United States Telecommunications Training Institute

Radio Frequency Spectrum Management

Introduction to Spectrum Engineering

September 23, 2019

Presentation

by

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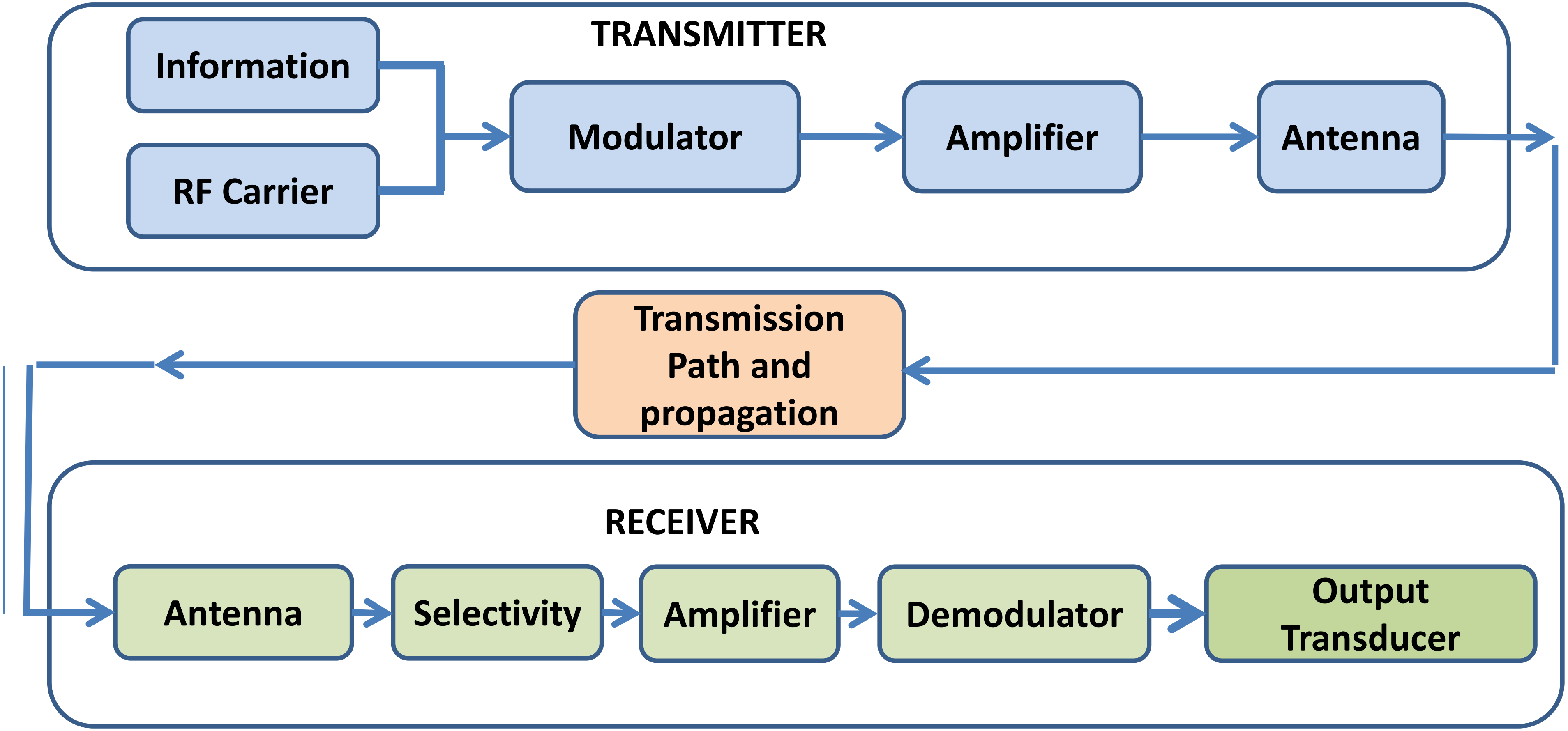
OUTLINE

- The Communications System Blocks
- The Spectrum Chart and Designations
- Abbreviations , and Spectrum Management Units
- Basics of Modulation
- Analog vs. Digital Systems
- Multiple Access Concepts
- Fundamentals of Propagation
- Antennas
- Applications and Examples

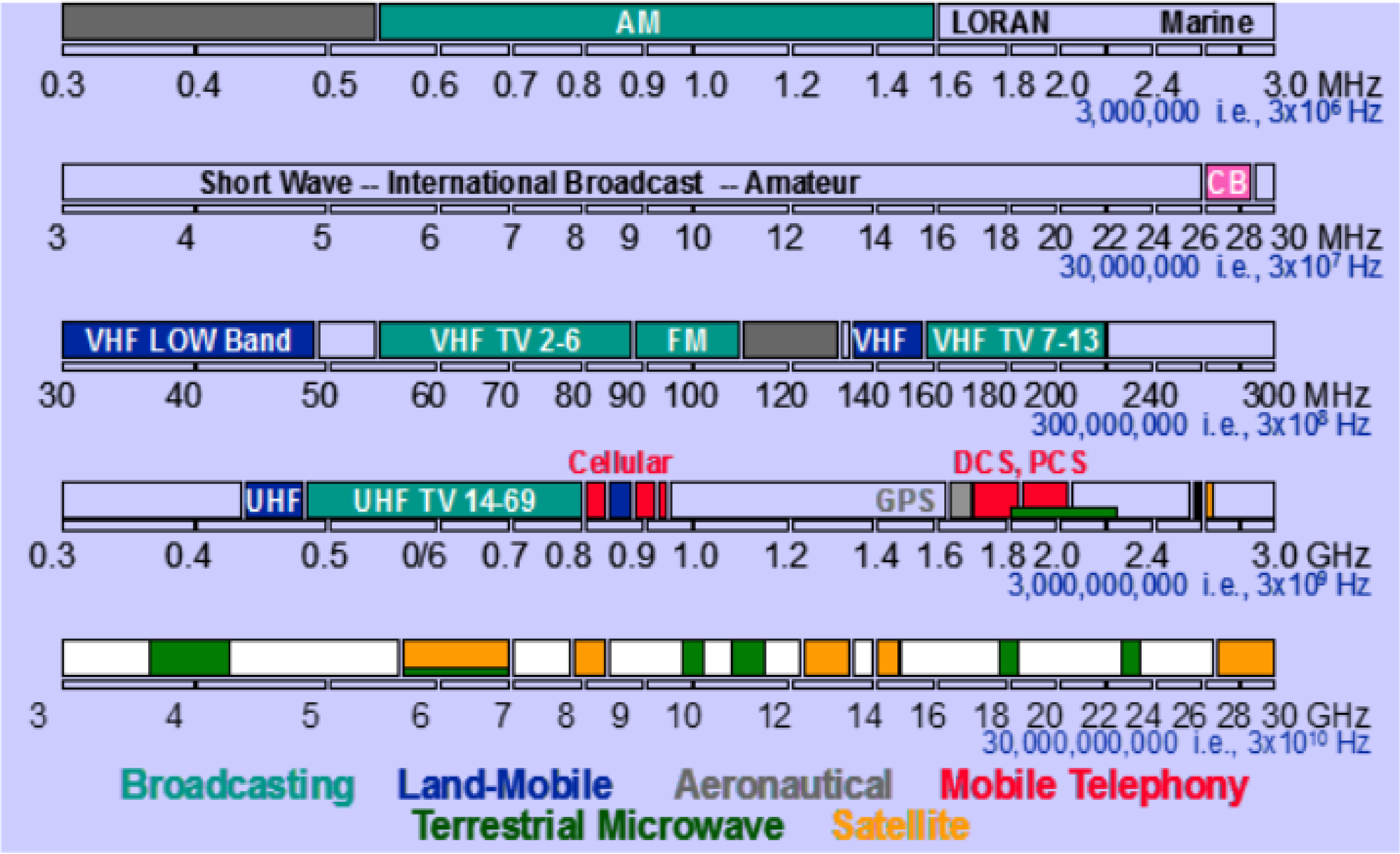
THE COMMUNICATIONS SYSTEM BLOCKS

COMMUNICATIONS SYSTEM



THE SPECTRUM CHART AND DESIGNATIONS

The Spectrum Chart



Frequency Band Designations

VLF ....3-30 kHz...............Submarine Communications

LF ....30-300 kHz..........Submarine/Navigation

MF ....300-3000 kHz......Navigation/Time Signals/AM

HF ....3-30 MHz.............Shortwave/Amateur

VHF ....30-300 MHz........Police/Fire/LMR, FM

UHF ....300-3000 MHz....Police/Fire/LMR, HDTV

SHF ....3-30 GHz ....Radar/Satellite/Telemetry

EHF ....30-300 GHz.........Radar/Sat/Microwaves

Source: ITU

LETTER BAND ABBREVIATIONS

- L ………………………. 1000-2000 MHz
- S ………………………. 2000-4000 MHz
- C ………………………. 4000-8000 MHz
- X ………………………. 8000-12,000 MHz
- Ku ……………………… 12-18 GHz
- K ………………………. 18-27 GHz
- Ka ……………………… 27-40 GHz
- V ………………………. 40-75 GHz
- W ………………………. 75-110 GHz

Source: IEEE Standard 521-2002

ABBREVIATIONS , AND SPECTRUM MANAGEMENT UNITS

BASIC SPECTRUM MANAGEMENT UNITS

Watts (W) – Power
Milliwatts (mW)
Kilowatts (KW)
Megawatts (MW)

Volts (V) – Potential
Microvolts (µvolts)
Millivolts (mV)

Hertz (Hz) – Frequency
Kilohertz (kHz)
Megahertz (MHz)
Gigahertz (GHz)
Terahertz (THz)

SPECTRUM MANAGEMENT PREFIXES

Prefix	Symbol	Value	Prefix	Symbol	Value
pico-	P	10^{-12}	tera-	T	10^{12}
nano-	n	10^{-9}	giga-	G	10^{9}
micro-	µ	10^{-6}	mega-	M	10^{6}
milli-	m	10^{-3}	kilo-	k	10^{3}

What is a Decibel (dB)?

- Very important
- Language of spectrum managers and engineers
- Origin – telephone audio circuits
- “Bell” is named after Alexander Graham Bell
- A logarithmic ratio term, base 10
- Dimensionless, but often used as a dimension
- A ratio term, always used in comparison to standard units, such as watts, milliwatts, etc.
- Easy to use logarithmic form – values can be easily added or subtracted rather than multiplied

dB TERMS

- Voltage Ratio: dB = 20 log (V2/V1)
- Power Ratio: dB = 10 log (P2/P1)
- Voltage Level: dBμV = 20 log (V/1μV)
- Power Level: dBm = 10 log (P/1mW)

MOST USED dB TERMS

- dBm number of dB compared to 1 milliwatt (mW)
- dBW number of dB compared to 1 watt
- dBi is an antenna gain term, meaning the “directivity”, “intensity” or “gain” of an antenna compared to an isotropic radiator
- dBd is an antenna gain term, compared to a dipole antenna

dBm CALCULATION EXAMPLE

Converting watts to dBm

$$\text{Power (dBm)} = 10\, Log_{10} \frac{\text{P (watts)}}{10^{-3}\text{ (watts)}}$$

$$\text{Power (dBm)} = 10\, Log_{10} \frac{\text{P (watts)}}{\text{0.001 watts}}$$

Example: 150 watts

$$\text{Power (dBm)} = 10\, Log_{10} \frac{\text{150 watts}}{\text{0.001 watts}}$$

$$\text{Power (dBm)} = 10\, Log_{10}\ 150{,}000$$

$$\text{Power (dBm)} = 10\ (5.18) \quad = \quad 51.8$$

Results: 150 watts = 51.8 dBm

dBm Calculation Examples

1) 25mW max. allowed radiated power in the EU Short Range Devices (SRD) band

   Converting to dBm:

   $$dBm = 10 \log (25mW/1mW) = 10 \log 25$$

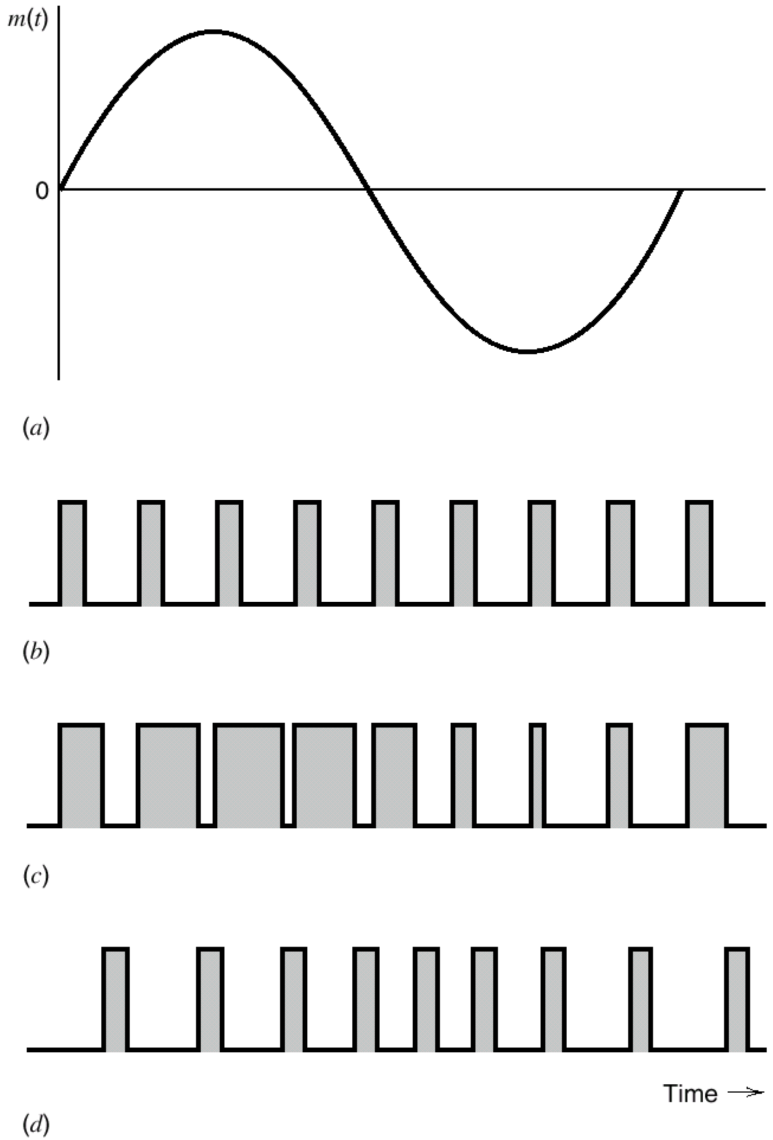
   $$= 10 (1.397) = 13.97 = 14 \text{ dBm}$$

