Basic broadband wireless communication

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Our programs:

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- Molecular physics
- Electronics
- Nuclear and atomic physics
- Theoretical physics
- Solid state physics
- Condensed matter physics
- Laser and optical communication
- Communication networks
- Software engineering
- Computer science

Objective of the lecture

- To refresh basic physics of Electro Magnetic fields and propagation of radio waves
- To better understand the operation of wireless (Microwave) LAN/ WAN and broadband wireless systems
- Highlight challenges in broadband and wireless communication

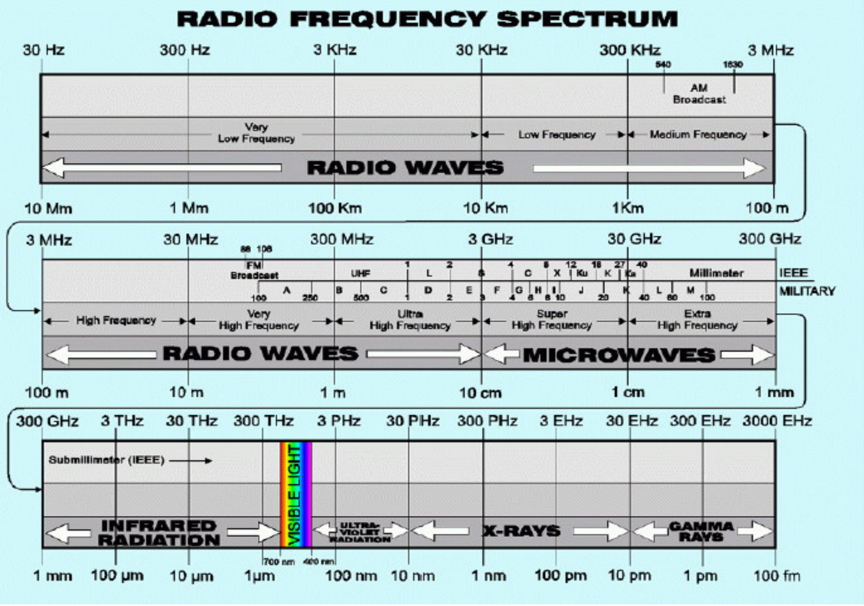
Areas of discussion:

- **Basic concepts in radio communication**
- **Technical challenges**
- **Modulation techniques**
- **Regulations (ITU , IEEE, FCC)**
- **Summary**

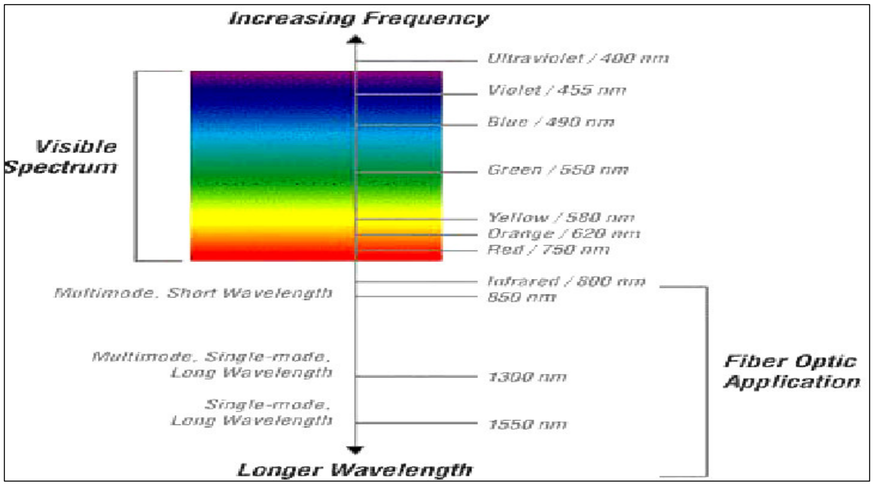
1. Basic concepts in Radio communication:

RF Technology defined:

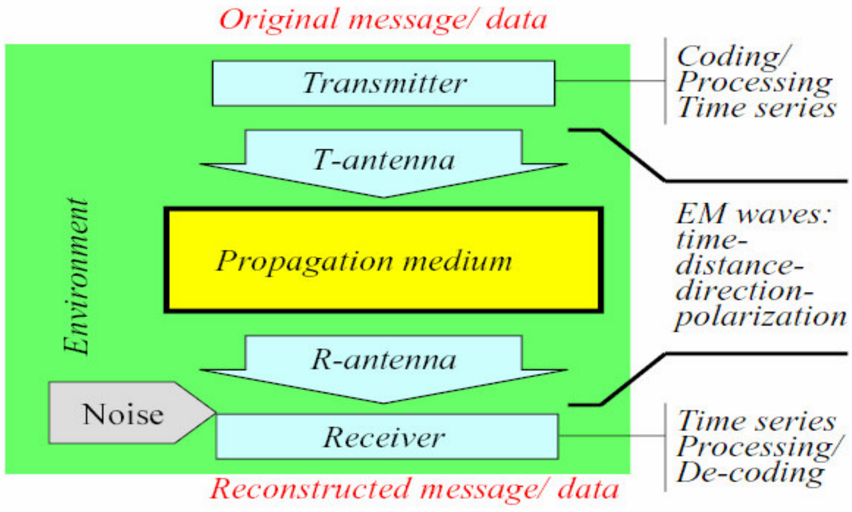
- The technology involving the generation, manipulation, transmission and reception of radio waves and the usage of the transmitted information is called RF technology.
- RF stands for Radio Frequency.
- Electromagnetic waves differ from mechanical waves in that they require no medium in which to propagate.
- Electromagnetic waves will even propagate through the vacuum of space



