Satellite Communications

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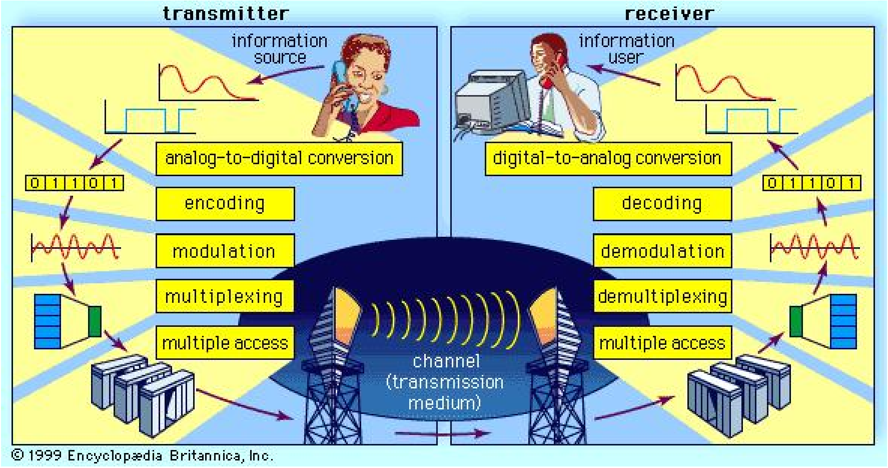
Academic year 2024-2025
`https://orbi.uliege.be/handle/2268/133976`

Example of an analog communication system



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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 ≡ 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, GLONASS]: they use radio time signals transmitted to enable mobile receivers on the ground to determine their exact location (positioning).
- *Earth observation* satellites: for environmental monitoring, meteorology, map making (Sentinel constellations).
- *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

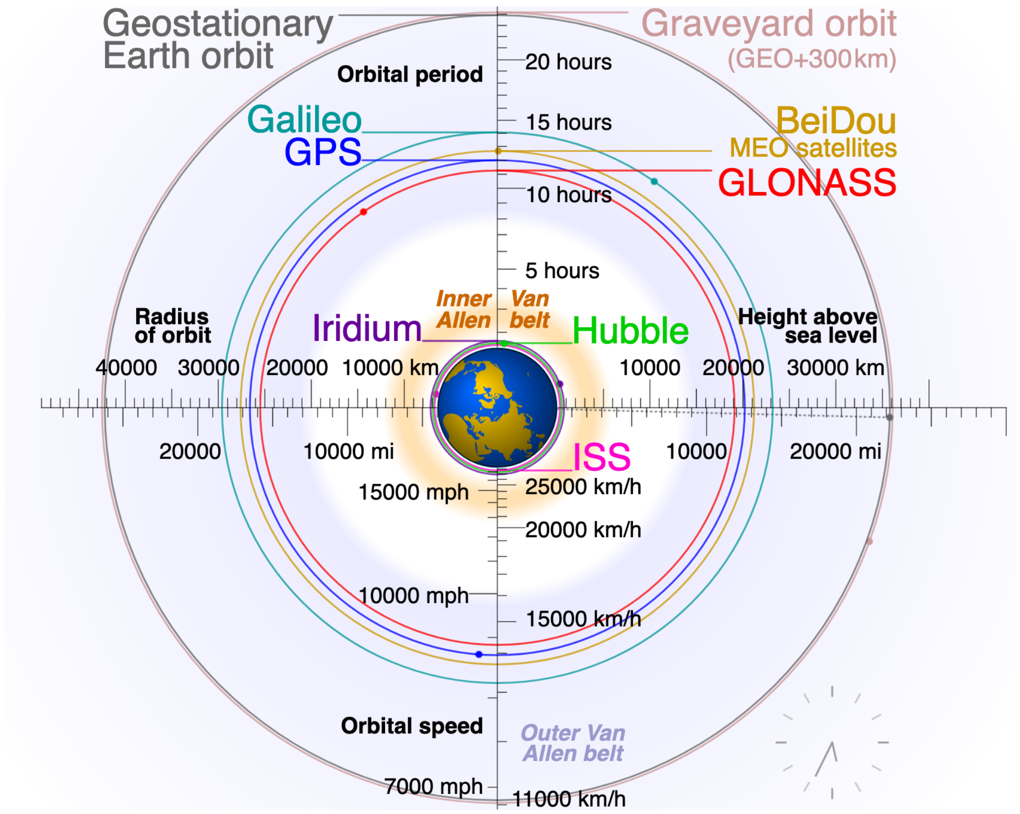
Types of data	**Characteristics**
Control data	Must be very reliable
Payload	Unicast communication for mobile ground station
▷ Measurements	Accurate signals with constant monitoring
▷ Remote sensing data	High volume of downstream data
▷ Positioning data	Accurate time reference (synchronization)
▷ Broadcasting	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 *typology* of data streams:

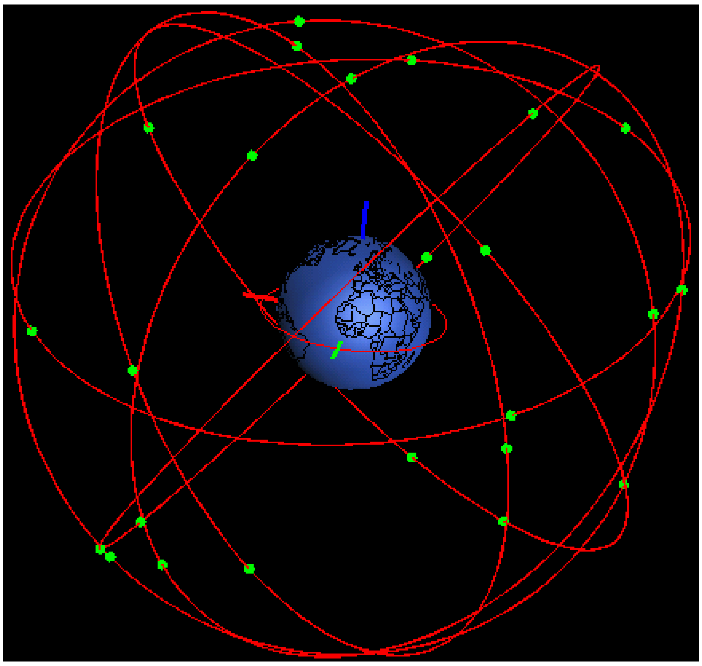
- control data (this communication channel needs a backup!)
- payload (+ some unavoidable *overhead*)

Positioning systems



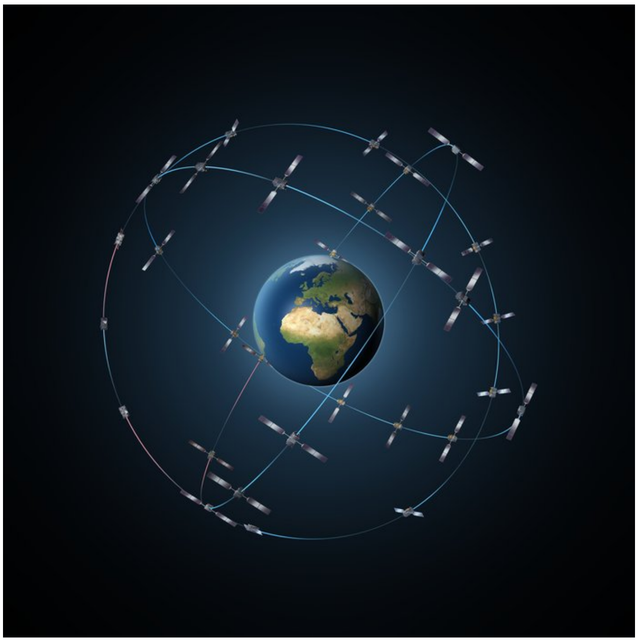
Example: constellation of GPS satellites

- 6 planes with a 55^0 angle with the equator, spaced by 60^0 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]



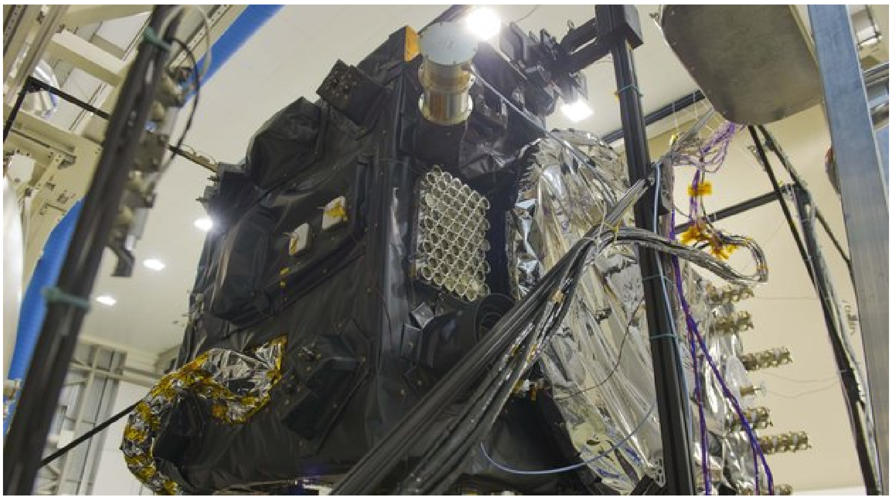
Galileo

- Orbital altitude: $23,222$ [km] (MEO - Medium Earth Orbit)
- 3 orbital planes, 56^0 inclination, separated by 120^0 longitude
- Constellation of 30 satellites (with working 24 [3x8] satellites and 6 [3x2] spares)

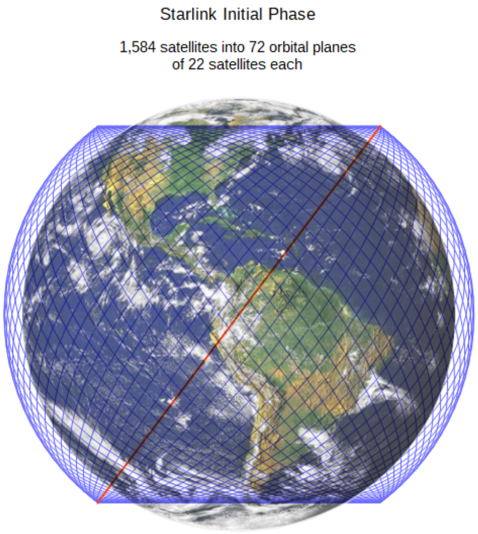


Deployment of Galileo

- 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).
- October 2022: 23 satellites fully operational, 1 unavailable, and 4 not usable.



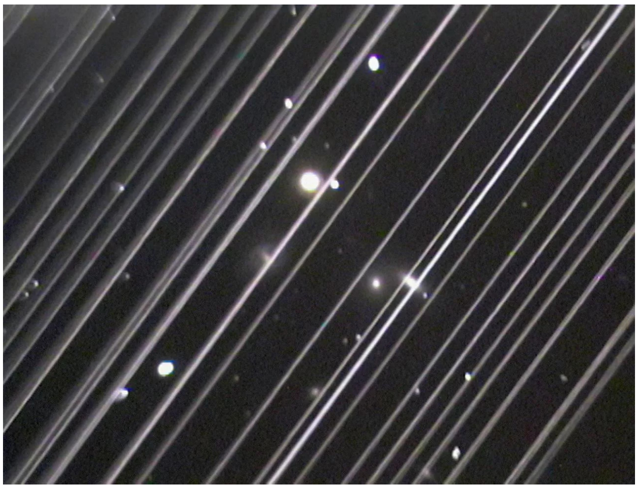
Starlink



Main characteristics:

- LEO orbits (550 km for phase 1)
- 6,500 launched and on orbit (October 2024)
- American regulator (FCC) approved 12.000 satellites
- Internet service: 4.000.000 subscribers (September 2024)

Starlink: controversy



Main issues:

- light pollution; ground based astronomy is jeopardized (creation of trails in the sky)
- presence of space debris, danger for satellite collision
- technology not fully tested
- usefulness ?! (it's available in Belgium)

IRIS^2

IRIS²: the new EU Secure Satellite Constellation

Infrastructure for Resilience, Interconnectivity and Security by Satellite

IRIS² at a glance

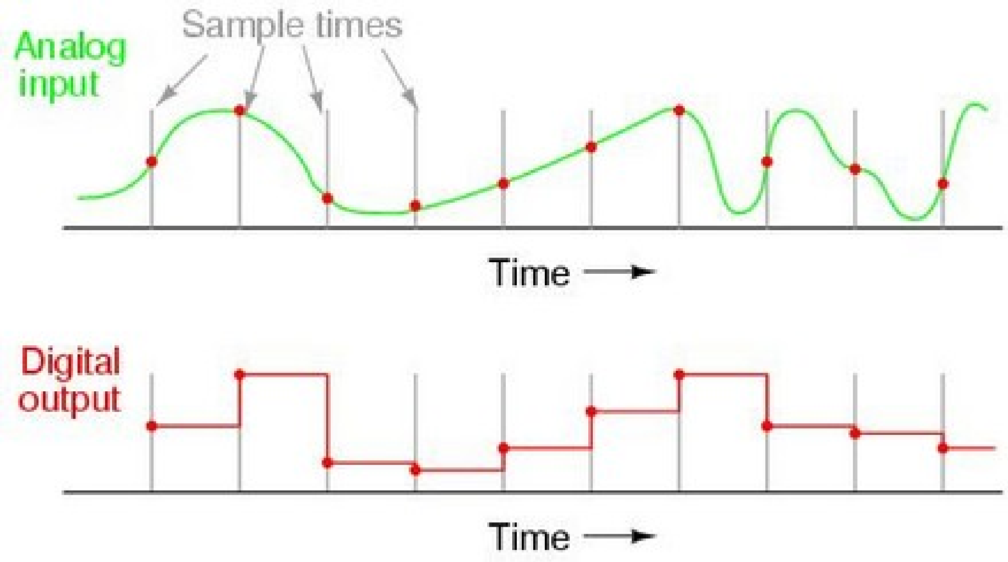
The **IRIS² Satellite Constellation** is the European Union's third flagship, addressing long-term challenges of EU's security, safety and resilience by offering enhanced connectivity services to **governmental users.**

The new multi-orbital constellation of 290 satellites will combine the benefits offered by Medium Earth Orbit (MEO) and Low Earth (LEO) satellites. It is set to provide secure connectivity services to the EU and its Member States as well as broadband connectivity for governmental authorities, private companies and European citizens, while ensuring high-speed internet broadband to cope with connectivity dead zones.

