Satellite Communications

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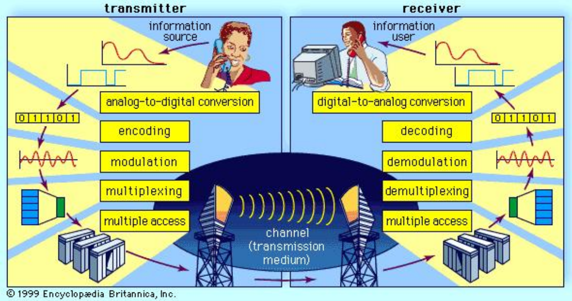
Example of an analog communication system



Main components:

1. signal
2. transmitting channel (cable, *radio*)
3. electronics (amplifiers, filters, modems, etc)

and a lot of engineering!

Outline

1. Signal processing elements
   - Signal $\equiv$ information!
   - Source coding (dealing with the information content)
   - Modulation
   - Multiplexing
2. Propagation and radio communications
   - Introduction to radio communications
   - Radiowave propagation
   - Examples of antennas
3. Engineering
   - Noise
   - Link budget

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Main *types* of satellite → different *types* of information

- *Astronomical* satellites: used for the observation of distant planets, galaxies, and other outer space objects.
- *Navigational* satellites [GPS, Galileo, Beidou]: they use radio time signals transmitted to enable mobile receivers on the ground to determine their exact location (positioning).
- *Earth observation* satellites: used for environmental monitoring, meteorology, map making (Sentinel 2).
- *Miniaturized* satellites: satellites of unusually low masses and small sizes. For example, for educational purposes (OUFTI-1/2).
- *Communications* satellites: stationed in space for the purpose of telecommunications. Modern communications satellites typically use geosynchronous orbits, or Low Earth orbits (LEO).

Types of data streams

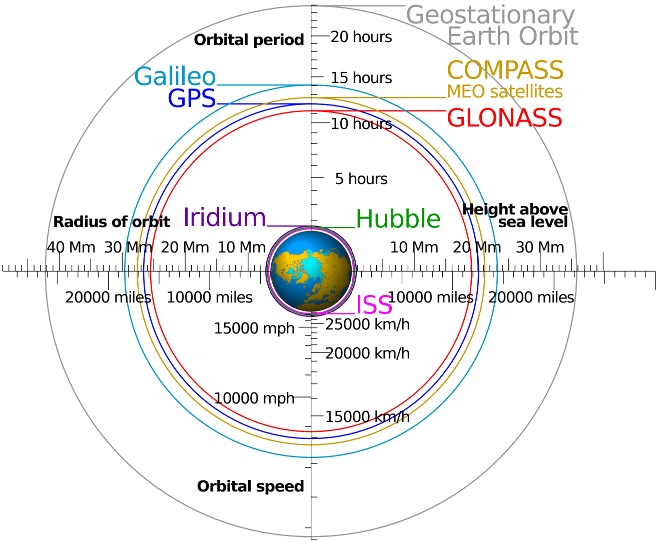
Types of data	Characteristics
Control data	Must be very reliable
Payload	Unicast communication for mobile ground station
▷ Measurements	Accurate signals with constant monitoring
▷ Remote sensing data	High volume of downstream data
▷ Localization data	Accurate time reference (synchronization)
▷ Broadcasting	Digital television channels
▷ Digital data	Voice + data (Internet) for remote areas

Because the purposes of data sent are different, the mechanisms to transmit the data are designed according to the constraints.

Simplified *typography* of data streams:

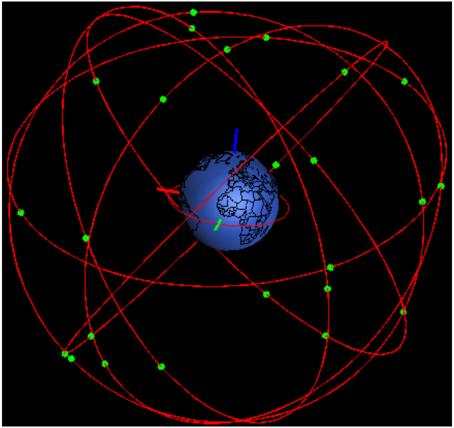
- control data (this communication channel needs a backup!)
- payload (+ some unavoidable *overhead*)

Positioning systems



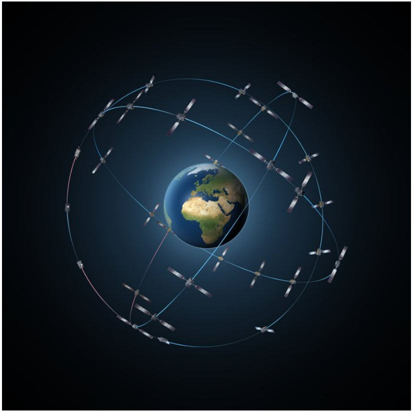
Example: constellation of GPS satellites

- 6 planes with a 55° angle with the equator, spaced by 60° and with 4 satellites per plane (24 satellites in total)
- Located on high orbits (but sub-geostationary)/revolution in 12 hours
- Transmitting power of 20 to 50 [W]



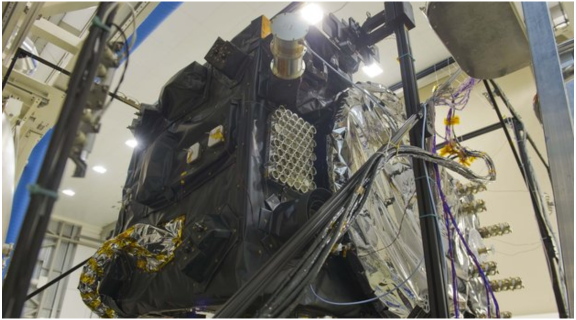
Galileo I

- Orbital altitude: 23,222 [km] (MEO - Medium Earth Orbit)
- 3 orbital planes, 56° inclination, separated by 120° longitude
- Constellation of 30 satellites (with working 24 [3x8] satellites and 6 [3x2] spares)



Deployment of Galileo

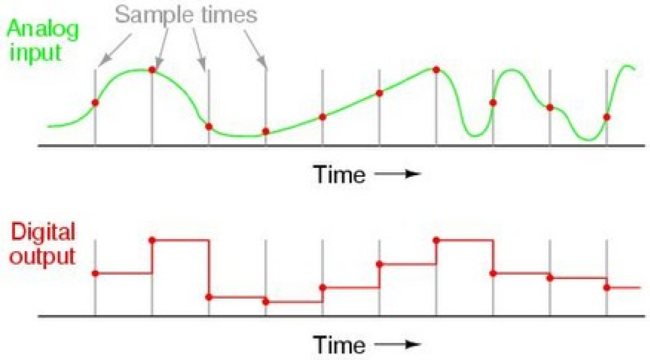
- First launches: 2 satellites in October 2011, 2 satellites in October 2012. These were test satellites.
- First *Full Operational Capability* satellite launched in November 2013.
- August 2014, two more satellites (but ... injected on a wrong orbit).
- November 2019: 23 satellites fully operational, 3 for testing or not available.



Main issues related to signals

1. Signal source handling (*preparation of the signal*, at the source, in the transmitter):
   - filtering (remove what is useless for communications)
   - **analog ↔ digital (digitization)**
   - remove the redundancy in the signal: compression
2. Signal over the channel:
   - signal shaping to make it suitable for transmission (*coding*, *modulation*, *multiplexing*, etc)
   - signal power versus the noise signal (protect the signal against noise effects)

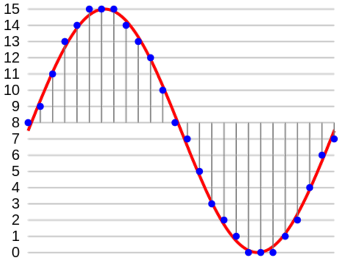
Digitization I



Reasons for going digital:

1. possibility to **regenerate** a digital signal
2. **better bandwidth usage**

Digitization II



Digitization $=$ from analog to digital

analog	digital
$g(t)$	samples $g[iT]$, with $i = 0, 1, 2, \ldots$ and $T =$ a time period
signal over time	*sampling rate*
	$\Rightarrow$ series of *samples*
	each sample is coded with n bits (*quantization*)
	in the end, we have a bit stream: 01110...

Digitization III

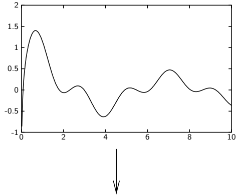
Digitization in numbers:

1. f_s: sampling frequency
   - Let W be the highest frequency of the signal to be converted
   - theoretical lower bound: $f_s > 2\,W$ [SHANNON/NYQUIST theorem]
   - practical rule (NYQUIST criterion): $f_s > 2.2\,W$
2. n: number of bits par sample (quantization)
3. bit rate $= f_s \times n$

signal	band	W	f_s	n	bit rate
units	Hz	Hz	sample/s	b/sa.	b/s
audio (telephone)	[300 Hz, 3400 Hz]	3400 Hz	8000 sa./s	8	64 kb/s
audio (CD)	[0 Hz, 20 kHz]	20 kHz	44.1 ksa./s	16	705.6 kb/s

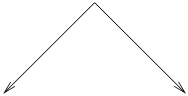
Analog and digital signals: don't confuse *information* and its *representation*!