RF Spectrum



Radio Link model



Original message/ data

Transmitter

Coding/ Processing Time series

T-antenna

Environment

Propagation medium

EM waves: time-distance-direction-polarization

R-antenna

Noise

Receiver

Time series Processing/ De-coding

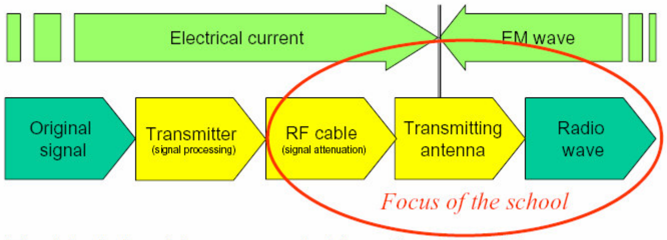
Reconstructed message/ data

1.1 Radio Signal

A radio signal is an electromagnetic wave that has the following quantifiable and measurable discrete parameters:

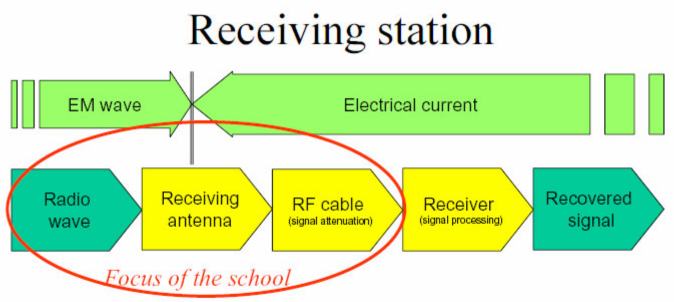
- Frequency,
- Wavelength,
- Bandwidth ,
- Amplitude/Power level.
- Signal to Noise Ratio (S/N),
- Carrier to Interference Ratio (C/I)
- Bit Error Ratio (BER
- Spectral Efficiency (B/T)

Transmitting station



Electrical signal is represented by a function of time.
Radio wave transmitted is represented by a function of time, distance, direction, and polarization.

Receiver



Radio wave received is represented by a function of time, distance, direction, and polarization that depends on signal-path environment
Electrical signal is represented by a function of time.

1.2 Frequency:

– The number of complete cycles per second in alternating current direction. The standard unit of frequency is the Hertz, abbreviated Hz.
  - Higher radio frequency means high free space losses and lower range for the radio signal
  - Lower radio frequency means less power losses and long range hence the rush for lower frequencies for IMT 2000 (400-700 MHz) and UMTS, TV, Cellular

1.3 Wavelength:

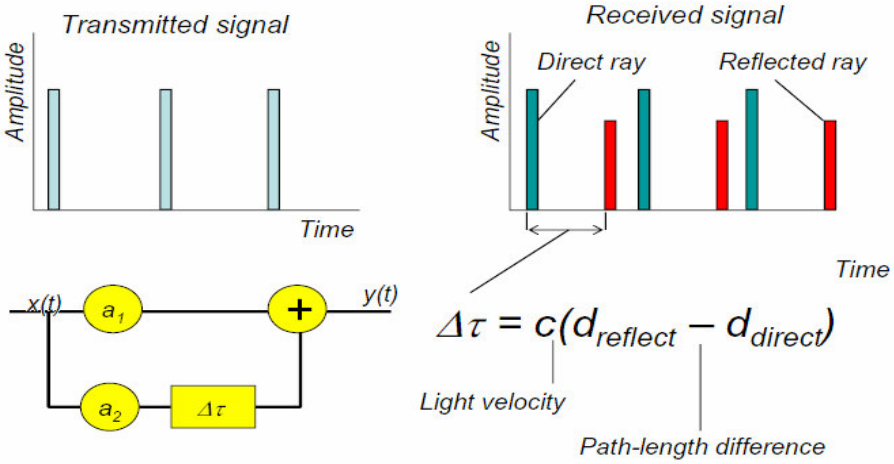
- The distance between identical points in the adjacent cycles of a waveform.
  - The wavelength can be calculated using the following equation:

    Wavelength (meter) = C / Frequency (MHz).