2) Receiver sensitivity is typically 1 microvolt (1µV)

   Converting to dBm (50 ohm input impedance)

   Using web-based calculator = -107 dBm

MODULATION



Pulse Modulation

-The Carrier is a pulse train

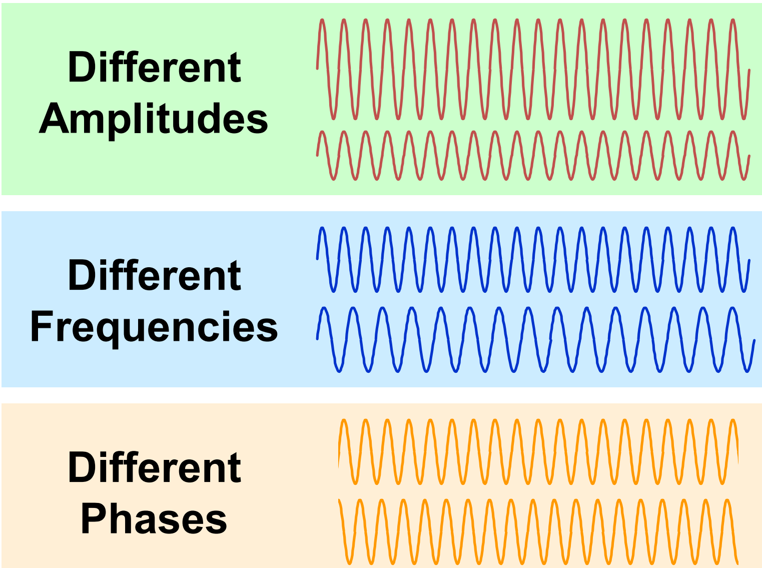
-One of Amplitude, Pulse Duration, or position varied based on samples of input message (which may be coded samples for digital)

SIGNAL CHARACTERISTICS

$$S(t) = A \cos[\omega_c t + \varphi]$$

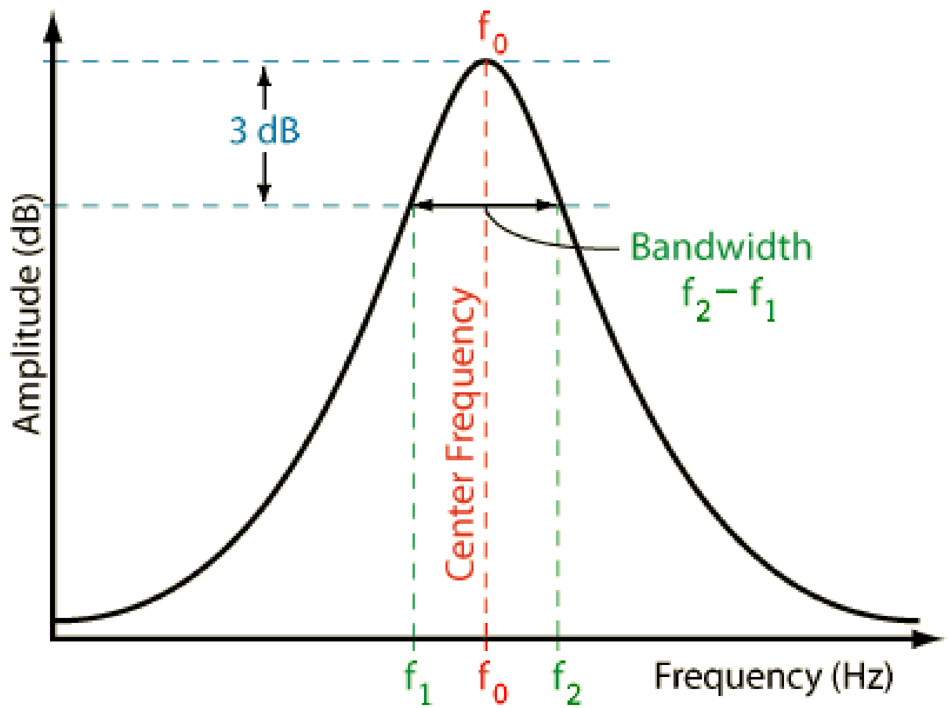
- The complete, time-varying radio **signal** → $S(t)$
- Natural **Frequency** of the signal → ω_c
- **Amplitude** (strength) of the signal → A
- **Phase** of the signal → φ

Compare these Signals:



- **some characteristic of the radio signal must be altered (I.e., 'modulated') to represent the information**
- **The main purpose of telecommunications is to send information from one location to another**
- **The sender and receiver have common understanding of how to send and receive.**
- **Three commonly-used RF signal characteristics which can be varied for information transmission:**
  - **Amplitude**
  - **Frequency**
  - **Phase**

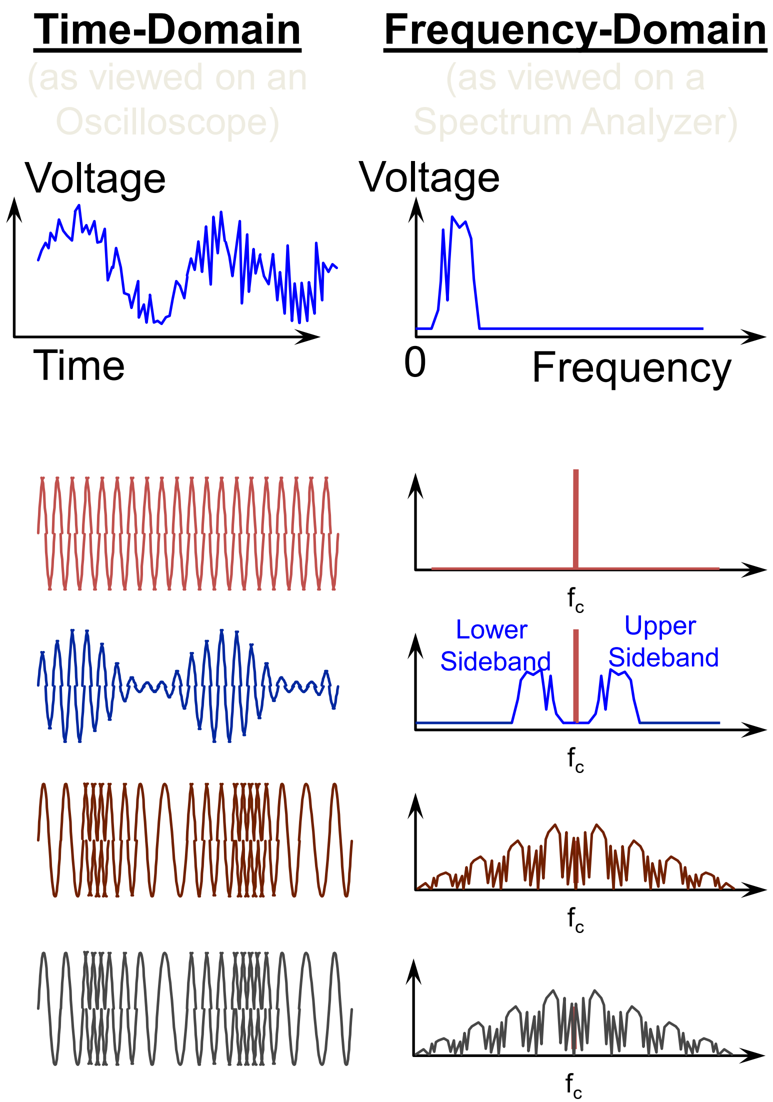
WHAT IS BANDWIDTH?



Many Definitions of BW exist, Some are -3dB, others -20 dB, others are based on power total. Always check which definition is to being used

- Morse-code telegraphy is 300-400 Hz;
- Voice communications over a single-sideband (SSB) radio is 2.7 kHz; and
- Music over AM radio broadcasting is about 10,000 Hz or 10 kHz
- VoIP 200 kHz, compared to 3 kHz over telephone

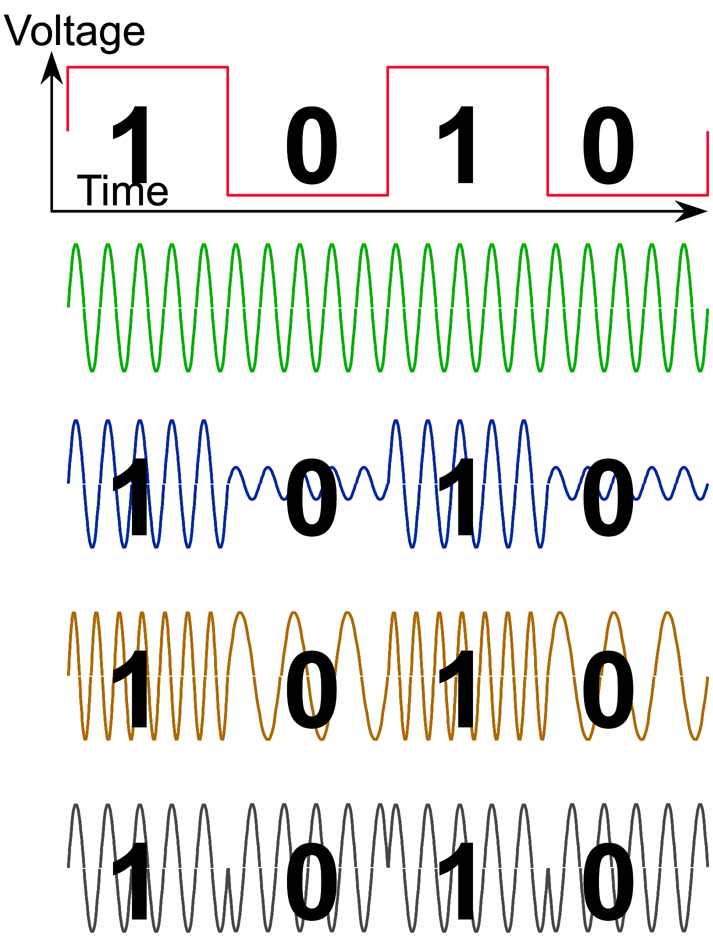
Analog Modulation



- **The bandwidth occupied by a signal depends on:**
  - **input information bandwidth**
  - **modulation method**
- **Information to be transmitted, called "input" or "baseband"**
  - bandwidth usually is small, much lower than frequency of carrier
- **Unmodulated carrier**
  - the carrier itself has **Zero** bandwidth!!
- **AM-modulated carrier**
  - Notice the upper & lower sidebands
  - total bandwidth = 2 x baseband BW
- **FM-modulated carrier**
  - Many sidebands! bandwidth is a complex Bessel function
  - Carson's Rule approximate 2(F+D)
- **PM-modulated carrier**
  - Many sidebands! bandwidth is a complex Bessel function

Digital Modulation

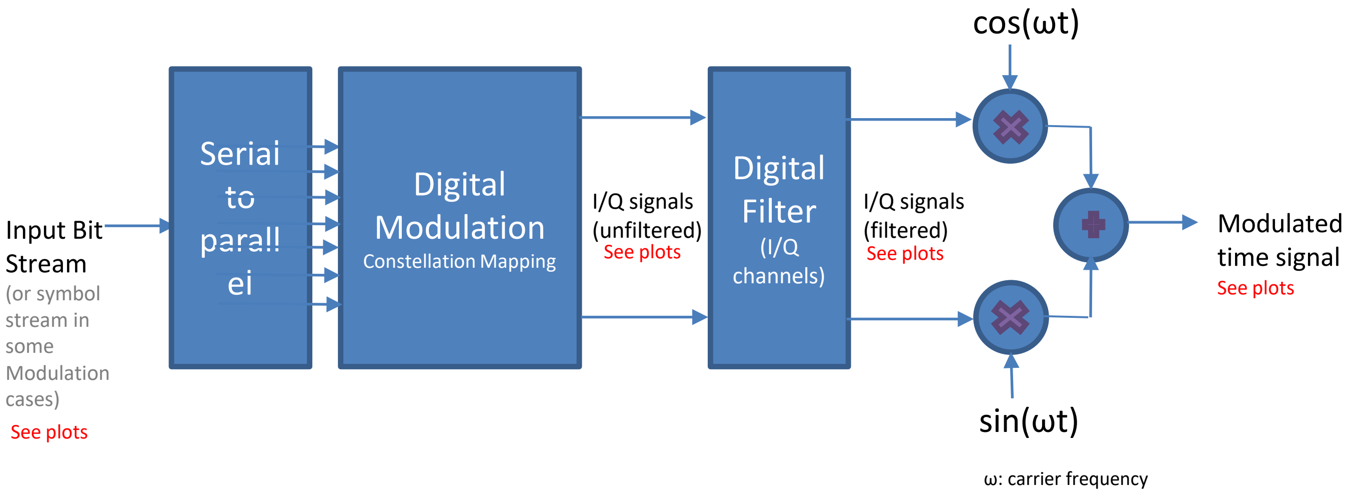
The continuos inputs are quantized restricting them to digital values, this will produce digital modulation.



