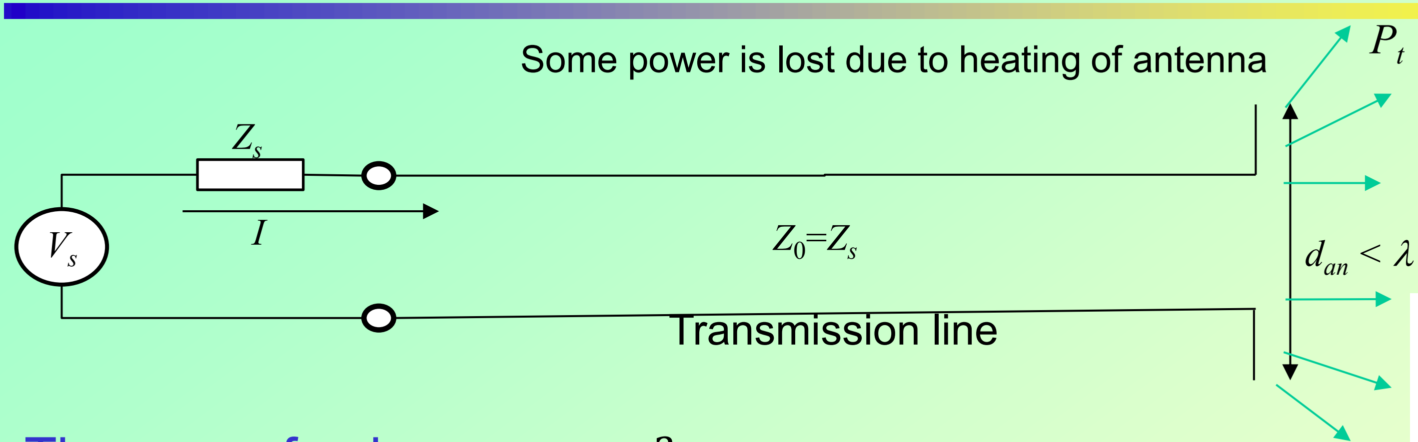


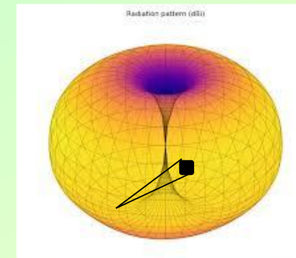


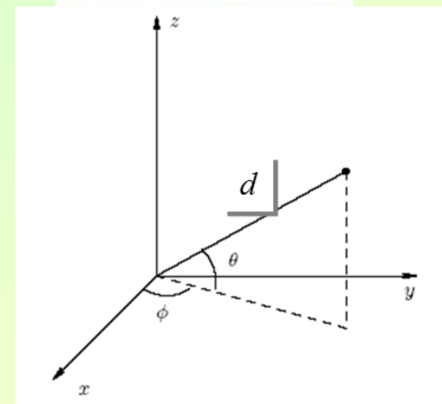
- d = distance directly away from the   antenna.
- ϕ = azimuth, or angle in the horizontal plane.
- θ = zenith, or angle above the horizon.

E.g., for 3 GHz, A_{e-I} = 8 cm^2

Antenna - *contd.*







- The area of ■ is: $\Delta A = d^2 \sin\theta\, \Delta\theta \Delta\emptyset$
- The solid angle: $\delta\Omega = \sin\theta\, \Delta\theta\Delta\emptyset$ i.e., Normalised to d^2.
- The time average power from antenna:

$$\underset{S}{\rightarrow} = \underset{E}{\rightarrow} \times \underset{H}{\rightarrow}$$

X - Cross-product

$$\underset{S_{\text{ave}}}{\longrightarrow} = \int_0^T \underset{E}{\rightarrow} \times \underset{H}{\rightarrow} \partial t$$

Impedance of the free space

$$S(d,\theta,\emptyset) = \sqrt{\frac{\mu_o}{\varepsilon_o}} \frac{(I \quad d_{an} k)^2}{32(\pi d)^2} \sin^2\theta$$

Antenna - *contd.*

Total power radiated:

$$P_t = \int_{\emptyset=0}^{2\pi} \int_{\theta=0}^{\pi} S(d,\theta,\emptyset)\Delta A$$

$$P_t = d^2 \int_{\emptyset=0}^{2\pi} \int_{\theta=0}^{\pi} S(d,\theta,\emptyset)\sin\theta\Delta\theta\Delta\emptyset$$

Adding up all the small areas that make out the sphere.

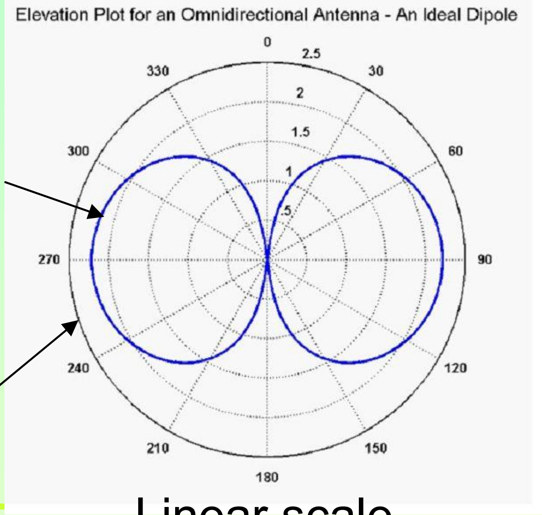
Normalised radiation intensity:

$$F(\theta,\emptyset) = \frac{S(d,\theta,\emptyset)}{\max\{S(d,\theta,\emptyset)\}} = \sin^2\theta$$

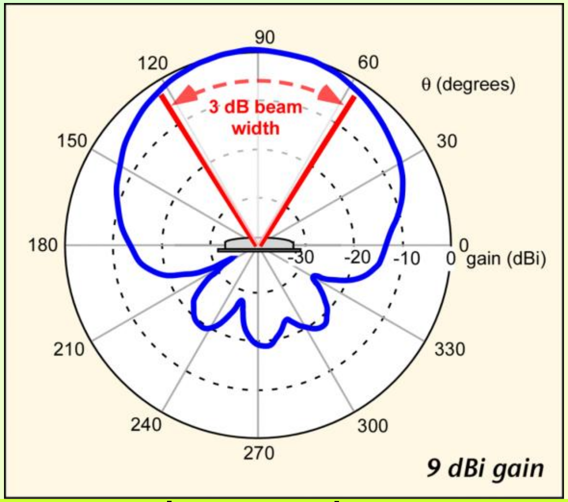
Note, Max of S is at $\theta = 90^o$.