    C=3 x 10 exp 8 m/s is the speed of light in vacuum.
  - Wavelength is Important in antenna design
    - 1/2 wavelength dipole
    - ¼ wavelength dipole
    - Parabolic antennas

1.5 Radio signal transmission

Time Response, 2 Rays



$$\Delta\tau = c(d_{reflect} - d_{direct})$$

1.6 RF in time- space domains and Fourier response frequency_time display

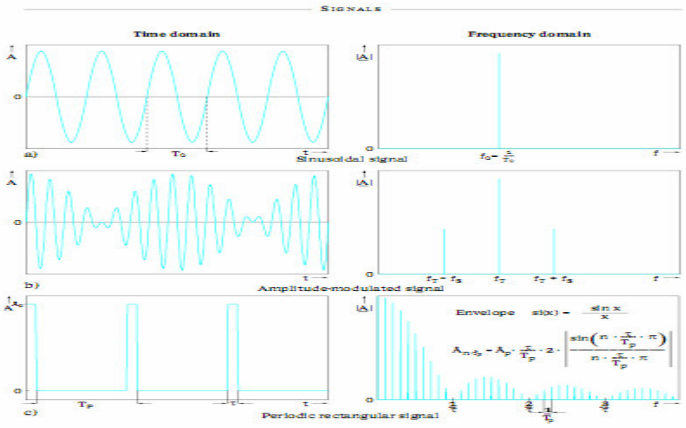


Fig. 2-5 *Periodic signals in time and frequency domain (magnitude spectra)*

1.7 Transmit Power (TX)

A radio has a certain level of radiated power that it generates at the RF interface.

- –The RF interface for our reference is the Antenna.

- This power is calculated as the amount of energy given across a defined bandwidth measured in dB or dBm.

1 dBm = 10 x log [Power in Watts / 0.001W]

1.8 Receiver Sensitivity (Rx)

- **Each radio has a Receiver Sensitivity**; Rx sensitivity is stated in dBm or W.
- **A Bit Error Rate (BER) of 10-5 (99.999%) is** normally used. In WiFi and WiMax equipments the receiver sensitivity is in the range of (–79 to –80) dBm.
  - » The noise level must be lower than the receiver sensitivity for successful communication.
  - » In WiFi equipments, the nominal RX sensitivity is (–90 to –96) dBm noise level.
  - » Noise is any unwanted signal arriving at a receiver.

1.9 Radiated Power (RF Power)

- In a wireless system, Antennas are used to convert electrical waves into electromagnetic waves for propagation
- Antennas also amplify the RF signal before transmitting to the receiver.
- The actual energy radiated by an antenna is called:

Effective Isotropic Radiated Power (EIRP)

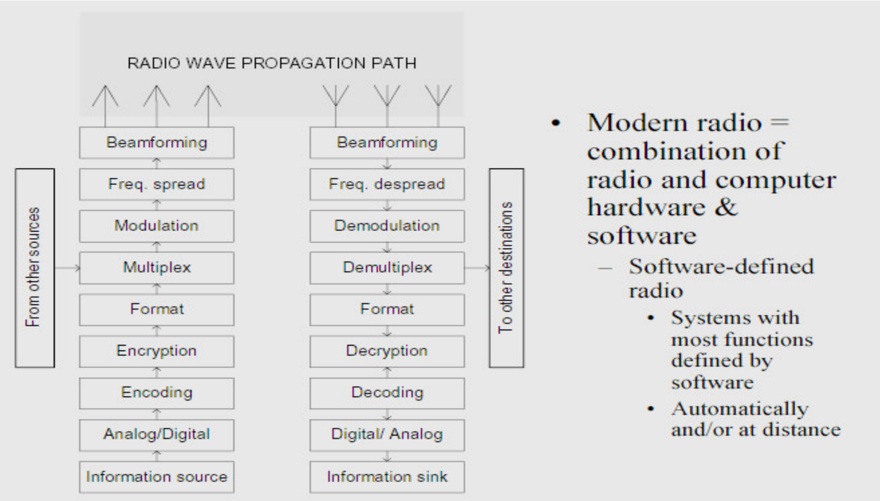
- **The amount of EIRP is controlled by the regulator in each country and by ITU-R standards.**

1.10 Antenna gain GA

The amount of energy the antenna can ‘boost’ the transmit and received signal.

- An antenna amplifies RF signals both in the transmit and receive paths.
- GA depends on the design, materials used and on the geometry. Antenna gain is measured in dB:
- GA = 20 log (Pout/Pin) dB

Radio wave propagation path



- Modern radio = combination of radio and computer hardware & software
  - Software-defined radio
    - Systems with most functions defined by software
    - Automatically and/or at distance

2. Challenges in radio communication:

Noise sources:

- automobile, ignitions, Aircrafts, lightning, transients and thermal noise in the receiver itself.
- The ratio of the signal strength to the noise level is called the ***signal to-noise ratio* (SNR).**
- If SNR is high (the signal power is much greater than the noise) few errors will occur.- As the SNR reduces, the noise may cause errors.
- **The *bit error rate* (BER)** of a system indicates the quality of the link.
- Thermal noise can be modelled as ***Additive White Gaussian Noise* (AWGN).**
- A BER of 10 exp(-3) for voice, A BER of 10 exp(-9) for a data link.
- A coherent QPSK system requires a SNR of greater than approximately 12dB for a BER of better than 10-3.

2.2 The Noise problem cont..

- Noise in RF channels causes distortion of the signals and creates errors in reception.
- Noise in a radio channel can be defined by:
  - Signal to Noise Ratio (S/N)
  - Carrier to Interference Ratio (C/I)
  - Bit Error Ratio (BER)

2.3 Interference in the radio channel

Interference is the result of other man-made radio transmissions.