Analog information signal



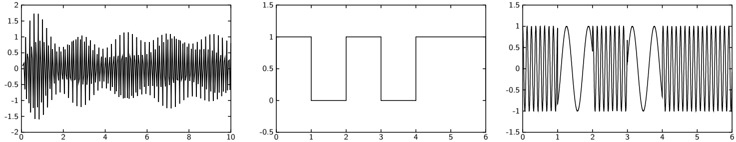
Digital information signal

1 0 1 0 1 1



Analog representation

Analog representation



Characterization of signals over the channel

Analog signal	Digital signal
bandwidth [Hz]	bit rate [bit/s]
Signal to Noise Ratio (S/N or SNR)	Bit Error Rate (BER)
bandwidth of the underlying channel [Hz]	

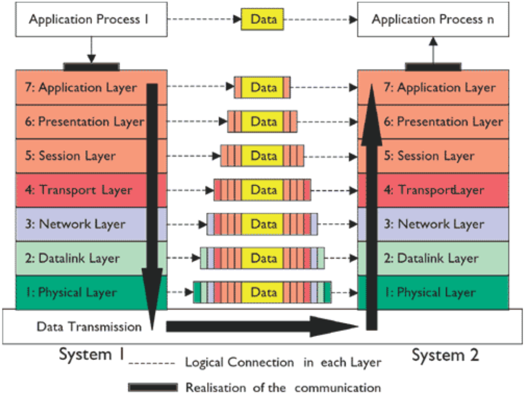
Reasons for going digital:

- possibility to **regenerate** a digital signal
- **better bandwidth usage**

Example (better bandwidth usage: from analog to digital television)

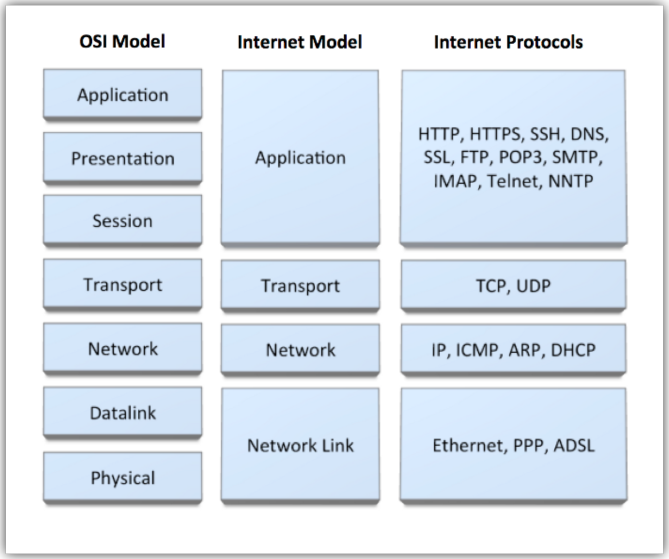
- analog PAL television channel: bandwidth of 8 [MHz]
- digital television, PAL quality ~ 5 [Mb/s]
  - With a 64-QAM modulation, whose *spectral efficiency* is 6 b/s per Hz. A bandwidth of 8 [MHz] allows for 48 [Mb/s].
  - Conclusion: thanks to digitization, there is room for 10 digital television channels instead of 1 analog television channel.

Software organization of a transmitter/receiver: the OSI reference model



Consequence: encapsulation ⇒ overhead

OSI reference model vs Internet model (+ some corresponding Internet protocols)



Elements of a communication system I

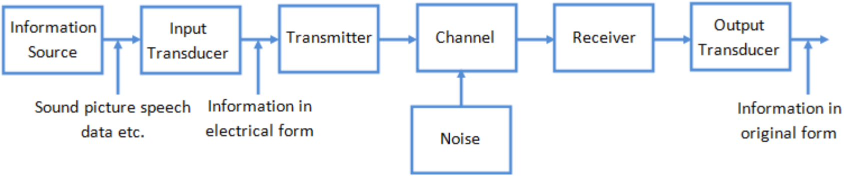


Figure : Block diagram of a communication channel for a **single signal/user** (no sharing of the channel).

Elements of a communication system II

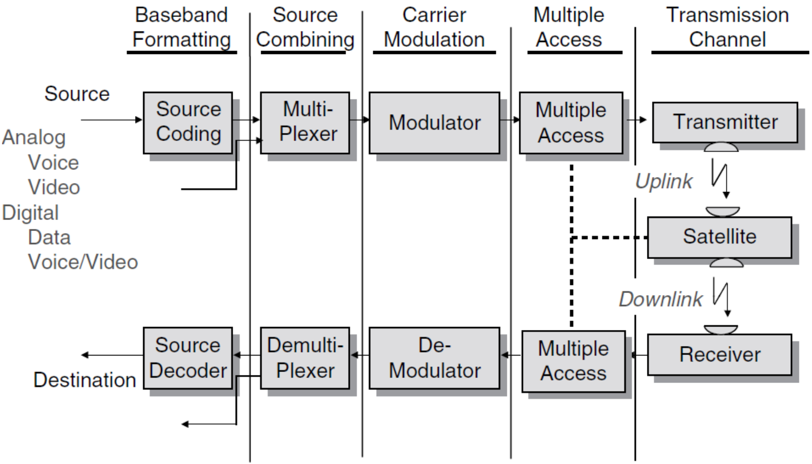


Figure : Block diagram of a communication channel for **multiple users** (multiplexing, modulation and multiple access are added).

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Information theory and channel capacity: there is a *maximum* bit rate (the sky is not the limit...)! I

Theorem (Shannon-Hartley)

The channel capacity C (condition for the Bit Error Rate $BER \rightarrow 0$) is expressed in bits (of information) per second and given by

$$C\,[b/s] = W \log_2\left(1 + \frac{S}{N}\right) \quad (1)$$

where

- W is the channel bandwidth in Hz
- $\frac{S}{N}$ the Signal to Noise ratio (in watts/watts, not in dB).

Consequences of the capacity theorem

Let R_b be the bit rate [b/s] and E_b the energy per bit [Joule/b], we have $S = E_b R_b$ [W], and $N = N_0 W$ (where N_0 is the noise spectral power density; $N_0 = k_B T$ as shown later). Therefore:

$$C = W \log_2 \left(1 + \frac{E_b}{N_0} \frac{R_b}{W}\right) \qquad (2)$$

The ratio $\frac{R_b}{W}$ is defined as the *spectral efficiency* η given in [b/s] per [Hz].

Consequences: **3 degrees of freedom** (but not more)

1. the $\frac{E_b}{N_0}$ ratio. We only have control over E_b (it is our own design); N_0 is not under control.
2. the spectral efficiency $\eta = \frac{R_b}{W}$ (which depends on the technology $\rightarrow$ this is also our choice).
3. for a fixed $\frac{E_b}{N_0}$ ratio and spectral efficiency, C can only be increased by increasing the bandwidth. But the bandwidth W is a scarce resource.

Impact of errors on the transmission: bit/packet error rate

Assume a packet of size N and let P_e be the probability error on one bit ($\equiv$ Bit Error Rate, BER).
The probability for the packet to be correct is

$$(1 - P_e)^N. \tag{3}$$

Therefore the *packet error rate* is

$$P_P = 1 - (1 - P_e)^N. \tag{4}$$

For large packets and small P_e, this becomes

$$P_P \simeq 1 - (1 - NP_e) = N \times P_e. \tag{5}$$

Example

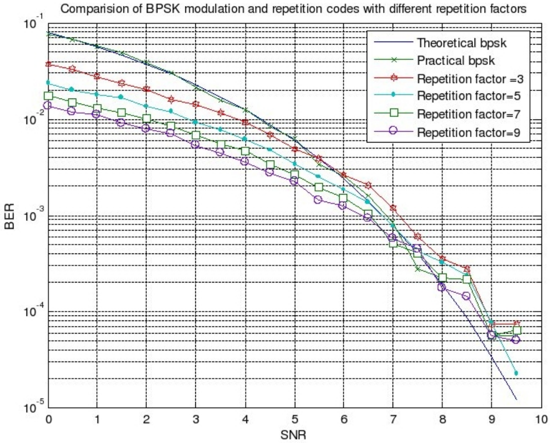
With $N = 10^5$ bits and a bit error rate of $P_e = 10^{-7}$, $P_P \simeq 10^{-2}$.

We thus need to lower P_e $\Rightarrow$ error detection/correction mechanisms

Forward Error Coding

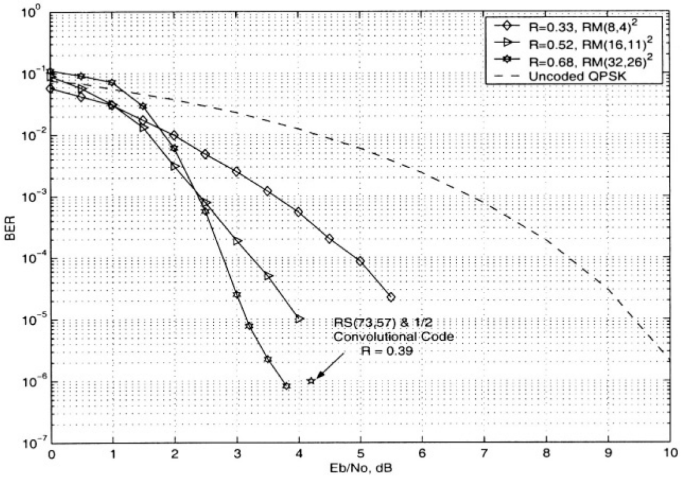
A simplistic example of Forward Error Coding (*FEC*) consists to transmit each data bit 3 times, known as a (3,1) repetition code.

Received bits	Interpreted as
000	0 (error free)
001	0
010	0
100	0
111	1 (error free)
110	1
101	1
011	1



Other forward error codes

- Hamming code
- Reed–Solomon code
- Turbo code, ...