$S(\theta)$

$S(\phi)$



Linear scale



Log scale

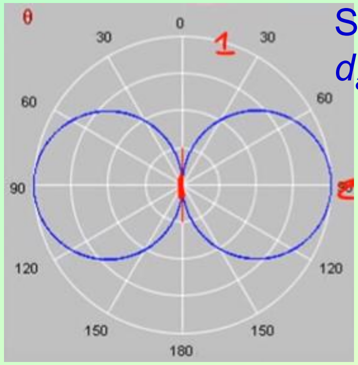
Less sensitive to small changes

Antenna - *contd.*

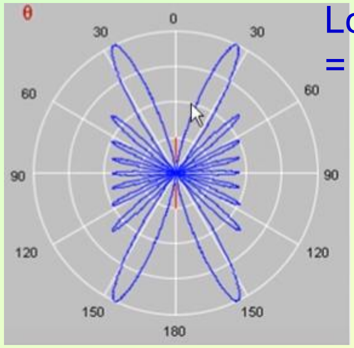
Directivity of an antenna: Indication of the antenna radiation directionality:

$$D_{an} = \frac{\max\{F(\theta,\emptyset)\}}{\text{mean}\,\{F(\theta,\emptyset)\}} = \frac{\max\{S(d,\theta,\emptyset)\}}{4\pi d^2/P_t}\sin^2\theta$$

Antenna with low D_{an} (i.e., 1 is the lowest) radiates equally in all directions



Short dipole, $d_{an} << \lambda$, $D = 1.5$



Long dipole, $d_{an} = 9\,\lambda$, $D = 6.1$

The **radiation efficiency** defines how much of the power that drives the antenna actually radiates into the space:

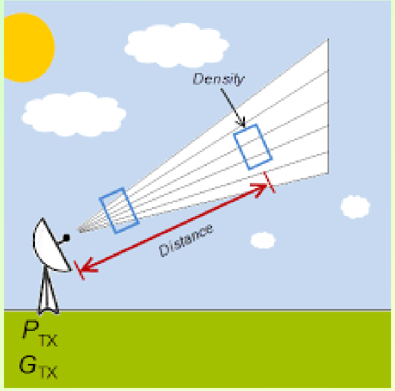
$$\xi = \frac{P_t}{P_{total}}$$

where P_t is the transmit (radiated) power and P_{total} is the total power derived with

Antenna - *contd.*

- The **power density** of an ideal loss-less antenna at a distance *d* away from the transmitting antenna is:

$$P_a = \frac{P_t}{4\pi d^2} \quad \text{W/m}^2$$



For a directive antenna the power density

$$P_a = \frac{P_t G_t}{4\pi d^2} \quad \text{W/m}^2$$

Note: the area is for a sphere.

- P_t is the transmit power and $G_t = \xi D_{an}$ is the transmitting antenna gain in dB – This is relative to a transmission link with no antennas
- The product $P_t G_t$: **Equivalent Isotropic Radiation Power (EIRP)**

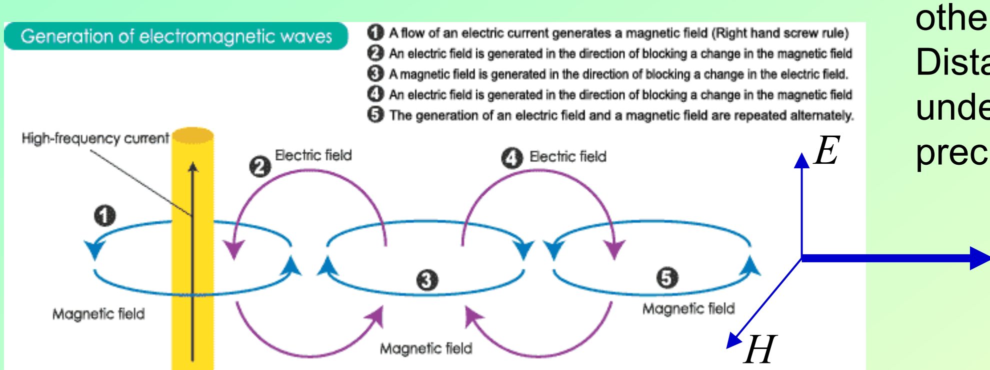
ERIP is the power fed to a perfect isotropic antenna to get the same output power of the practical antenna.

Antenna - *contd.*

- Strength of signal - defined in terms of its **Electric Field Intensity** *E (V/m)* or **Magnetic Intensity** *H* (*A/m*), because it is easier to measure it.

Note:

- Direction of E field defines the polarization of the wave.
- At a sufficiently large distance from the transmitting antenna, E and H field strength are proportional to each other. "Sufficiently large" means more than 4λ. Distances from λ/2π to 4λ give good results, though under certain circumstances the values may not be too precise.



$$P_a = E.H$$

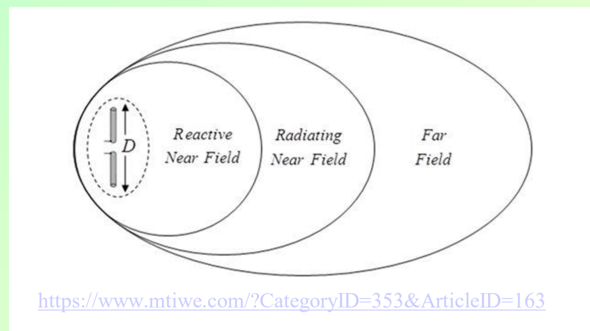
where R_m is the impedance of the medium. For free space R_m = 377 Ohms.

$$E^2 = \frac{P_t R_m}{4\pi d^2} \quad and \quad E = \sqrt{\frac{P_t R_m}{4\pi d^2}}$$

V/m

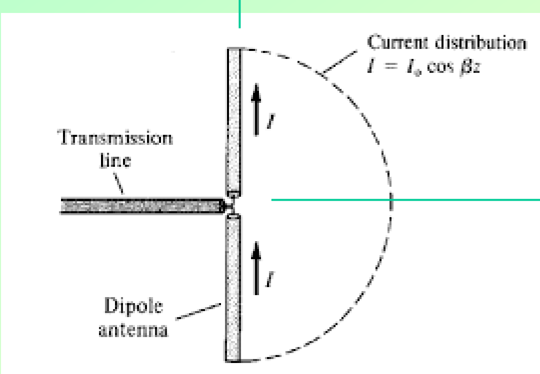
Antenna - Real

- Not isotropic radiators, but always have directive effects (vertically and/or horizontally)
- A well defined radiation pattern measured around an antenna
- Patterns are visualised by drawing the set of constant-intensity surfaces



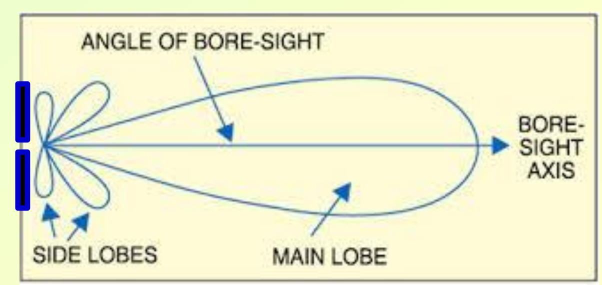
Rx

Minimum or no radiation



Rx

Maximum radiation

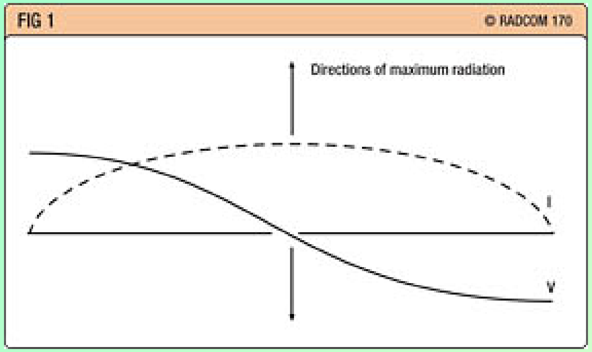


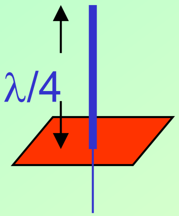
Radiation pattern (due to interference)

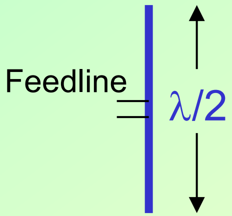
Antenna – Real - Simple Dipoles

- Not isotropic radiators, e.g., dipoles with lengths $\lambda/4$ on car roofs or $\lambda/2$ as Hertzian dipole