- » **(a)** ***Adjacent channel interference*** occurs when energy from a carrier spills over into adjacent channels.
- » (b) ***Co-channel interference*** occurs when another transmission on the same carrier frequency affects the receiver
- » © The ratio of the carrier to the interference (from both sources) is called the ***carrier-to-interference ratio*** **(C/I).**
- » **(d)** Increasing the carrier power at the receiver will increase the interference for other mobiles in the network.

2.4 RF Power Losses

As the radio signal propagates in the free space from the transmitter station to receiver station, it encounters numerous power losses.

- » Free space air attenuation/loss
- » Cable loss
- » Connector loss
- » Jumpers loss
- » Obstructions
- » Scattering
- » Dispersion
- » Reflections

2.5 **Limiting the Radiated Power**

The regulator and ITU will set a certain guidelines of the maximum amount of energy radiated out of an antenna.

(a) Effective Isotropic Radiated Power (EIRP) measured in dBm = power at antenna input [dBm] –connector loss + Relative antenna gain [dBi]

(b) Effective Radiated Power (ERP) measured in dBm
= power at antenna input [dBm]-connector loss
+ Relative antenna gain [dBd]

- » Nominal EIRP : 36 dBm.
- » Maximum EIRP for Point-to-Point (P2P) links 36 dBm
- » Max EIRP for Point-to-Multi-Point (P2MP) : 30 dBm

2.6 Free Space Propagation Losses

As the RF signal leaves the antenna it propagates, or disperses, into space.

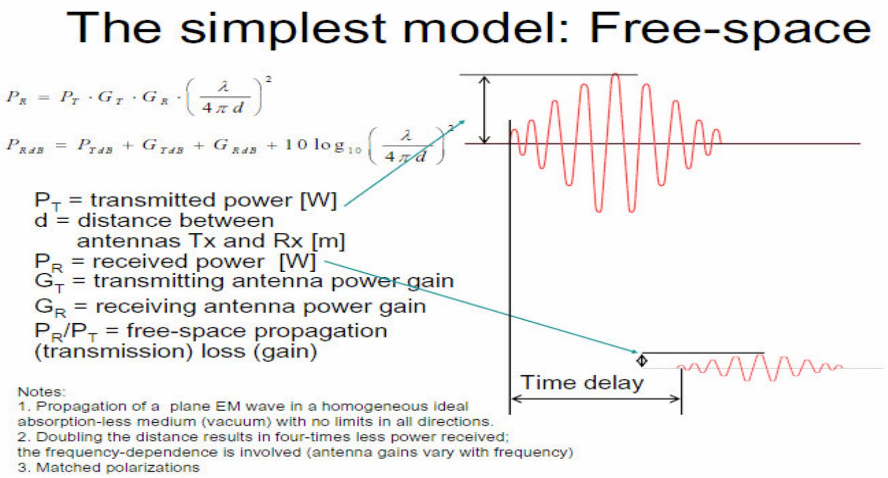
- The antenna type and gain will determine how much propagation will occur.
- it is extremely important to ensure a path (or tunnel) between the two antennas is clear of any obstructions. (LOS)
- Degradation in the signal will likely to occur if the propagating signal encounters any obstructions in the path.
- Trees, buildings, power lines and towers are common examples of path obstructions.
- The greatest amount of loss in a radio system will be from Free Space Propagation also known as free space loss (FSL)

2.6.1 The Free Space Loss

FSL(dB) = 32.45 + 20Log10 F(MHz) + 20Log10 D(km)

- The Free Space Loss at one (1) km using a 2.4 GHz system is:
  - FSL(dB) = 32.45 + 20Log10(2400) + 20Log10(1) = 32.45 + 67.6 + 0 = 100.05 dB
  - 100 dBm Free Space Loss (FSL) is quite large. Considering the Effective Radiated Isotropic Power (EIRP), the energy of the signal radiated out of the antenna is only around 30-36 dBm.
- Receiver Power: –70 to about –80 dBm of energy at the receiver antenna.
- Antenna Gain: Radio 1 Antenna (dBi) + Radio 2 Antenna (dBi) = Total Antenna Gain
- Losses: Radio 1 + Cable Loss (dB) Radio 2 + Cable Loss (dB) + Free Space Path Loss (dB) = Total Loss (dB)

2.6.2 Free space model



The simplest model: Free-space

$$P_R = P_T \cdot G_T \cdot G_R \cdot \left(\frac{\lambda}{4\pi d}\right)^2$$

$$P_{RdB} = P_{TdB} + G_{TdB} + G_{RdB} + 10\log_{10}\left(\frac{\lambda}{4\pi d}\right)^2$$

P_T = transmitted power [W]
d = distance between antennas Tx and Rx [m]
P_R = received power [W]
G_T = transmitting antenna power gain
G_R = receiving antenna power gain
P_R/P_T = free-space propagation (transmission) loss (gain)

Notes:
1. Propagation of a plane EM wave in a homogeneous ideal absorption-less medium (vacuum) with no limits in all directions.
2. Doubling the distance results in four-times less power received; the frequency-dependence is involved (antenna gains vary with frequency)
3. Matched polarizations

2.6.3 Okumara model

The Okumara model is useful in the frequency range : 500 to 900 MHz

Propagation loss (Lp):

$Lp = K1 + k2 * \log (d)$

Whereby:

$K1 = 69.55 + 26.16 \log (f) - 1.82 \log (hb)$, $K2 = 44.9 - 6.55 \log (hb)$,

d = distance in meters, f = frequency, hb = Antenna height

$Lp' = Lp - A$, terrain correction factor

$A = 4.78 [\log (f)]^2 + 18.33 \log (f) - A'$, A’ = environmental factor

For rural areas, A’ = 35.94 dB

2.6.4 Cost Hata model

Cost Hata model is useful in the frequency range :

2 GHz to 30 GHz

Propagation Loss (Lp):

$Lp = K1' + K2 * \log (d)$

Whereby:

$K1 = 46.3 + 33.9 \log (f) - 13.82 \log(hb)$

$K2 = 44.9 - 6.55 \log (hb)$,

d = distance in meters, f = frequency,

hb = Antenna height ,

$Lp' = Lp - A$, $A = 4.78 \log (f)^2 + n\ 18.33 \log(f) - A$

2.7 The Fresnel Zone clearance and Line of sight LOS

- The Fresnel Zone theory is used to quantify Radio Line of Sight.
- Acceptable Radio Line of Sight that at least 60% of the first Fresnel Zone plus 3 meters is clear of any obstructions.
- 80% of the first Fresnel Zone as the acceptable Radio Line of Sight.
- When obstructions intrude on the acceptable Fresnel Zone many issues can arise which will affect the performance of the system.

2.7.1 Freznel zone clearance

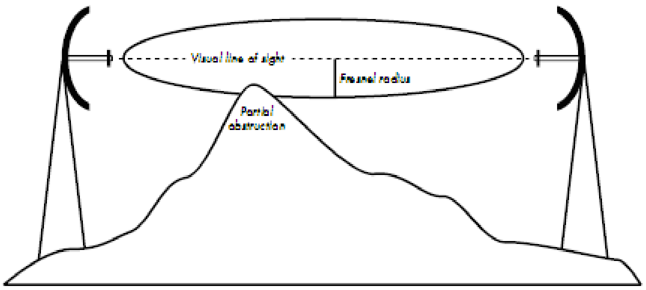
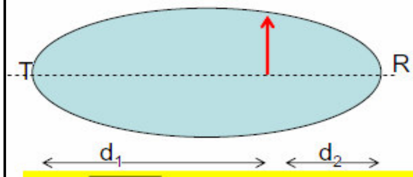


Figure 2.10: The Fresnel zone is partially blocked on this link, although the visual line of sight appears clear.

Fresnel Zone



$$r_1 = \sqrt{\frac{\lambda d_1 d_2}{d}} \leq \frac{1}{2}\sqrt{\lambda d}$$

r_1 : radius of the 1st Fresnel zone, m

$d = d_1 + d_2$: distance T-R, m

λ : wavelength, m

d_1, d_2 : distance to R and to T, m

Example: max. radius of the 1st Fresnel zone at 3 GHz (λ= 0.1m) with T – R distance of 4 km:
= (1/2)sqrt(0.1*4000) = 10m

- Fresnel zones are loci of points of constant path-length difference of $\lambda/2$
  - constant phase difference of 180^0
  - The n-th zone is the region enclosed between the 2 ellipsoides giving path-length differences $n(\lambda/2)$ and $(n-1)(\lambda/2)$
- The 1st Fresnel zone corresponds to n = 1

2.7.3.1 Reflection.

» The abrupt change in direction of a wave front at an interface between two dissimilar media so that the wave front returns into the medium from which it originated.

» The reflecting object is large compared to wavelength.The incident wave propagates away from smooth scattering plane.

2.7.3.2 Fading.

- Multi-path fading occur when secondary waves arrive out-of-phase with the incident wave causing signal degradation at the receiver.
- Fading types:
  - Multipath fading
  - Rayleigh fading

2.7.3.3 Refraction.

The incident wave propagates through scattering plane but at an angle.

- Frequencies less than 10 GHz are not affected by heavy rains, snow, fog.
- At 2.4 GHz, attenuation is 0.01 dB/Km for 150 mm/hr of rain.

2.7.3.4 Diffraction.

The incident wave passes around obstruction into shadow regions.

2.7.3.5 Scattering

- Scattering is a phenomenon in which the direction or polarization of the wave is changed when the wave encounters propagation medium discontinuities smaller than the wavelength (e.g. foliage, street signs, …)
- Scattering results in a disordered or random change in the incident energy distribution

2.7.4 Modulator & demodulator loss

The modulator and the demodulator in radio transceivers are sources of

noise and distortion .

They are sources of **non linear distortions** that must be filtered out at the receiver.