Continuous signals are first made into digital by representing them with two levels only such as the one shown left.Then modulated…

- Steady **Carrier** without modulation
- **Amplitude Shift Keying**
  - **ASK** applications: digital microwave
- **Frequency Shift Keying**
  - **FSK** applications: control messages in AMPS cellular; TDMA cellular
- **Phase Shift Keying**
  - **PSK** applications: TDMA cellular, GSM & PCS-1900

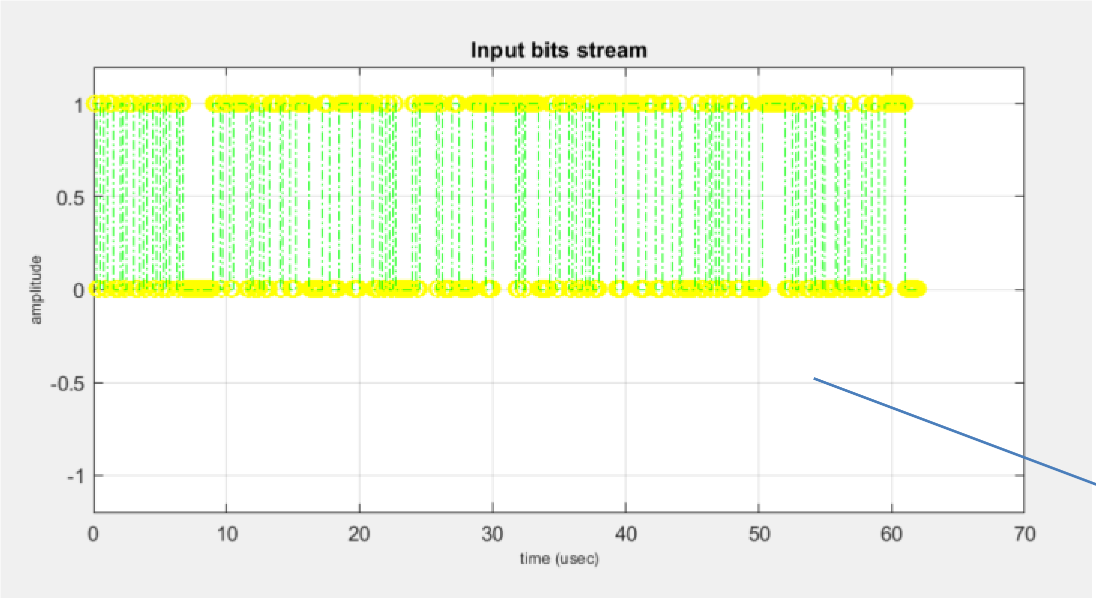
A simplified block diagram of digital complex modulations



Example of Plot/Results

Input_seq_plot

Example input bit width of 0.25 microsec random sequence

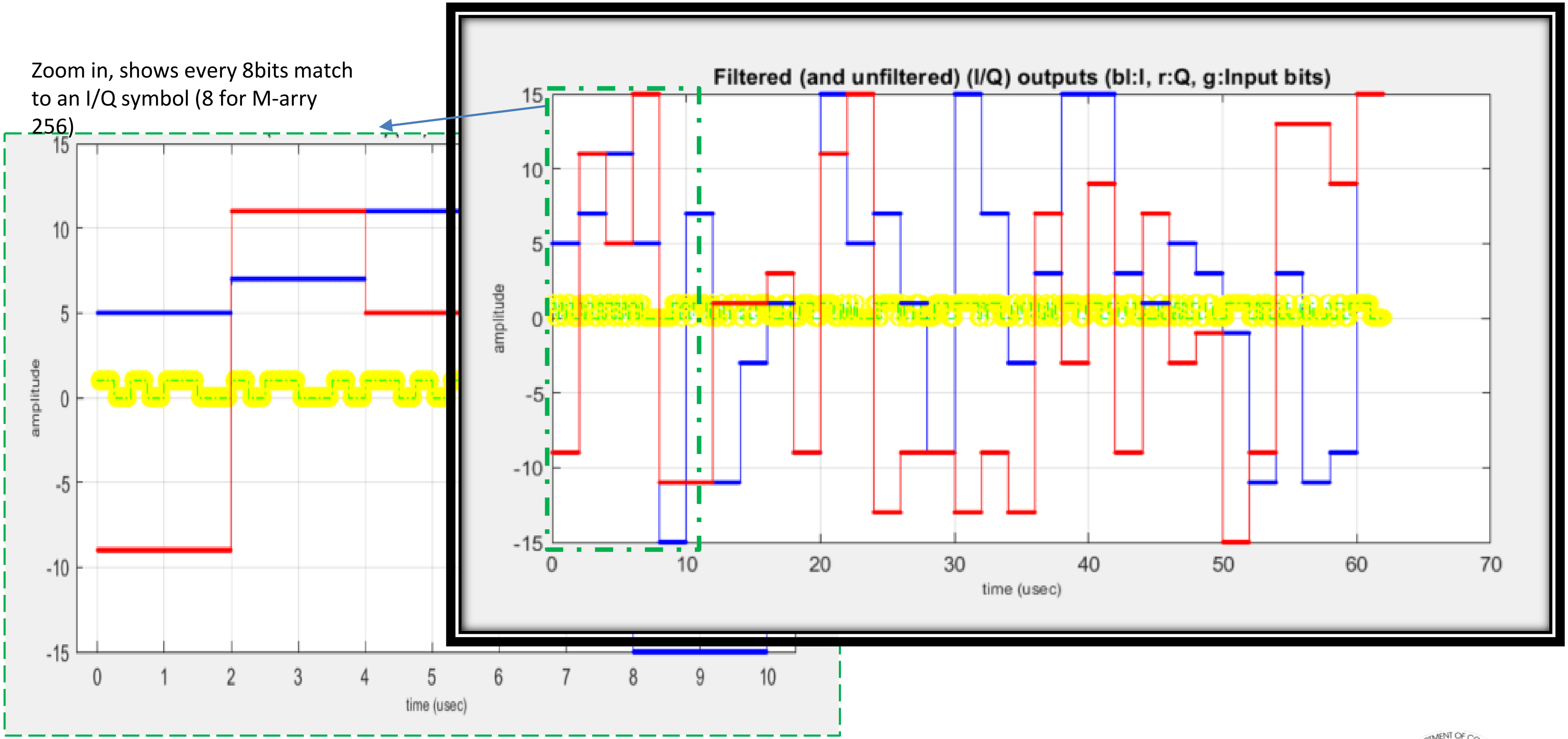


Zoom in shows 0.25 microsec period

Example of Plot/Results options

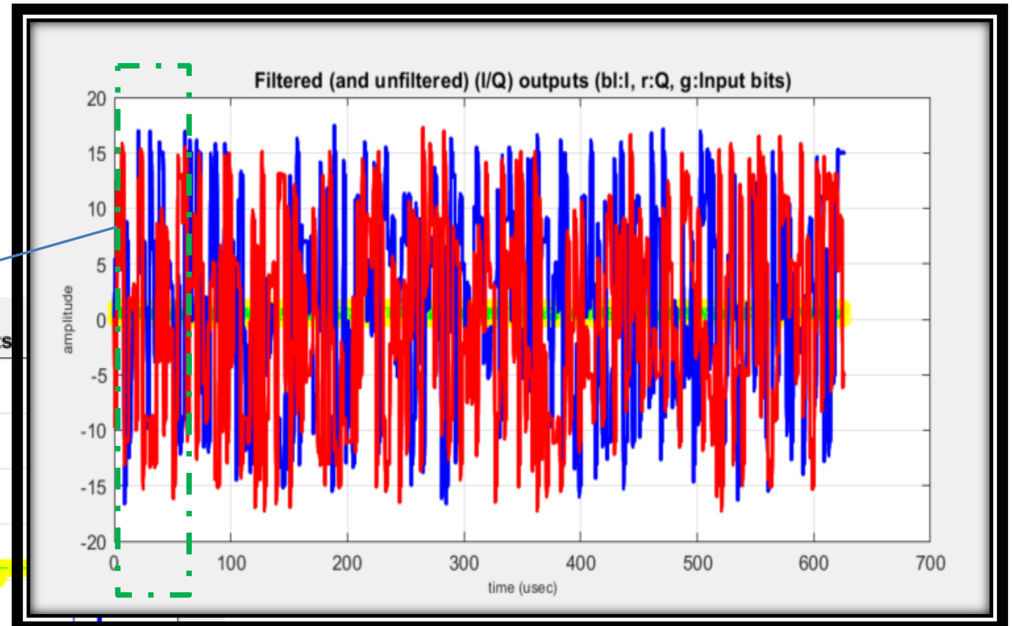
filtered_input_seq_IQ_plot (without filter case)

Zoom in, shows every 8bits match to an I/Q symbol (8 for M-arry 256)

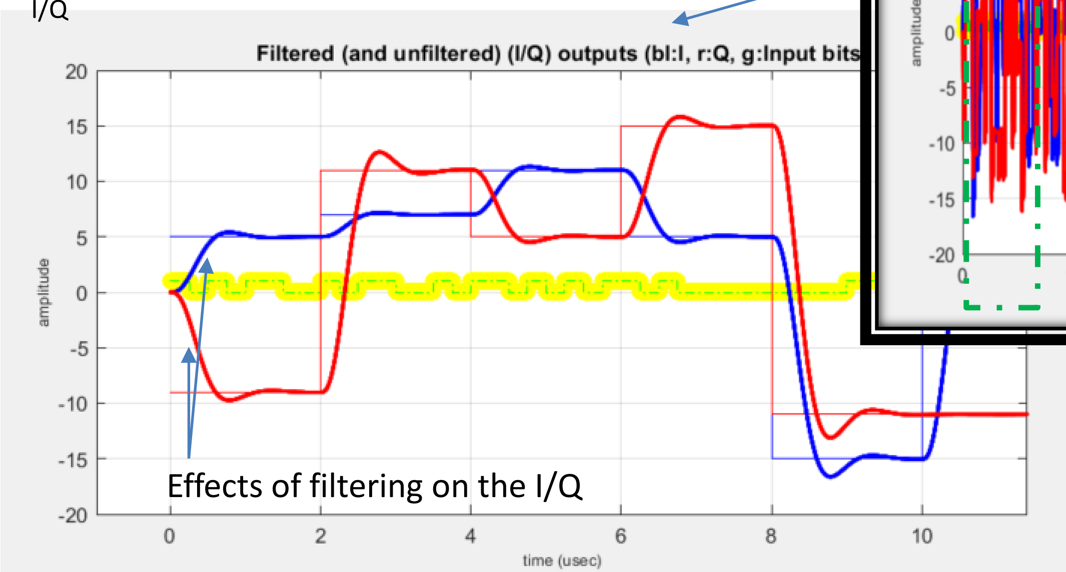


Example of Plot/Results

filtered_input_seq_IQ_plot (with filter case)



Zoom in, shows every 8bits match to an I/Q symbol (8 for M-arry 256) and the effects of Filtering on I/Q

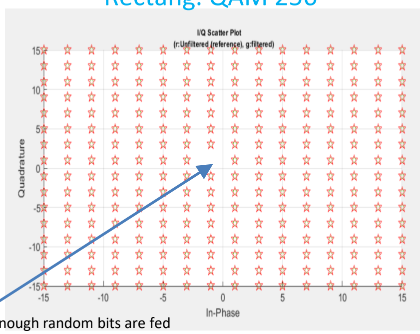


Example of Plot/Results

I/Q scatter plots (filtered and unfiltered)

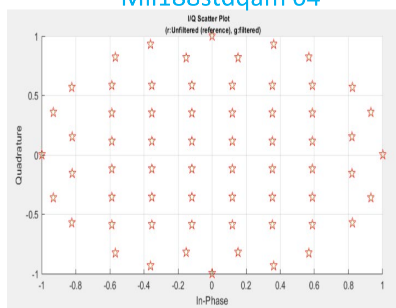
Examples I/Q scatter plots (without filtering…hence no transitions trajectories …)

Rectang. QAM 256



When not enough random bits are fed in, some of the I/Q symbols may not be matched. Only way to have all show up properly is to increase bits stream size

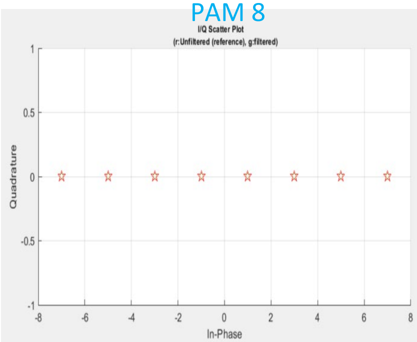
Mil188stdqam 64



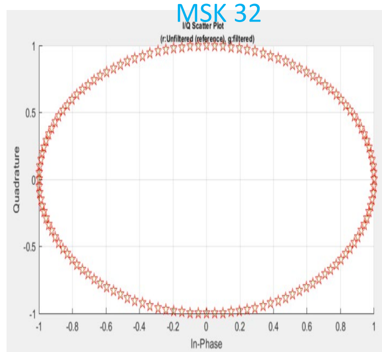
Multitude other examples based on Mod type and its specifications

■ ■ ■ ■ ■

PAM 8

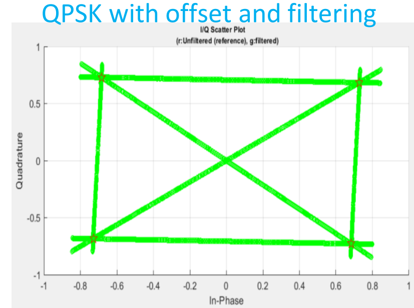


MSK 32



Examples I/Q scatter plots (with filtering and shows transitions trajectories …)

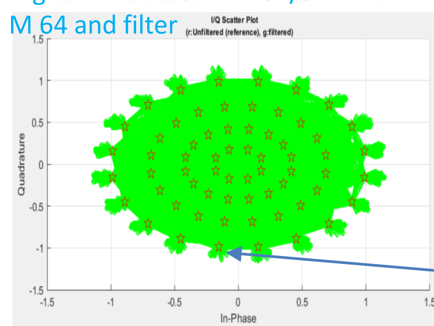
QPSK with offset and filtering



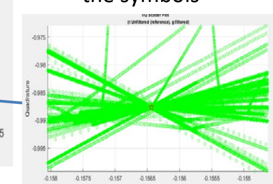
Multitude other examples based on Mod type and its specifications