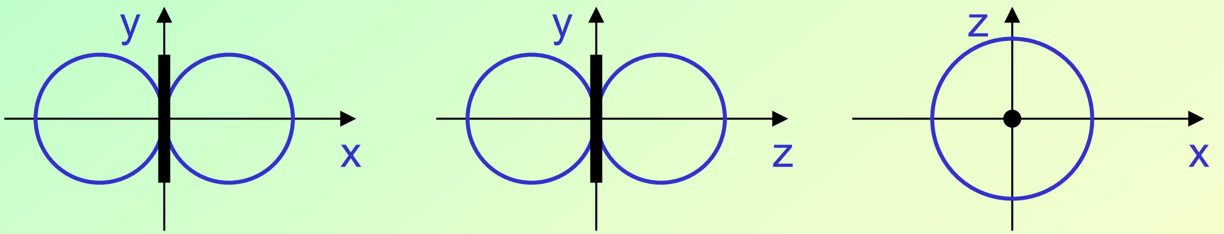
Largest dimension of the antenna $L_a = \lambda/2$







$$A_{e-R} = \frac{\lambda^2 G}{4\pi}$$



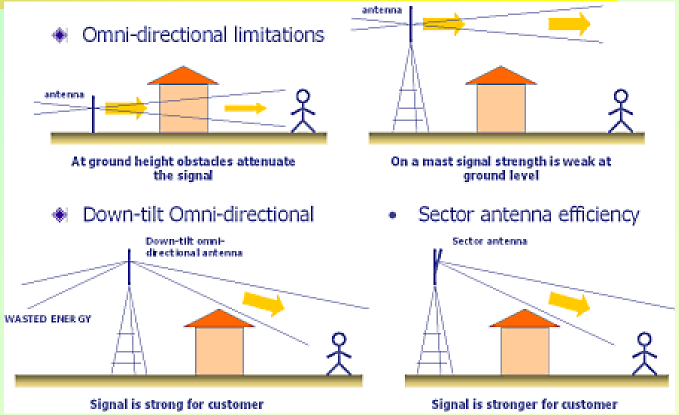
side view (xy-plane) side view (yz-plane) top view (xz-plane)

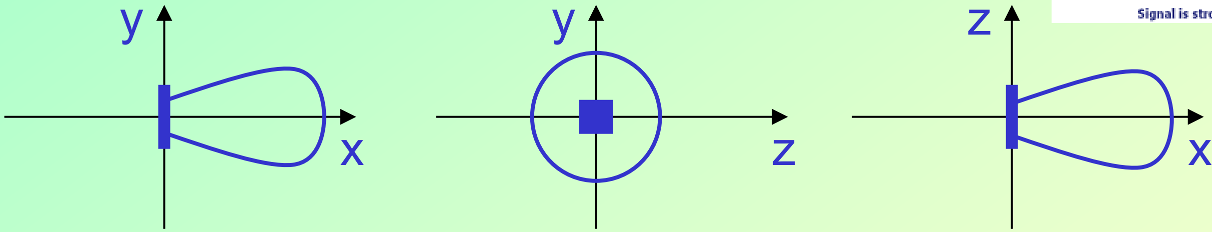
simple dipole

- Example: Radiation pattern of a simple Hertzian dipole shape of antenna is proportional to the wavelength

Antenna – Real - Sdirected and Sectorized

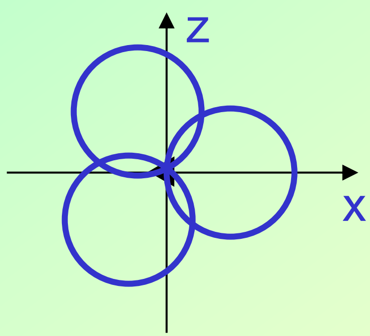
- Used for microwave or base stations for mobile phones (e.g., radio coverage of a valley)

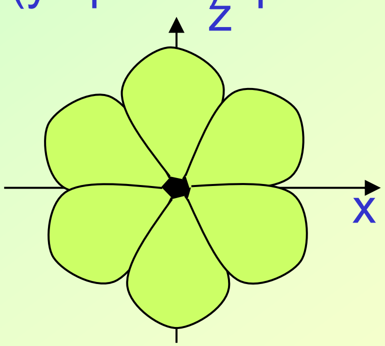




Directed

side view (xy-plane) side view (yz-plane) top view (xz-plane)



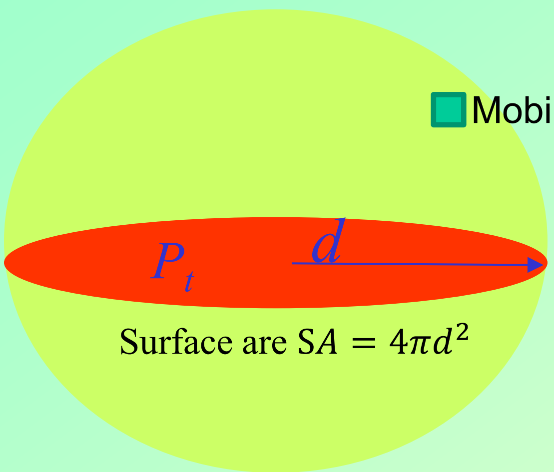


top view, 3 sector

top view, 6 sector

Sectorized

Received Antenna



- The size of antenna in the mobile device is:

$$A_{e-I} = \frac{\lambda^2}{4\pi}$$

E.g., for 3 GHz, A_{e-I} = 8 cm^2

The area ratio $= \frac{\lambda^2/_{4\pi}}{4\pi d^2} = \left(\frac{\lambda}{4\pi}\right)^2 \cdot \frac{1}{d^2}$

The channel gain $= 10\log_{10} = \underbrace{\left(\frac{\lambda}{4\pi}\right)^2}_{\text{Constant}} \cdot \frac{1}{d^2}$

- So, the mobile device will receive a portion of the P_t.
- **Therefore, what matters is the received power P_r against the noise. I.e. SNR.**

Receiving Antenna - *contd.*

- The receiving antenna is characterized by its effective aperture A_e, which describes how well an antenna can pick up power from an incoming electromagnetic wave
- The effective aperture A_e
  - for an ideal antenna is:

$$A_e = P_r / P_a \Rightarrow \qquad A_{e\text{-}I\text{-}Rx} = \lambda^2/4\pi$$

  - For a real antenna

$$A_{e\text{-}R\text{-}Rx} = G_r\lambda^2/4\pi$$

which is the equivalent power absorbing area of the antenna.

G_r is the receiving antenna gain and $\lambda = c/f$

And

$$E = \sqrt{\frac{P_r}{A_{e-Rx}} R_m}$$

Antenna - *contd.*

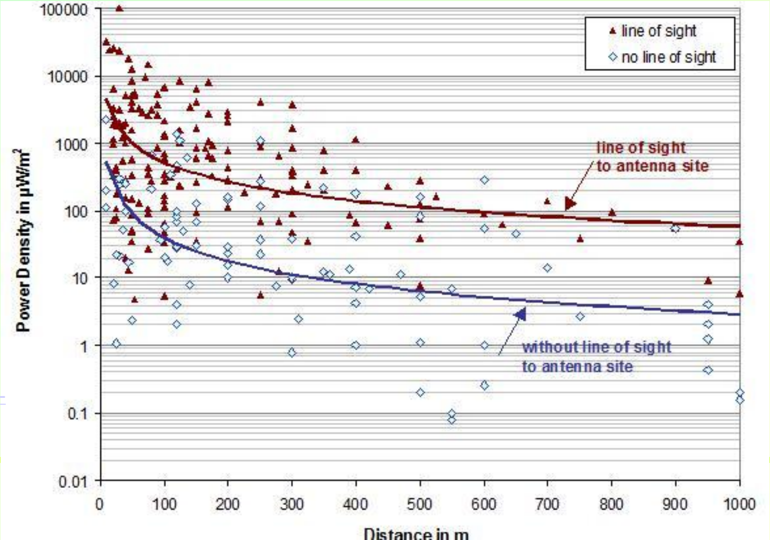
Example: A GSM base station about 100 m away from the wooden pole on the left.