Outline

Modulation: principles

Principle

Modulation is all about using of a carrier cosine at frequency f_c for transmitting information. The carrier is $A_c \cos(2\pi f_c t)$

Frequency modulation [FM]

$$s(t) = A(t) \cos(2\pi f(t)t + \phi(t))$$

Amplitude

Phase

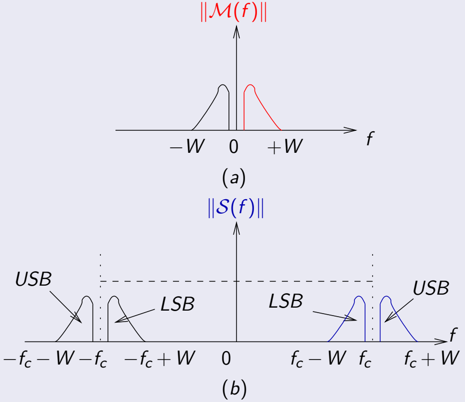
Amplitude modulation [AM]

Phase modulation [PM]

Consequences of modulation

- frequency band is shifted towards the carrier frequency ($\Rightarrow f_c$)
- bandwidth modification, compared to that of the modulating signal $m(t)$

Effects of Amplitude Modulation on the spectrum ($s(t) = A_c m(t) \cos(2\pi f_c t)$)



Demodulation of an AM modulated signal: principles

Received signal: $s(t) = m(t)\cos(2\pi f_c t)$. Task: recover $m(t)$.

Principles of a synchronous demodulation. At the receiver:

1. acquire a local, synchronous, copy of the carrier f_c $\Rightarrow$ build a local copy of $\cos(2\pi f_c t)$
2. multiply $s(t)$ by $\cos(2\pi f_c t)$:
   $[\cos a \cos b = \frac{1}{2}\cos(a-b) + \frac{1}{2}\cos(a+b)]$

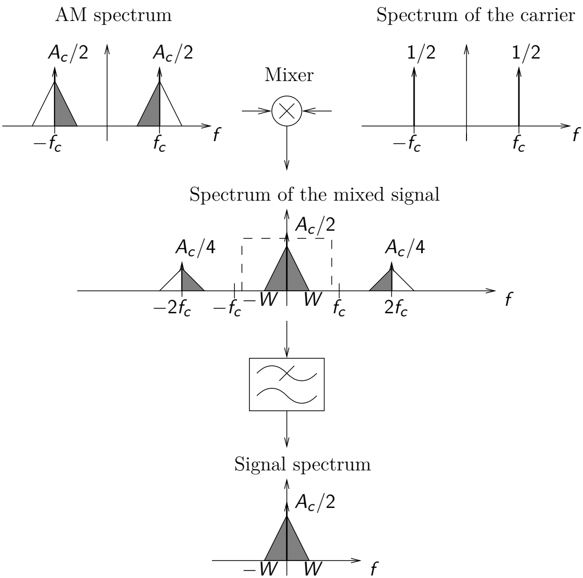
$$s(t)\cos(2\pi f_c t) = m(t)\cos^2(2\pi f_c t) \quad (6)$$

$$= m(t)\left[\frac{1}{2} + \frac{1}{2}\cos(2\pi(2f_c)t)\right] \quad (7)$$

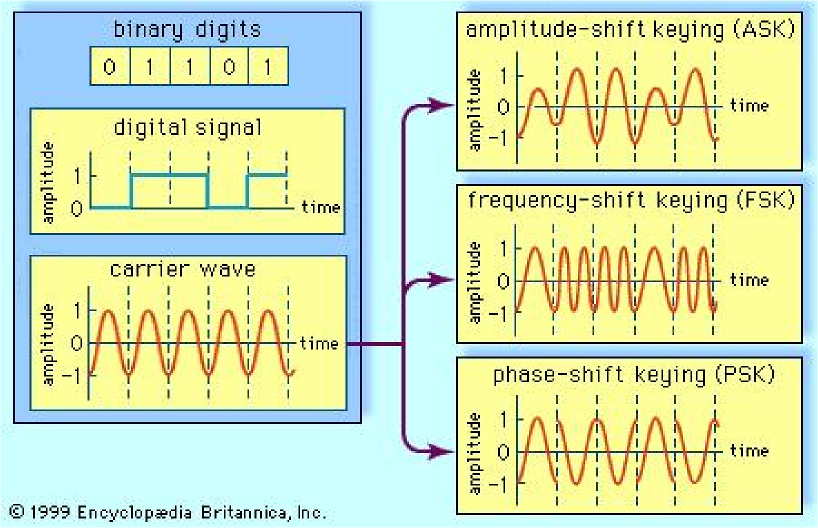
$$= \frac{1}{2}m(t)) + \frac{1}{2}m(t)\cos(2\pi(2f_c)t)] \quad (8)$$

3. filter out the $2f_c$ components $\rightarrow \frac{1}{2}m(t)$

Demodulation of an AM modulated signal: interpretation in the spectral domain



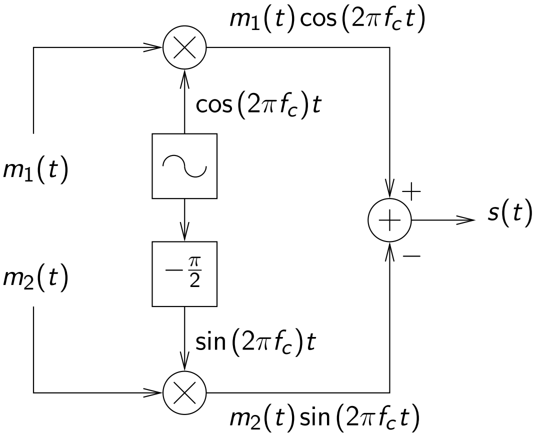
Basic digital modulation (coding) techniques



Quadrature modulation

It is possible to use **both** a cosine and a sine:

$$s(t) = m_1(t)\cos(2\pi f_c t) - m_2(t)\sin(2\pi f_c t) \qquad (9)$$



Quadrature demodulation: principles

$s(t) = m_1(t)\cos(2\pi f_c t) + m_2(t)\sin(2\pi f_c t)$ is the modulated signal.

We want to recover $m_1(t)$ and $m_2(t)$

- *Step 1:* multiply by $\cos(2\pi f_c t)$
  [remember that $\cos a \times \cos b = \frac{1}{2}\cos(a-b) + \frac{1}{2}\cos(a+b)$ and that $\cos a \times \sin a = \frac{1}{2}\sin(2a)$]

$$\begin{aligned} s(t) \times \cos(2\pi f_c t) &= m_1(t)\cos^2(2\pi f_c t) + m_2(t)\sin(2\pi f_c t)\cos(2\pi f_c t) \\ &= \frac{1}{2}m_1(t) + \frac{1}{2}m_1(t)\cos(2\pi(2f_c)t) + \frac{1}{2}m_2(t)\sin(2\pi(2f_c)t) \end{aligned}$$

- *Step 2:* filter to keep the baseband signal

$$\frac{1}{2}m_1(t)$$

- *Steps 3 and 4:* multiply by $\sin(2\pi f_c t)$ and low-pass filter to get $m_2(t)$

Purposes of the quadrature modulation

There are 2 *possible uses/advantages* for a quadrature modulation:

1. [*Bandwidth savings* by a factor of 2]
   Send two signals in the same bandwidth

   $$s(t) = m_1(t)\cos(2\pi f_c t) + m_2(t)\sin(2\pi f_c t) \tag{10}$$

   Both $m_1(t)\cos(2\pi f_c t)$ and $m_2(t)\sin(2\pi f_c t)$ have exactly the same bandwidth, that is $[f_c - W, f_c + W]$ where W denotes the original bandwidth of $m_1(t)$ and $m_2(t)$.
2. [*Easier demodulation*]
   A coherent demodulation of $m(t)\cos(2\pi f_c t + \phi_c)$ requires the perfect knowledge of f_c and ϕ_c at the receiver. However, it is sometimes difficult to synchronize the receiver. Therefore,

   $$s(t) = m(t)\cos(2\pi f_c t + \phi_c) + m(t)\sin(2\pi f_c t + \phi_c) \tag{11}$$

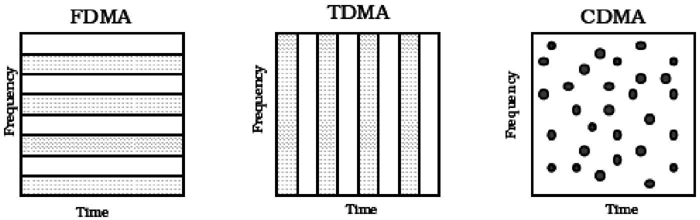
   is sometimes used.
   At the receiver, $m(t)$, the signal of interest can be obtained by $\sqrt{m^2(t)\cos^2(.) + m^2(t)\sin^2(.)} = |m(t)|$.