■ ■ ■ ■ ■

Digital Broadcast DVB S2/S2X with M 64 and filter

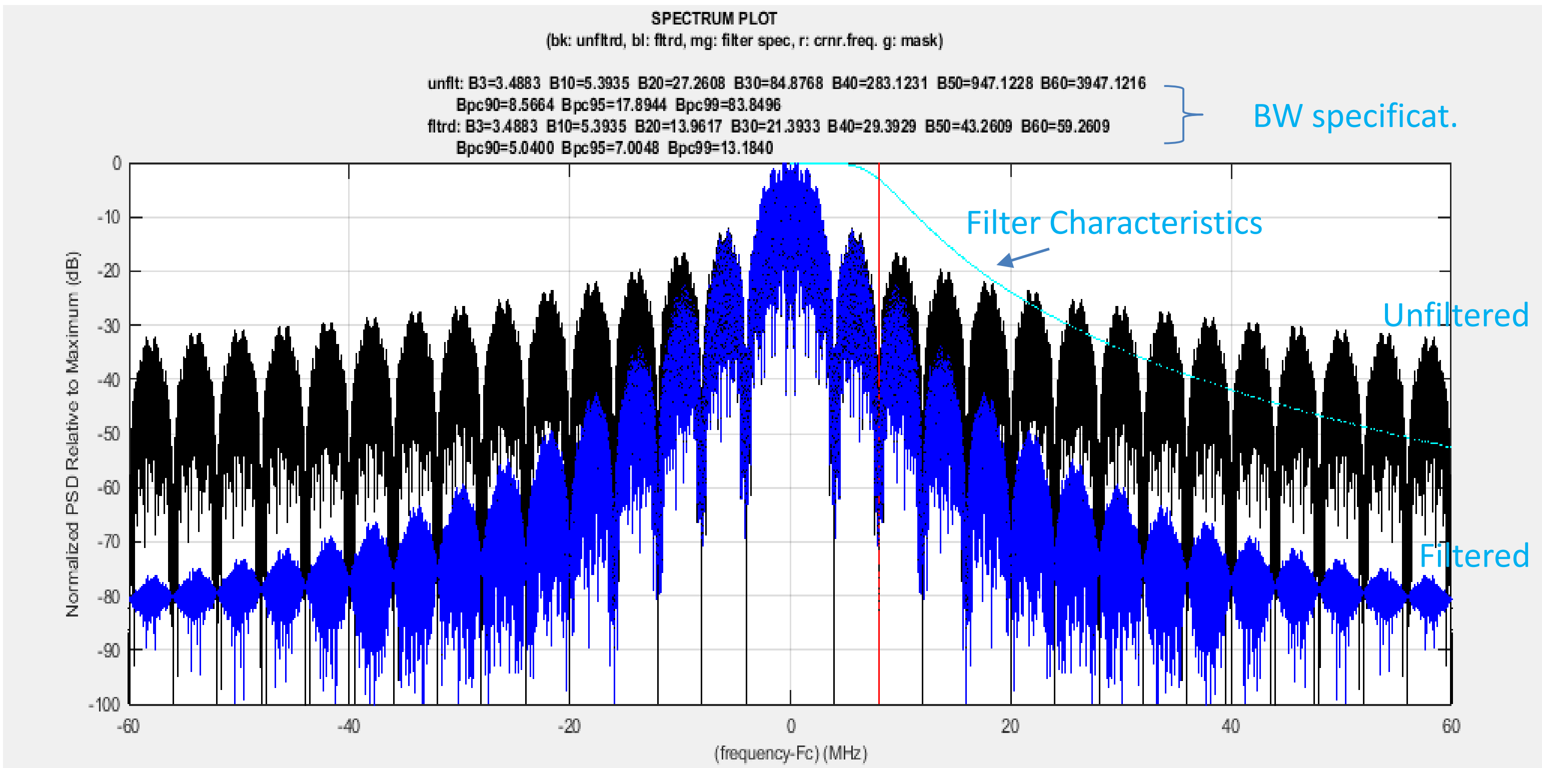


Zoom in to show trajectory points around one of the symbols



Example of Plot/Results

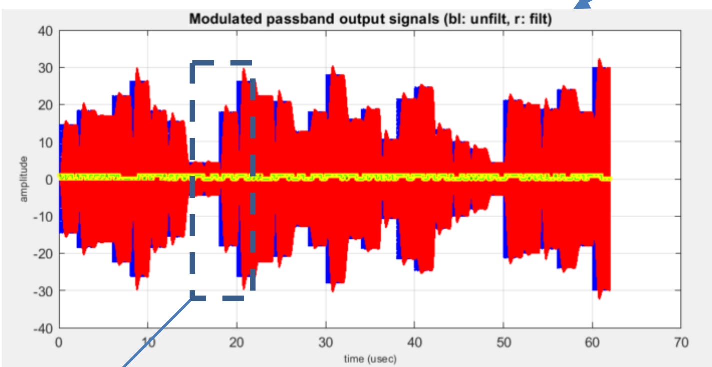
Spectrum_plot_(linear) with/without filtering

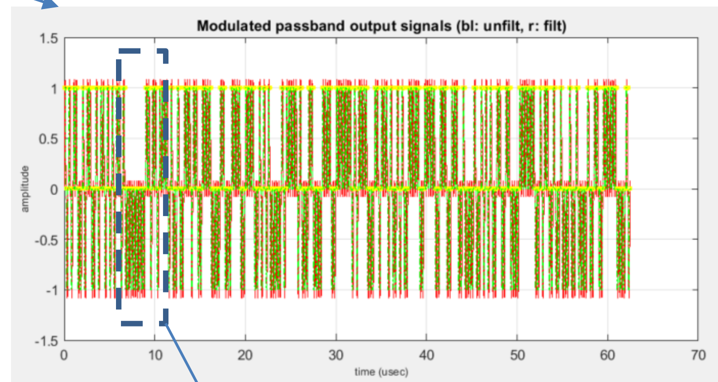


Example of Plot/Results

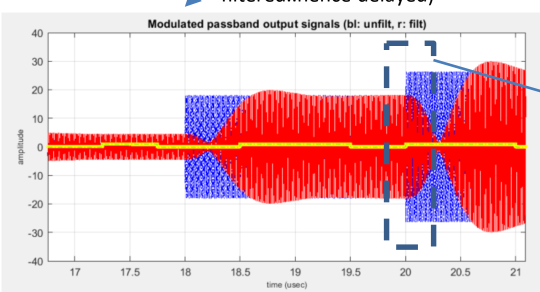
Modulated_signal_plot

Examples of time modulated signals for "passband" and "baseband"

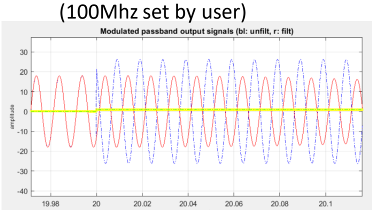




Zoom in (blue unfiltered, red filtered..hence delayed)



More Zoom in to show Carrier Freq. (100Mhz set by user)

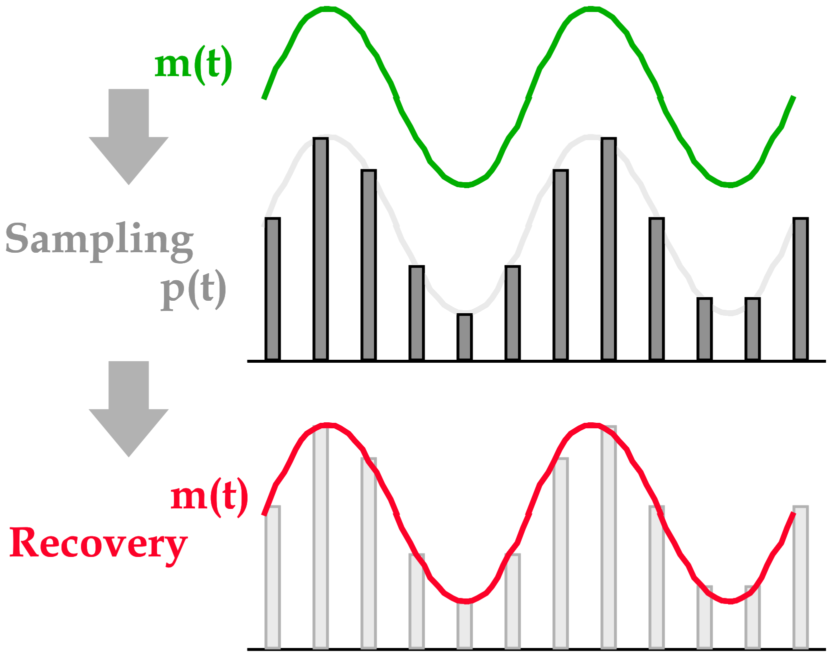


Zoom in to see Bit width 0.25msec. Return to Zero half way

Baseband not using any carrier and follow Line Code outputs…

ANALOG VS. DIGITAL

Sampling



The Sampling Theorem: Two Parts

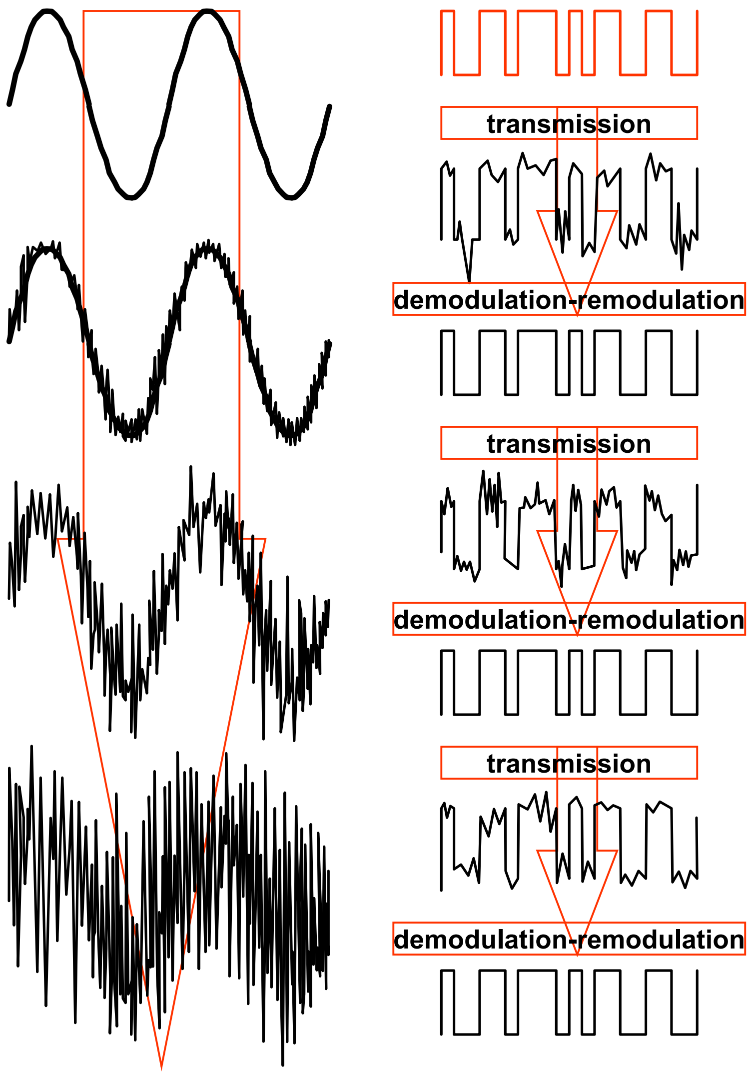
•If the signal contains no frequency higher than f_M Hz., it is completely described by specifying its samples taken at instants of time spaced 1/2 f_M s.

•The signal can be completely recovered from its samples taken at the rate of 2 f_M samples per second or higher.

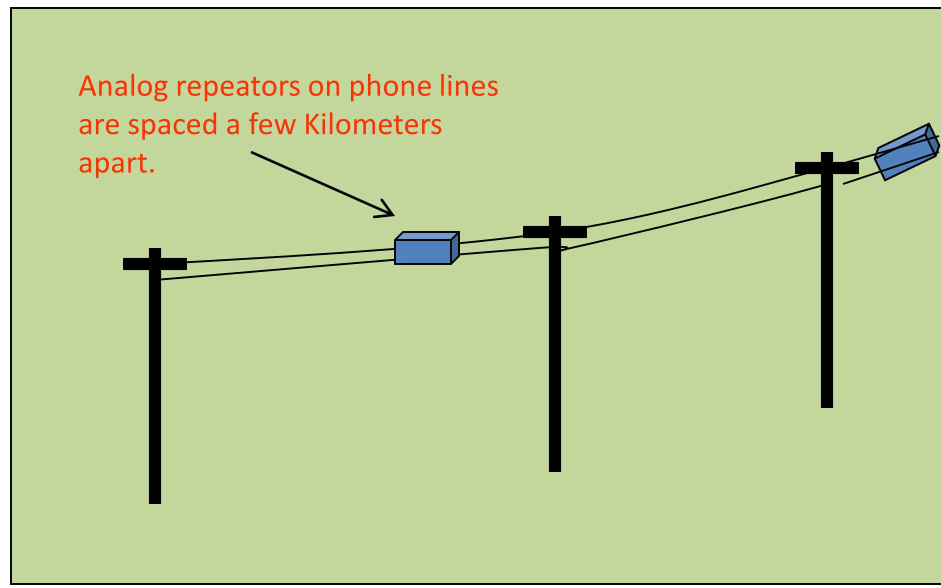
- Voice and other analog signals first must be converted to digital form ("sampled") before they can be transmitted digitally
- The ***sampling theorem*** gives the requirements for successful sampling
  - The signal must be sampled at least twice during each cycle of f_M , its highest frequency. 2 x f_M is called the ***Nyquist Rate.***
  - to prevent "aliasing", the analog signal is low-pass filtered so it contains no frequencies above f_M
- Required Bandwidth for Samples, p(t)
  - If each sample p(t) is expressed as an n-bit binary number, the bandwidth required to convey p(t) as a digital signal is at least N*2* f_M
  - this follows ***Shannon's Theorem***: at least one Hertz of bandwidth is required to convey one bit per second of data
  - *Notice: lots of bandwidth required!*

Benefits of Digital Communications

1) Less effected by noise and interference because of only two possible levels (on / off).
2) Makes signal retransmission easier and more reliable.
3) Digital Circuits are reliable and can be produced with lower cost, and more flexibility.
4) Time Division Multiplexing is simpler than Frequency division multiplexing which is what is used in Analog Communications.
5) Computers are digital hence it is more natural to use digital transmissions.
6) Better security via encryption coding.
7) More intelligent ways to recover signals via error correcting coding techniques.
8) More Capacity within the allocated Bandwidths.



One of the Main benefits of Digital Modulation is in regenerating signals with noise. The Two levels of representing signals make it easier to regenerate without errors.