Assume:

P_t = *20 W*, cable loss = *3 dB* and G_t = *18 dBi*,

The field strength at *100 m* distance can be estimated. *E = 1.4 V/m*, *H = 3.7 mA/m* and the $P_a = 5.0\ mW/m^2$.

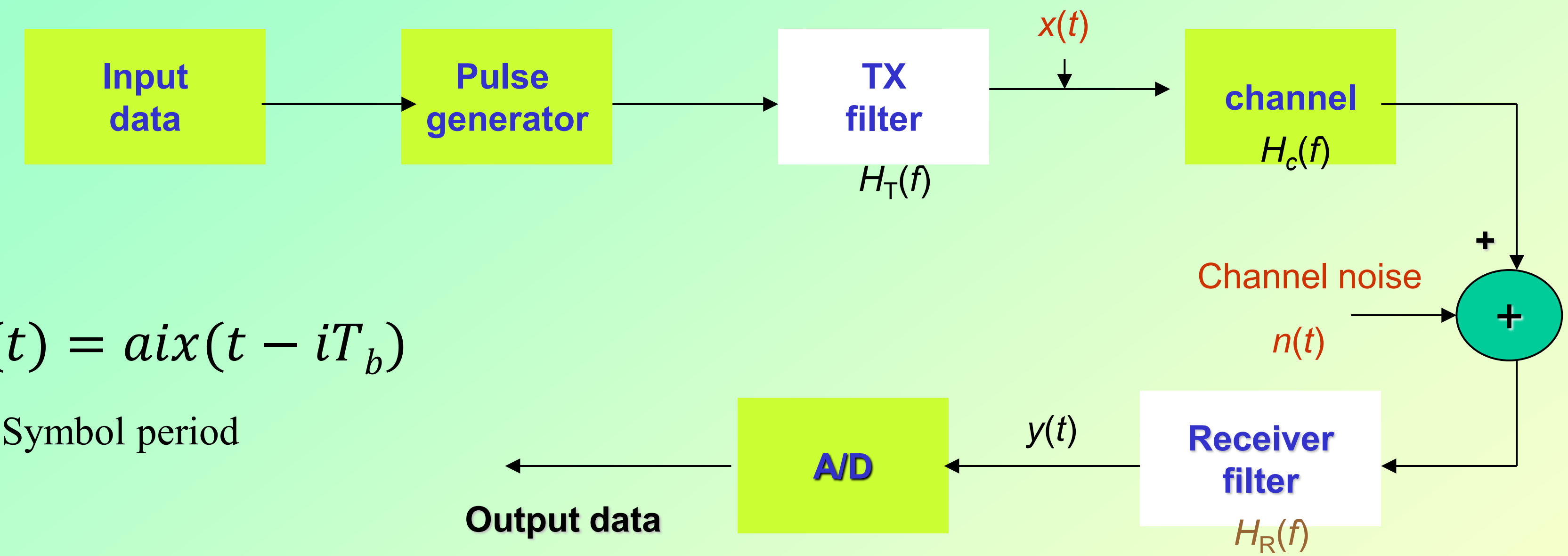
We also find the effective isotropic radiated power P_{EIRP} = *633 W.*



http://www.emfrf.com/rf-radiation-levels-from-cellular-towers/gsm-cellular-tower-base-station-power-density-levels2/

Signal Propagation
(Channel Models)

Basic Digital Communication System Model



$$x(t) = aix(t - iT_b)$$

T_b: Symbol period

$$y(t) = x(t) * h(t) + n\,(t) + i(t)$$
$$y(t) = x(t) * [h_T(t) * hc(t) * hR(t)] + n(t) + i(t)$$
$$y(t) = \sum_i \; A_i h_c(t - t_d - iT_b) + n\;\;(t)\;) + i(t)$$

Time varying channel with the time delay t_d (Just considering $h_c(t)$)

Noise

Interference

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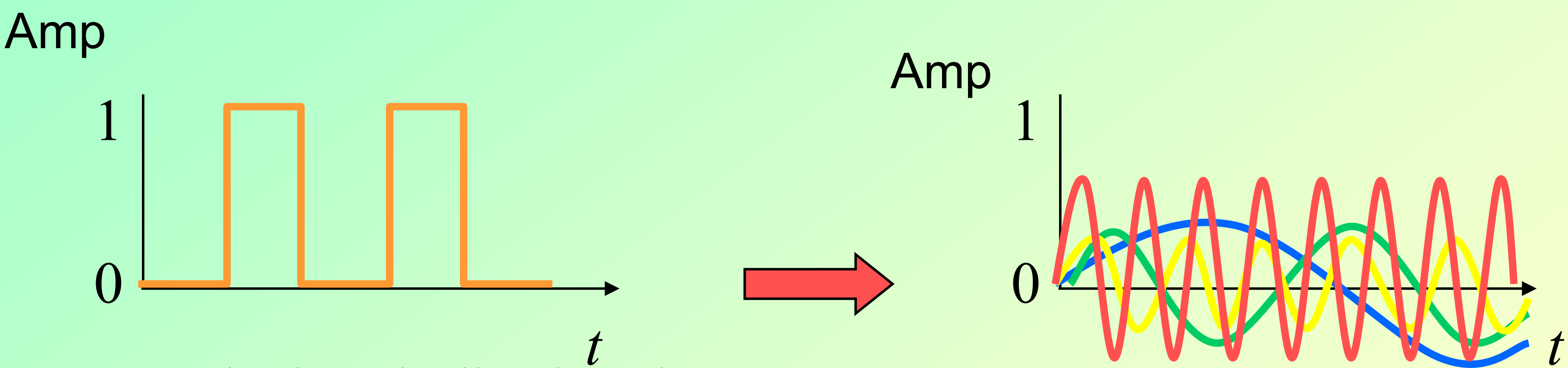
Fourier Representation of Periodic Signals

$$g(t) = \frac{1}{2}c + \sum_{n=1}^{\infty} a_n \sin(2\pi nft) + \sum_{n=1}^{\infty} b_n \cos(2\pi nft)$$

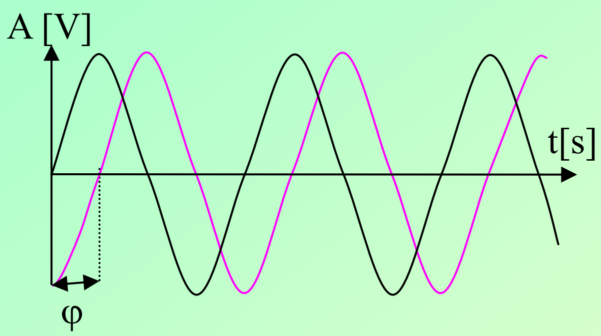


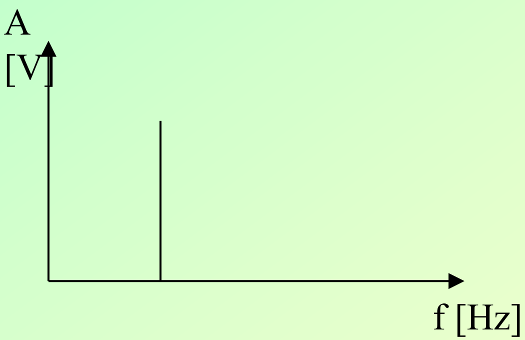
Ideal periodic signal

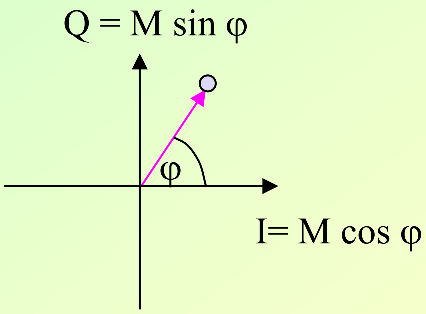
Real composition (based on harmonics)

Signals II

- Different representations of signals
  - amplitude (amplitude domain)
  - frequency spectrum (frequency domain)
  - phase state diagram (amplitude M and phase φ in polar coordinates)







- Composite signals mapped into frequency domain using Fourier transformation
- Digital signals need
  - infinite frequencies for perfect representation
  - modulation with a carrier frequency for transmission (->analog signal!)