2.7.5 Other sources of error

Other sources of error in a radio channel include:

- Signal delay between transmitter and receiver
- Echo
- Jitter spread
- Sampling, alias and quantization errors
- Electromagnetic disturbances from the environment
- Transients and power surges
- Lightning and thunderstorms
- RF signals from other illegal users and hackers

2.7 The Link Budget

For our radio link to work, we must calculate the link budget between the transmitter and the receiver:

- Radio 1 TX Power + Antenna Gain - Total Loss = RX Signal at Radio 2
- Radio 2 TX Power + Antenna Gain - Total Loss = RX Signal at Radio 1

Link Test:

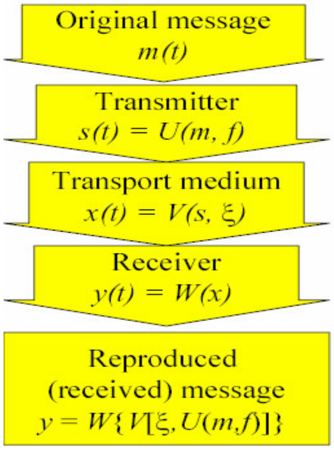
The Radio link is feasible if RX – RXs > 0

3. Modulation Techniques:

3.1 Common modulation techniques used in radio communication:

- Amplitude modulation (AM)
- Frequency Modulation (FM)
- Quadrature amplitude Modulation (QAM)
- Gaussian minimum shift keying (GMSK)

Modulation

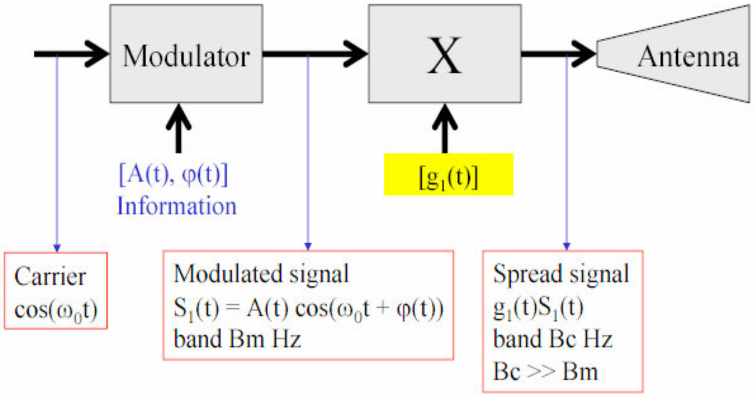


Communication Channel

$m(t) =$ message (information, data)
$s(t) =$ signal carrying the message
$f = f(a,b,c,\ldots, t)$ (carrier function)
$a,b,c, \ldots =$ modulation parameters
$U, V, W =$ operators
$\xi =$ noise, fading, perturbations
$x(t) =$ perturbed signal at the receiver input
$y(t) =$ reproduced message

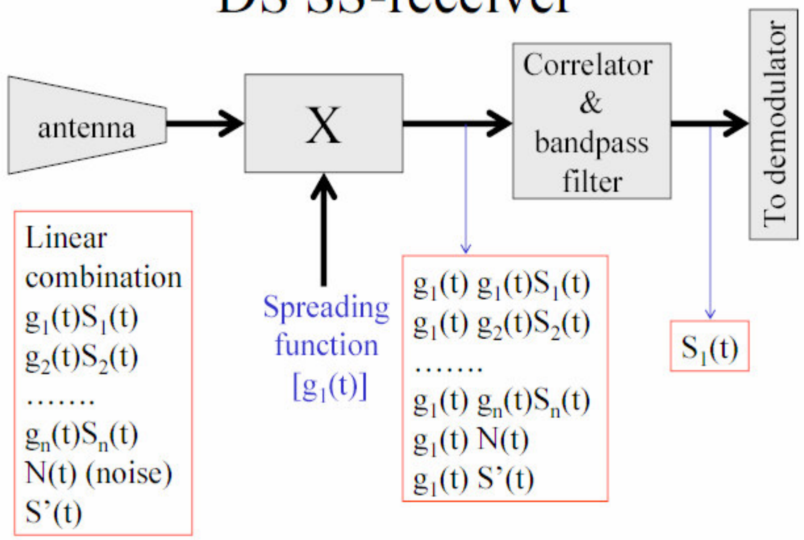
Task: make $y \approx m$ (within an acceptable error)

DS SS: transmitter



$g_i(t)$: pseudo-random noise (PN) spreading functions that spreads the energy of $S_1(t)$ over a bandwidth considerably wider than that of $S_1(t)$: ideally $g_i(t)\, g_j(t) = 1$ if $i = j$ and $g_i(t)\, g_j(t) = 0$ if $i \neq j$

DS SS-receiver



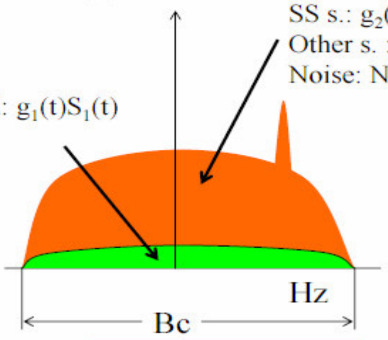
Linear combination
$g_1(t)S_1(t)$
$g_2(t)S_2(t)$
…….
$g_n(t)S_n(t)$
N(t) (noise)
S'(t)

Spreading function
$[g_1(t)]$

$g_1(t)\ g_1(t)S_1(t)$
$g_1(t)\ g_2(t)S_2(t)$
…….
$g_1(t)\ g_n(t)S_n(t)$
$g_1(t)\ N(t)$
$g_1(t)\ S'(t)$