Outline

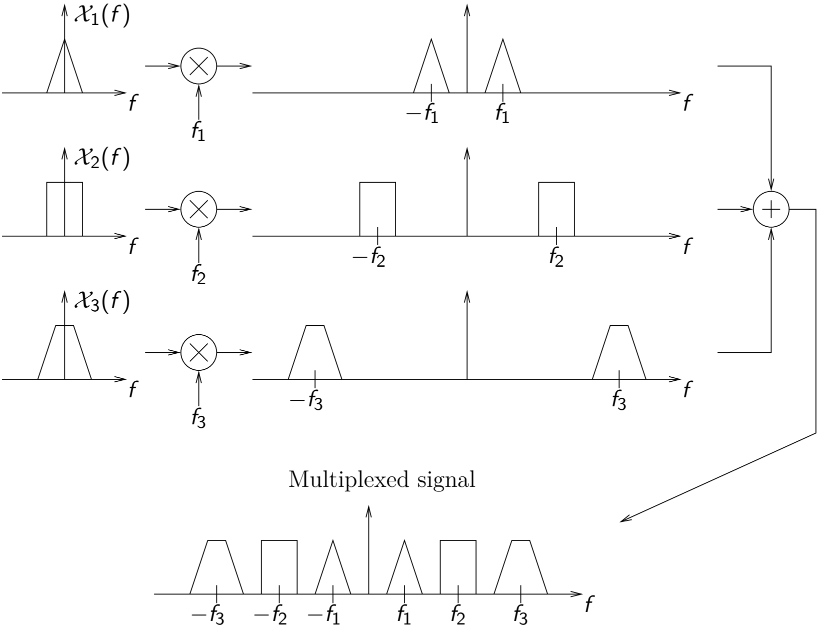
Multiplexing: combining several sources

Mechanisms to share resources between users:

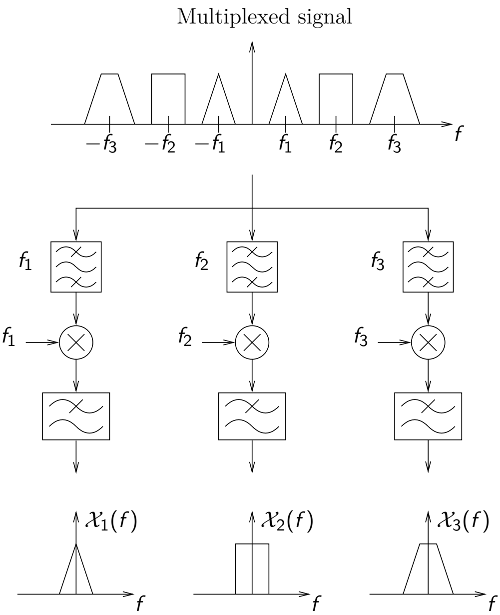
- Frequency Division Multiplexing (FDM)
- Time Division Multiplexing (TDM)
- Code Division Multiplexing (CDM)
- Space Division Multiplexing
- + combinations !



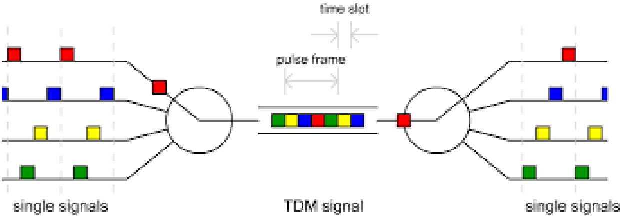
Frequency Division Multiplexing (FDM)

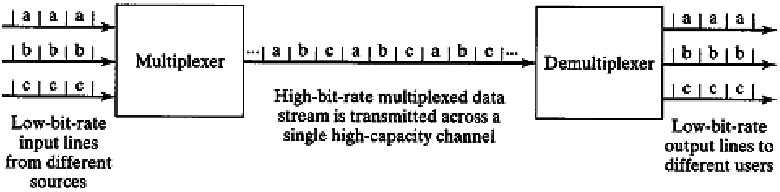


Demultiplexing



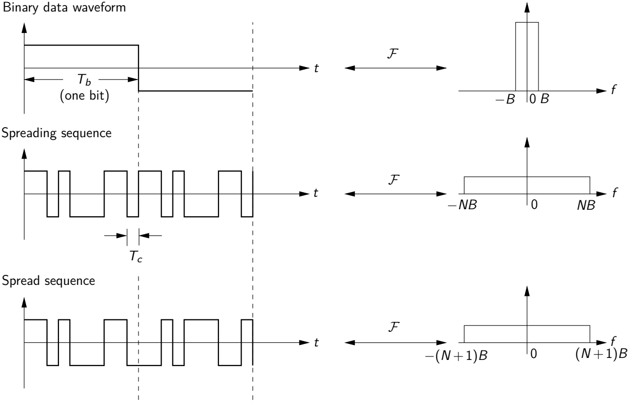
Time Division Multiplexing (TDM)





Spread spectrum for Code Division Multiplexing

Principle of spread spectrum: multiply a digital signal with a faster pseudo-random sequence (spreading step)

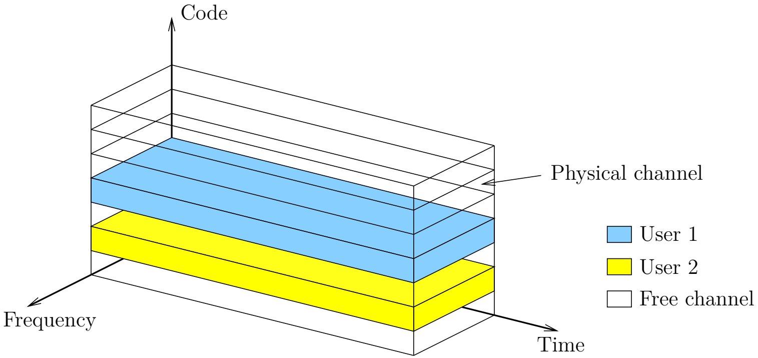


At the receiver, the *same*, *synchronized*, pseudo-random sequence is generated and used to despread the signal (despreading step)

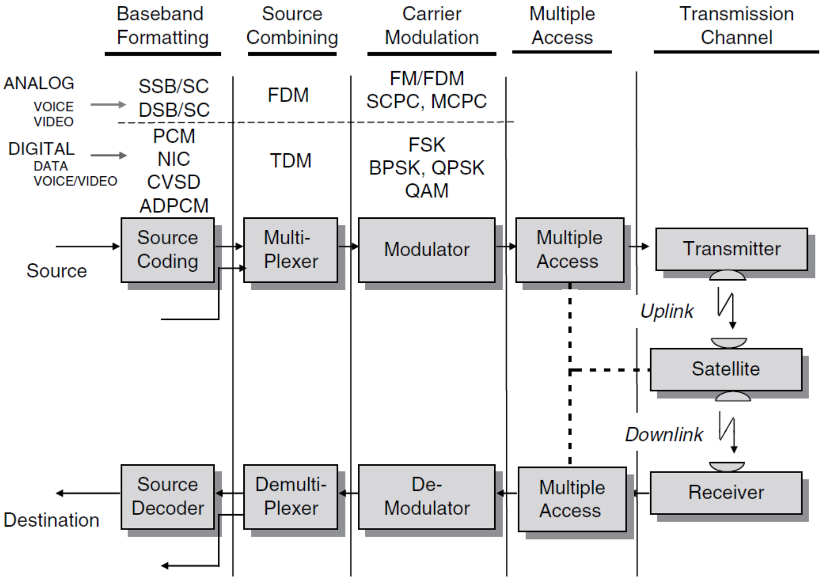
Code Division Multiple Access

- Each user is given its own code (multiple codes can be used simultaneously).
- All the users occupy the same bandwidth

→ very convenient when the number of users is dynamic



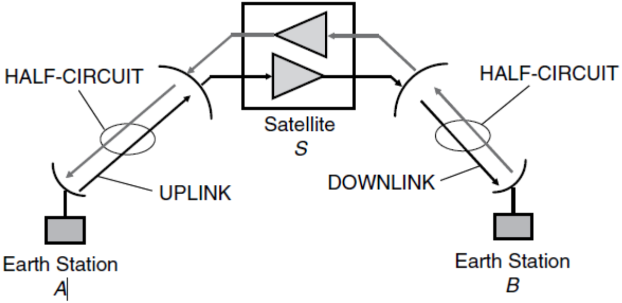
Summary



Baseband Formatting
Source Combining
Carrier Modulation
Multiple Access
Transmission Channel
ANALOG
VOICE
VIDEO
SSB/SC
DSB/SC
FDM
FM/FDM
SCPC, MCPC
DIGITAL
DATA
VOICE/VIDEO
PCM
NIC
CVSD
ADPCM
TDM
FSK
BPSK, QPSK
QAM
Source
Source Coding
Multi-Plexer
Modulator
Multiple Access
Transmitter
Uplink
Satellite
Downlink
Receiver
Destination
Source Decoder
Demulti-Plexer
De-Modulator
Multiple Access

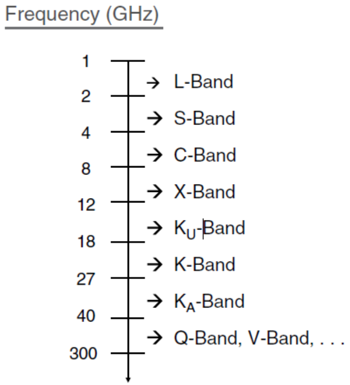
Outline

Satellite link definition



CHANNEL – one way link from $A \rightarrow B$ or $B \rightarrow A$
CIRCUIT – full duplex link – $A \rightleftarrows B$
HALF CIRCUIT – two way link – $A \rightleftarrows S$ or $S \rightleftarrows B$
TRANSPONDER – ▷ basic satellite repeater electronics, usually one channel

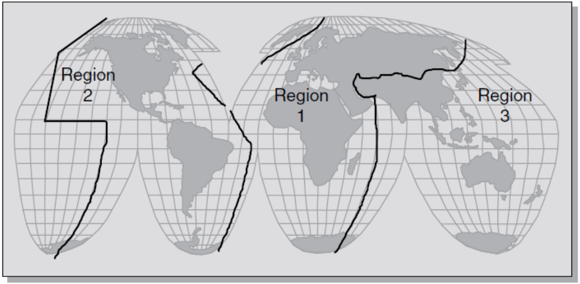
Frequency bands



But it is also common to designate the carrier frequency and bandwidth directly.