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 sent in the channel:
    - signal shaping to make it suitable for transmission (*coding*, *modulation*, *multiplexing*, etc.)
    - signal power versus the noise signal

Digitization I



Digitization II

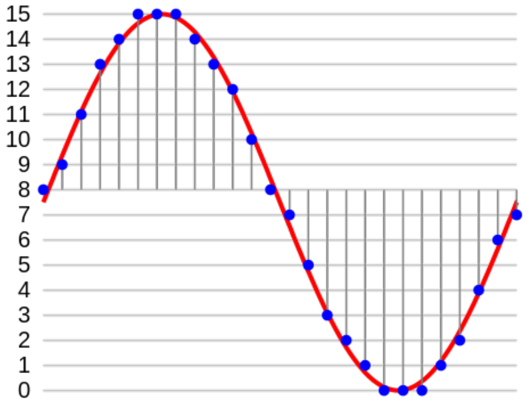
Reasons for going digital:

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

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

- analog PAL television channel: bandwidth of 8 [MHz]
- digital television, PAL quality $\sim 5\,[\text{Mb/s}]$
  - 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.

Digitization III



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*
	⇒ series of *samples*
	each sample is encoded with n bits (*quantization*)
	finally, we have a bit stream: 01110...

Digitization IV

Digitization in numbers:

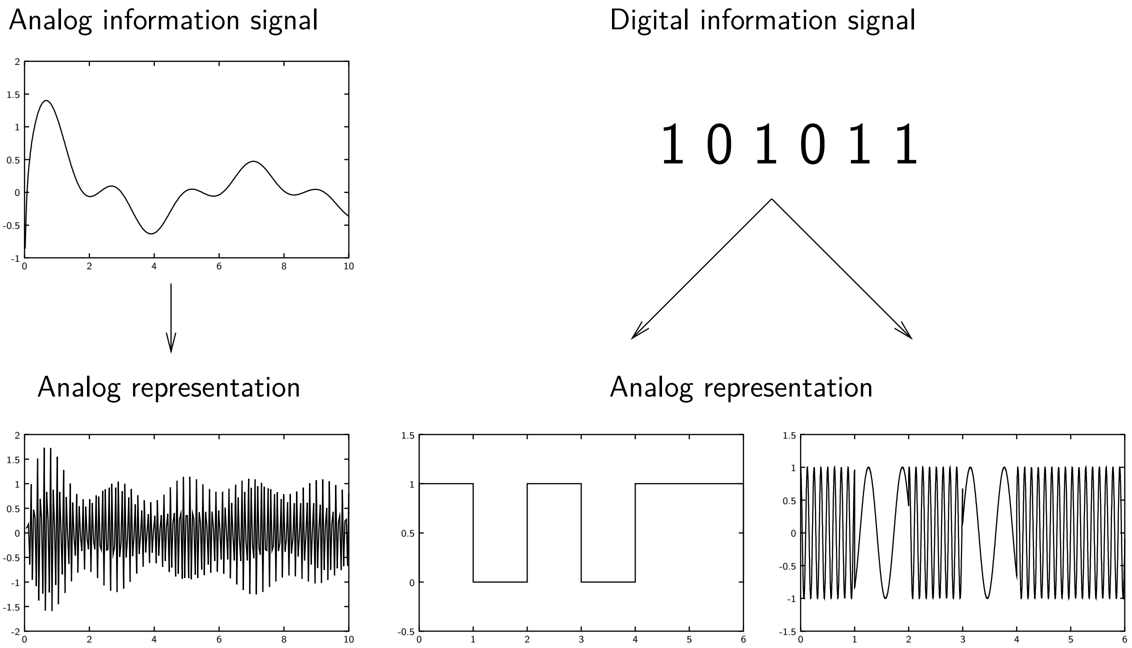
1. f_s: sampling frequency
   - Let W be the highest frequency of the signal to be converted
   - theoretical lower bound: $f_s > 2\,W$ [Shannon/Nyquist's theorem]
   - practical rule (Nyquist criterion): $f_s > 2.2\,W$
2. n: number of bits par sample (quantization)
3. bit rate $= f_s \times n$

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

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]	

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



Analog information signal

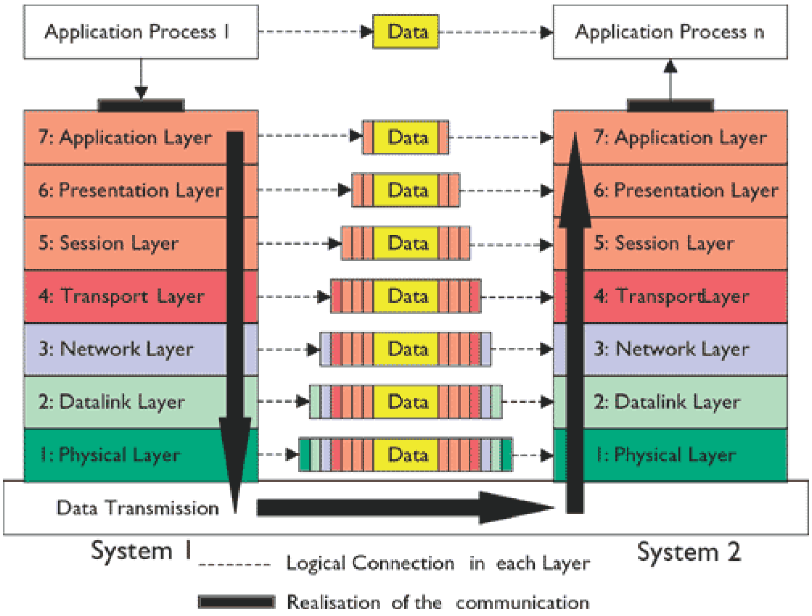
Digital information signal

1 0 1 0 1 1

Analog representation

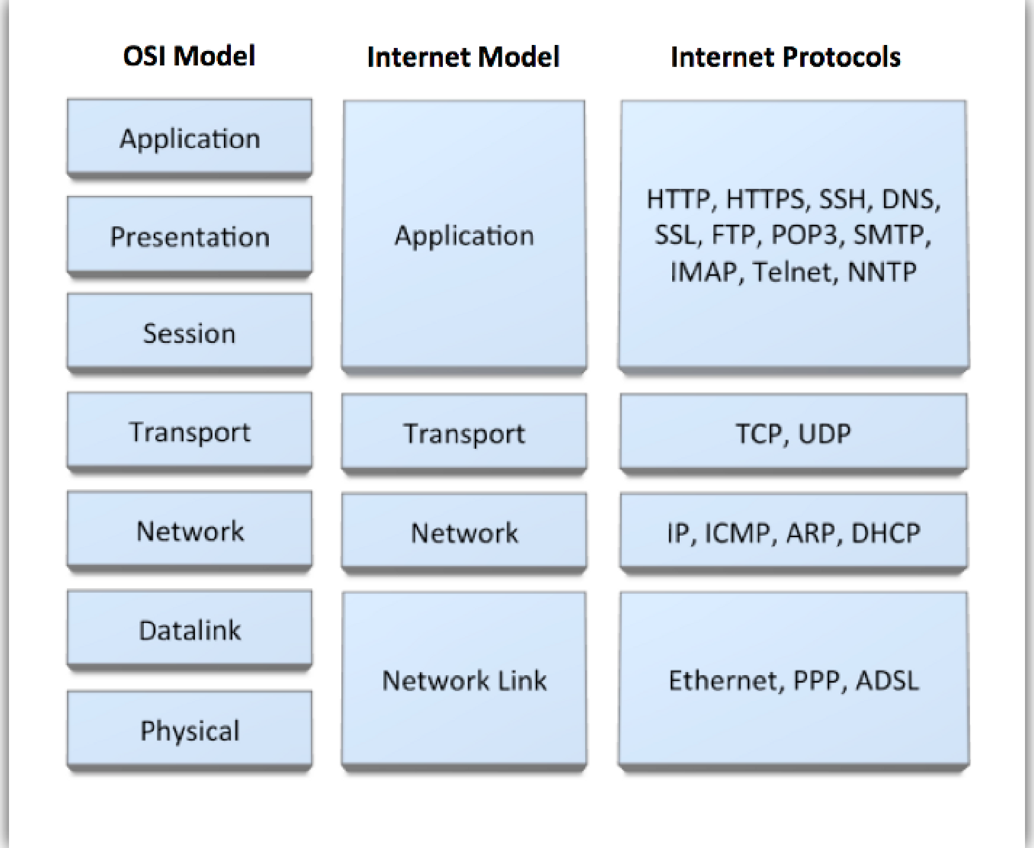
Analog representation

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



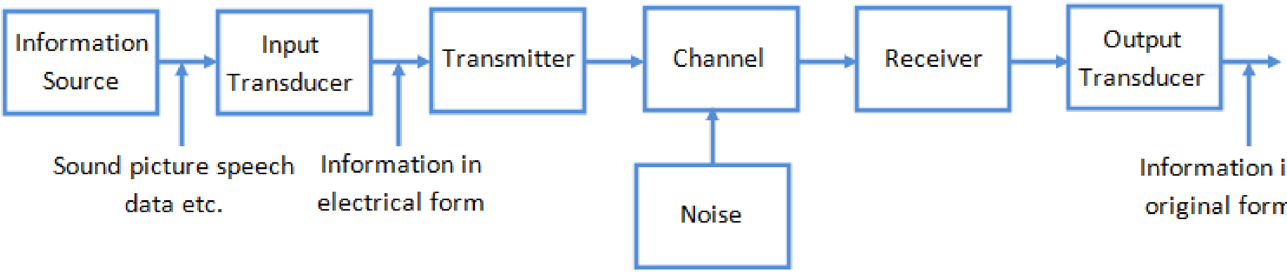
Consequence: encapsulation ⇒ overhead

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



OSI Model	Internet Model	Internet Protocols
Application Presentation Session	Application	HTTP, HTTPS, SSH, DNS, SSL, FTP, POP3, SMTP, IMAP, Telnet, NNTP
Transport	Transport	TCP, UDP
Network	Network	IP, ICMP, ARP, DHCP
Datalink Physical	Network Link	Ethernet, PPP, ADSL

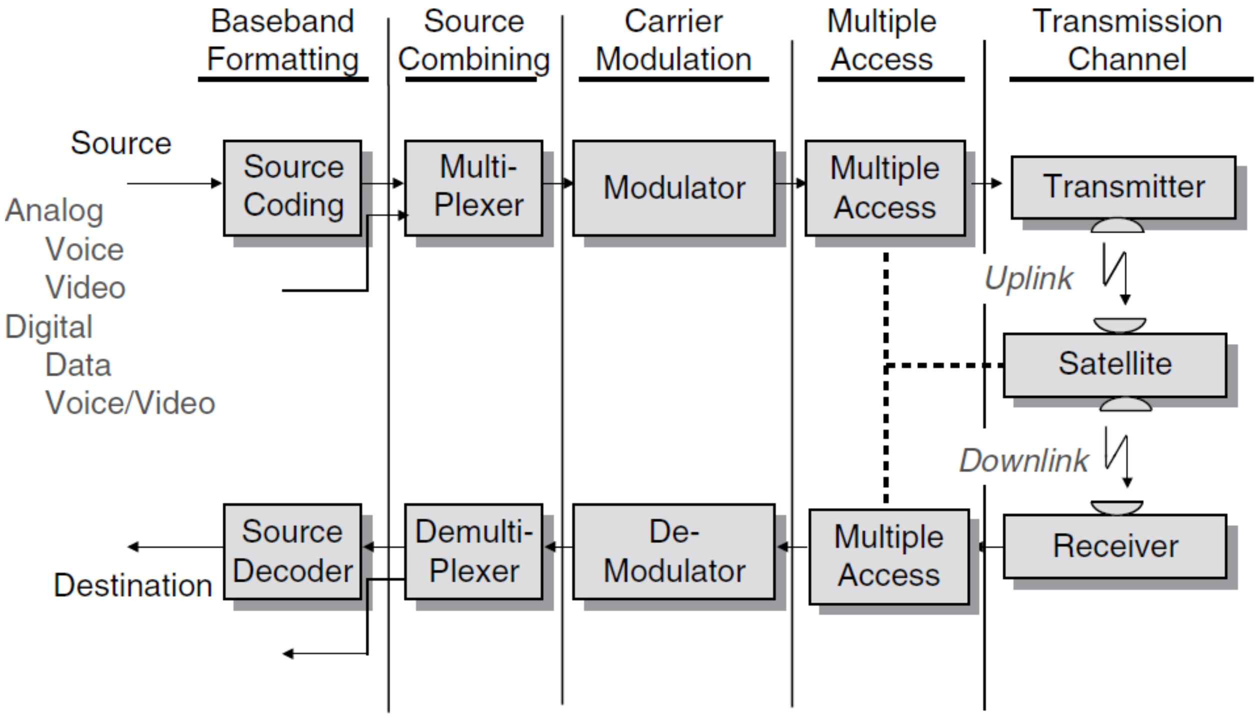
Elements of a communication system I



Information Source
Input Transducer
Transmitter
Channel
Receiver
Output Transducer
Noise
Sound picture speech data etc.
Information in electrical form
Information in original form

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

Elements of a communication system II



Baseband Formatting
Source Combining
Carrier Modulation
Multiple Access
Transmission Channel
Source
Analog
Voice
Video
Digital
Data
Voice/Video
Source Coding
Multi-Plexer
Modulator
Multiple Access
Transmitter
Uplink
Satellite
Downlink
Receiver
Multiple Access
De-Modulator
Demulti-Plexer
Source Decoder
Destination

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 → 0) is expressed in bits (of information) per second and given by

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

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 (engineering rules)

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 discussed later). Therefore:

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

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

Consequences: **3 degrees of freedom for engineering**

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 → 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.

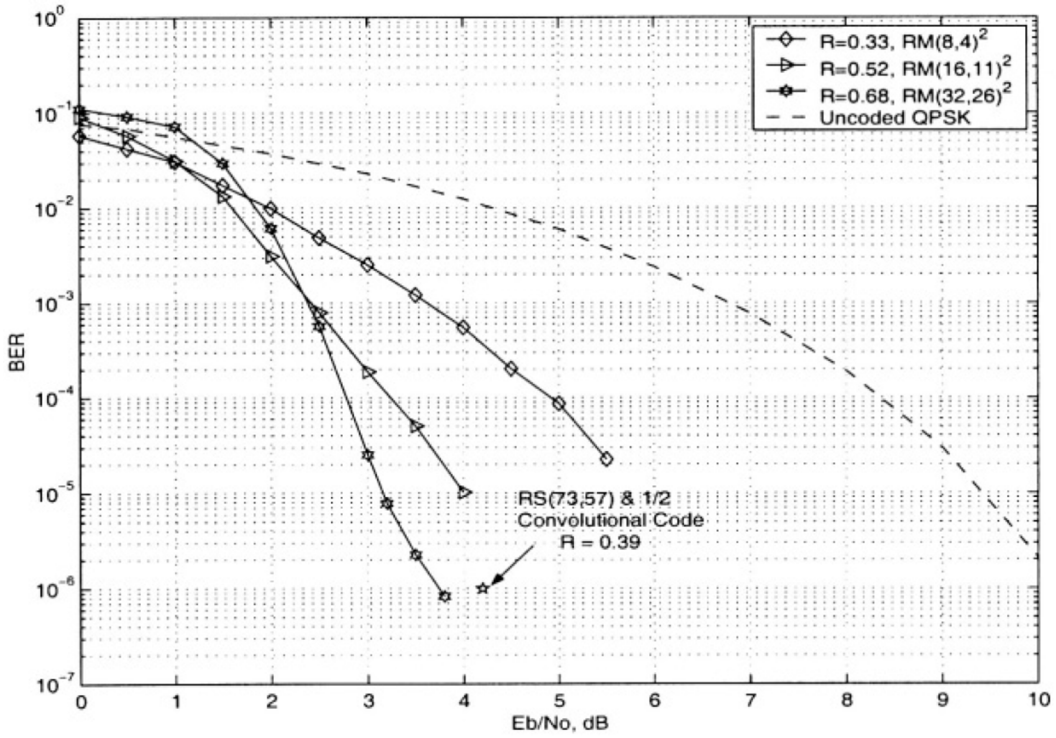
Forward Error Coding

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, ...