$S_1(t)$

SS-receiver's Input

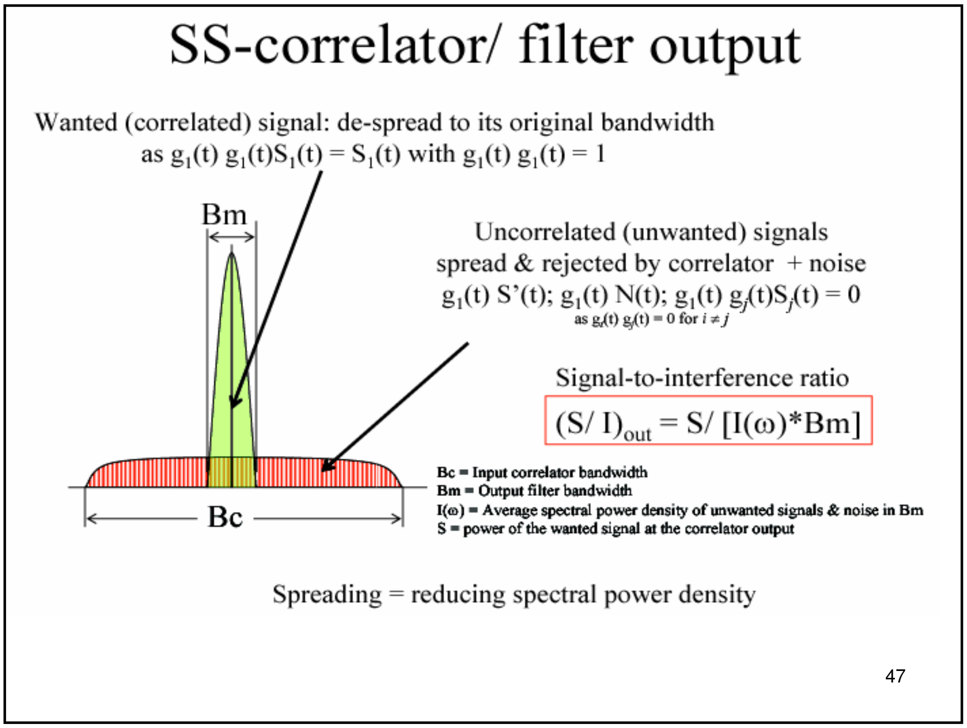


Unwanted signals
SS s.: $g_2(t)S_2(t)$; …; $g_n(t)S_n($
Other s. : S'(t)
Noise: N(t)

Wanted (spread) signal: $g_1(t)S_1(t)$

Signal-to-interference ratio $(S/I)_{in} = S/[I(\omega)*Bc]$

Bc =	Input correlator bandwidth
I(ω) =	Average spectral power density of unwanted signals in Bc
S =	Power of the wanted signal



SS-correlator/ filter output

Wanted (correlated) signal: de-spread to its original bandwidth as $g_1(t)\, g_1(t) S_1(t) = S_1(t)$ with $g_1(t)\, g_1(t) = 1$

Uncorrelated (unwanted) signals spread & rejected by correlator + noise $g_1(t)\, S'(t)$; $g_1(t)\, N(t)$; $g_1(t)\, g_j(t) S_j(t) = 0$

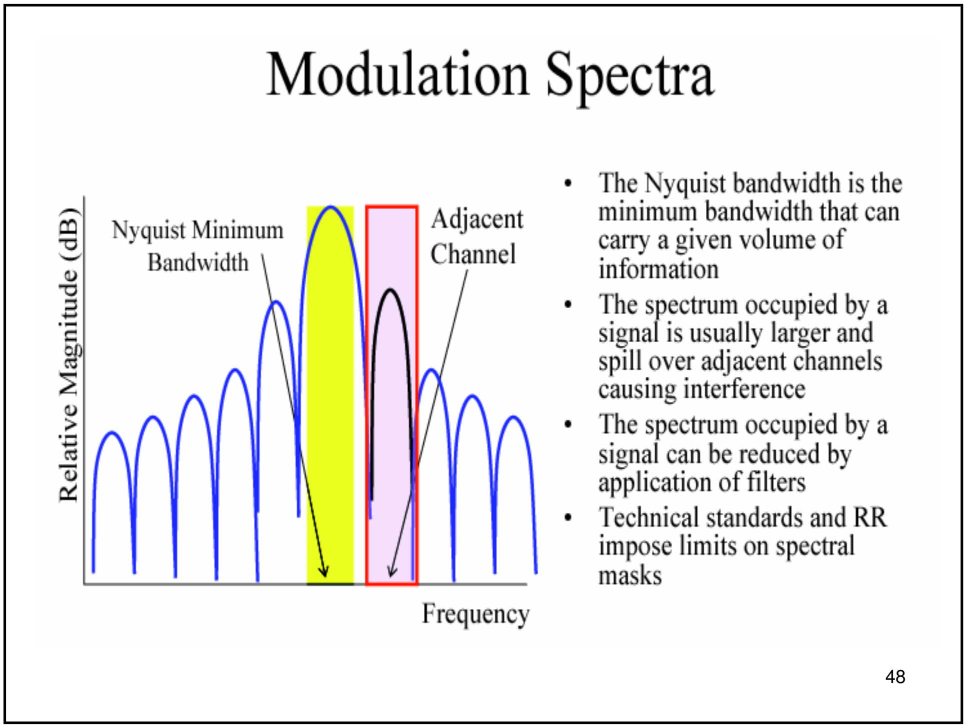
as $g_i(t)\, g_j(t) = 0$ for $i \neq j$

Signal-to-interference ratio

$$\boxed{(S/\, I)_{out} = S/\, [I(\omega)*Bm]}$$

Bc = Input correlator bandwidth
Bm = Output filter bandwidth
I(ω) = Average spectral power density of unwanted signals & noise in Bm
S = power of the wanted signal at the correlator output