Regulatory bodies

- International Telecommunications Union (ITU): Radio-communications Sector (ITU-R)
  - service regions



  - organizes WARC (World Administrative Radio Conference) - worldwide allocation of frequencies
- Regional body: European Conference of Postal and Telecommunications Administrations (CEPT)

Excerpt of the allocation plan/radio spectrum (by the ITU)

1610-1670 MHz (UHF)					
International Table			United States Table		Remarks
Region 1	Region 2	Region 3	Federal Government	Non-Federal Government	
1610-1610.6 MOBILE-SATELLITE (Earth-to-space) AERONAUTICAL RADIONAVIGATION S5.341 S5.355 S5.359 S5.363 S5.364 S5.366 S5.367 S5.368 S5.369 S5.371 S5.372	1610-1610.6 MOBILE-SATELLITE (Earth-to-space) AERONAUTICAL RADIONAVIGATION RADIODETERMINATION-SATELLITE (Earth-to-space) S5.341 S5.364 S5.366 S5.367 S5.368 S5.370 S5.372	1610-1610.6 MOBILE-SATELLITE (Earth-to-space) AERONAUTICAL RADIONAVIGATION Radiodetermination-Satellite (Earth-to-space) S5.341 S5.355 S5.359 S5.364 S5.366 S5.367 S5.368 S5.369 S5.372	1610-1610.6 MOBILE-SATELLITE (Earth-to-space) US319 AERONAUTICAL RADIONAVIGATION US260 RADIODETERMINATION-SATELLITE(Earth-to-space) S5.341 S5.364 S5.366 S5.367 S5.368 S5.372 US208		Satellite Communications (25) Aviation (87)
1610.6-1613.8 MOBILE-SATELLITE (Earth-to-space) RADIO ASTRONOMY AERONAUTICAL RADIONAVIGATION S5.149 S5.341 S5.355 S5.359 S5.363 S5.364 S5.366 S5.367 S5.368 S5.369 S5.371 S5.372	1610.6-1613.8 MOBILE-SATELLITE (Earth-to-space) RADIO ASTRONOMY AERONAUTICAL RADIONAVIGATION RADIODETERMINATION-SATELLITE (Earth-to-space) S5.149 S5.341 S5.364 S5.366 S5.367 S5.368 S5.370 S5.372	1610.6-1613.8 MOBILE-SATELLITE (Earth-to-space) RADIO ASTRONOMY AERONAUTICAL RADIONAVIGATION Radiodetermination-satellite (Earth-to-space) S5.149 S5.341 S5.355 S5.359 S5.364 S5.366 S5.367 S5.368 S5.369 S5.372	1610.6-1613.8 MOBILE-SATELLITE (Earth-to-space) US319 RADIO ASTRONOMY AERONAUTICAL RADIONAVIGATION US260 RADIODETERMINATION-SATELLITE (Earth-to-space) S5.341 S5.364 S5.366 S5.367 S5.368 S5.372 US208		
1613.8-1626.5 MOBILE-SATELLITE (Earth-to-space) AERONAUTICAL RADIONAVIGATION Mobile-satellite (space-to-Earth) S5.341 S5.355 S5.359 S5.363 S5.364 S5.365 S5.366 S5.367 S5.368 S5.369 S5.371 S5.372	1613.8-1626.5 MOBILE-SATELLITE (Earth-to-space) AERONAUTICAL RADIONAVIGATION RADIODETERMINATION-SATELLITE (Earth-to-space) Mobile-satellite (space-to-Earth) S5.341 S5.364 S5.365 S5.366 S5.367 S5.368 S5.370 S5.372	1613.8-1626.5 MOBILE-SATELLITE (Earth-to-space) AERONAUTICAL RADIONAVIGATION Mobile-satellite (space-to-Earth) Radiodetermination-satellite (Earth-to-space) S5.341 S5.355 S5.359 S5.364 S5.365 S5.366 S5.367 S5.368 S5.369 S5.372	1613.8-1626.5 MOBILE-SATELLITE (Earth-to-space) US319 AERONAUTICAL RADIONAVIGATION US260 RADIODETERMINATION-SATELLITE (Earth-to-space) Mobile-satellite (space-to-Earth) S5.341 S5.364 S5.365 S5.366 S5.367 S5.368 S5.372 US208		

Frequency allocations [2]

Radio-communications service	Typical up/down link	Terminology
Fixed satellite service (FSS)	6/4 [GHz]	C band
	8/7 [GHz]	X band
	14/12.1 [GHz]	Ku band
	30/20 [GHz]	Ka band
	50/40 [GHz]	V band
Mobile satellite service (MSS)	1.6/1.5 [GHz]	L band
	30/20 [GHz]	Ka band
Broadcasting satellite service (BSS)	2/2.2 [GHzz]	S band
	12 [GHzz]	Ku band
	2.6/2.5 [GHz]	S band

- Note that *frequencies for down links are* usually *lower than for up links*: this is because the power loss increases with the frequency.
- The *use of higher frequencies* allows larger bandwidths, better tracking capability, and minimizes ionospheric effects. But it also requires greater pointing accuracy

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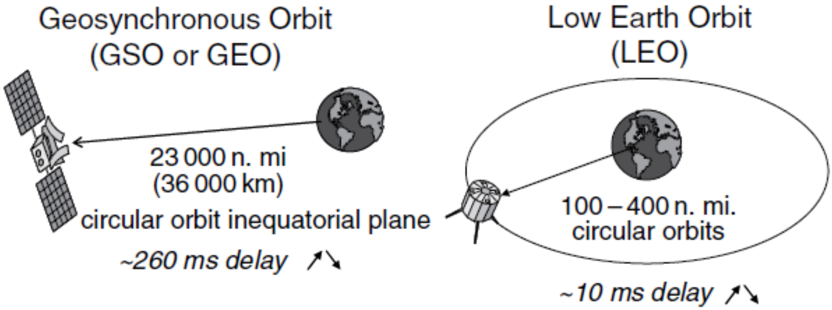
Orbits



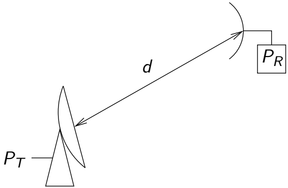
Engineering considerations:

- distance between user and satellite.
  - delay (increases with the distance)
  - attenuation of the signal (increases with the distance)
- relative position of the user/satellite pair (orientation)

Outline

1. Signal processing elements
   - Signal ≡ information!
   - Source coding (dealing with the information content)
   - Modulation
   - Multiplexing
2. Propagation and radio communications
   - Introduction to radio communications
   - Radiowave propagation
   - Examples of antennas
3. Engineering
   - Noise
   - Link budget

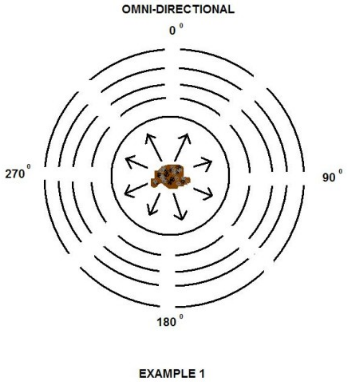
Radiowave propagation

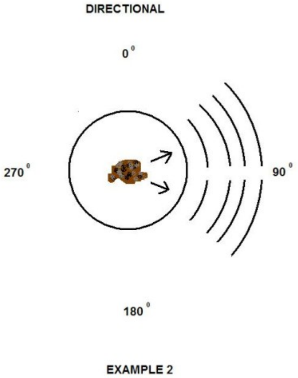


Important issues:

- channel characteristics
  - attenuation (distance)
  - atmospheric effects
    - wave polarization
    - rain mitigation
- antenna design
- power budget (related to the Signal to Noise ratio)

Two main types of radiation pattern





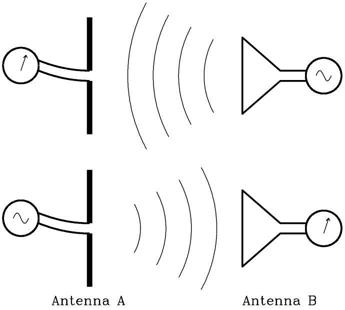
Reciprocity

Theorem (Reciprocity for antennas)

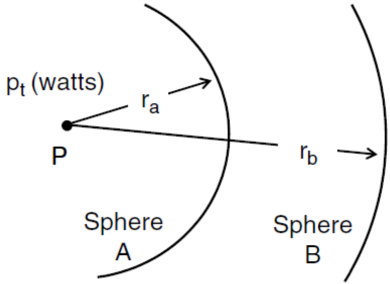
The electrical characteristics of an antenna such as gain, radiation pattern, impedance, bandwidth, resonant frequency and polarization, are the same whether the antenna is transmitting (T) or receiving (R).

Theorem (Strong reciprocity)

If a voltage is applied to an antenna A and the current is measured at another antenna B, then an equal current (in both amplitude and phase) will appear at A if the same voltage is applied to B.



Inverse square law of radiation



The *power flux density* (or *power density*) S, over the surface of a sphere of radius r_a from the point P, is given by (POYNTING vector)

$$S_a = \frac{P_t}{4\pi r_a^2} \left[\frac{\mathrm{W}}{\mathrm{m}^2}\right] \tag{12}$$

Effective Isotropic Radiated Power [EIRP]

Definition (EIRP)

The Effective Isotropic Radiated Power (EIRP) of a transmitter is the power that the transmitter appears to have if the transmitter were an isotropic radiator (if the antenna radiated equally in all directions).