MULTIPLE ACCESS METHODS

Multiple Access Technologies

- FDMA (example: AMPS)

  Frequency Division Multiple Access

  – each user has a private frequency (at least in their own neighborhood)

- TDMA (examples: IS-54/136, GSM)

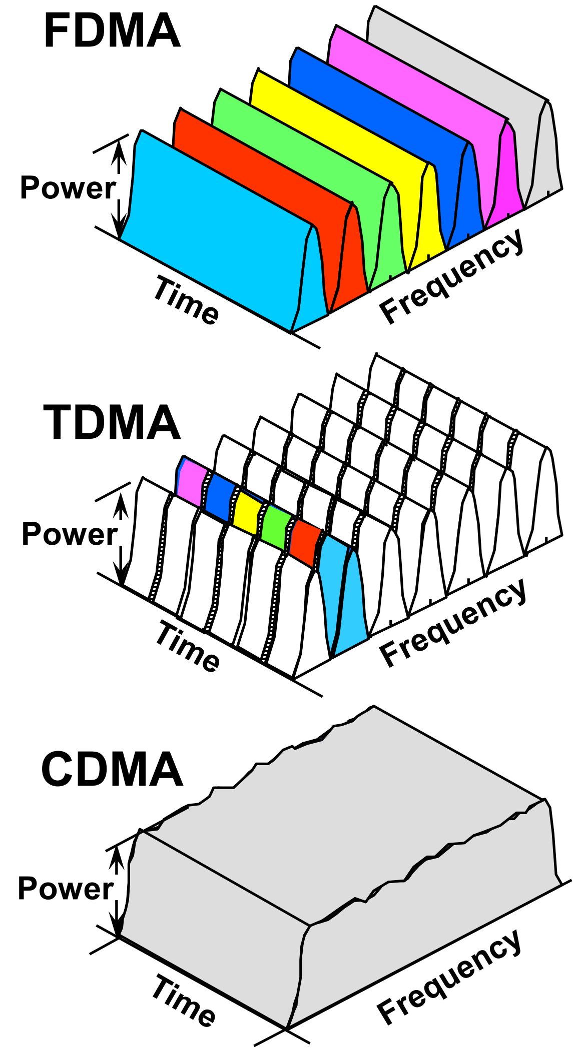
  Time Division Multiple Access

  – each user has a private time on a private frequency (at least in their own neighborhood)

- CDMA (examples: IS-95, J-Std. 008)

  Code Division Multiple Access

  – users co-mingle in time and frequency but each user has a private code (at least in their own neighborhood)



RF PROPAGATION

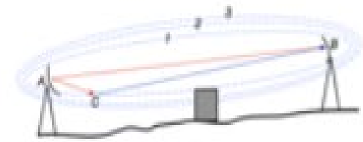
Modes of Propagation Summary

Radio waves

Ground waves

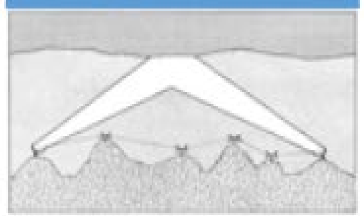
Space waves

Direct Waves

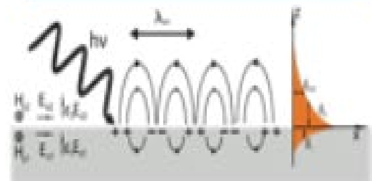


Ground-Reflected waves

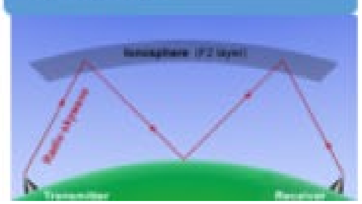
Tropospheric waves



Surface waves



Ionosperic / Sky waves



Space Waves modeling is the mai
topic of the remainder content

Radio wave physical properties:

- LOS direct (free space)
- Reflect (atmosphere, ground, buildings)
- Refract (atmosphere, clutter)
- scatter (rain, cloud, objects)
- Absorb (rain, oxygen, vapor) Multipath and fading (buildings, clutter)
- Polarization (all)
- Doppler and frequency shift
- Ducting

Models exist for all the physical attributes listed above either individually, or together

Propagation Models for Space Waves

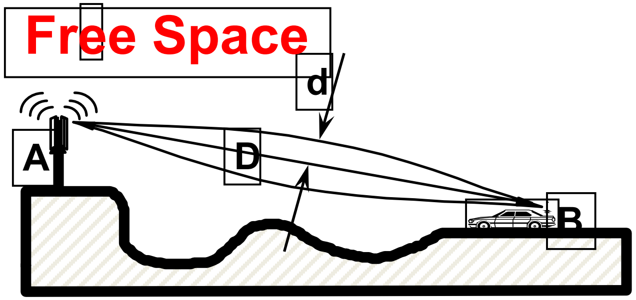
- Free Space
- Propagation over flat earth
- Diffraction single and multiple knife Edge
- Effective Antenna Height
- Log distance path loss
- Egli Model
- Young
- Lee
- Okamura
- Hata-Okamura
- Cost 231-Hata
- Cost 231 Walfisch-Ikegami
- Micro-cell propagation Lee
- Irregular Terrain Model ITM
- TIREM/SEM
- Microwave Link
- Multipath Fading

Theoretically derived: Free Space; Propagation over flat earth; Diffraction single and multiple knife Edge

Empirically derived: Effective Antenna Height through Micro-cell propagation Lee

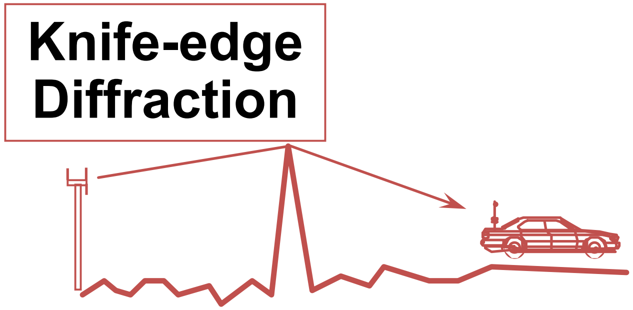
Database driven: Irregular Terrain Model ITM; TIREM/SEM

In Wireless systems main sources of propagation losses:



- **Free space**
  - No reflections or obstructions
    - first Fresnel Zone clear
  - Signal decays 20 dB/decade

- **Reflection (prop. Over flat Earth)**
  - Signal decays 30-40 dB/decade



- **Knife-edge diffraction**
  - Direct path is blocked by obstruction

Free Space Path Loss

$$P_r = \frac{P_t\, G_t\, G_r\, \lambda^2}{(4\pi)^2\ d^2}$$

P_r is the received power in watts;

P_t is the transmitter power in watts;

G_t and G_r are the transmitter and receiver antenna gains respectively, in real dimensionless terms; equal 1 to determine generic path loss;

λ is the wavelength in meters, where **λ** is related to frequency **f** by **c/f**, where **f** is in Hertz, **c** is the speed of light in meters per second, (300,000,000); and

d is the distance in meters.

$$\frac{P_r}{P_t} = \text{Free Space Path Loss (FSPL)} = \frac{\lambda^2}{(4\pi)^2\ d^2}$$

Free Space Loss (dB)= 36.5 +20*Log$_{10}$(F$_{MHZ}$)+20Log$_{10}$(Dist$_{MILES}$)

Free Space Loss (dB) = 32.44+20*Log$_{10}$(F$_{MHZ}$) + 20Log$_{10}$(Dist$_{Km}$)

20 db per decade of distance or frequency

Note Free space formulas work only when the Fresnel Zone is not obstructed by any obstacles

Propagation Over flat Earth

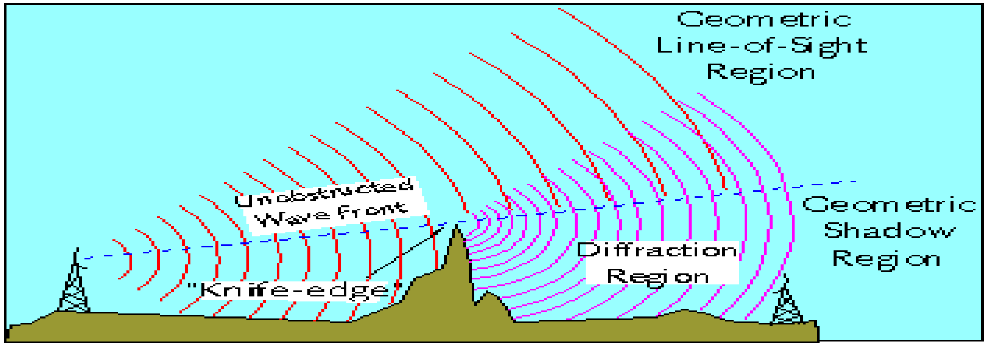
In cases where there is Reflections we Get about 40 db/decade of loss based on:

$$\text{Path Loss [dB]} = 172 + 34 \times \text{Log}(D_{Miles}) - 20 \times \text{Log}(\text{Base Ant. Ht}_{Feet}) - 10 \times \text{Log}(\text{Mobile Ant. Ht}_{Feet})$$

The decay rates are in real life are somewhere between 30 and 40 dB per decade of distance, that is some where between free space, and Reflection formulas above.

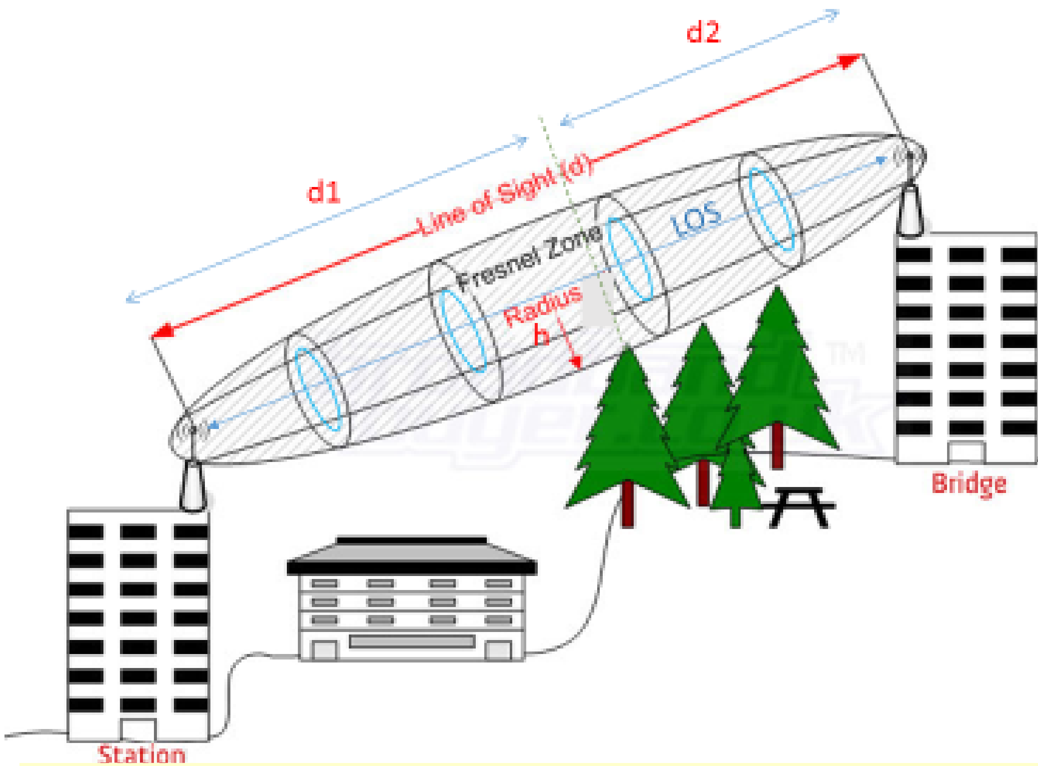
Diffraction

- A physical phenomena based on Huygens's Principle that make signal propagate into the geometrical shadow of an object that is placed in its path
- It is important to allow for signal to reach to receivers behind buildings and other locations that are obstructed from the LOS to transmitter (including mountains, or large objects)
- Modeling Diffraction is difficult, but it is simplified using knife Edge model of object (i.e. assumes object is sharp)



knife-edge effect

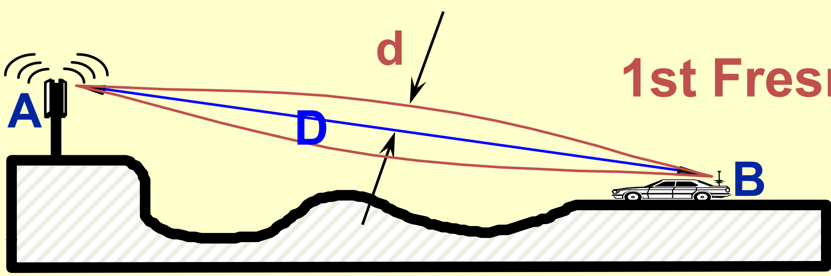
Diffraction (and Fresnel Zones) Continued



- Picture shows Fresnel Zones around LOS
- Zones are segmented typically into n zones
- These n zones have radius of:

$$h_n = \left(\frac{n\lambda d_1 d_2}{d_1 + d_2}\right)^{\frac{1}{2}}$$

- The heights in Equation above valid for d1,d2 >>h which is usually the case when away from Tx or Rx
- Equations of height found from differences in length of paths of LOS vs. from Tx. To Diffraction object to Rx
- d1, d2 are distances to obstruction point to be analyzed



1st Fresnel Zone

First Fresnel Zone =
{ any point x where Ax + xB - AB < λ/2 }

Fresnel Zone radius d = 1/2 (λD)^(1/2)

Diffraction Single Knife Edge (continued)

- The losses can be calculated as follows:
  - Step 1: Calculate Fresnel Kirdroff Parameter: $v = h_o \left(\frac{2(d_1+d_2)}{\lambda d_1 d_2}\right)^{\frac{1}{2}}$