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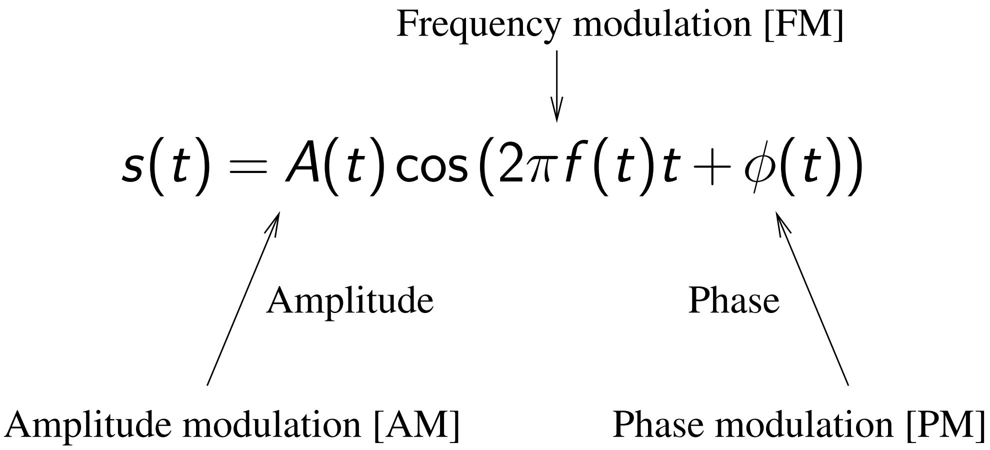
Modulation: principles

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]

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

Amplitude

Phase

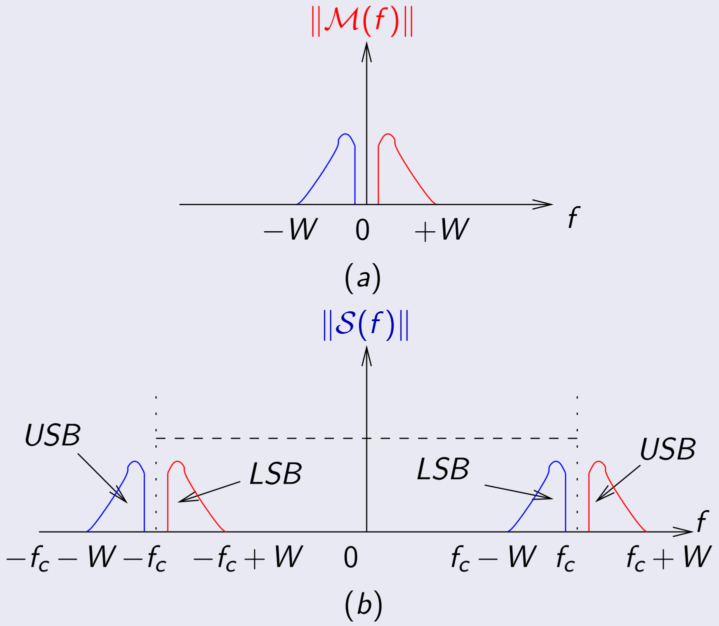
Amplitude modulation [AM]

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 $m(t)$.

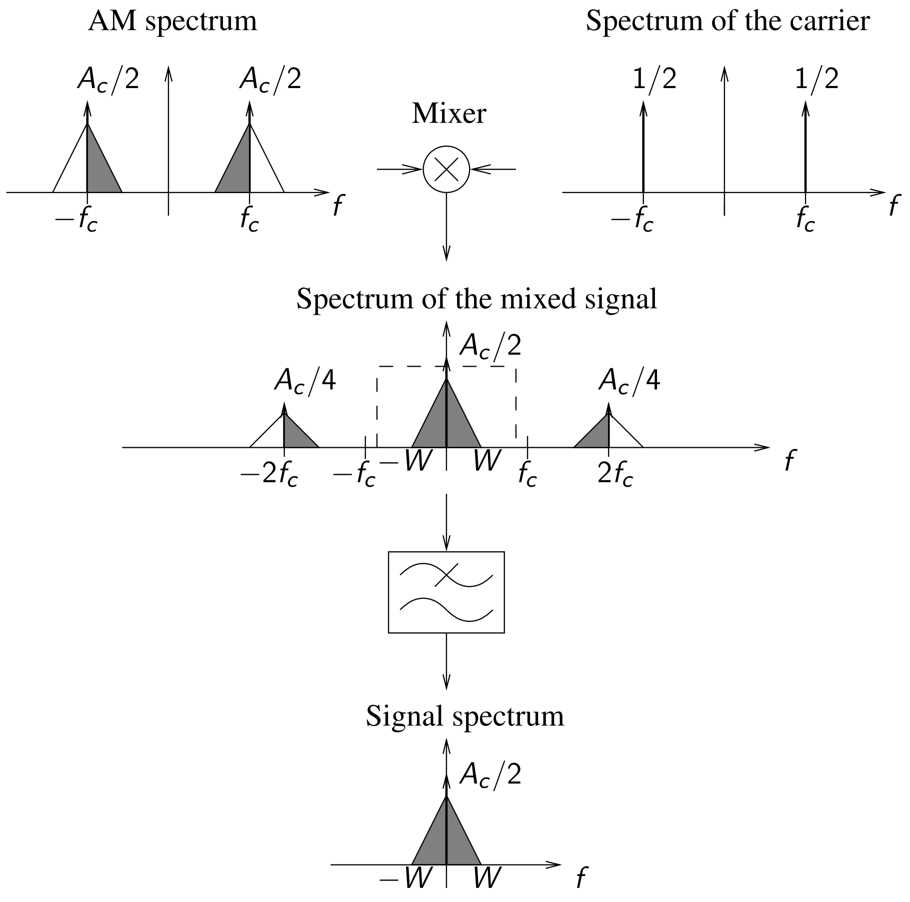
Principles of a synchronous demodulation. At the receiver:

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 $\cos(2\pi f_c t)$:
   $[\cos a \cos b = \frac{1}{2}\cos(a-b) + \frac{1}{2}\cos(a+b)]$

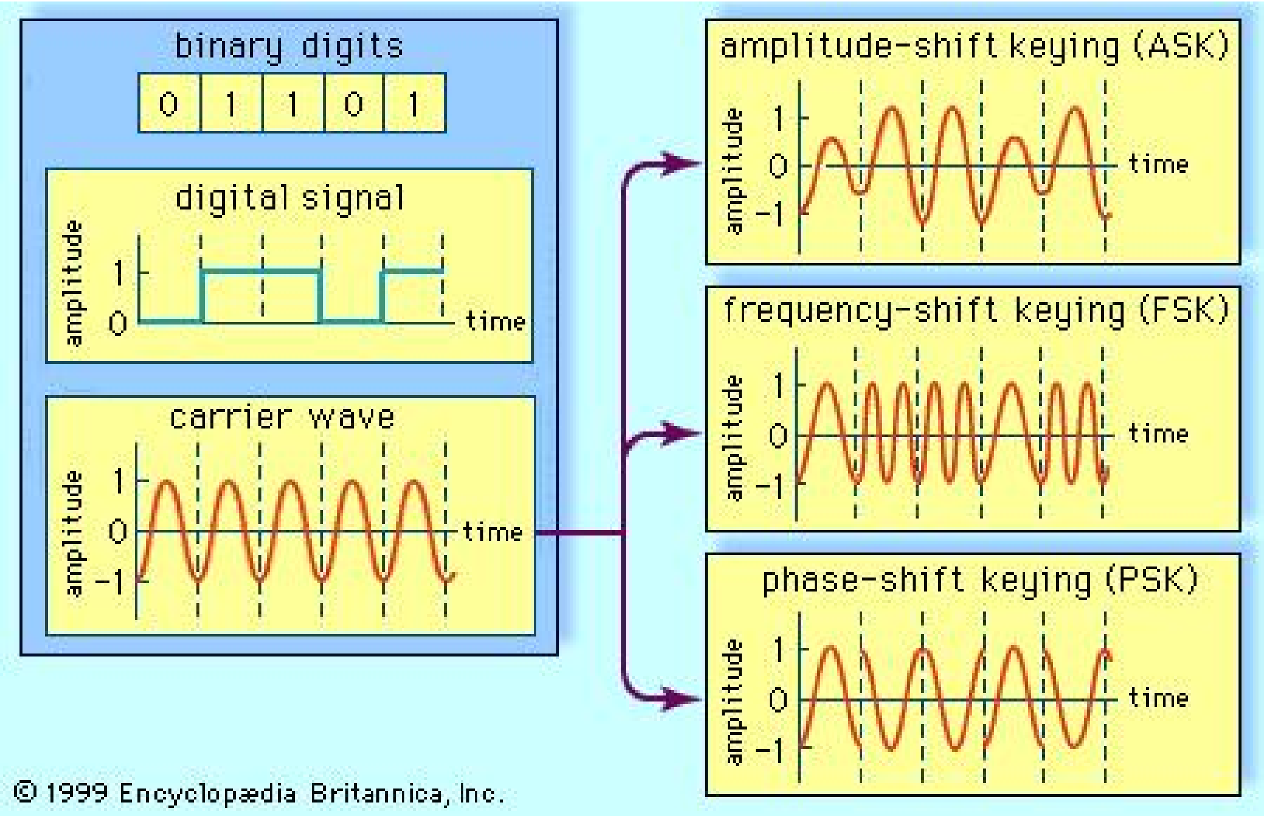
$$
\begin{aligned}
s(t)\cos(2\pi f_c t) &= m(t)\cos^2(2\pi f_c t) && (3)\\
&= m(t)\left[\frac{1}{2} + \frac{1}{2}\cos(2\pi(2f_c)t)\right] && (4)\\
&= \frac{1}{2}m(t) + \frac{1}{2}m(t)\cos(2\pi(2f_c)t)] && (5)
\end{aligned}
$$

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



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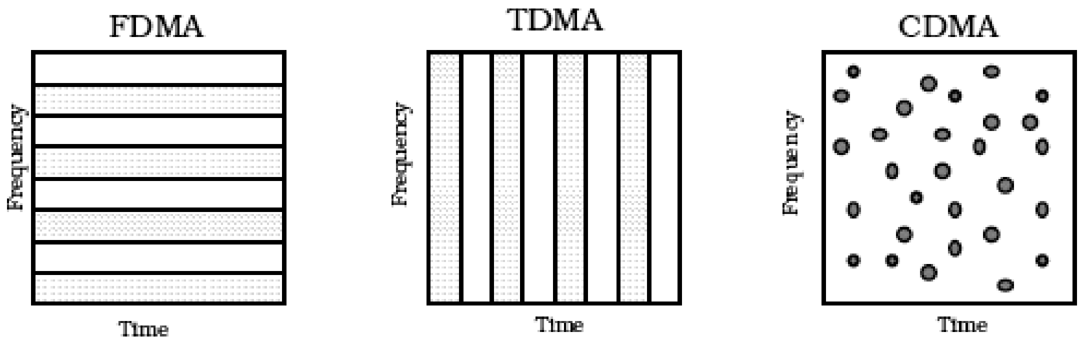
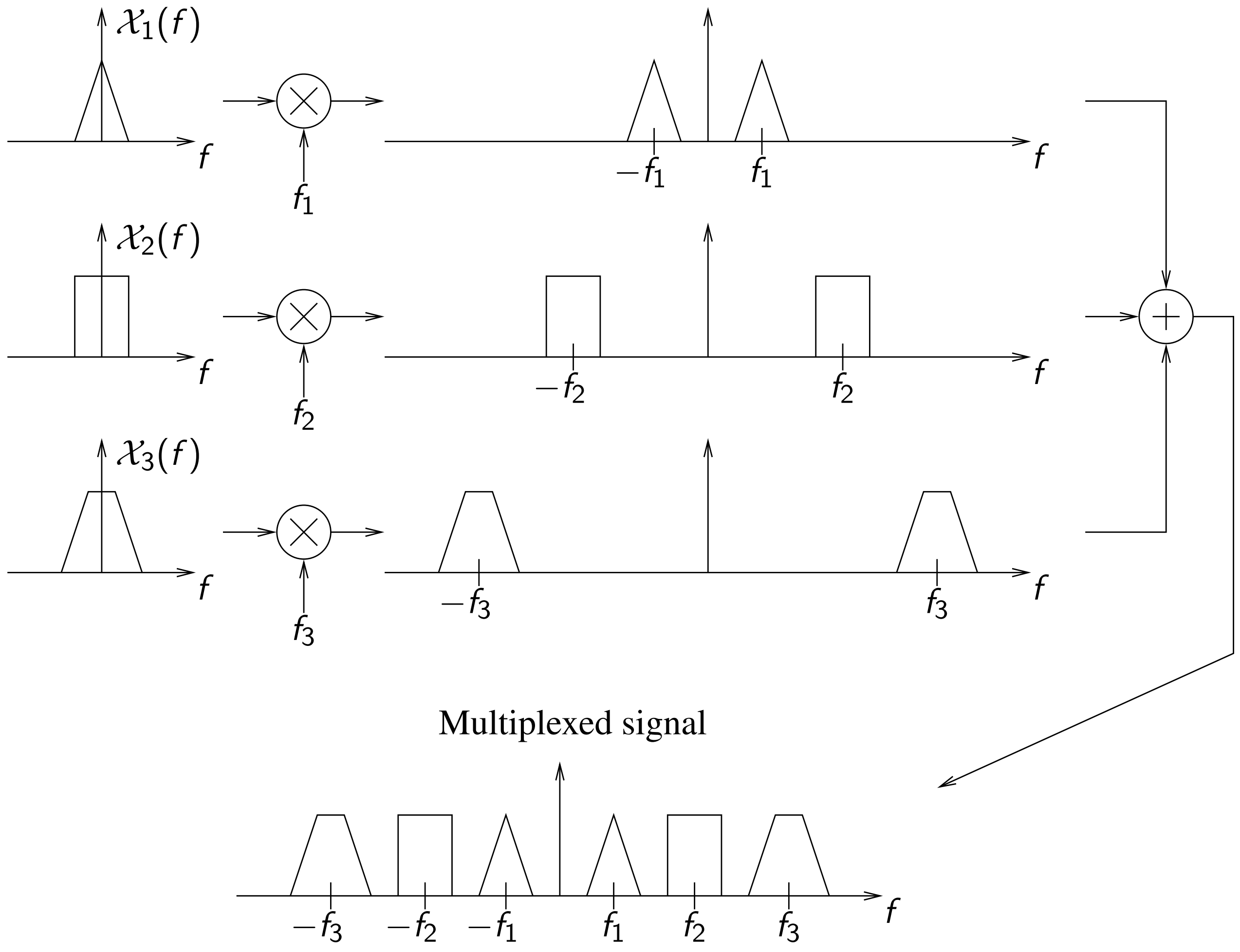
Multiplexing: combining several sources