From the receiver's point of view,

$$P_t = P_T G_T \tag{13}$$

where:

- P_t is the power of an fictive isotropic antenna.
- P_T is the transmitter power and G_T is its gain (in that direction).

If the cable losses can be neglected, then $\text{EIRP} = P_T G_T$.

Effective area

Definition (Effective area)

The effective area of an antenna is the ratio of the available power to the power flux density (POYNTING vector):

$$A_{eff,R} = \frac{P_R}{S_{eff,R}} \tag{14}$$

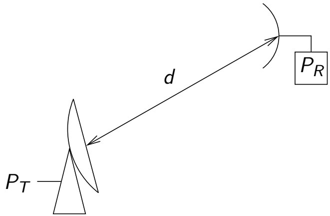
Theorem

The effective area of an antenna is related to its gain by the following formula

$$A_{eff,R} = G_R \frac{\lambda^2}{4\pi} \tag{15}$$

By reciprocity, all these results are equally valid for a transmitting antenna T.

Friis's relationship



We have

$$
\begin{aligned}
P_{\color{blue}R} &= S_{eff,{\color{blue}R}} A_{eff,{\color{blue}R}} \\
&= \left(\frac{P_{\color{red}T} G_{\color{red}T}}{4\pi d^2}\right) A_{eff,{\color{blue}R}} = \left(\frac{P_{\color{red}T} G_{\color{red}T}}{4\pi d^2}\right)\left(\frac{\lambda^2}{4\pi}\right) G_{\color{blue}R} = P_{\color{red}T} G_{\color{red}T} G_{\color{blue}R} \left(\frac{\lambda}{4\pi d}\right)^2
\end{aligned}
$$

Free space path loss	FRIIS's relationship
$L_{FS} = \left(\frac{\lambda}{4\pi d}\right)^2$	$\epsilon = \frac{P_{\color{red}T}}{P_{\color{blue}R}} = \left(\frac{4\pi d}{\lambda}\right)^2 \frac{1}{G_{\color{red}T} G_{\color{blue}R}}$

Decibel as a common power unit

$$x \leftrightarrow 10\log_{10}(x)\,[\text{dB}] \tag{16}$$

$$P\,[\text{dB}m] = 10\log_{10}\frac{P\,[m\text{W}]}{1\,[m\text{W}]} \tag{17}$$

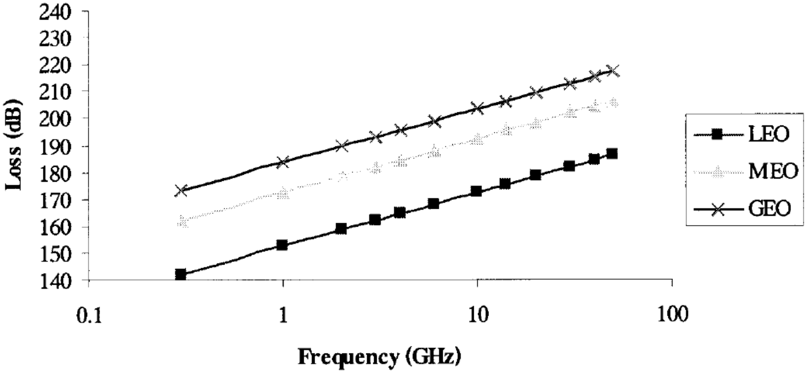
x [W]	$10\log_{10}(x)$ [dBW]
1 [W]	0 [dBW]
2 [W]	3 [dBW]
0,5 [W]	−3 [dBW]
5 [W]	7 [dBW]
10^n [W]	$10 \times n$ [dBW]

Orders of magnitude in satellite communications:

- transmitter power: 100 [W]≡20 [dB]
- received power: $100\,[p\text{W}] = 100 \times 10^{-12}\,[\text{W}] \equiv -100\,[\text{dB}]$

$$L_{FS} = \left(\frac{\lambda}{4\pi d}\right)^2 = \left(\frac{c}{4\pi d f}\right)^2 \tag{18}$$

where c is the speed of light.



Are high frequencies less adequate?

In [dB], Friis's relationship becomes

$$\epsilon = 32.5 + 20 \log f_{[\text{MHz}]} + 20 \log d_{[\text{km}]} - G_{T\,[\text{dB}]} - G_{R\,[\text{dB}]} \tag{19}$$

The attenuation (loss) increases with f. So ?!

In fact, $G_{T\,[\text{dB}]}$ and $G_{R\,[\text{dB}]}$ also depend on the frequency; the gains increase with the frequency.

There is thus a trade-off, that depends on the antenna gains!

In the end, the attenuation still increases with the frequency but not as $20 \log f_{[\text{MHz}]}$

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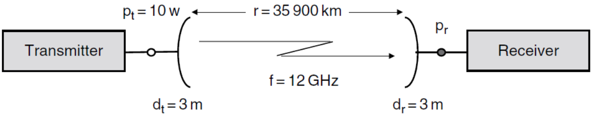
Practical case: VSAT in the Ku-band [1]



Antenna gains: 48.93 [dB]

The *free space path loss* is, in [dB],

$$L_{FS} = 32.5 + 20 \log f_{[\mathrm{MHz}]} + 20 \log d_{[\mathrm{km}]} = 205.1\,[\mathrm{dB}] \qquad (20)$$

The *received power* is, in [dB],

$$P_R = P_T + G_T + G_R - L_{FS} \qquad (21)$$

$$= 10 + 48.93 + 48.93 - 205.1 = -97.24\,[\mathrm{dB}] \qquad (22)$$

In [W], the *received power* is

$$P_R = 10^{-\frac{97.24}{10}} = 1.89 \times 10^{-10}\,[\mathrm{W}] = 189\,[p\mathrm{W}] \qquad (23)$$

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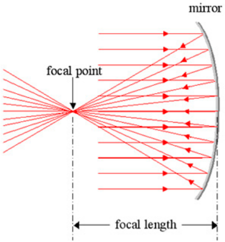
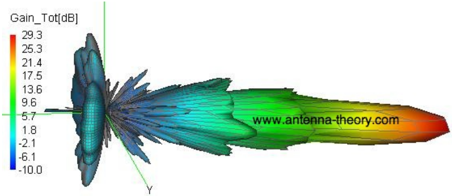
Terrestrial antennas