Channel Models

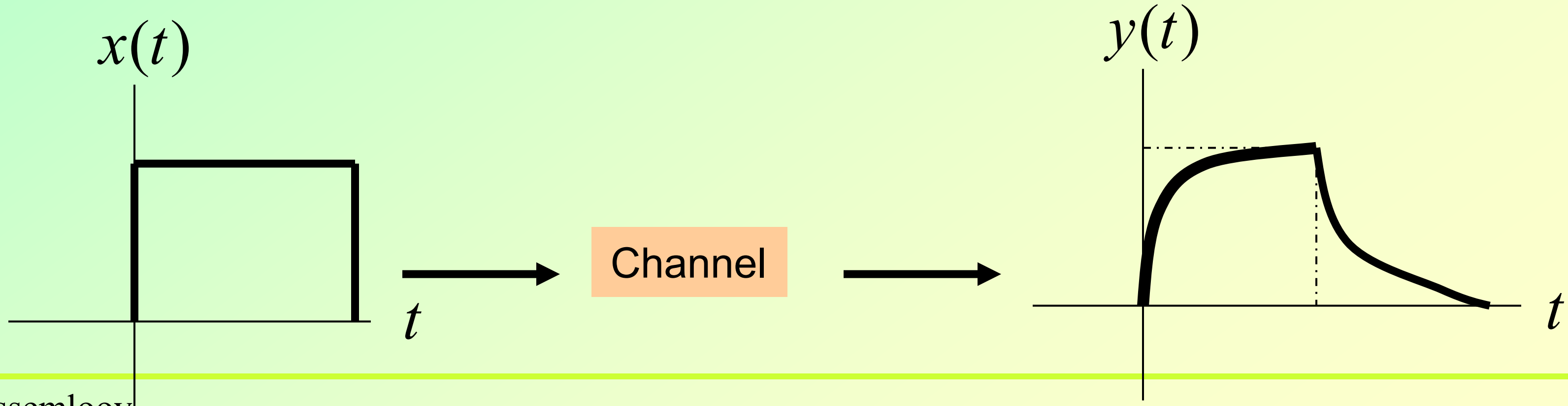
- High degree of variability (in time, space etc.)
- Large signal attenuation
- Non-stationary, unpredictable and random
  - Unlike wired channels it is highly dependent on the environment, time space etc.
- Modelling is done in a statistical fashion
- The location of the base station antenna has a significant effect on channel modelling
- Models are only an approximation of the actual signal propagation in the medium.
- Are used for:
  - performance analysis
  - simulations of mobile systems
  - measurements in a controlled environment, to guarantee repeatability and to avoid the expensive measurements in the field.

Channel Models - Classifications

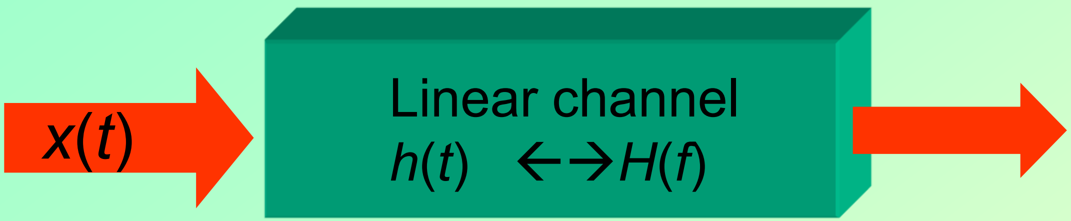
- System Model - *Deterministic*
- Propagation Model- *Deterministic*
  - Predicts the received signal strength at a distance from the transmitter
  - Derived using a combination of theoretical and empirical method.
- Stochastic Model - *Rayleigh channel*
- Semi-empirical (Practical +Theoretical) Models

Channel Models - Linear

- This can be modelled as an
  - ideal low pass filter
  - non-ideal low pass filter
    - This smears the transmitted signal x(*t*) in time causing the effect of a symbol to spread to adjacent symbols when a sequence of symbols are transmitted.
    - The resulting interference, intersymbol interference (ISI), degrades the error performance of the communication system.



Channel Models – Linear Time Varying



No Noise

Constant; Finite delay (due to channel)

$$y(t) = k\,x(t-t_d)$$

$$Y(f) = F[y(t)]$$
$$= k e^{-j\omega t_d} X(f)$$
$$= H(f)X(f)$$
$$where \quad H(f) = k e^{-j\omega t_d}$$

- Therefore for a linear channel:

$$|H(f)| = |k|, \arg H(f) = -2\pi f t_d$$

Amplitude distortion ($|k|$); Phase distortion ($-2\pi f t_d$)

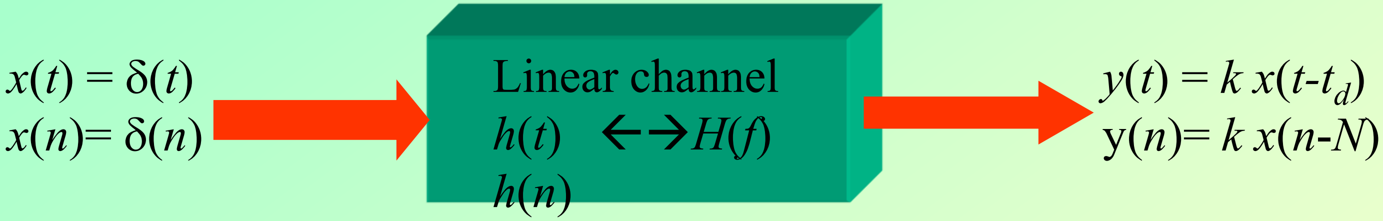
- The phase delay

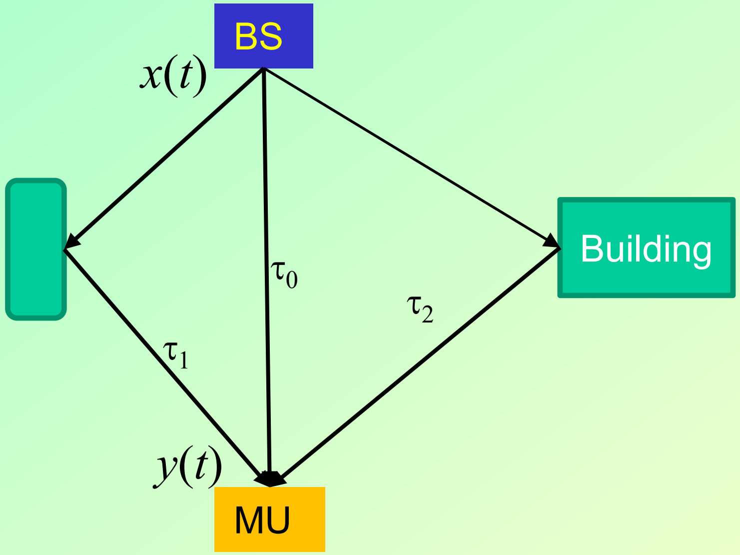
$$t_d(f) = -\arg H(f)/2\pi f$$

Describes the phase delayed experienced by each frequency component

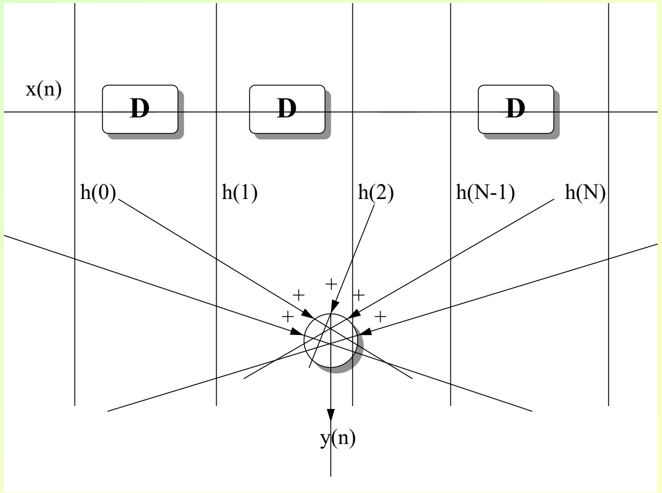
Channel Models – Multipath Link

- The mathematical model of the multipath can be presented using the method of the impulse response used for studying linear systems.