Mechanisms to share resources between users:

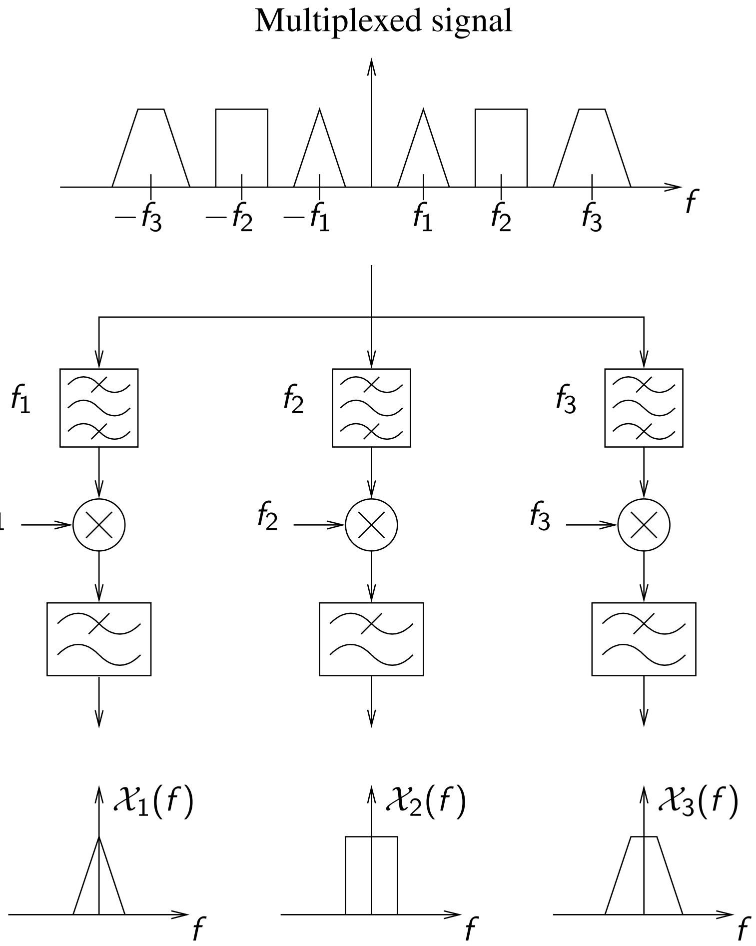
- Frequency Division Multiplexing (FDM)
- Time Division Multiplexing (TDM)
- Code Division Multiplexing (CDM)
- Space Division Multiplexing
- + combinations !



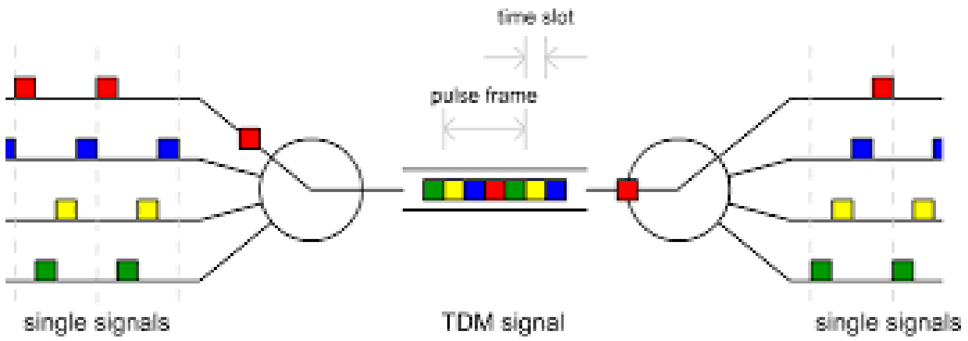
Frequency Division Multiplexing (FDM)

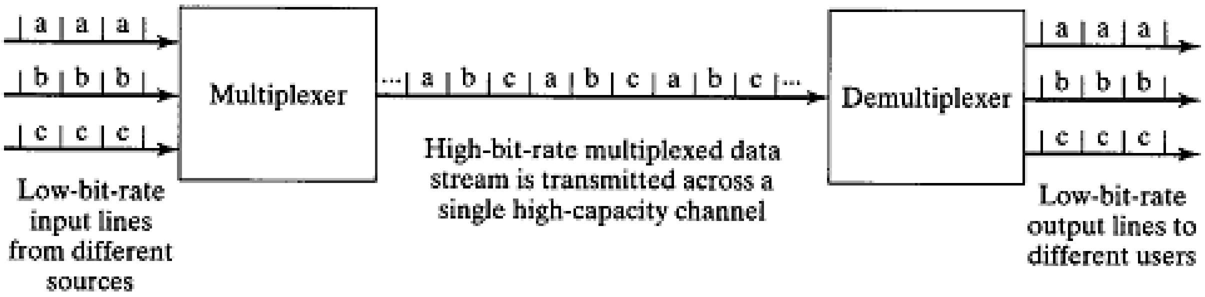


Demultiplexing



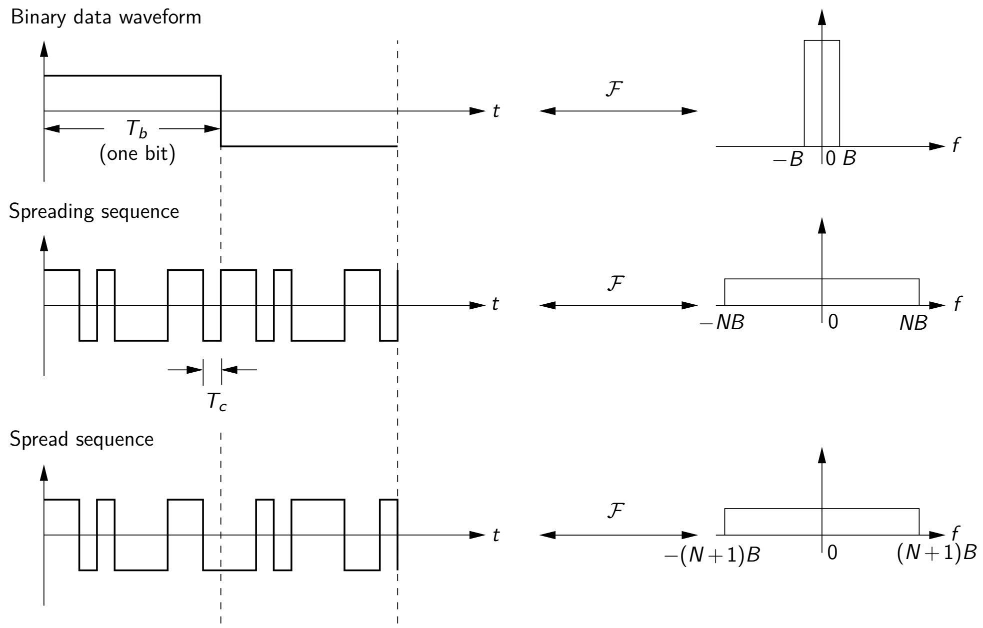
Time Division Multiplexing (TDM)





Spread spectrum for Code Division Multiplexing

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

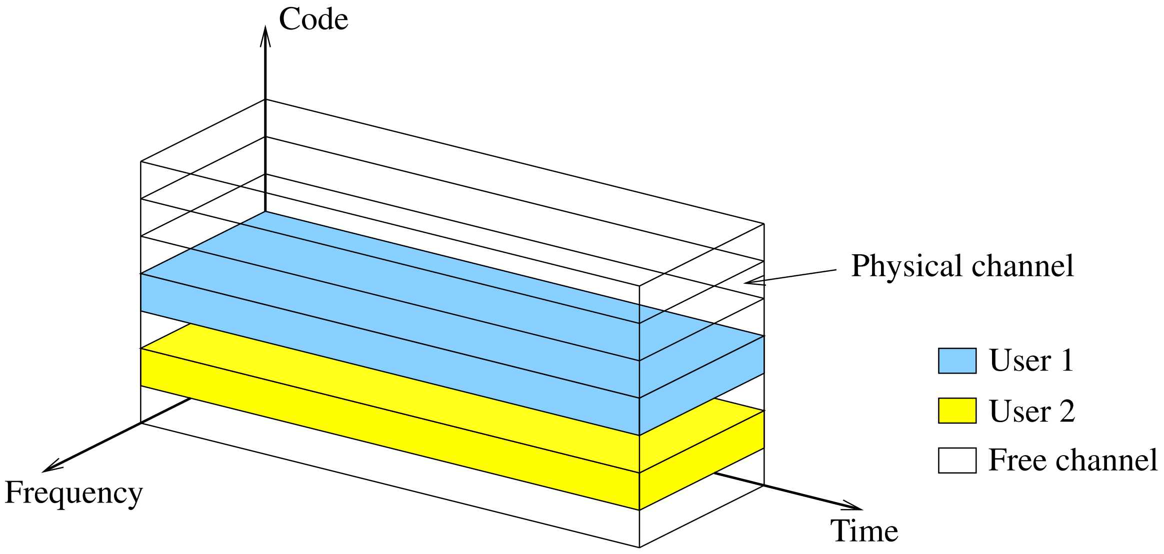


At the receiver, the *same*, *synchronized*, pseudo-random sequence is generated and used to “despread” the signal (despreading step)

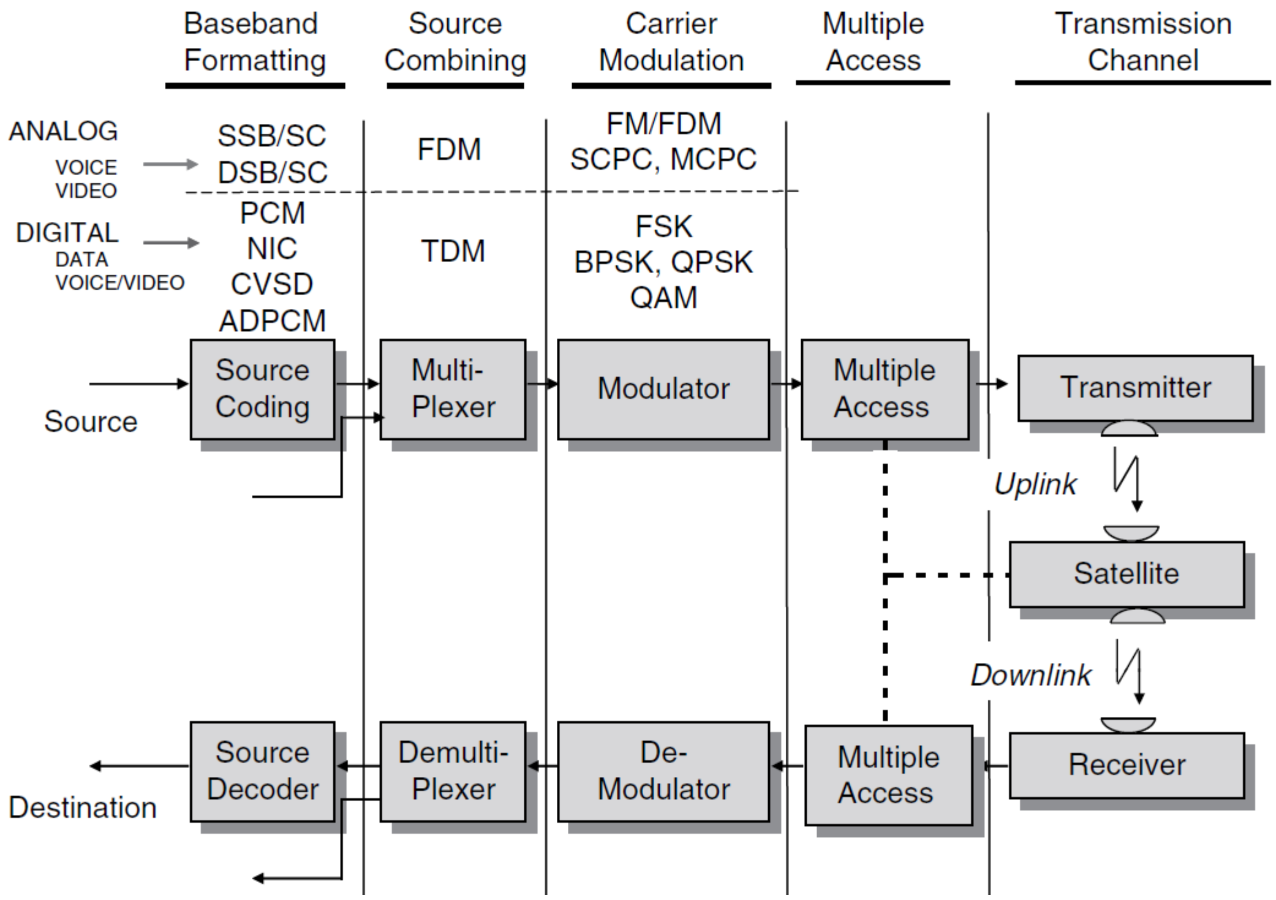
Code Division Multiple Access

- 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



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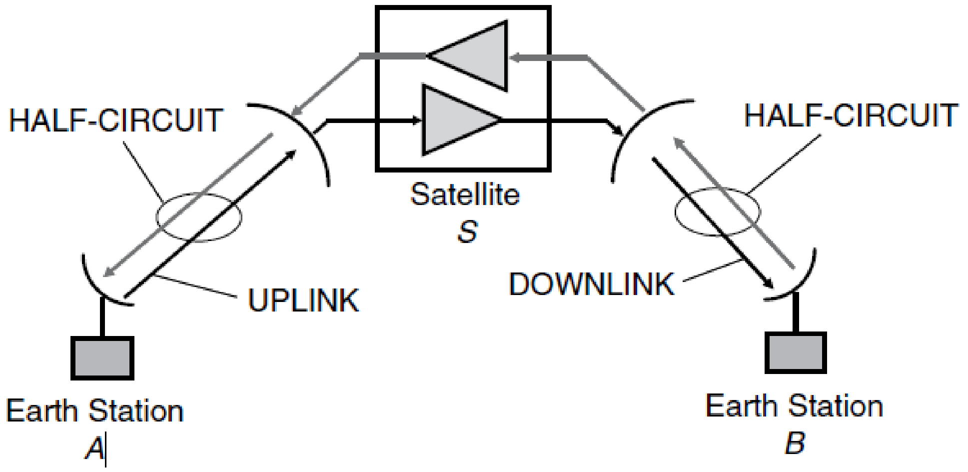
Satellite link definition