Spreading = reducing spectral power density



Modulation Spectra

- The Nyquist bandwidth is the minimum bandwidth that can carry a given volume of information
- The spectrum occupied by a signal is usually larger and spill over adjacent channels causing interference
- The spectrum occupied by a signal can be reduced by application of filters
- Technical standards and RR impose limits on spectral masks

3.2 Common multiplexing techniques

- Time Division Multiple Access (TDMA)
- Code Division Multiplexing (CDMA) also known as spread spectrum
- Time Division Multiplexing (TDM)
- Orthogonal Frequency Division Multiplexing (OFDM)
- Time Division Duplexing (TDD)

Modern communication systems use one or a combination of the above modulation and coding techniques.

3.3 Channel capacity

Available channel capacity expression:

C = B * log2 (1 + S/N)

B: Bandwidth

S/N: Signal to Noise Ratio

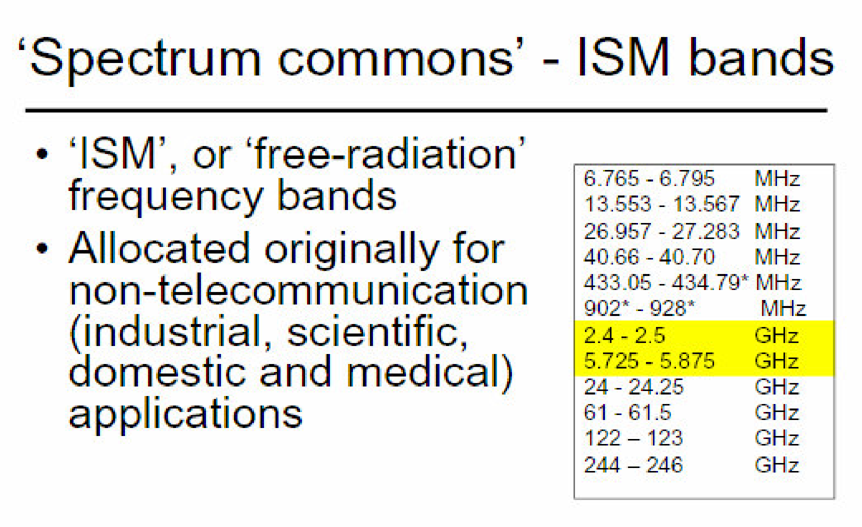
In CDMA, S/N is made very large to make the noise level small with an increase in B (spreading the bandwidth)

C = B * log2 (S/N)

4.1 Candidate RF Bands for UMTS/IMT 2000

• 450- 470 MHz	925-935 MHz
• 470-600 MHz	925-960 MHz
• 470-790 MHz	
• 806-960 MHz	1710-1880 MHz
• 880-915 MHz	1920-1980 MHz
• 880-890 MHz	2110-2170 MHz

Source UMTS Forum Report No 38 of January 2005



'Spectrum commons' - ISM bands

- 'ISM', or 'free-radiation' frequency bands
- Allocated originally for non-telecommunication (industrial, scientific, domestic and medical) applications

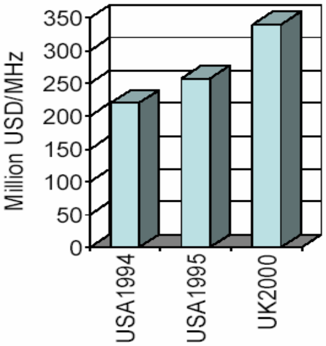
6.765 - 6.795	MHz
13.553 - 13.567	MHz
26.957 - 27.283	MHz
40.66 - 40.70	MHz
433.05 - 434.79*	MHz
902* - 928*	MHz
2.4 - 2.5	GHz
5.725 - 5.875	GHz
24 - 24.25	GHz
61 - 61.5	GHz
122 – 123	GHz
244 – 246	GHz

Spectrum price

Valued When Used

USA1994: 3x1mhz (~1gHz) $0.65 billion
USA1995: 2x15mhz (~2ghz) $7'74 billion
UK200: ~100 mhz (~2ghz) $34 billion

But it is always the end consumer who pays…



5. **Summary:**

Radio is a very important tool for transmission:

1. Radio will be predominantly used in IMT 2000 and UMTS systems as the access.
2. As the demand for higher transmission speed and bandwidth continues to grow, the available frequency spectrum is diminishing.
3. It is important to design radio systems that require narrow bandwidths per channel and yet achieve high transmission speeds.
4. Modern communication applications such as fixed Voice, mobile, Internet, Video, Multimedia depend very much on the broadband radio systems.
5. It is also important to regulate the radio spectrum in order to achieve maximum spectrum efficiency and to minimize interference between operators.
6. Some radio systems may have to be removed from operation if they are not efficient in spectrum utilization especially in the UMTS/IMT 2000 bands
7. The question of transmit power control should also be critically looked at by the regulators in order to reduce interference and protect citizens from harmful RF radiation.g

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