Channel is usually modeled as Tap-Delay-Line



Channel Models – Multipath Link

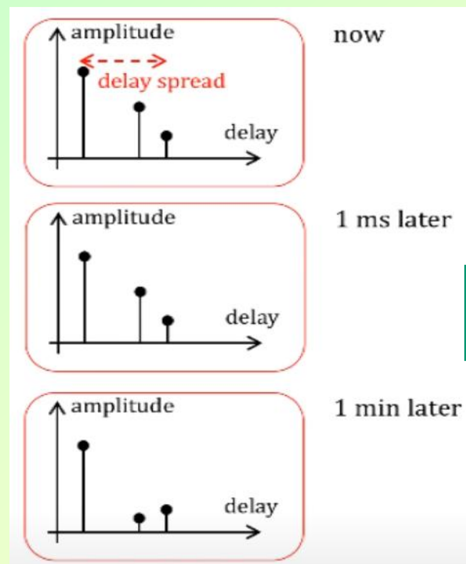
The channel impulse response

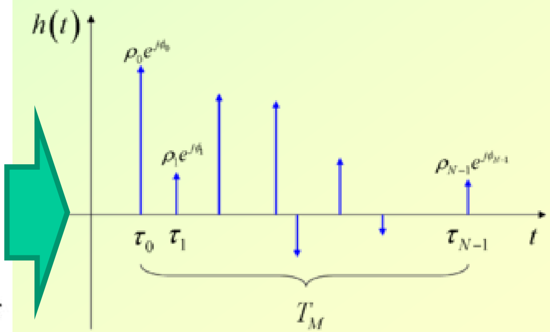
- Amplitude depends on the antenna pattern, environment
- Delay depends on environment → Delay spread
- Varies with time due to mobility of the Tx, Rx, changes in the environment → Coherence time

}
- Path loss
- Shadowing
- Multipath

So real base-band signal = Superposition of different path:

$$h_{BB}(t,\tau) = \sum_{i=0}^{N-1} A_i(t)\delta(\tau - \tau_i(t))$$



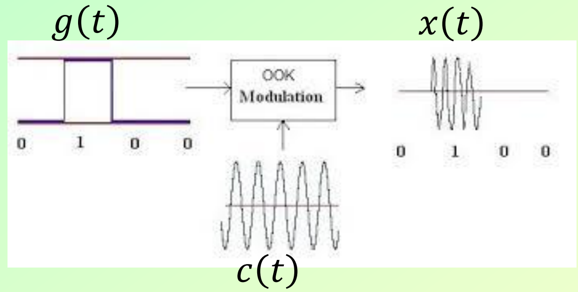


And complex pass-band signal with the carrier frequency f_c:

$$h_{PB}(t,\tau) = \sum_{i=0}^{N-1} \underbrace{A_i(t)e^{-j2\pi f_c \tau_i(t)}}_{\text{Complex number, which changes rapidly}} \delta(\tau - \tau_i(t))$$

Channel Models – Multipath Link

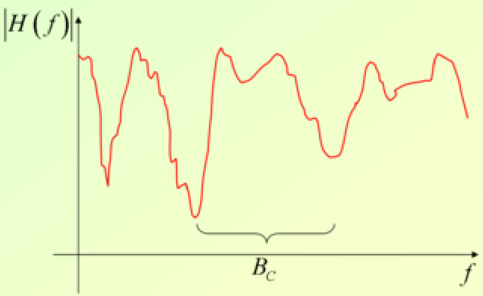
- Baseband signal: $g(t) = \sum_{k=-\infty}^{+\infty} a_k p(t - kT_b)$



- Passband signal: $x(t) = \mathrm{Re}\left\{g(t)e^{j2\pi f_c t}\right\}$

- Channel transfer function: $H(f) = \int_{-\infty}^{\infty} h(t)e^{-j2\pi ft}dt$

$$= \sum_{i=0}^{N-1} a_i e^{-j\theta_i} e^{-i2\pi f\tau_i}$$



- The received pass-band signal:

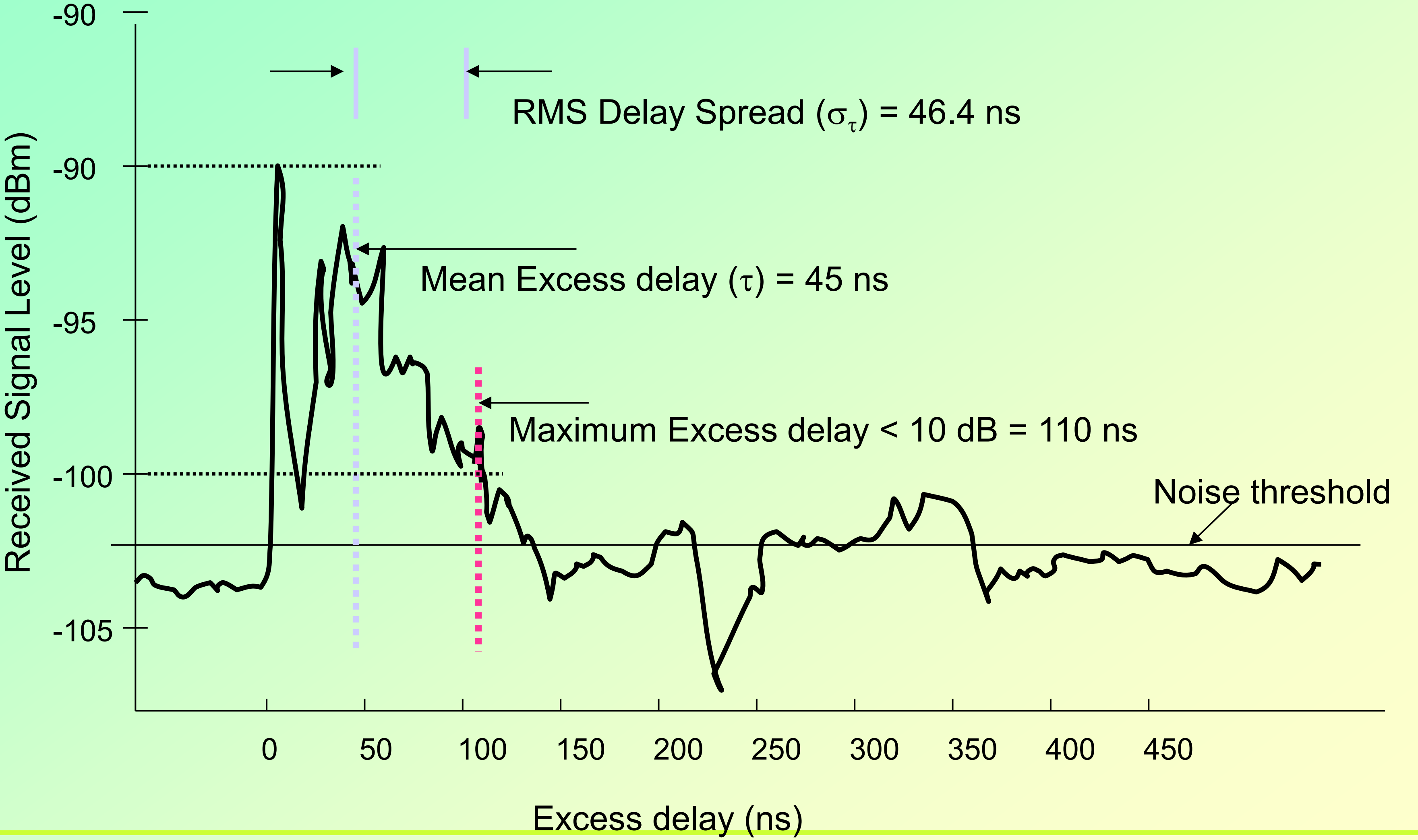
$$y(t) = x(t) * h(t) + n(t) + i(t)$$

$$y(t) = \mathrm{Re}\left\{(g(t) * h(t))e^{-j2\pi f_c(t)}\right\} + n(t) + i(t)$$

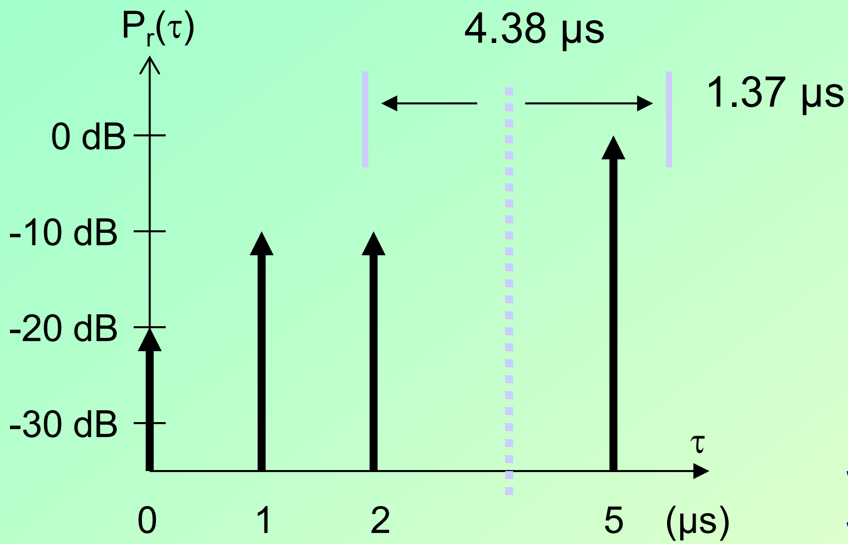
- The received pass-band signal for a perfect channel (i.e., *h*(*t*) =1:

$$y(t) = \sum_{i}^{N-1} a_i(t)x(-\tau_i(t))$$

Power Delay Profile



Power Delay Spread - Example



Indoor	$10-50\ n\sec$
Suburbs	$2\times 10^{-1}-2\ \mu\sec$
Urban	$1-3\ \mu\sec$
Hilly	3-10 $\mu\sec$

Signal bandwidth for Analog Cellular = 30 KHz
Signal bandwidth for GSM = 200 KHz

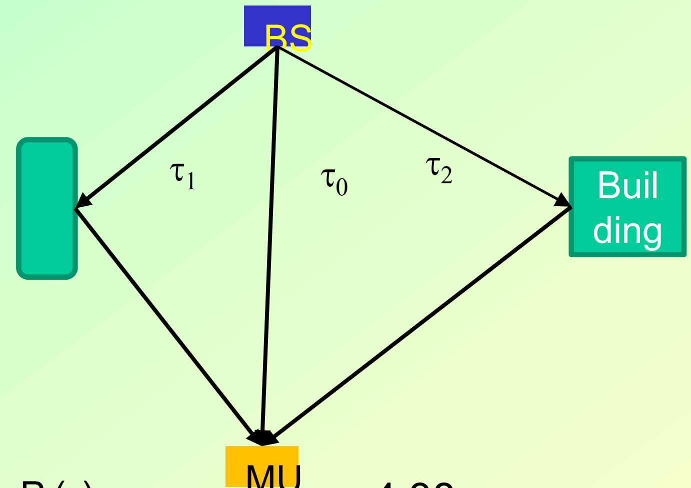
$$\bar{\tau}=\frac{(1)(5)+(0.1)(1)+(0.1)(2)+(0.01)(0)}{[0.01+0.1+0.1+1]}=4.38\mu s$$

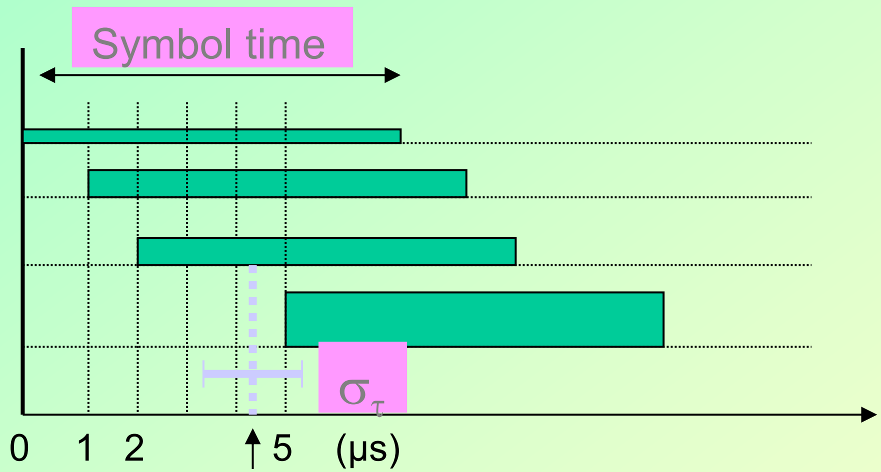
$$\bar{\tau^2}=\frac{(1)(5)^2+(0.1)(1)^2+(0.1)(2)^2+(0.01)(0)^2}{[0.01+0.1+0.1+1]}=21.07\mu s^2$$

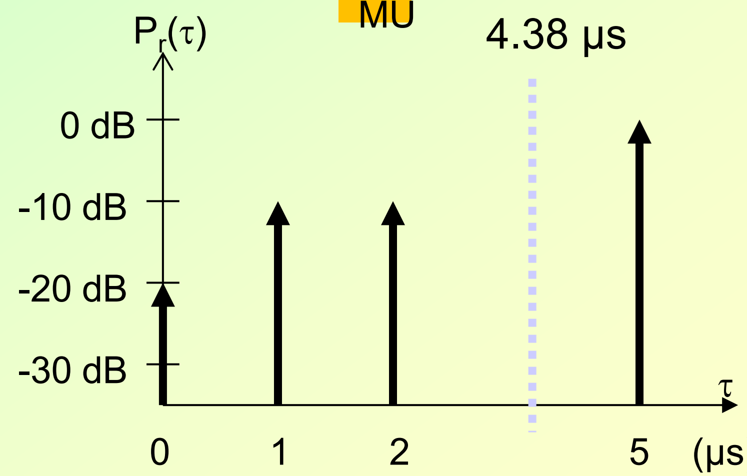
$$\sigma_\tau=\sqrt{21.07-(4.38)^2}=1.37\mu s \qquad (50\%-coherence)B_c\approx\frac{1}{5.\sigma_\tau}=146kHz$$