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

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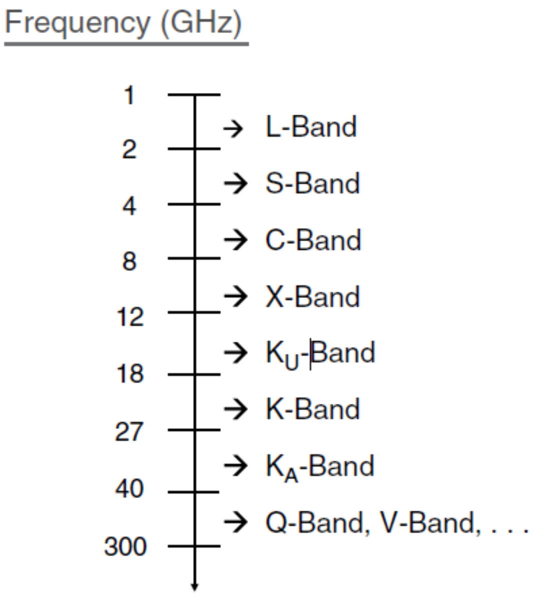
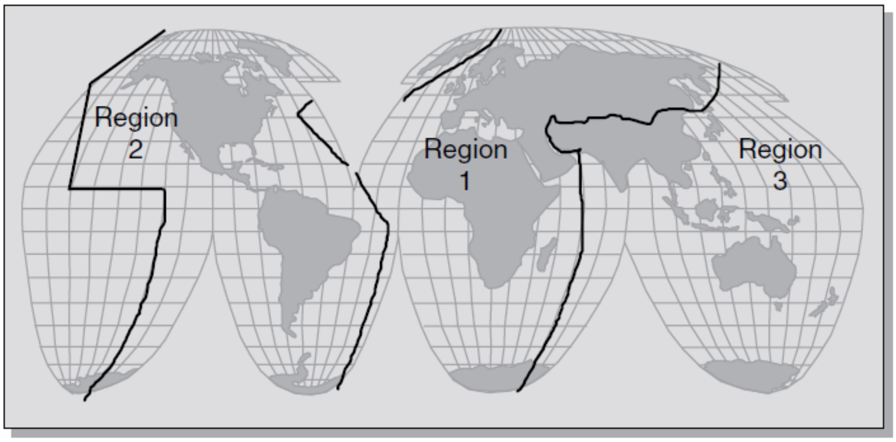
Frequency bands



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

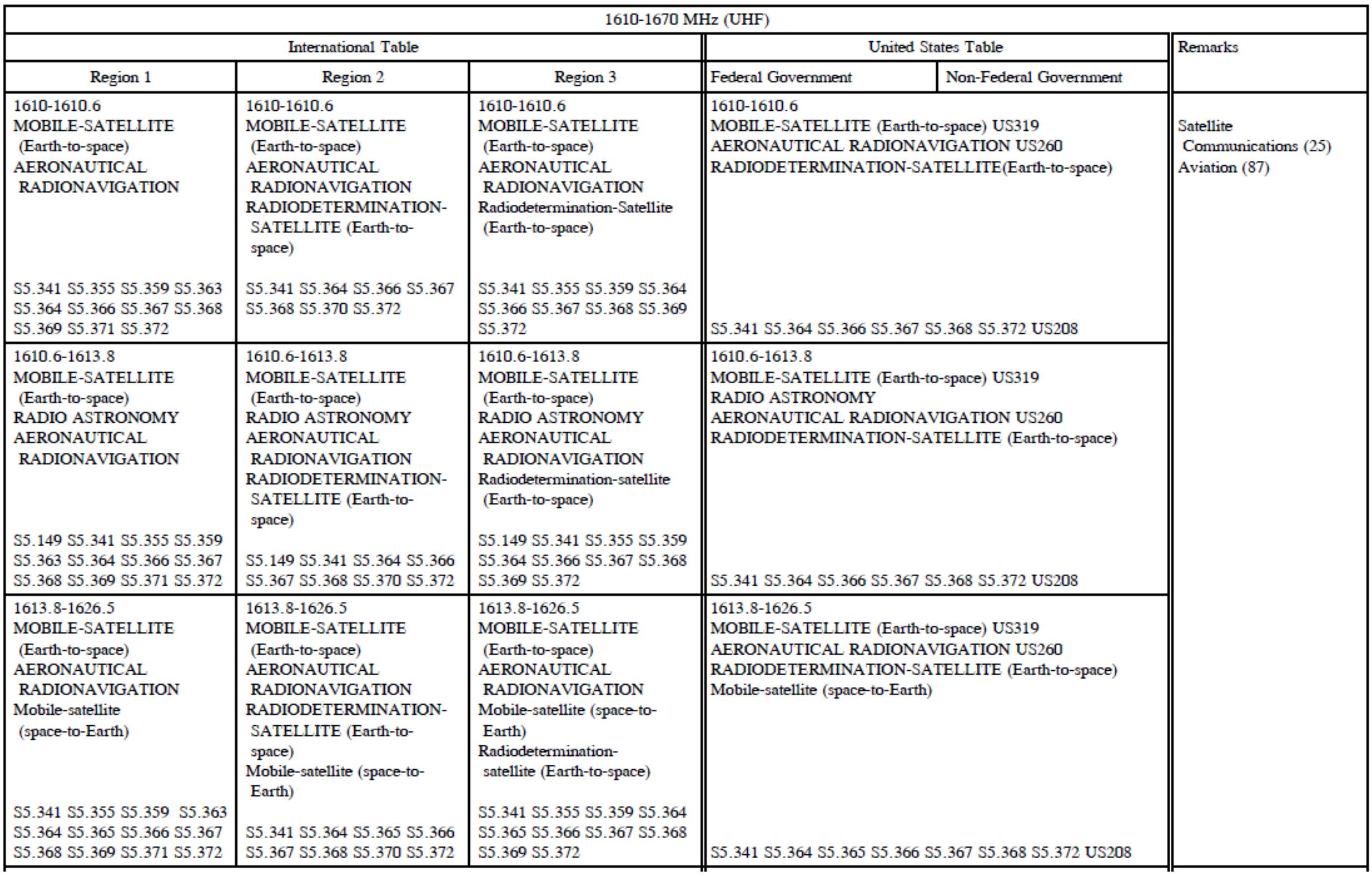
Regulatory bodies

- 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 (see [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

---

Frequency allocations (see [2])

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	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.
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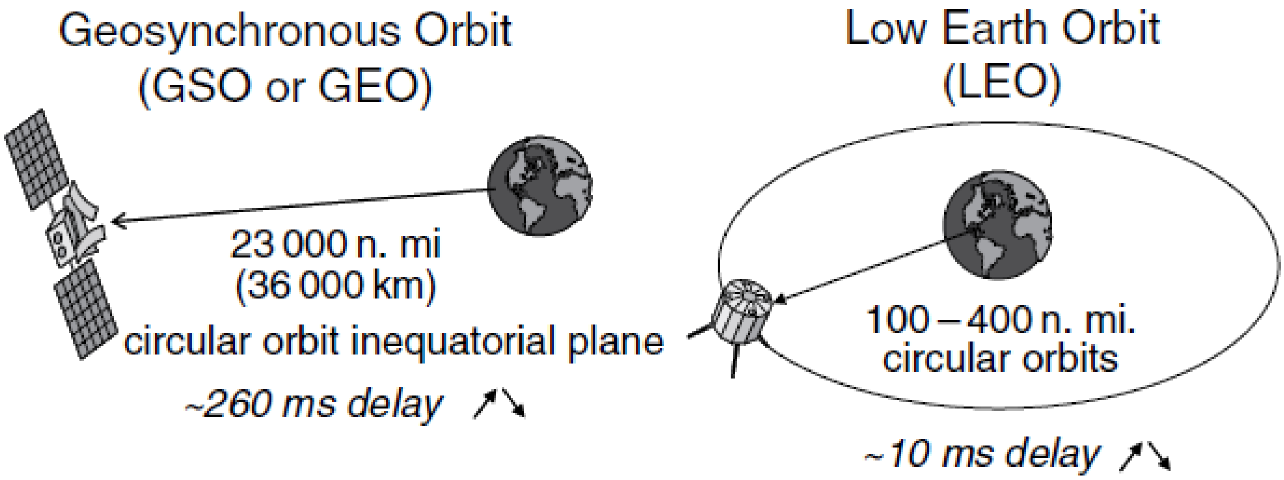
Orbits



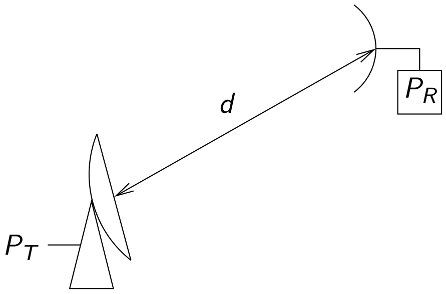
Engineering considerations:

- 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

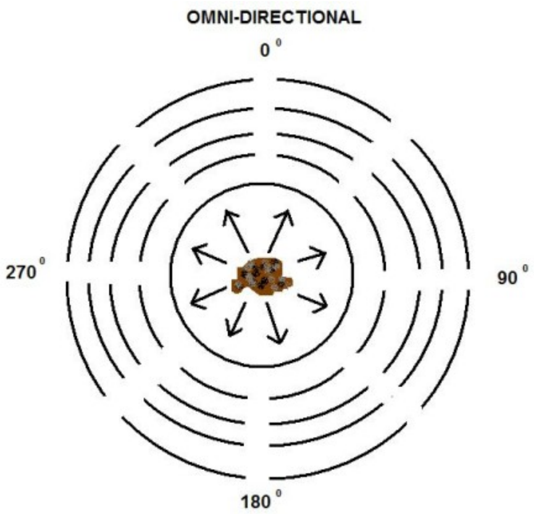
Radiowave propagation



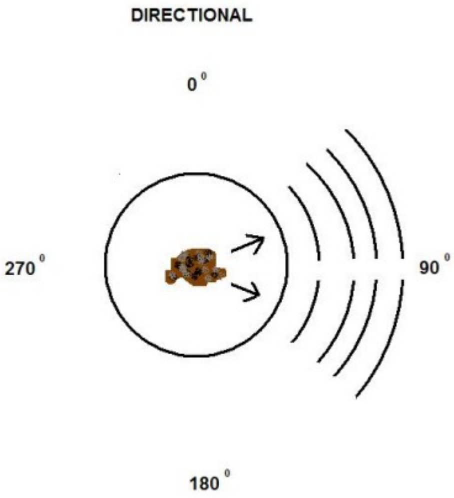
Important issues:

- channel characteristics
  - attenuation (distance)
  - atmospheric effects (rain mitigation, for example)
- antenna design
- power budget (related to the Signal to Noise S/N ratio)

Two main types of radiation pattern



EXAMPLE 1



EXAMPLE 2

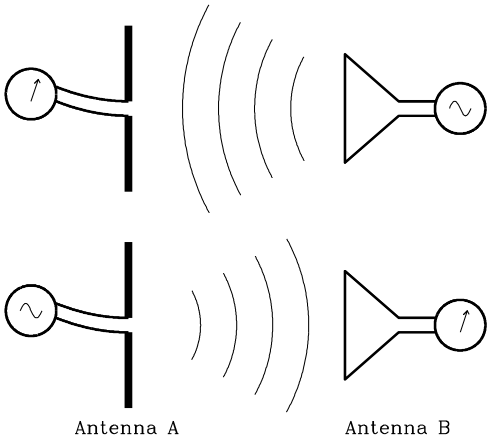
Reciprocity

Theorem (Reciprocity for antennas)

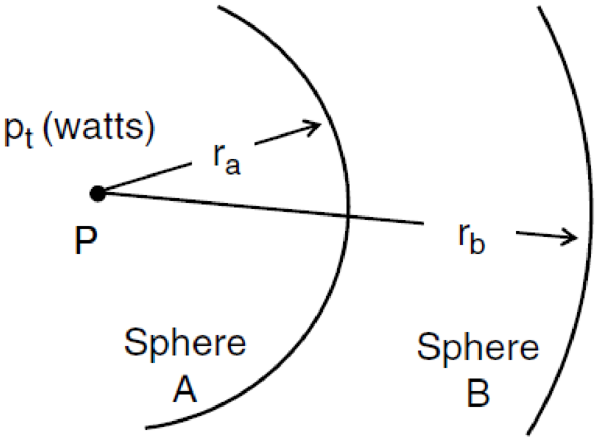
The electrical characteristics of an antenna such as gain, radiation pattern, impedance, bandwidth, resonant frequency and polarization, are the same whether the antenna is transmitting (T) or receiving (R).

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)

$$S_a = \frac{P_t}{4\pi r_a^2} \quad \left[\frac{\mathrm{W}}{\mathrm{m}^2}\right] \tag{6}$$

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,

$$P_t = P_T G_T \tag{7}$$

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):

$$A_{\text{eff},\,R} = \frac{P_R}{S_{\text{eff},\,R}} \tag{8}$$

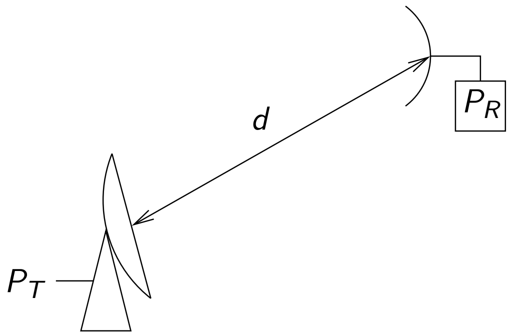
Theorem (no proof given)

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

$$A_{eff,\,R} = G_R \frac{\lambda^2}{4\pi} \tag{9}$$

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

Friis's relationship



We have

$$
\begin{aligned}
P_R &= S_{\text{eff},R} A_{\text{eff},R} \\
&= \left(\frac{P_T G_T}{4\pi d^2}\right) A_{\text{eff},R} = \left(\frac{P_T G_T}{4\pi d^2}\right)\left(\frac{\lambda^2}{4\pi}\right) G_R = P_T G_T G_R \left(\frac{\lambda}{4\pi d}\right)^2
\end{aligned}
$$

Free space path loss	FRIIS's relationship
$L_{FS} = \left(\frac{\lambda}{4\pi d}\right)^2$	$\epsilon = \frac{P_T}{P_R} = \left(\frac{4\pi d}{\lambda}\right)^2 \frac{1}{G_T G_R}$