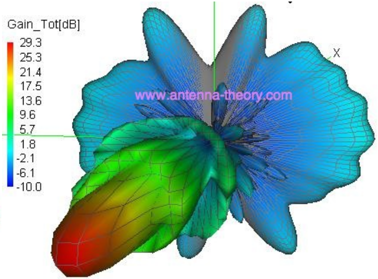
Ground station antenna

Parabolic (dish) antenna

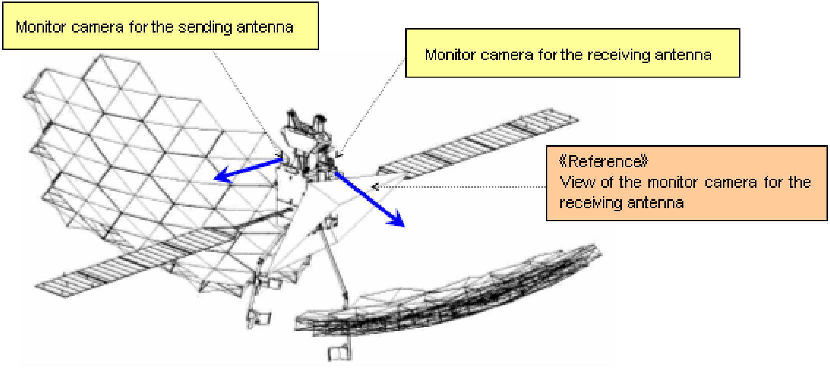


Radiation pattern

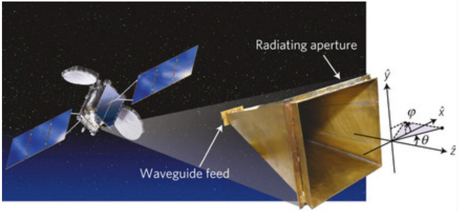


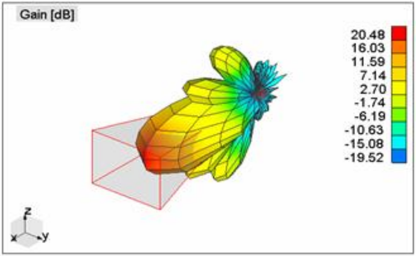


Deployable antenna

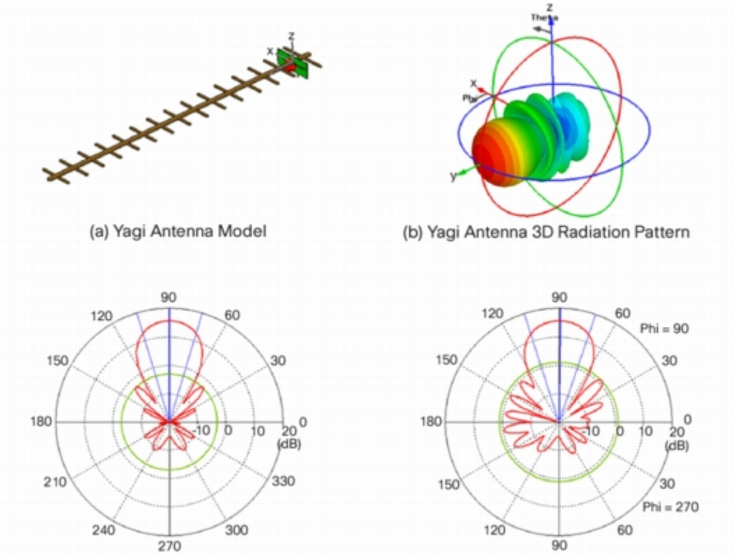


Horn antenna and waveguide feed





Yagi antenna



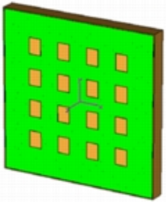
(a) Yagi Antenna Model

(b) Yagi Antenna 3D Radiation Pattern

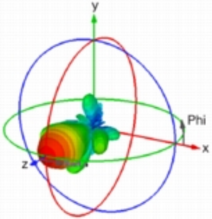
(c) Yagi Antenna Azimuth Plane Pattern

(d) Yagi Antenna Elevation Plane Pattern

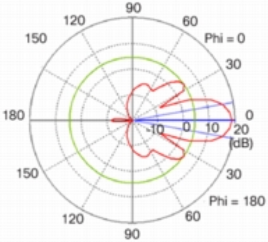
Patch array antenna



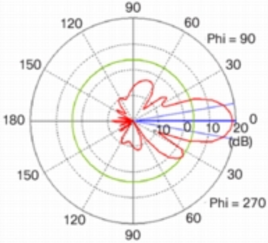
(a) 4x4 Patch Array Antenna



(b) 4x4 Patch Array 3D Radiation Pattern

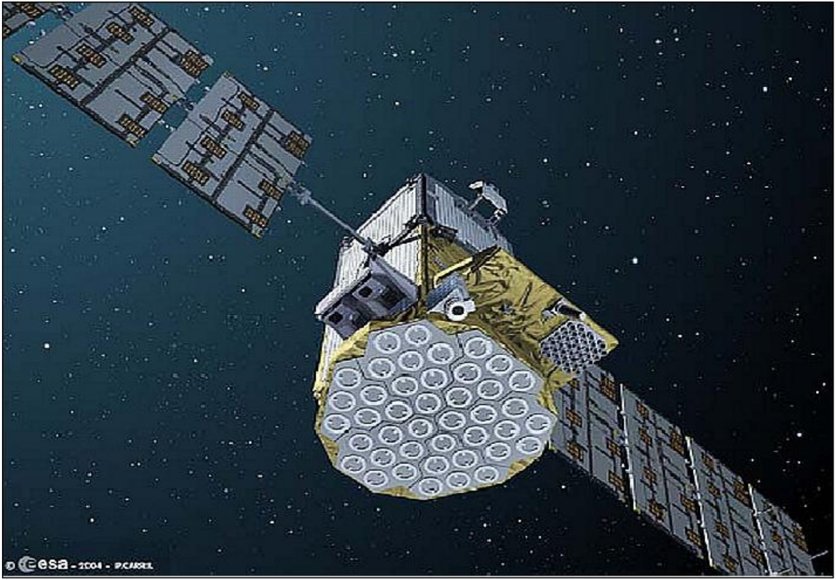


(c) 4x4 Patch Array Azimuth Plane Pattern

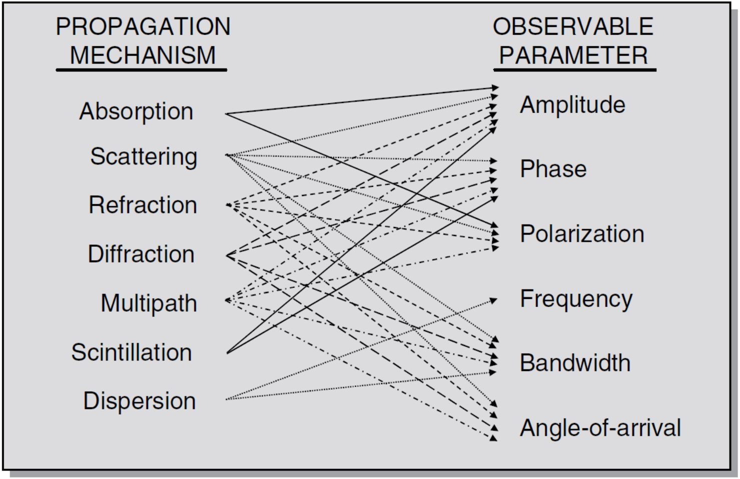


(d) 4x4 Patch Array Elevation Plane Pattern

Phased array antenna



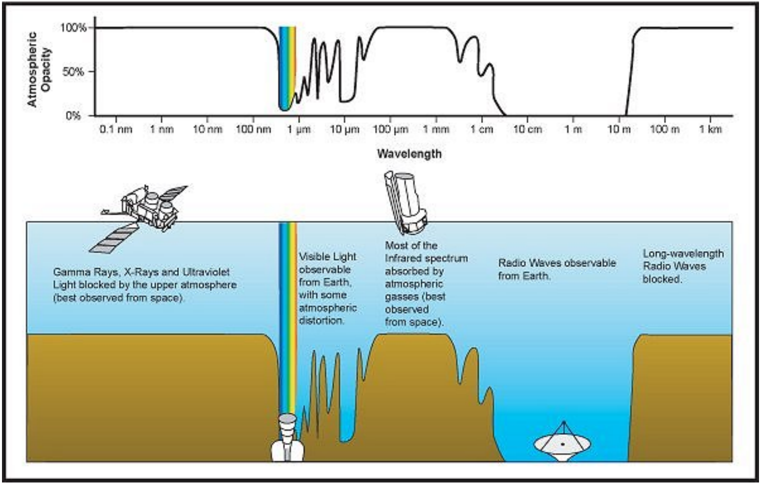
Radiowave propagation mechanisms



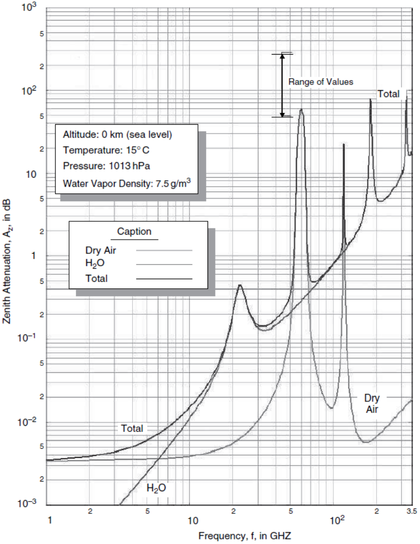
+ Doppler effect

Earth atmosphere absorption

Expressed in terms of the wavelength: $\lambda\,[\mathrm{m}] = \frac{c}{f} = \frac{3\times10^8\,[\mathrm{m/s}]}{f\,[\mathrm{Hz}]}$

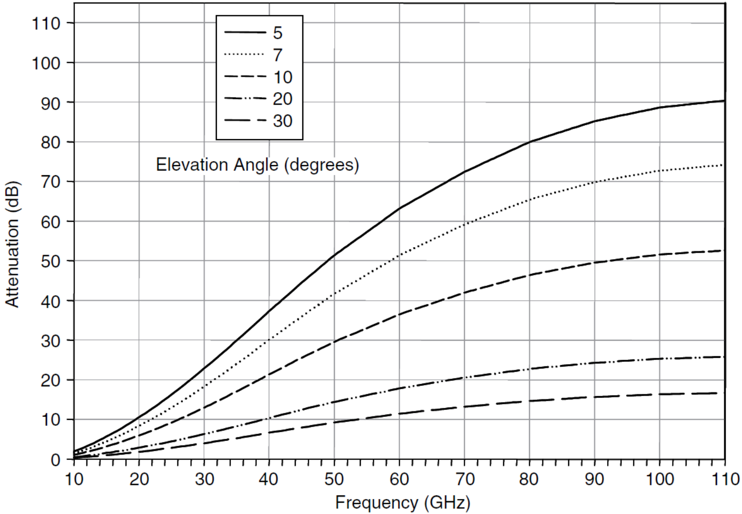


Attenuation due to atmospheric gases



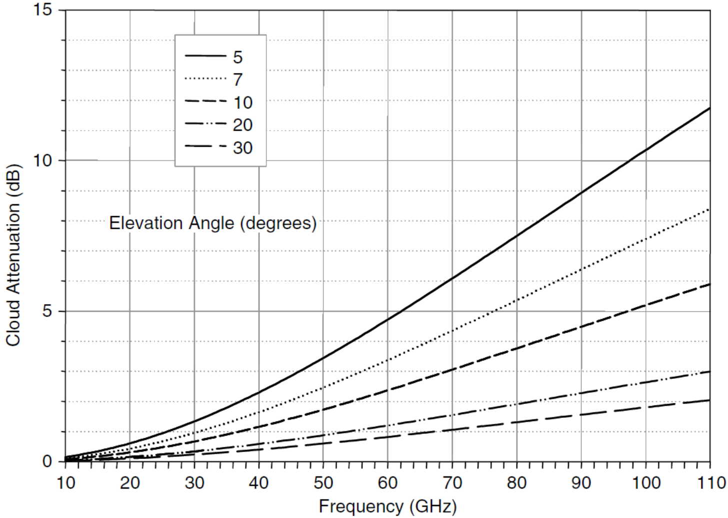
Zenith attenuation due to atmospheric gases (source: ITU-R P.676-6)
[O_2 and H_20 are the main contributors]

Rain attenuation



Total path rain attenuation as a function of frequency and elevation angle. Location: Washington, DC, Link Availability: 99%

Cloud attenuation



Cloud attenuation as a function of frequency, for elevation angles from 5 to 30°

Total attenuation

The ITU recommends that all tropospheric contributions to signal attenuation are combined as follows:

$$A_T(p) = A_G + \sqrt{(A_R(p) + A_c(p))^2 + A_s(p)} \qquad (24)$$

where:

- $A_T(p)$ is the total attenuation for a given probability
- $A_G(p)$ is the attenuation due to *water vapor* and *oxygen*
- $A_R(p)$ is the attenuation due to *rain*
- $A_c(p)$ is the attenuation due to *clouds*
- $A_s(p)$ is the attenuation due to *scintillation* (rapid fluctuations attributed to irregularities in the tropospheric refractive index)

Outline

Noise

A natural source of noise is thermal noise, caused by the omnipresent motion of free electrons in conducting material.