    With h_o the height of the object above LOS

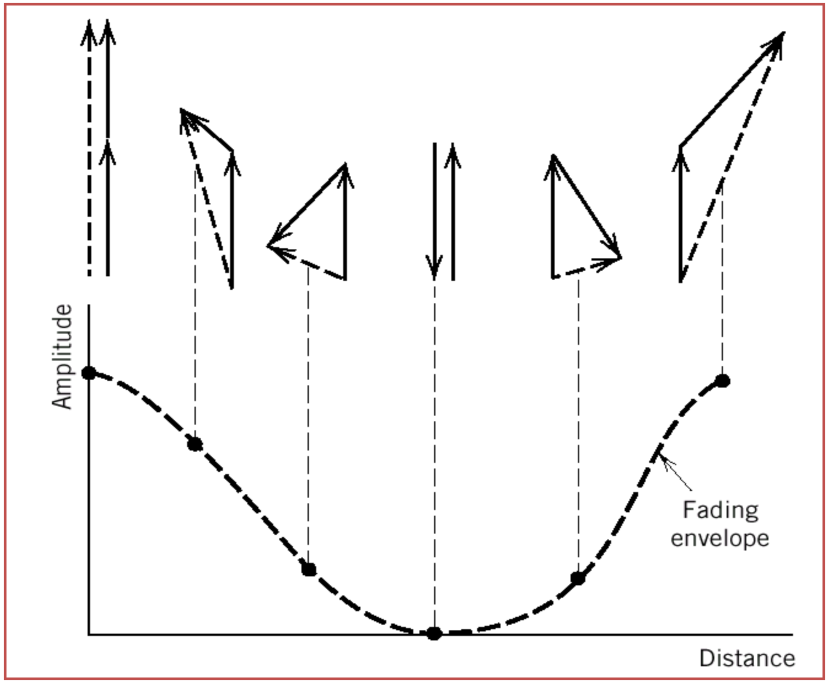
  - Step 2: Use the Table below to determine dB loss due to diffraction in the shadow area of the signal reaching the receiver

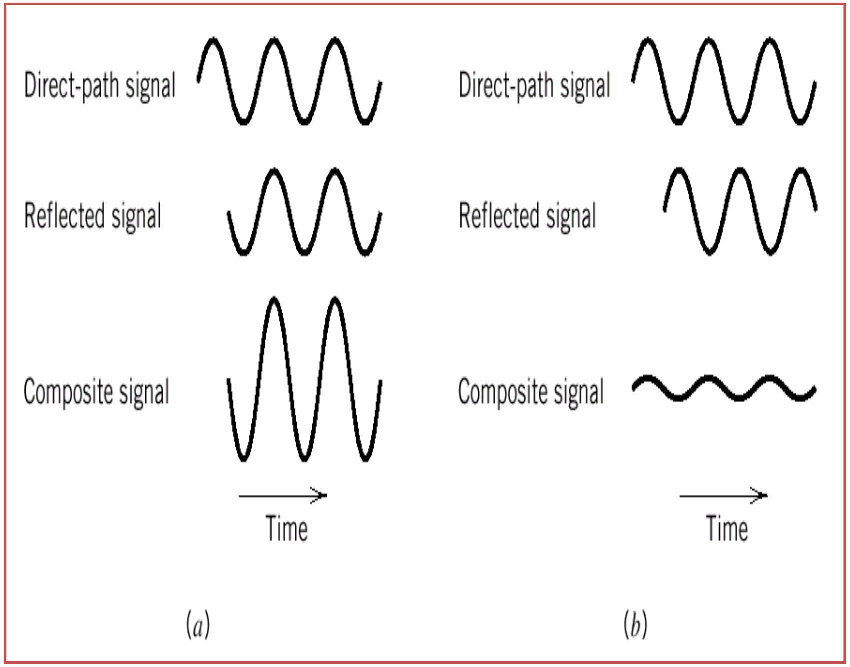
Fresnel Kirdroff Parameter v range	Loss due to diffraction in the path in (dB)
$v < -1$	0
$-1 \leq v < 0$	$20\log(0.5 - 0.62v)$
$0 \leq v < 1$	$20\log(0.5\exp(-0.95v))$
$1 \leq v < 2.4$	$20\log(0.4 - \sqrt{0.1184 - (0.38 - 0.1v)^2})$
$2.4 \leq v$	$20\log(0.225/v)$

Multipath Fading

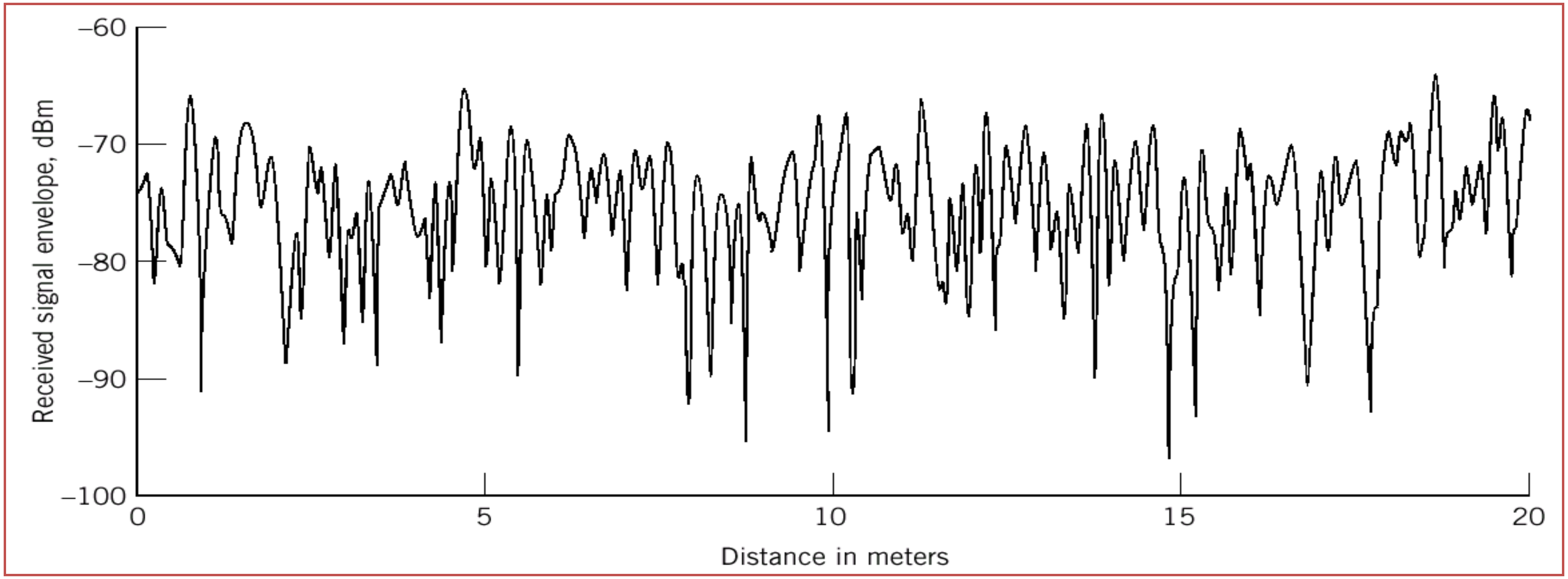
- In addition to the three main elements of propagation losses mentioned in last slides, there is also, Multi Path Causes:

  - The first is Slow Fading which occurs as the mobile node moves around hundreds of wavelengths due to shadowing by local obstructions

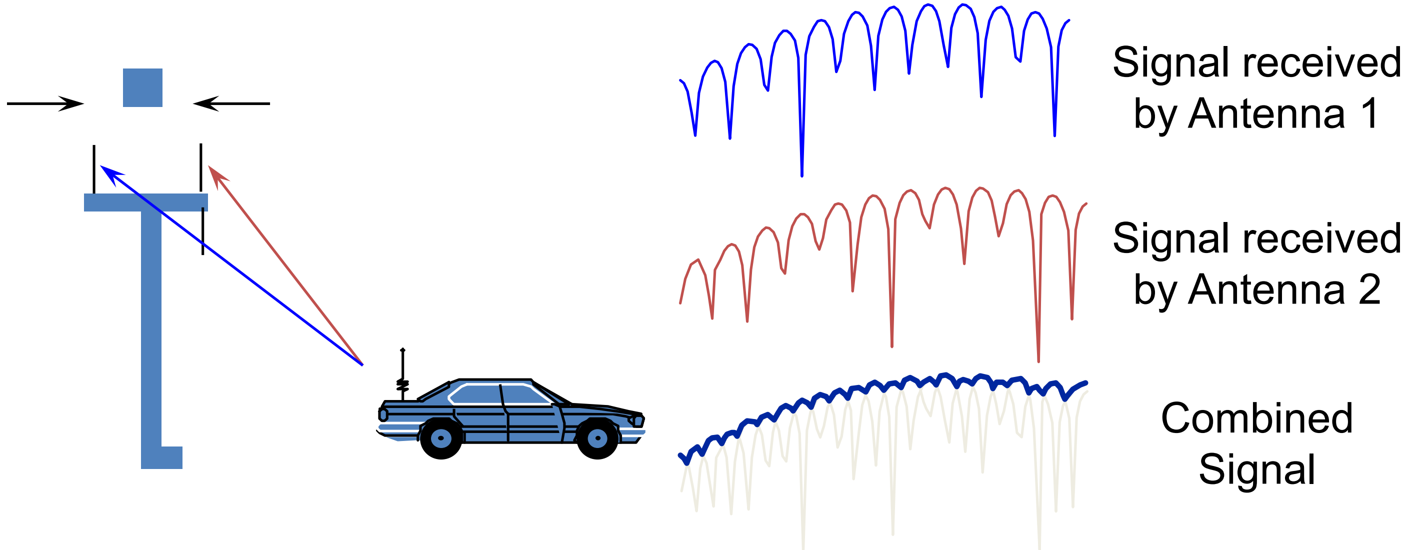


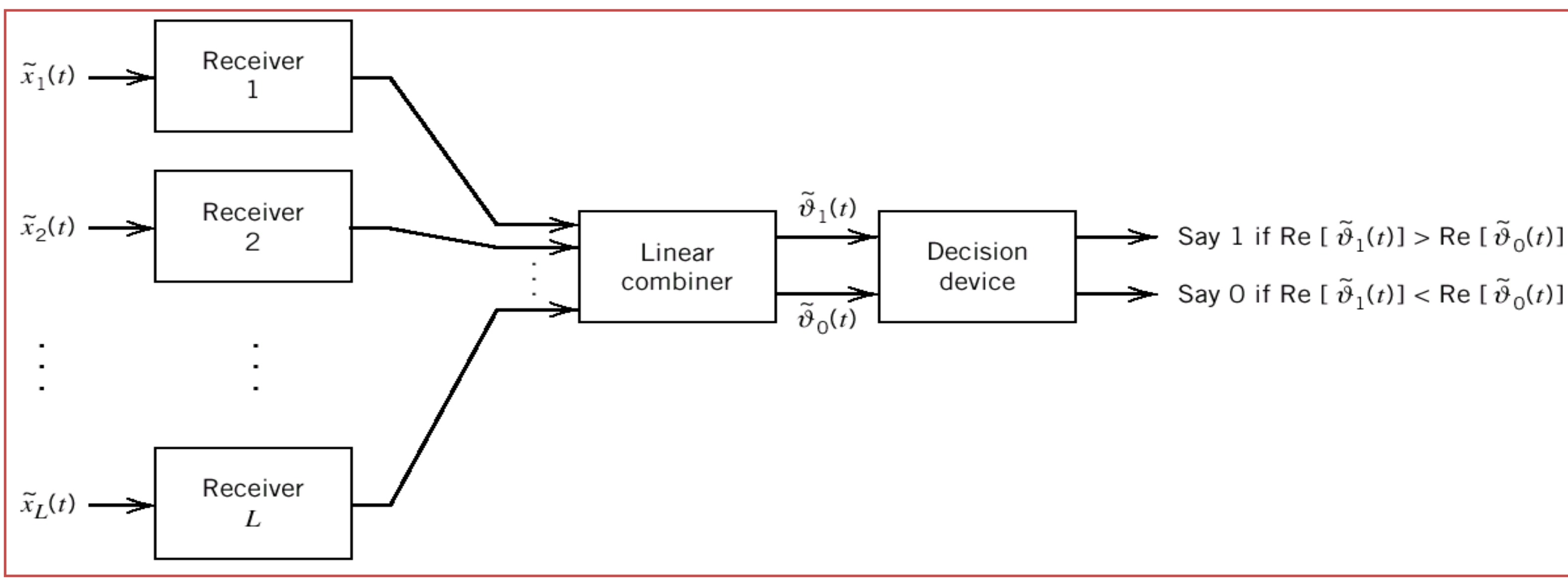


- The second is Fast Fading occurs as signals received from many paths drift into and out of phase
  - –the fades are about **λ/2** apart in space: 7 inches apart at 800 MHz., 3 inches apart at 1900 MHz
  - –fades appear in frequency and time domains
  - –Commonly 10-15 db deep,
  - –**Rayleigh distribution** is a good model for these fades and hence called Rayleigh Fades



The Multi Path Fading can be reduced via space diversity..Using two receiving antennas separated by 10-20λ Which is 5-10 ft. For the PCS 1900 MHz.





In addition to space diversity techniques, polarization diversity techniques also exist

ANTENNA

Why Antennas Are Important

- Antenna directivity may enhance spectrum sharing and frequency reuse.
- Antenna radiation pattern knowledge is necessary for spectrum analyses to prevent interference from occurring.
- To achieve desired system performance in network planning.