Decibel as a common power unit

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

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

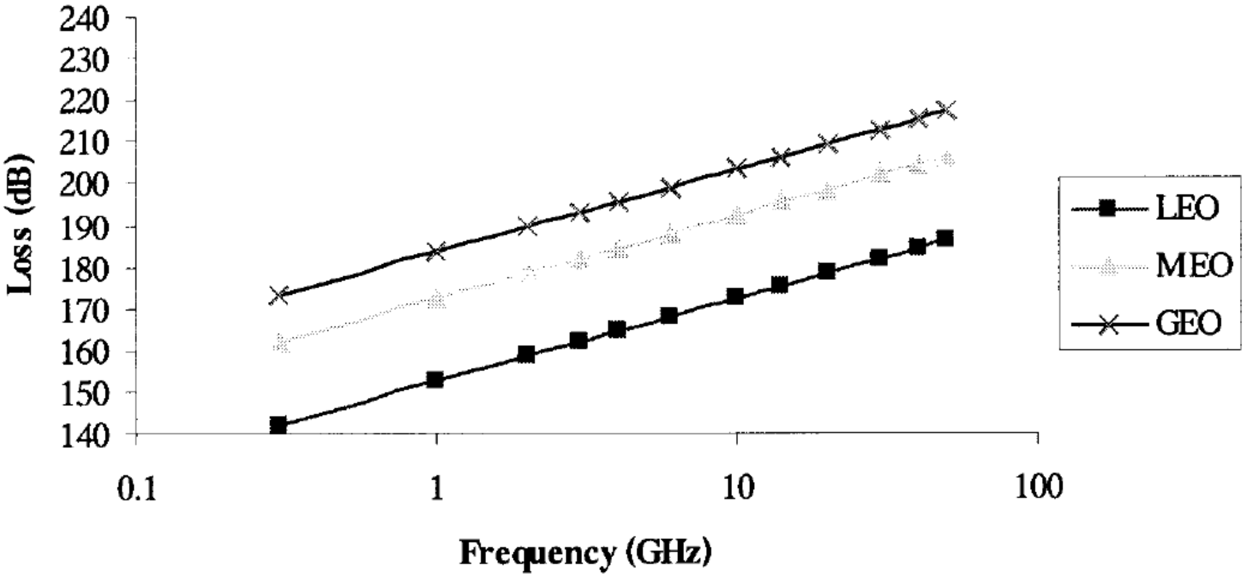
Typical orders of magnitude in satellite communications:

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

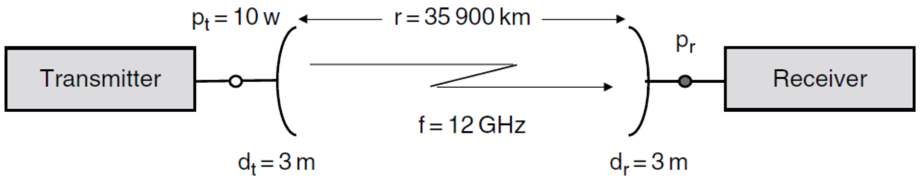
Free space losses

$$L_{FS} = \left(\frac{\lambda}{4\pi d}\right)^2 = \left(\frac{c}{4\pi d f}\right)^2 \tag{11}$$

where c is the speed of light.



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



Antenna gains: 48.93 [dB]
The *free space path loss* is, in [dB],

$$L_{FS} = 32.5 + 20\log f_{[\mathrm{MHz}]} + 20\log d_{[\mathrm{km}]} = 205.1\,[\mathrm{dB}] \tag{12}$$

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

$$\begin{aligned} P_R &= P_T + G_T + G_R - L_{FS} && (13)\\ &= 10 + 48.93 + 48.93 - 205.1 = -97.24\,[\mathrm{dB}] && (14)\end{aligned}$$

In [W], the *received power* is

$$P_R = 10^{-\frac{97.24}{10}} = 10^{-9.724} = 1.89 \times 10^{-10}\,[\mathrm{W}] = 189\,[p\mathrm{W}] \tag{15}$$

Outline

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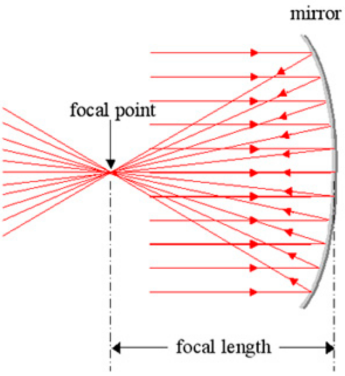
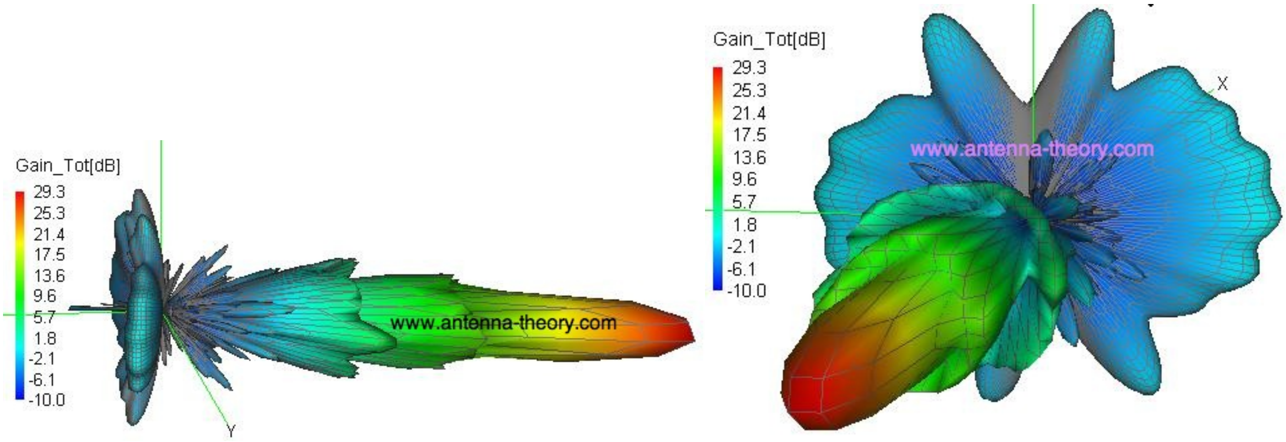
Terrestrial antennas

Ground station antenna

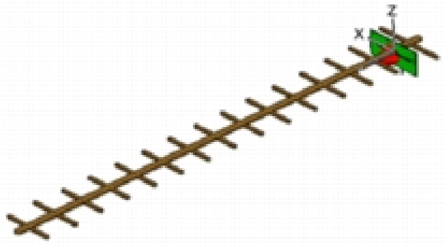
Parabolic (dish) antenna



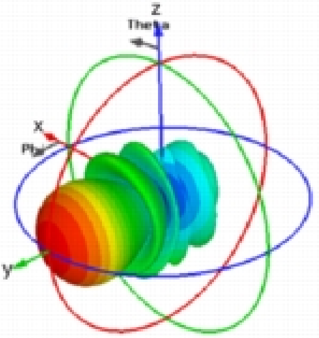
Radiation pattern



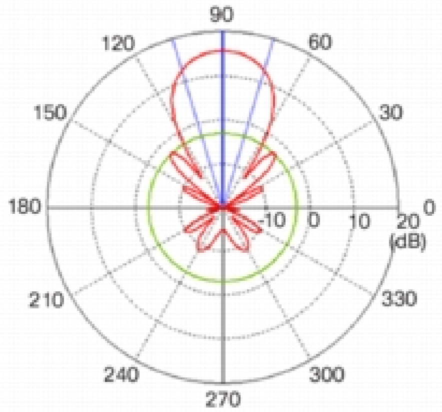
Yagi antenna (ground)



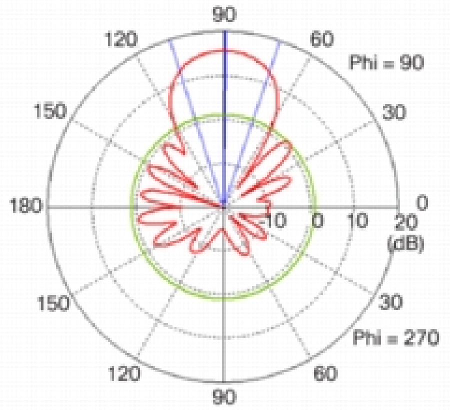
(a) Yagi Antenna Model



(b) Yagi Antenna 3D Radiation Pattern

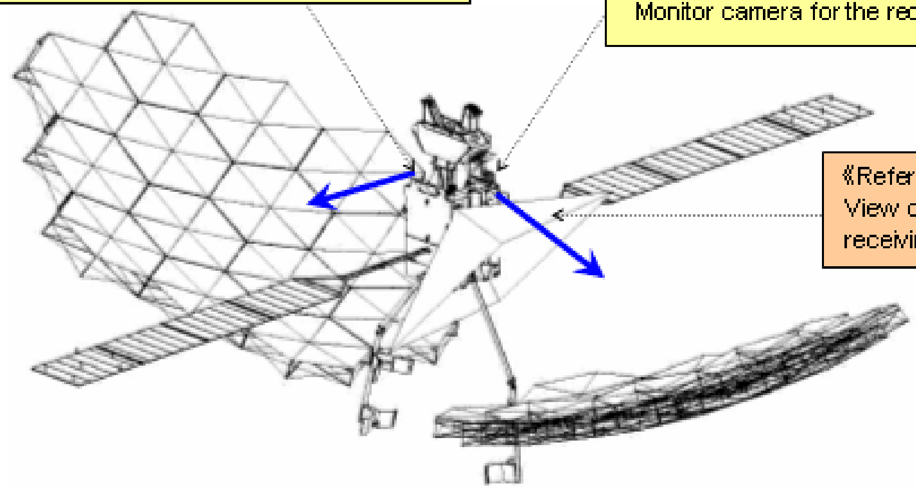


(c) Yagi Antenna Azimuth Plane Pattern



(d) Yagi Antenna Elevation Plane Pattern

Deployable antenna

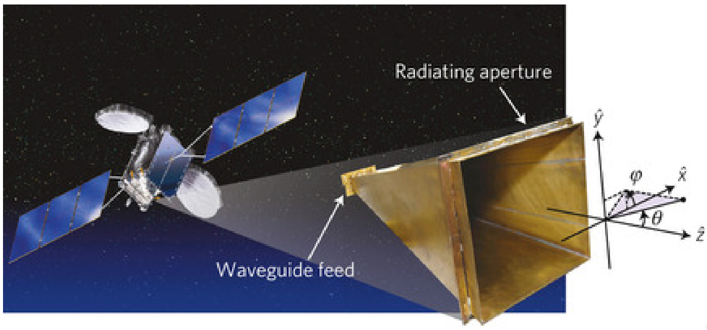


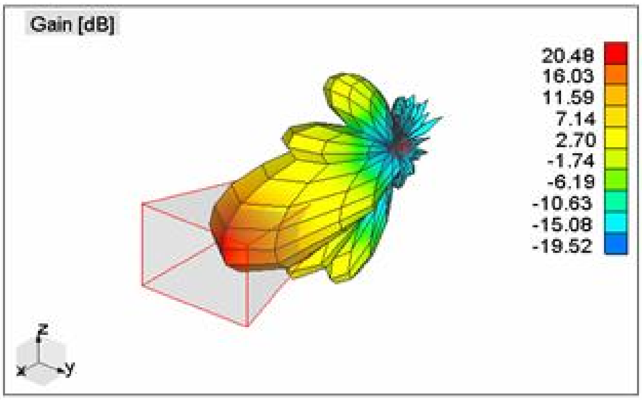
Monitor camera for the sending antenna

Monitor camera for the receiving antenna

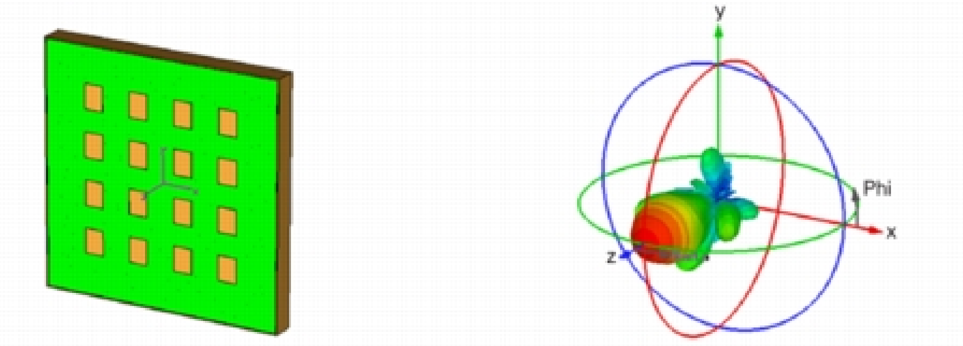
《Reference》
View of the monitor camera for the receiving antenna