Inter-symbol interference (ISI)

- Channel is band limited in nature: Limited frequency response → unlimited time response
- Channel is multipath
- Two major ways to mitigate the effect of ISI.
  - Use bandlimited pulses (i.e., Nyquist pulses) which minimize the effect of ISI.
  - Equalization







Symbol time > 10* σ_τ --- No equalization required

Symbol time < 10* σ_τ --- Equalization will be required to deal with ISI

Multipath Delay

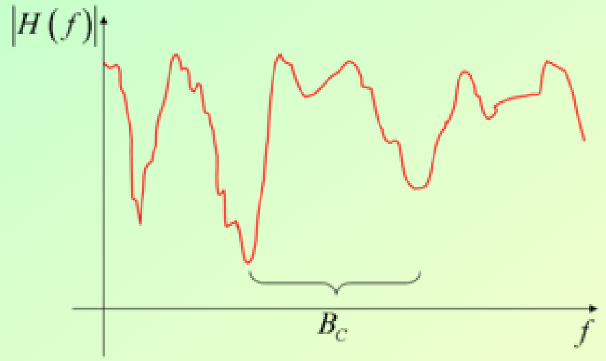
- LOS links - 52 meter, a large 753.5 ns excess delay
- NLOS excess delay over 423 meters extended to 1388.4 ns.
- Office building: RMS delay spread = 10-60 ns

	Cell size (km)	Max Delay Spread
Pico cell	0.1	300 nn
Micro cell	5	15 us
Macro cell	20	40 us

Channel Models – Multipath Link

- Channel transfer function

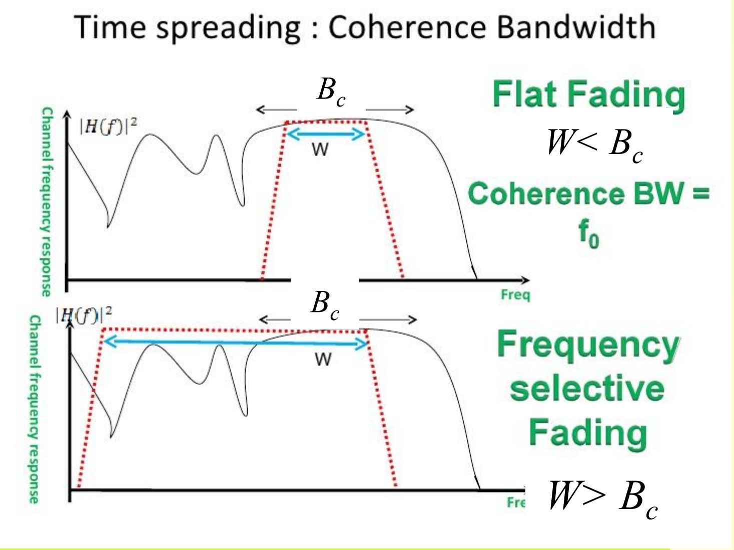
$$H(f) = \int_{-\infty}^{\infty} h(t) e^{-j2\pi f t} dt$$
$$= \sum_{i=0}^{N-1} a_i e^{-j\theta_i} e^{-i2\pi f \tau_i}$$



- Multipath Time
  - Mostly used to denote the severity of multipath conditions.
  - Defined as the time delay between the 1st and the last received impulses.

$$T_{MP} = \tau_{N-1} - \tau_0$$

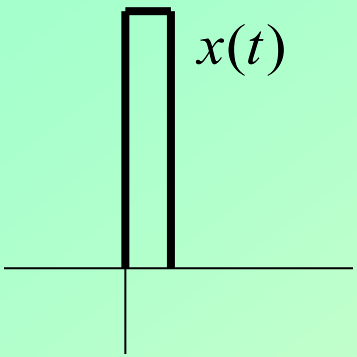
- Coherence bandwidth - is a statistical measurement of the range of frequencies over which the channel can be considered "flat", on average the distance between two notches



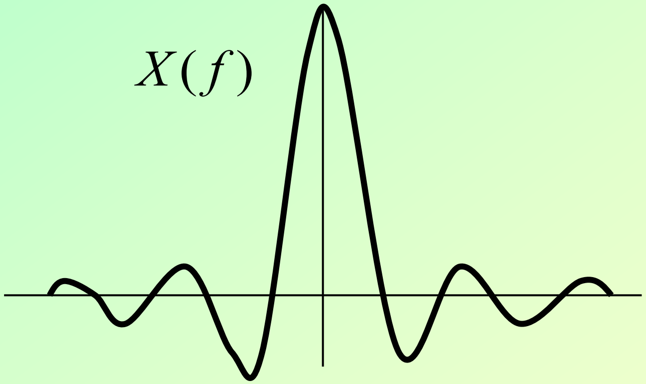
$$B_c \sim 1/T_{MP}$$

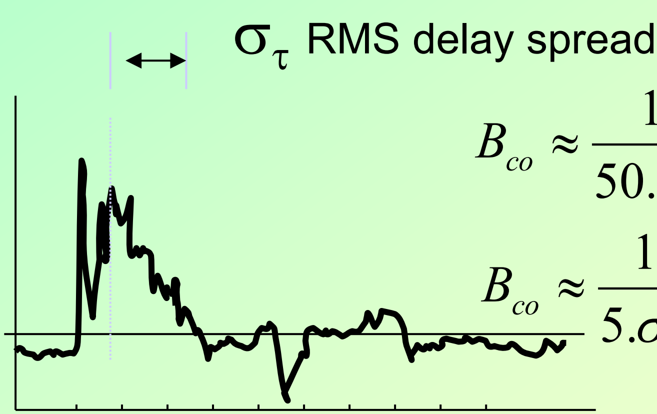
Channel Models – Multipath Link

Time domain view



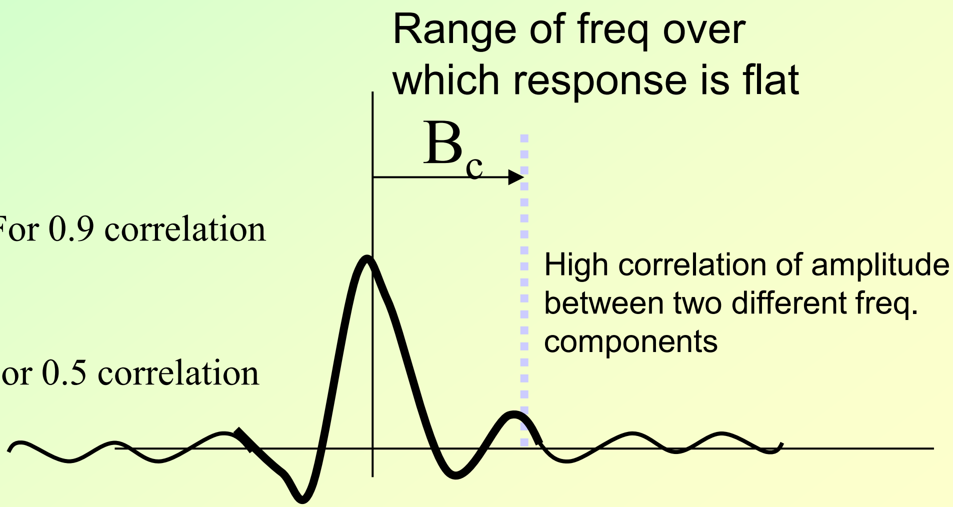
Freq. domain view





$B_{co} \approx \dfrac{1}{50.\sigma_\tau}$ For 0.9 correlation

$B_{co} \approx \dfrac{1}{5.\sigma_\tau}$ For 0.5 correlation



Summary

- Wireless communication systems
- Radiation from antenna
- Signal propagation
- Channel model
- Interference

- **Next lecture: Propagation Loss**