Antennas for Wireless Communications

DISH

OMNI

PLANE

IMPORTANT ANTENNA TERMS

Beamwidth

Mainlobe

Backlobe

Gain

Polarization

Sidelobe

Reciprocity

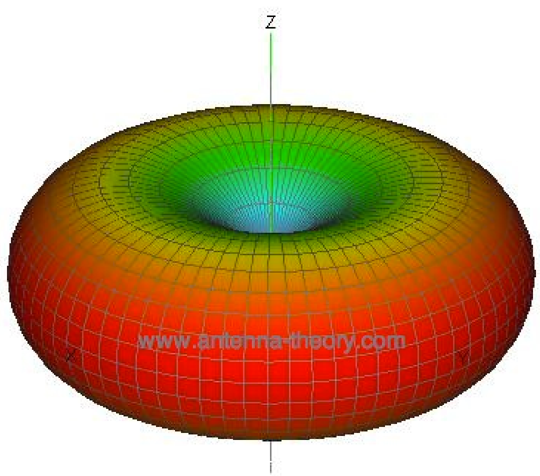
Null

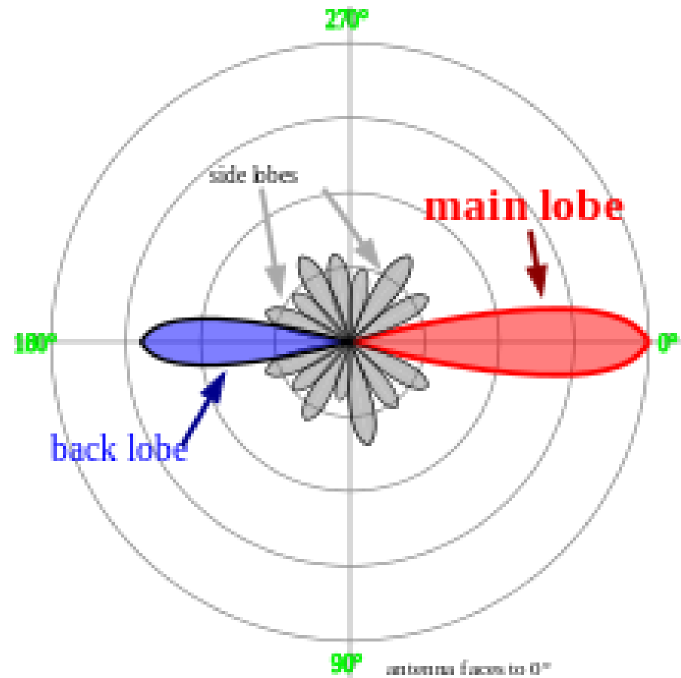
What Is Antenna Gain?

- **ITU definition: 1.160 *gain of an antenna*:** The ratio, usually expressed in decibels, of the power required at the input of a loss-free reference antenna to the power supplied to the input of the given antenna to produce, in a given direction, the same field strength or the same power flux-density at the same distance.
- **Reference antenna**: isotropic (dBi) or dipole (dBd)
- **dBi = dBd + 2.15**
- **dBd = dBi - 2.15**

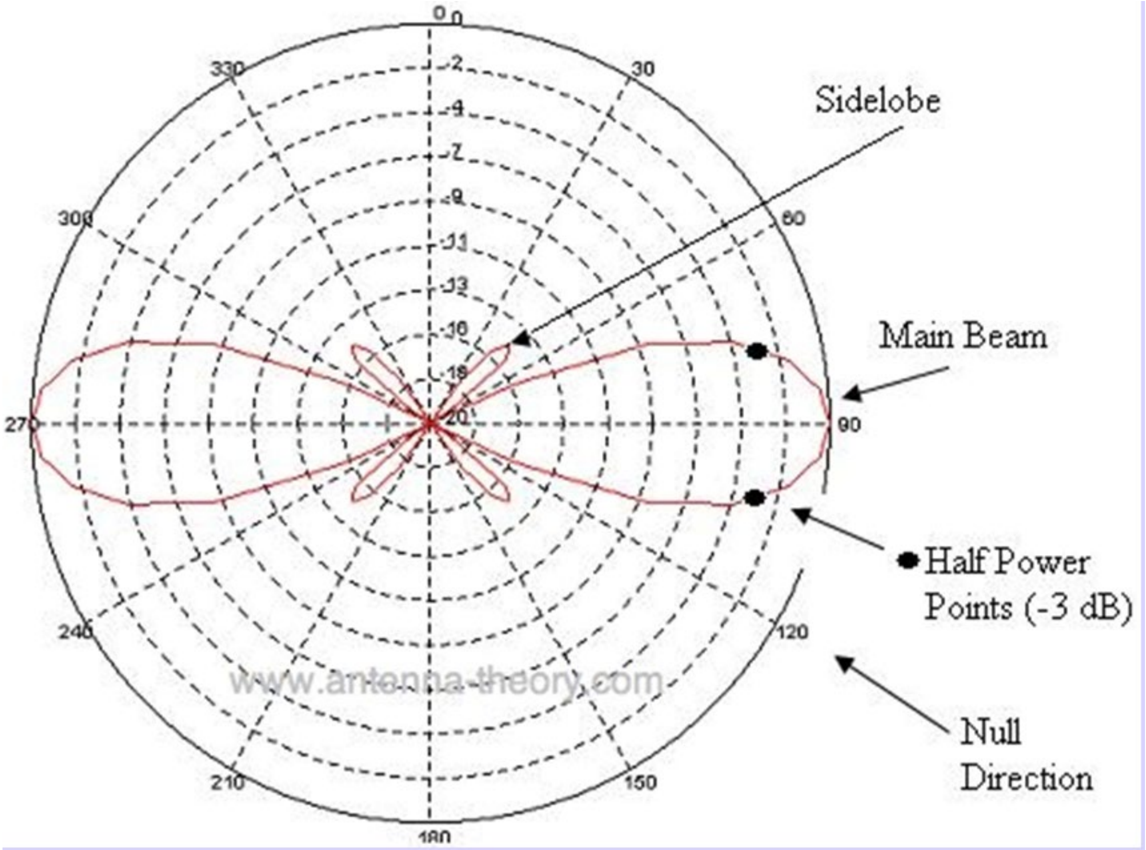
REFERENCES FOR GAIN OF ANTENNAS

- **ISOTROPIC ANTENNA (dBi):** Unity Gain
- **DIPOLE (dBd)** : Actual antenna (figure 8 pattern) gain = 1.64



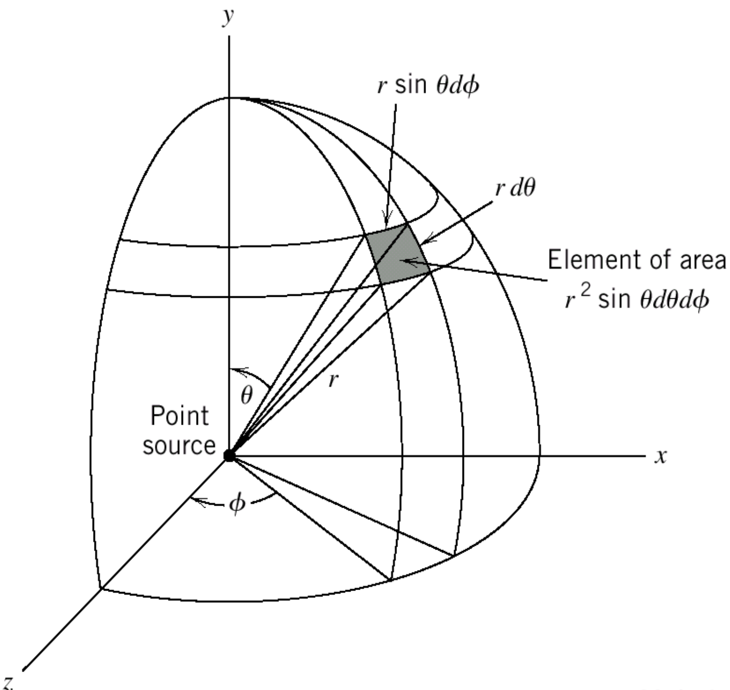


TYPICAL ANTENNA PATTERN

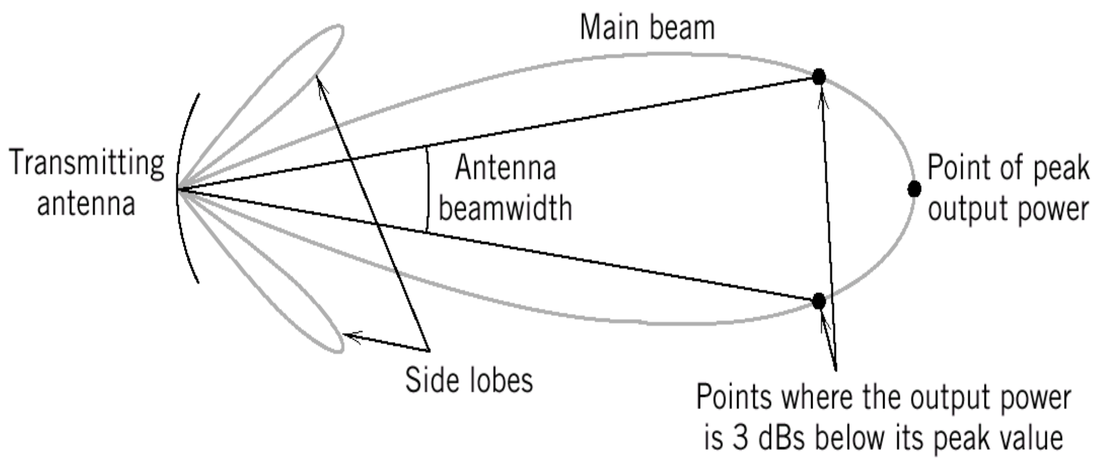


Horizontal (Azimuth) Plane Top View

Using spherical Geometry and point sources, it is possible to derive the formula for any directional or isotropic antennas. The Effective Radiated Power referenced to an isotropic source (EIRP) is given by: (where P_t is the transmitted power, and the G_t is the Gain specified for the transmitting antenna)



$$EIRP = P_t G_t \text{ Watts}$$



Gain of the antenna is determined by many factors but it is mainly due to focusing the radiation .. Like a flash light. In general smaller beam width give higher gain.

EXAMPLE EIRP CALCULATION

Transmitter output power = 300 watts

Antenna gain = 15 dBi

Calculation:

Transmitter power = 54.8 dBm

EIRP = 54.8 dBm + 15 dBi = 69.8 dBm

SECOND EXAMPLE EIRP CALCULATION

FM Broadcasting Station Authorized 50 KW

Transmitter output power = 10 kilowatts (KW)

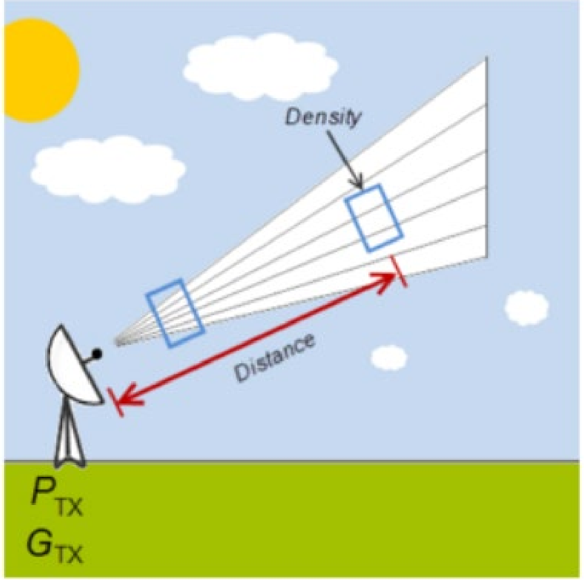
Antenna gain = 5 (linear units)

Calculation:

Transmitter power = 50

EIRP = 10 x 5 = 50 KW

Field Strength Power Density



$$P_D = \frac{P_t\, G_t}{4\pi\ R^2}$$

where:

P_D is power density w/m^2

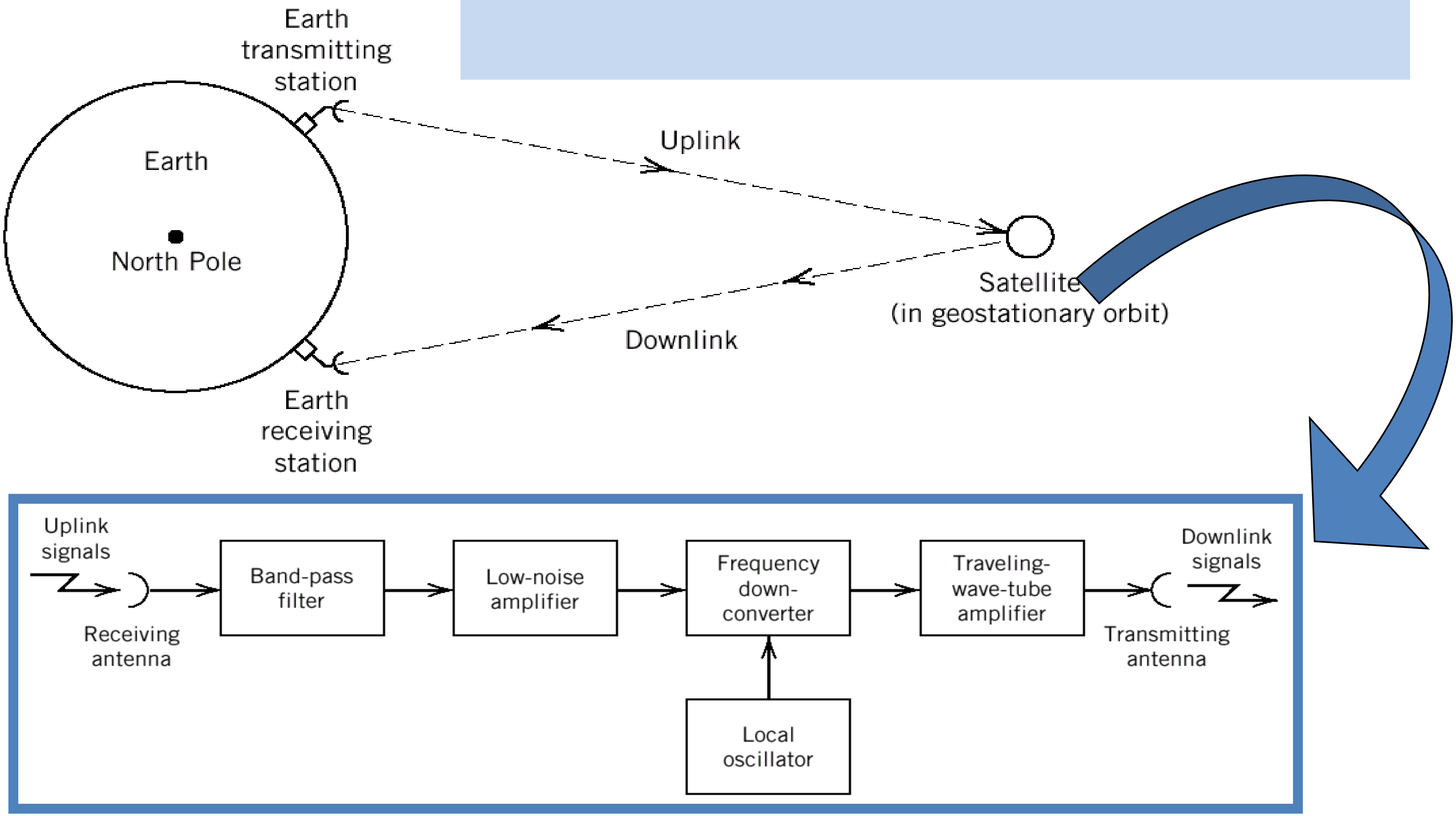
P_t is transmitter power in watts

G_t is antenna gain in real terms

R is distance in meters

APPLICATIONS AND EXAMPLES

Satellite Communications is essential for relaying signals over wide areas from one earth station to the other or for Broadcasting to many ground terminals