Horn antenna and waveguide feed



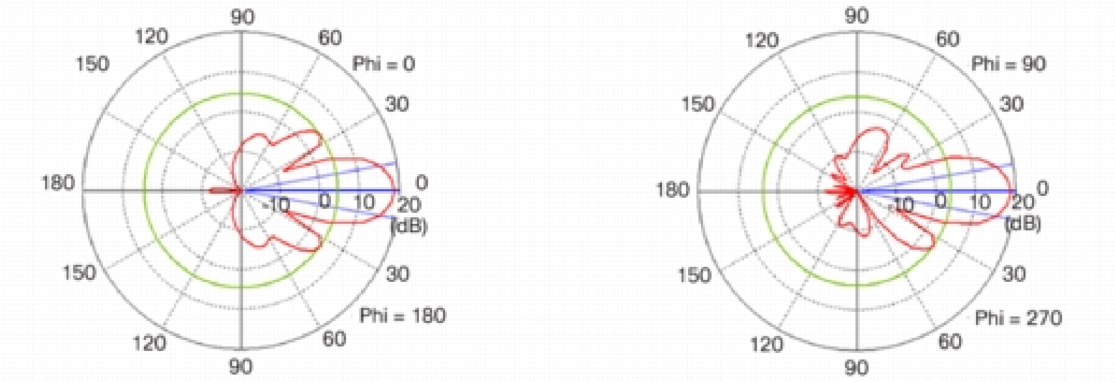


Patch array antenna



(a) 4x4 Patch Array Antenna

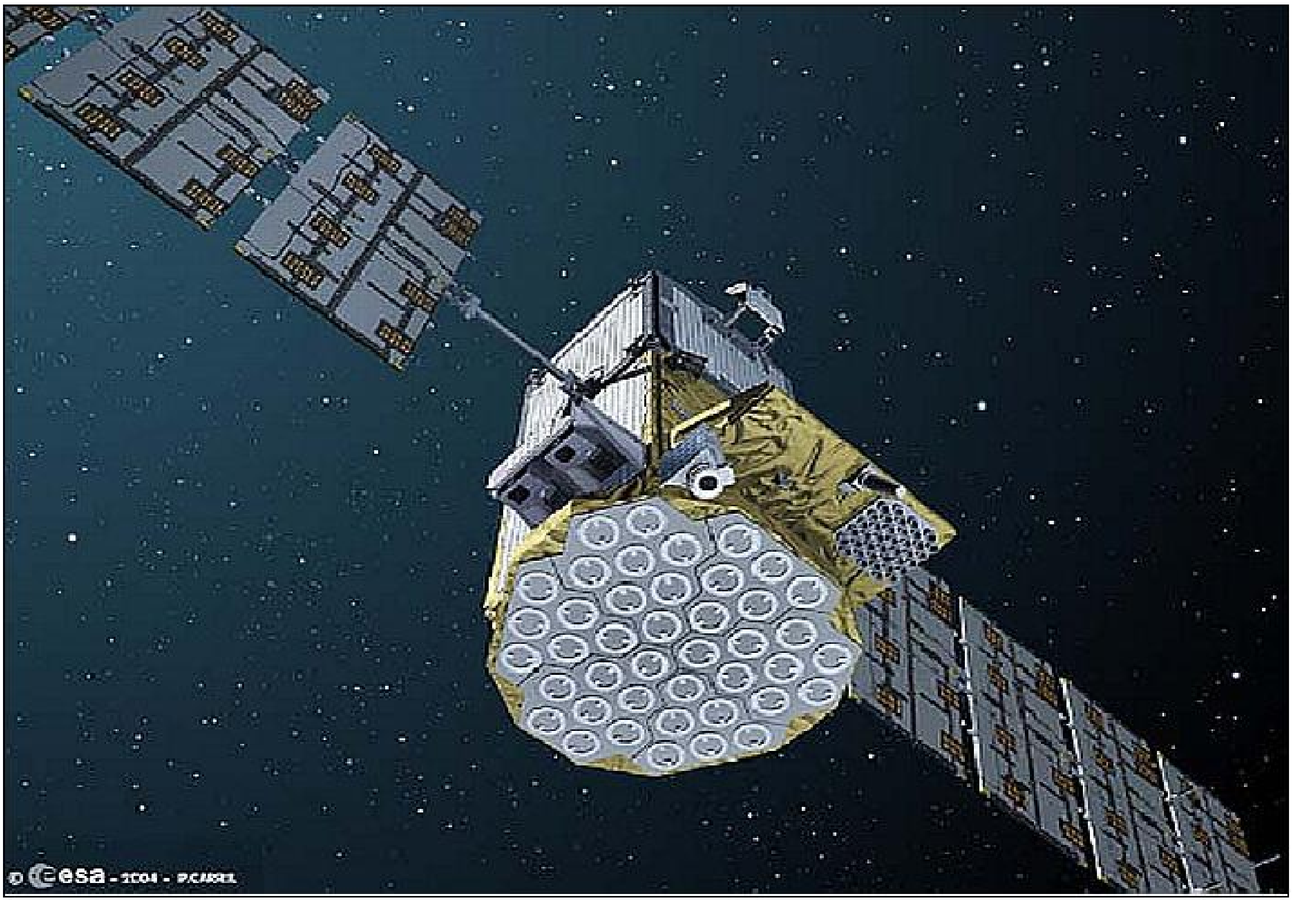
(b) 4x4 Patch Array 3D Radiation Pattern



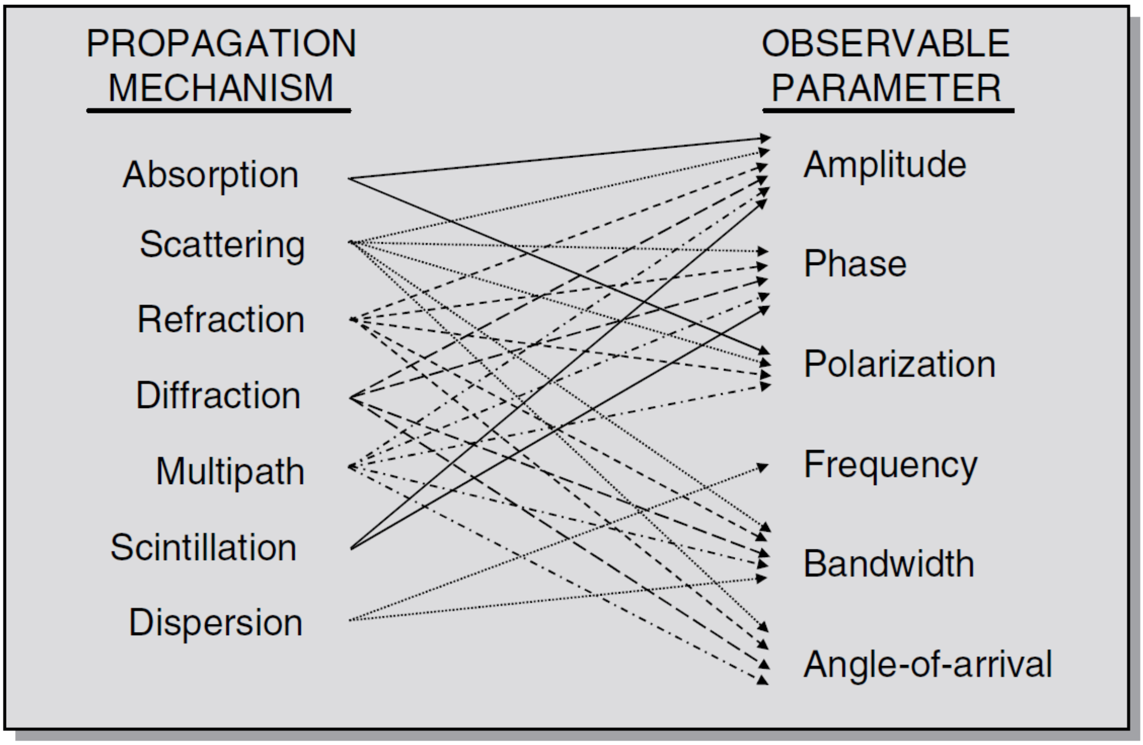
(c) 4x4 Patch Array Azimuth Plane Pattern

(d) 4x4 Patch Array Elevation Plane Pattern

Phased array antenna



Radiowave propagation mechanisms



PROPAGATION MECHANISM

- Absorption
- Scattering
- Refraction
- Diffraction
- Multipath
- Scintillation
- Dispersion

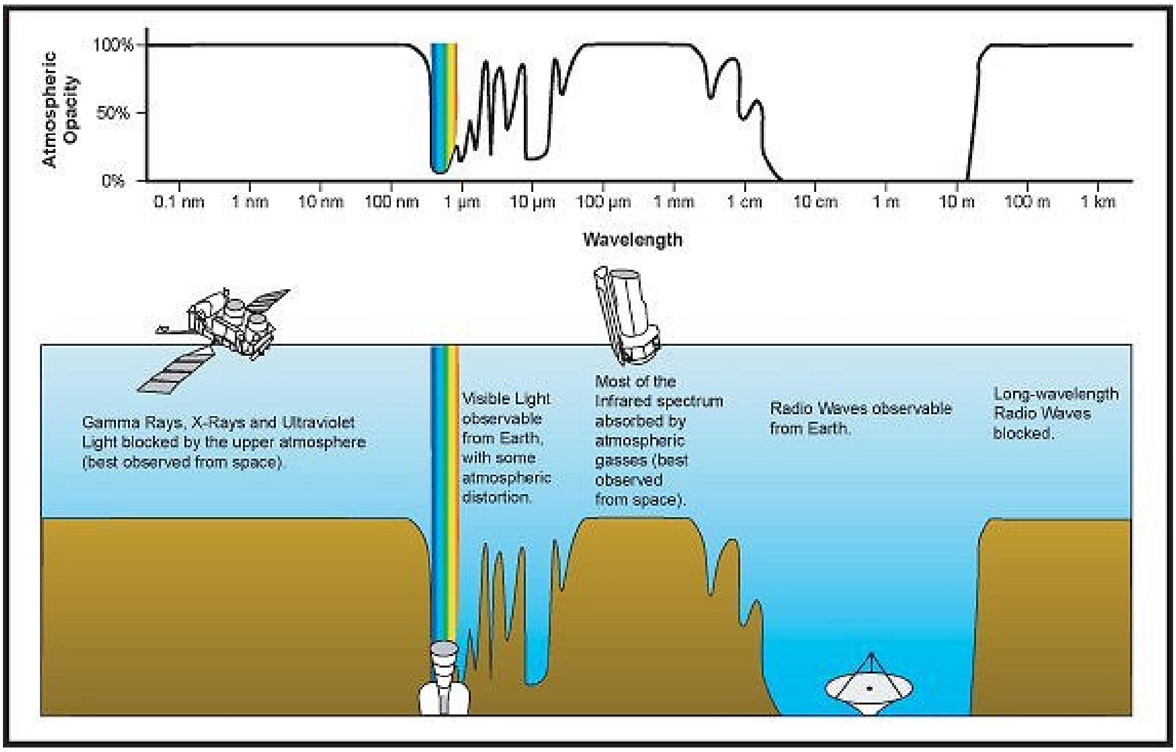
OBSERVABLE PARAMETER

- Amplitude
- Phase
- Polarization
- Frequency
- Bandwidth
- Angle-of-arrival

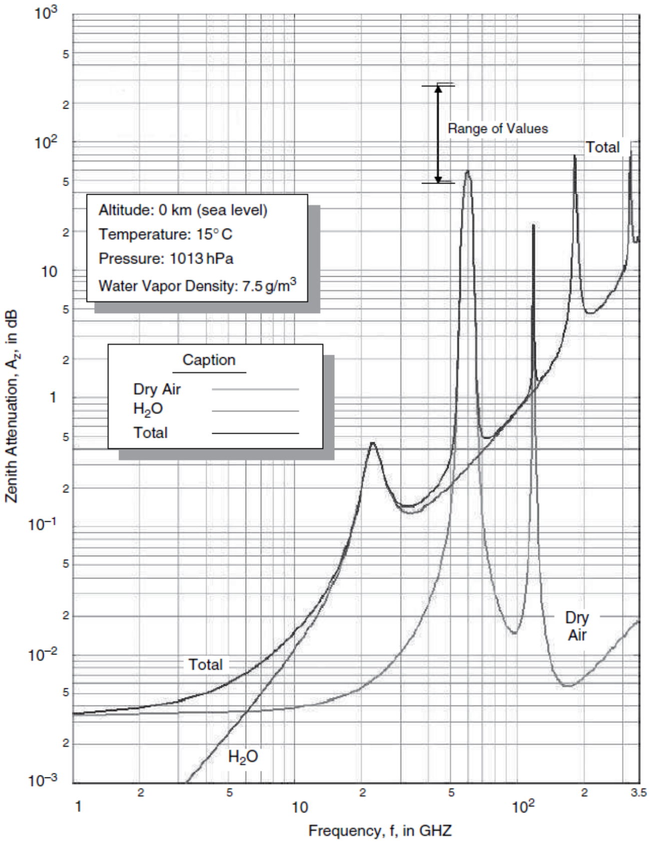
+ Doppler effect

Earth atmosphere absorption

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

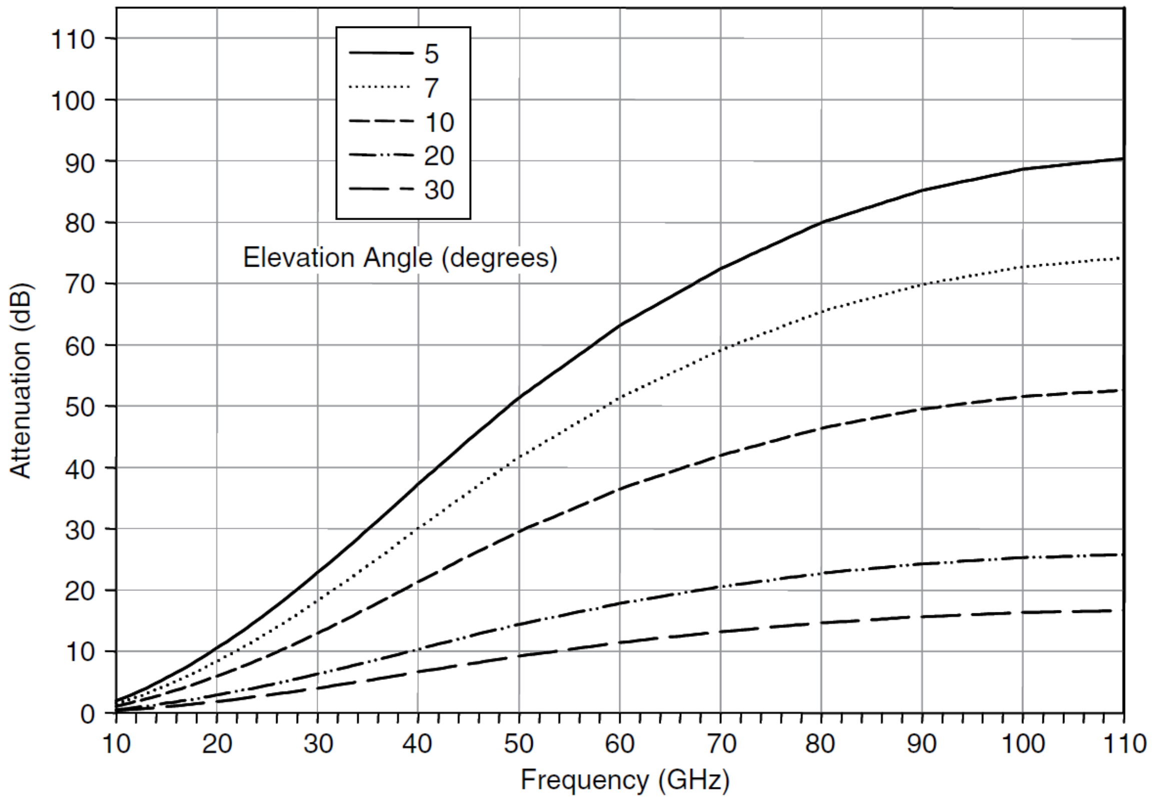


Attenuation due to atmospheric gases



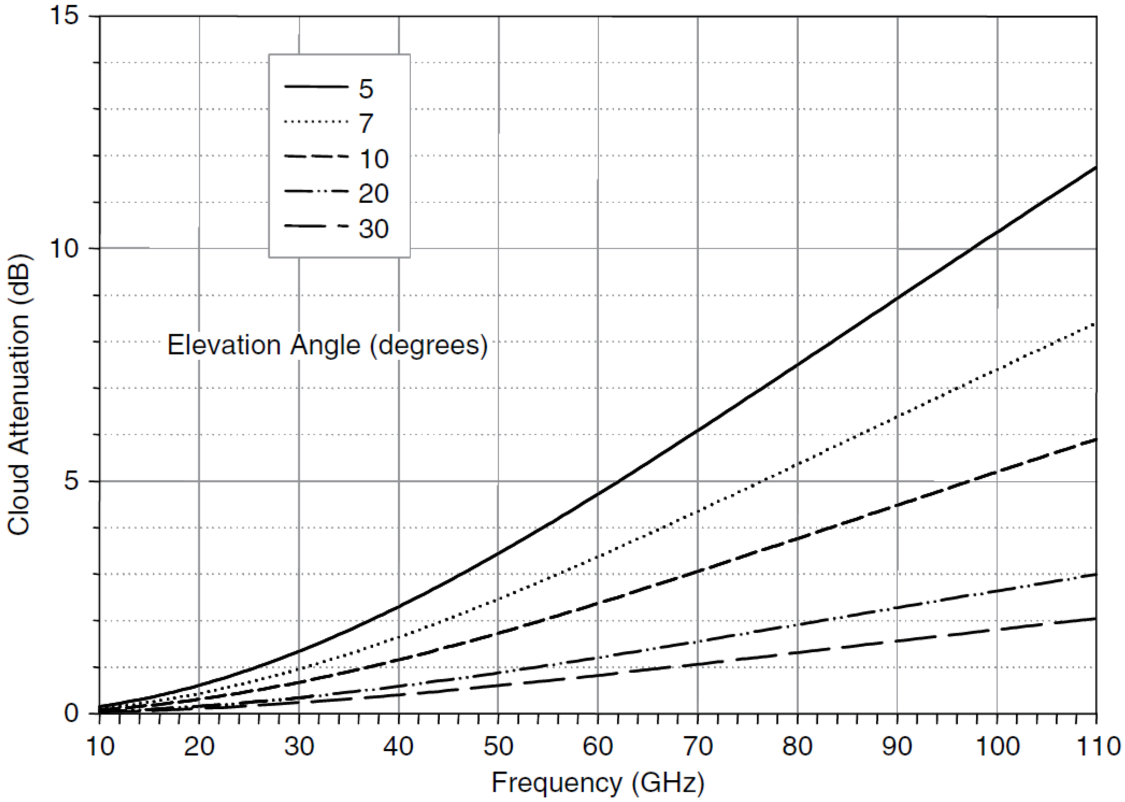
Zenith attenuation due to atmospheric gases (source: ITU-R P.676-6)
[O_2 and H_2O are the main contributors]