Theorem (Nyquist's formula for a one-port noise generator)

The available power from a thermal source in a bandwidth of W is

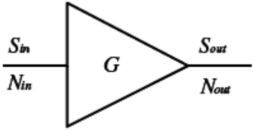
$$P_N = k_B T W \tag{25}$$

where

- $k_B = 1,38 \times 10^{-23}\,[J/K]$ is the constant of Boltzmann ($-198\,[\mathrm{dB}m/\mathrm{K}/\mathrm{Hz}] = -228.6\,[\mathrm{dBW}/\mathrm{K}/\mathrm{Hz}]$),
- T is the equivalent noise temperature of the noise source
- W is the bandwidth of the system

Thermal noise is one the main sources of noise in a satellite $\rightarrow$ put *electronics* in the *cold zone of a satellite*

Noise in two-port circuits



Definitions

Noise Factor (F): [**provided** by the **manufacturer**]

$$F = \frac{\left(\frac{S}{N}\right)_{\text{in}}}{\left(\frac{S}{N}\right)_{\text{out}}} > 1 \qquad (26)$$

Noise Figure (NF):

$$\text{NF}{=}10\log_{10} F \qquad (27)$$

Effective noise temperature T_e ($T_0 = 290\,[\text{K}]$):

$$T_e = T_0(F-1) \qquad (28)$$

Noise factor of a two-port cascade I

In a cascade, each two-port element is noisy $\longrightarrow$ it contributes to degrade the overall noise factor

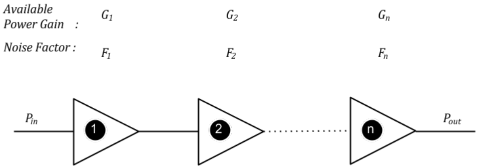


Figure : Cascading two-port elements.

For a two-port network with n stages,

$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \cdots = F_1 + \sum_{i=2}^{n} \frac{F_i - 1}{\prod_{j=1}^{i-1} G_j} \qquad (29)$$

Noise factor of a two-port cascade II

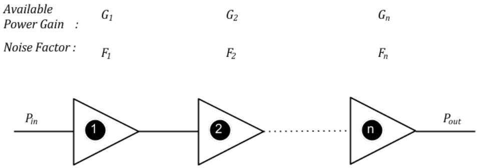


Figure : Cascading two-port elements.

Likewise,

$$T_e = T_{e1} + \frac{T_{e2}}{G_1} + \frac{T_{e3}}{G_1 G_2} + \cdots = T_{e1} + \sum_{i=2}^{n} \frac{T_{ei}}{\prod_{j=1}^{i-1} G_j} \qquad (30)$$

Receiver front end I

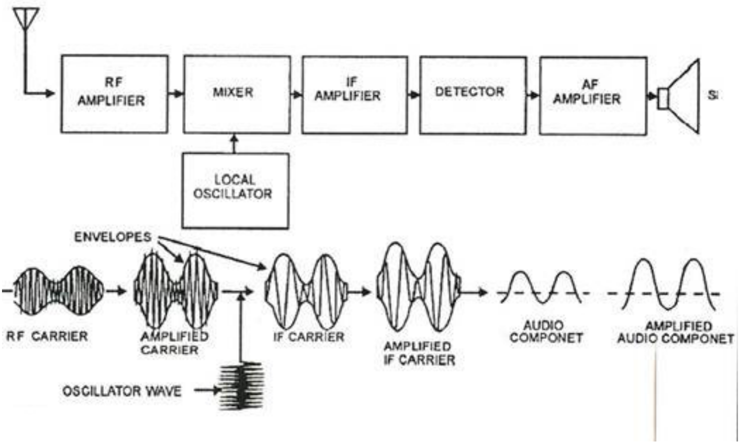
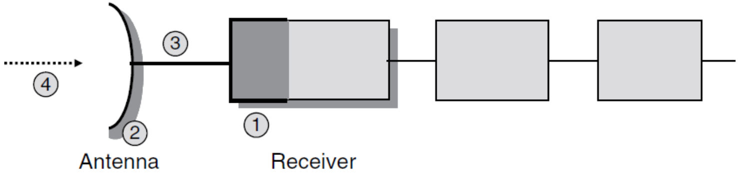


Figure : Block diagram of a typical receiver.

Receiver front end II



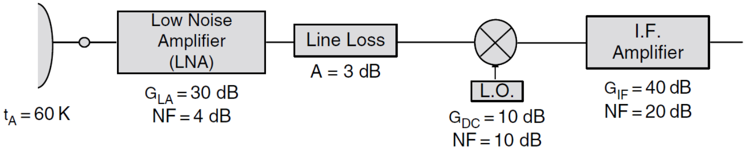
Rule of thumb: highest gain (G_1) and best noise figure (F_1) first.

Then

$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \cdots \simeq F_1 + \frac{F_2 - 1}{G_1} \quad (31)$$

$$T_e = T_{e1} + \frac{T_{e2}}{G_1} + \frac{T_{e3}}{G_1 G_2} + \cdots \simeq T_{e1} + \frac{T_{e2}}{G_1} \quad (32)$$

Example of the calculation of a noise budget [1]



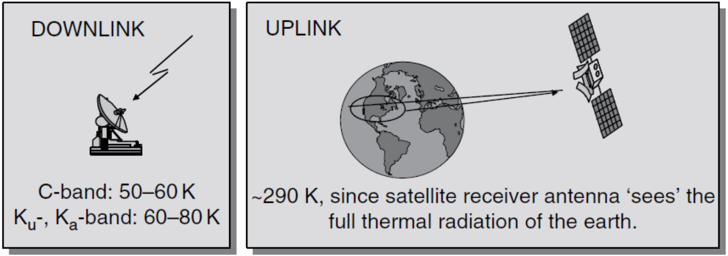
- Low Noise Amplifier: $T_{LA} = 290 \times (10^{\frac{4}{10}} - 1) = 438\,[\mathrm{K}]$
- Line. For a *passive* two-port circuit, the noise factor is equal to the attenuation: $F_0 = A$.
  - $T_{Line} = 290 \times (10^{\frac{3}{10}} - 1) = 289\,[\mathrm{K}]$,
  - $G_{Line} = \frac{1}{2}$

The effective noise temperature, including the antenna noise t_A, is

$$T_e = t_A + T_{e1} + \frac{T_{e2}}{G_1} + \frac{T_{e3}}{G_1 G_2} + \cdots \tag{33}$$

$$= \underbrace{60 + 438}_{498} + \frac{289}{1000} + \frac{2610}{1000 \times \frac{1}{2}} + \cdots = 509.3\,[\mathrm{K}] \tag{34}$$

Typical values for the increase in antenna temperature due to rain [1]



(a)

TYPICAL ANTENNA TEMPERATURE VALUES (NO RAIN)

Rain Fade Level (dB)	1	3	10	20	30
Noise Tempeature (°K)	56	135	243	267	270

(b)

ADDITIONAL RADIO NOISE CAUSED BY RAIN

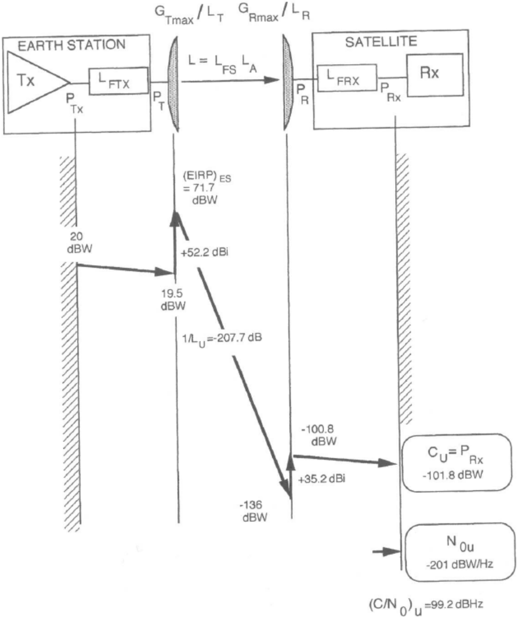
Outline

1. Signal processing elements
   - Signal ≡ information!
   - Source coding (dealing with the information content)
   - Modulation
   - Multiplexing
2. Propagation and radio communications
   - Introduction to radio communications
   - Radiowave propagation
   - Examples of antennas
3. Engineering
   - Noise
   - Link budget

Example of parameter values for a communication satellite [1]

Parameter	**uplink**	**downlink**
Frequency	14.1 [GHz]	12.1 [GHz]
Bandwidth	30 [MHz]	30 [MHz]
Transmitter power	100 – 1000 [W]	20 – 200 [W]
Transmitter antenna gain	54 [dB*i*]	36.9 [dB*i*]
Receiver antenna gain	37.9 [dB*i*]	52.6 [dB*i*]
Receiver noise figure	8 [dB]	3 [dB]
Receiver antenna temperature	290 [K]	50 [K]
Free space path loss (30° elevation)	207.2 [dB]	205.8 [dB]

Clear sky down link performance [2]



For further reading

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