Example of satellite operation: A satellite transmits (or relays a signal) and an earth antenna receives it). Given the following information:

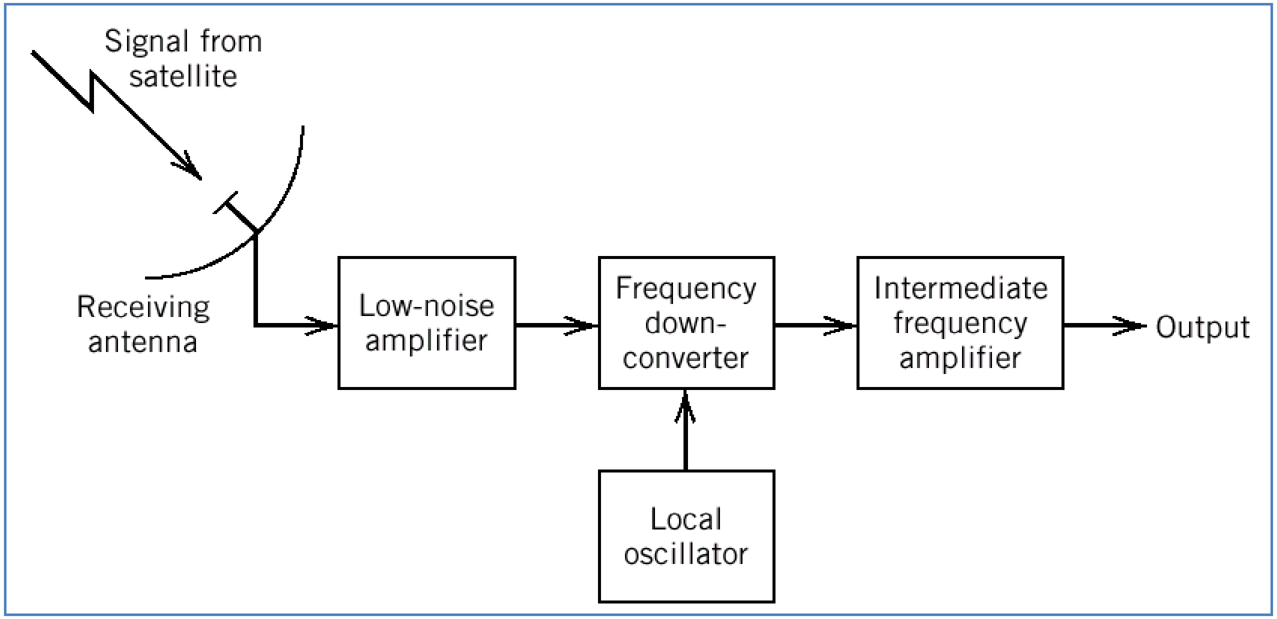
$EIRP_{satellite}$= 44668.36 watts radiated satellite power, or 46.5 in dBW

G_r=31622.78 or 45 dB which is the receiver antenna specified gain from manufacturer spec sheet.

T=107.5 K which is the effective noise temperature as seen at the receiver.

d=40,000,000 meters (or 40000 Km) distance from a Geo Sat to surface of the earth

f=12,000,000 hz (or 12 Ghz) typical L band frequency



The carrier to noise density ratio is an important performance measure in communication systems. So for this satellite example it is found at the receiving antenna:

$$\left(\frac{C}{N_0}\right)_{earth\_antenna} = EIRP_{satellite}\left(\frac{G_r}{T}\right)_{earth\_antenna}\left(\frac{\lambda}{4\pi d}\right)^2 \frac{1}{k}$$

In the above used the fact that C is defined as the carrier or signal power at the receiver end, also $EIRP=G_t*P_t$ (radiated power from satellite), and $N_0=kT$ from previous lecture, as the noise density at the receiver.

Taking the $10\log_{10}$ of both sides of the above so that to convert to db, and substituting all the parameter values given, we get:

$10\log_{10} EIRP$	$= 46.5dBW$
$10\log_{10}(\frac{G_r}{T})$	$= 24.7dB/K$
$-10\log_{10}\left(\frac{4\pi d}{\lambda}\right)^2$	$= -206dB$
$-10\log_{10} k$	$= 228.6dbW/K-Hz$
$10\log_{10}(C/N_0)$	$= 93.8dB-Hz$

Using the fact that C is the power and $E_b = C/f_b$ where f_b is the bit rate in bits/sec then:

$$10\log_{10}(C/N_0) = 10\log_{10}(E_b f_b/N_0) = 10\log_{10}(E_b/N_0) + 10\log_{10}(f_b)$$

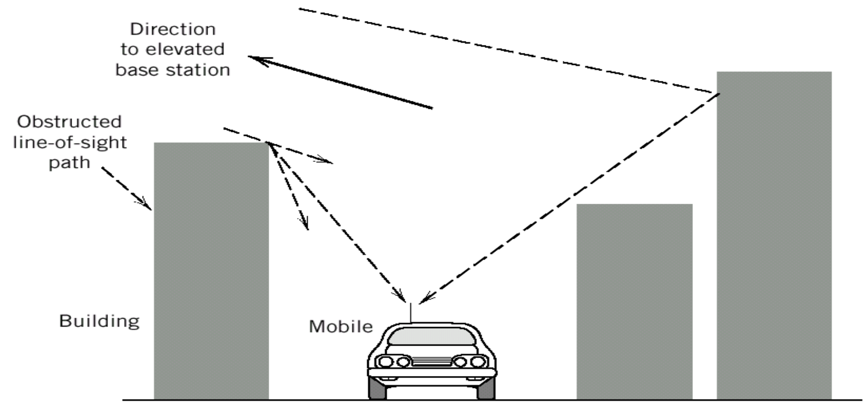
Hence if given a data rate of f_b =33.9 Mb/s or 75.3 dBHz, we get that $10\log_{10}(E_b/N_0)$=93.8-75.3=18.5 dB

- Wireless communications (Cellular/PCS) is similar to Sat communications but with some differences. One of which is the propagation losses sources.
- In Wireless we have to worry more about:
  - Objects that are bigger than a wavelength can reflect or obstruct RF energy
  - RF energy can enter into a building or vehicle if they have openings a wavelength in size, or greater

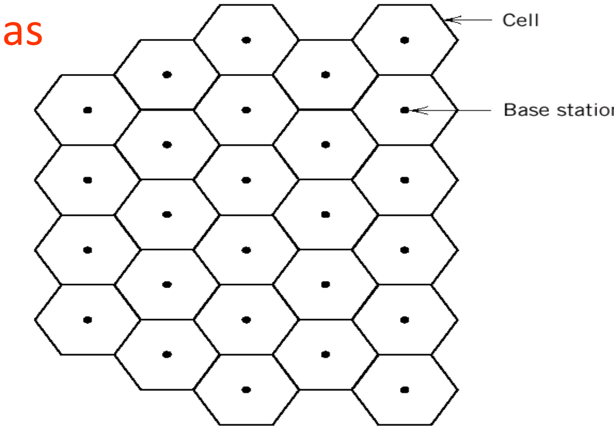
Example

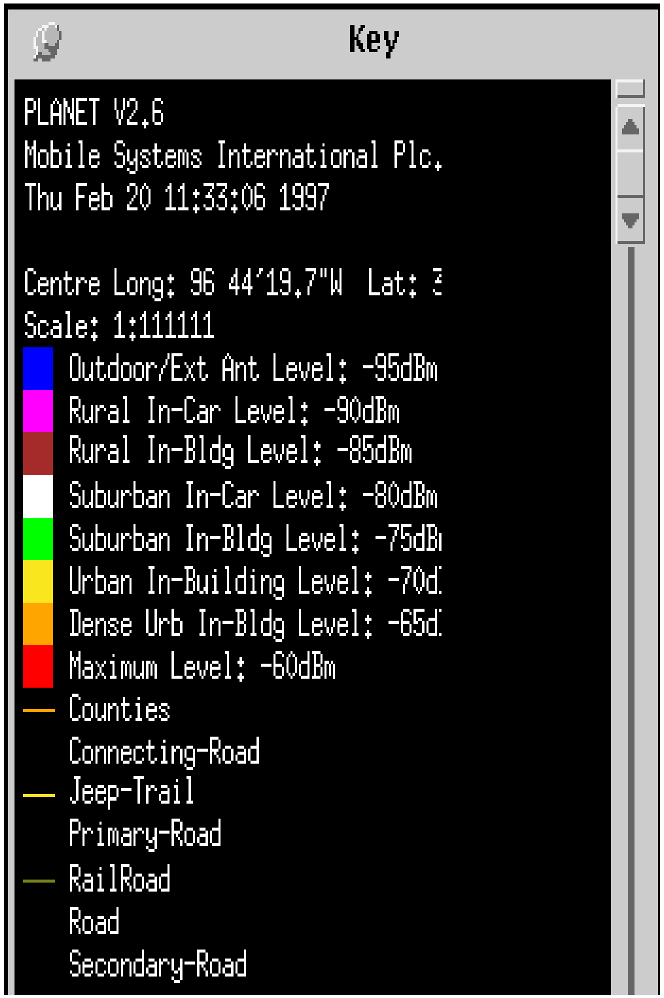
for PCS-1900:   F = 1960 MHz

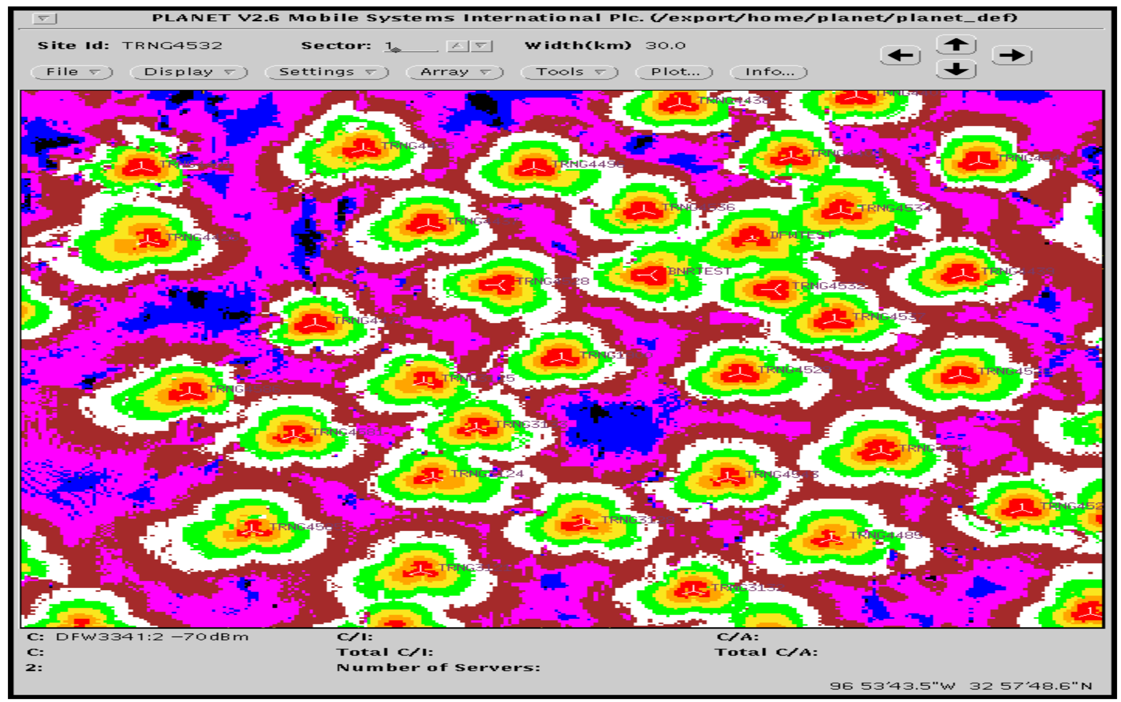
λ = 0.153 m = 6.0 inches



Typical outputs from Simulation tools such as Planet used to design PCS systems

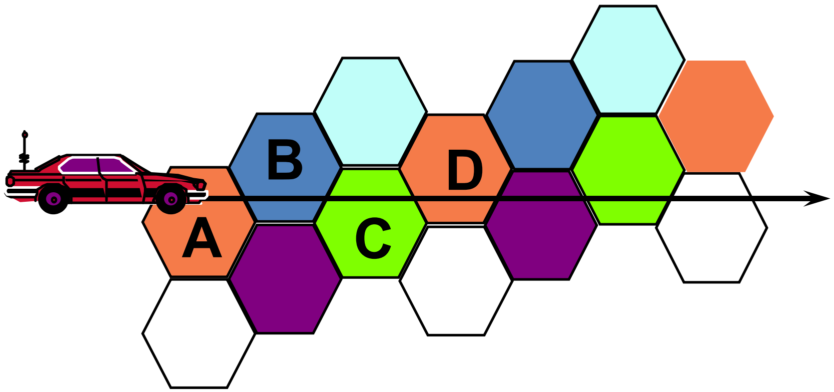






Handoffs and C/I

- One purpose of handoff is to keep the call from dropping as the mobile moves out of range of individual cells
- Another purpose of handoff is to ensure the mobile is using the cell with the best signal strength and best C/I at all times
- Notice in the signal graphs at lower right how the mobile's C/I is maintained at a usable level as it goes from cell to cell



Tech-nology	Modulation Type	Channel Bandwidth	Quality Indicator
AMPS	Analog FM	30 kHz.	C/I ≅ 17 dB
NAMPS	Analog FM	10 kHz.	C/I ≅ 17 dB
TDMA	DPQSK	30 kHz.	C/I ≅ 17 dB
GSM	GMSK	200 kHz.	C/I ≅ 17 dB
CDMA	QPSK/OQPSK	1,250 kHz.	$E_b/N_o \cong 6$dB