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 30^0

Total attenuation

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

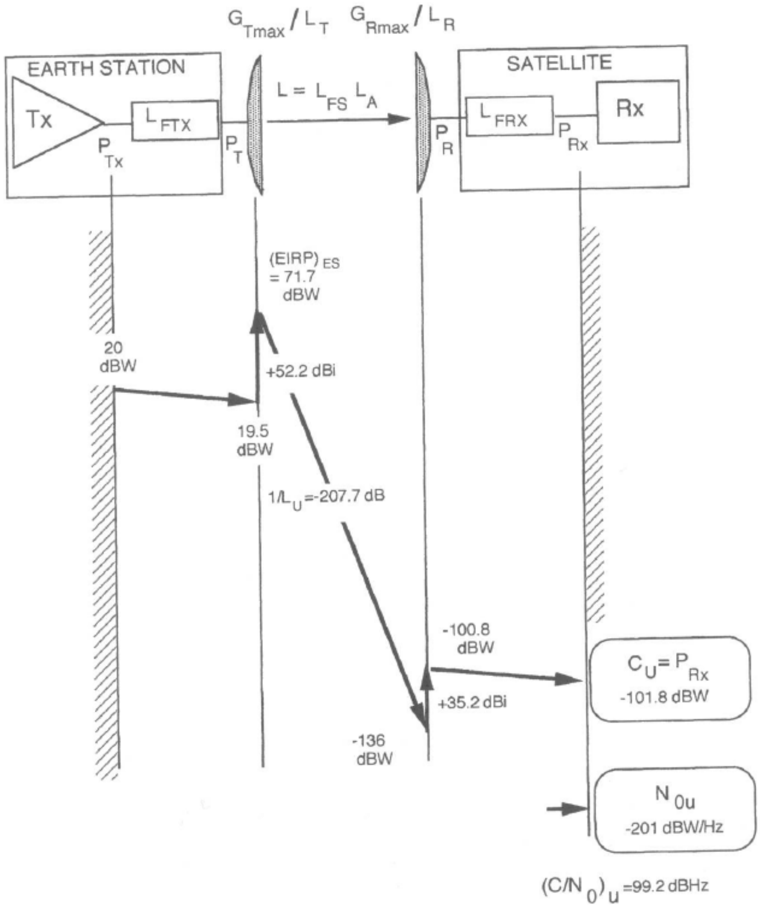
$$A_T(p) = A_G(p) + \sqrt{(A_R(p) + A_c(p))^2 + A_s(p)} \qquad (16)$$

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

Graphical representation of the power budget through a satellite system



Questions to address

1. What about the amount of noise generated by the equipment?
2. In a receiver, we cascade filter, line, amplifier, mixer, ...
    1. How do we characterize a single two-port circuit (≡ quadripole) in terms of noise?
    2. How do we characterize a cascade of two-port circuits?
3. Calculate the final signal to noise ratio (to determine the capacity or determine the BER, etc.).

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

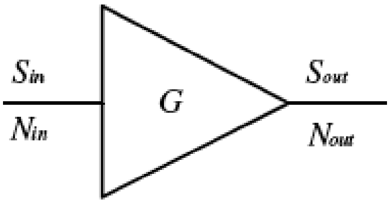
$$P_N = k_B T W \tag{17}$$

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 → put *electronics* in the *cold "zone" of a satellite*

Noise in two-port circuits



Definitions

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

$$F = \frac{\left(\frac{S}{N}\right)_{\mathrm{in}}}{\left(\frac{S}{N}\right)_{\mathrm{out}}} > 1 \tag{18}$$

Noise Figure (NF):

$$\mathrm{NF}{=}10\log_{10} F \tag{19}$$

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

$$T_e = T_0(F-1) \tag{20}$$

Noise factor of a two-port (quadripole) cascade I

In a cascade, each two-port element is noisy ⟶ each element contributes to degrade the overall noise factor

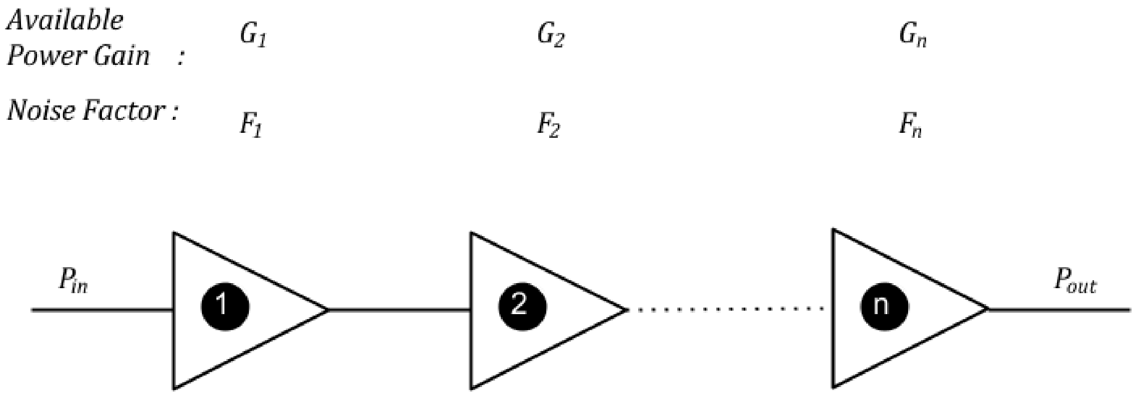


Figure: Cascading two-port elements.

Noise factor of a two-port (quadripole) cascade II

Formula to calculate the noise factor of a cascade of two-port circuits (quadripoles)

For a two-port network with n stages,

$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \cdots = F_1 + \sum_{i=2}^{n} \frac{F_i - 1}{\prod_{j=1}^{i-1} G_j} \qquad (21)$$

Noise factor of a two-port (quadripole) cascade III

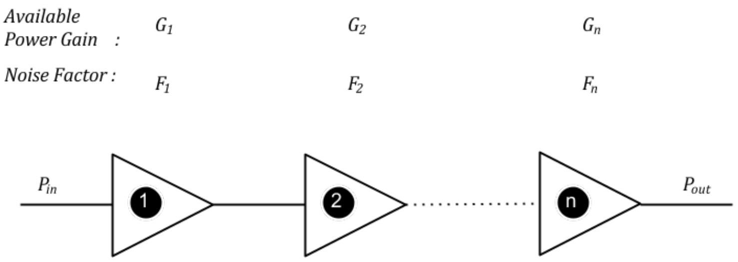


Figure: Cascading two-port elements.

Likewise,

$$T_e = T_{e1} + \frac{T_{e2}}{G_1} + \frac{T_{e3}}{G_1 G_2} + \cdots = T_{e1} + \sum_{i=2}^{n} \frac{T_{ei}}{\prod_{j=1}^{i-1} G_j} \tag{22}$$

Receiver front end I

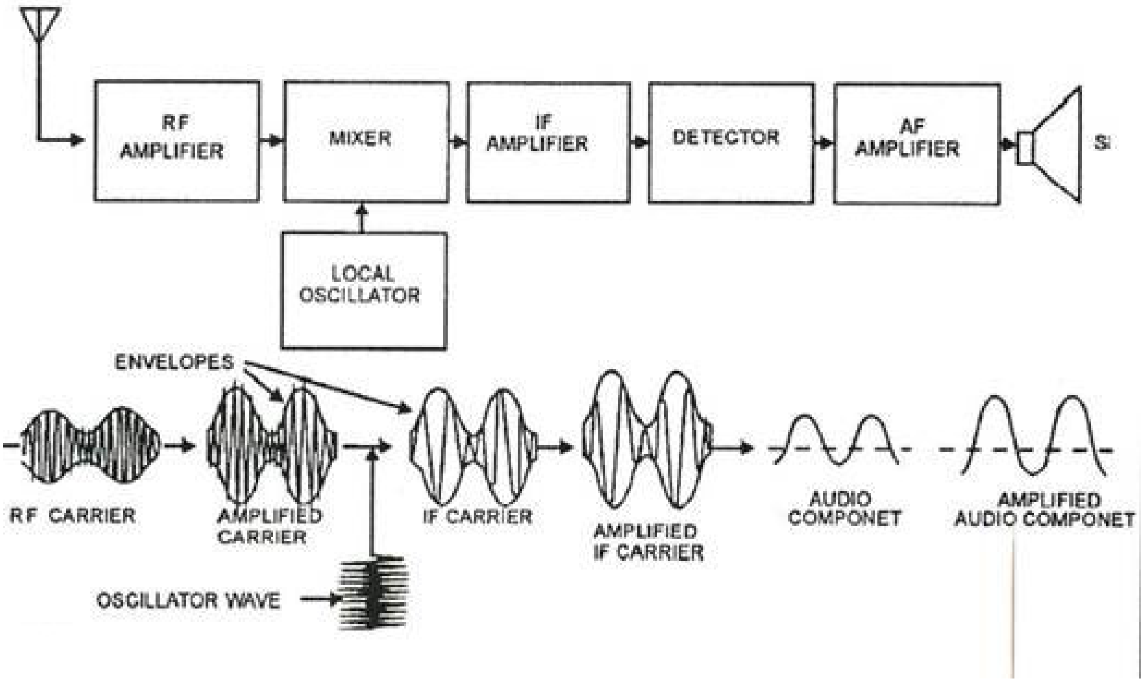
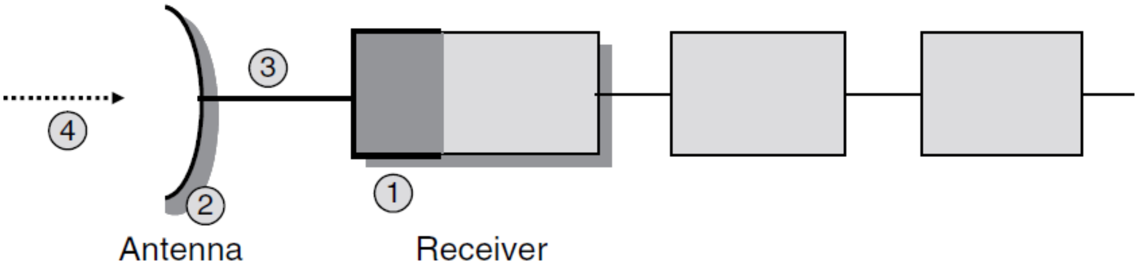


Figure: Block diagram of a typical receiver.

Receiver front end II



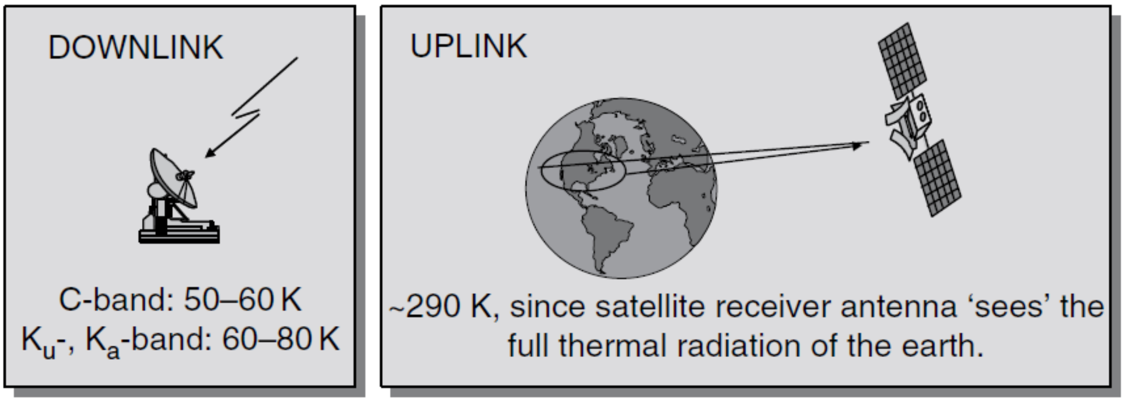
Rule of thumb: highest gain (G_1) and best noise figure (F_1) first.

Then

$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \cdots \simeq F_1 + \frac{F_2 - 1}{G_1} \tag{23}$$

$$T_e = T_{e1} + \frac{T_{e2}}{G_1} + \frac{T_{e3}}{G_1 G_2} + \cdots \simeq T_{e1} + \frac{T_{e2}}{G_1} \tag{24}$$

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



C-band: 50–60 K
K_u-, K_a-band: 60–80 K

~290 K, since satellite receiver antenna ‘sees’ the full thermal radiation of the earth.

(a)

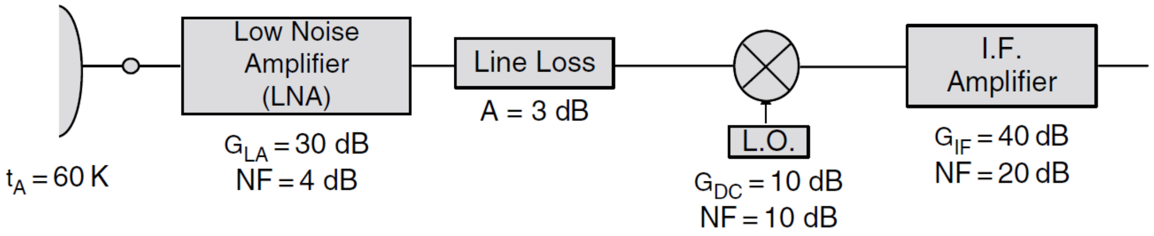
TYPICAL ANTENNA TEMPERATURE VALUES (NO RAIN)

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

(b)

ADDITIONAL RADIO NOISE CAUSED BY RAIN

Example of the calculation of a noise budget (see [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

$$T_e = t_A + T_{e1} + \frac{T_{e2}}{G_1} + \frac{T_{e3}}{G_1 G_2} + \cdots \tag{25}$$

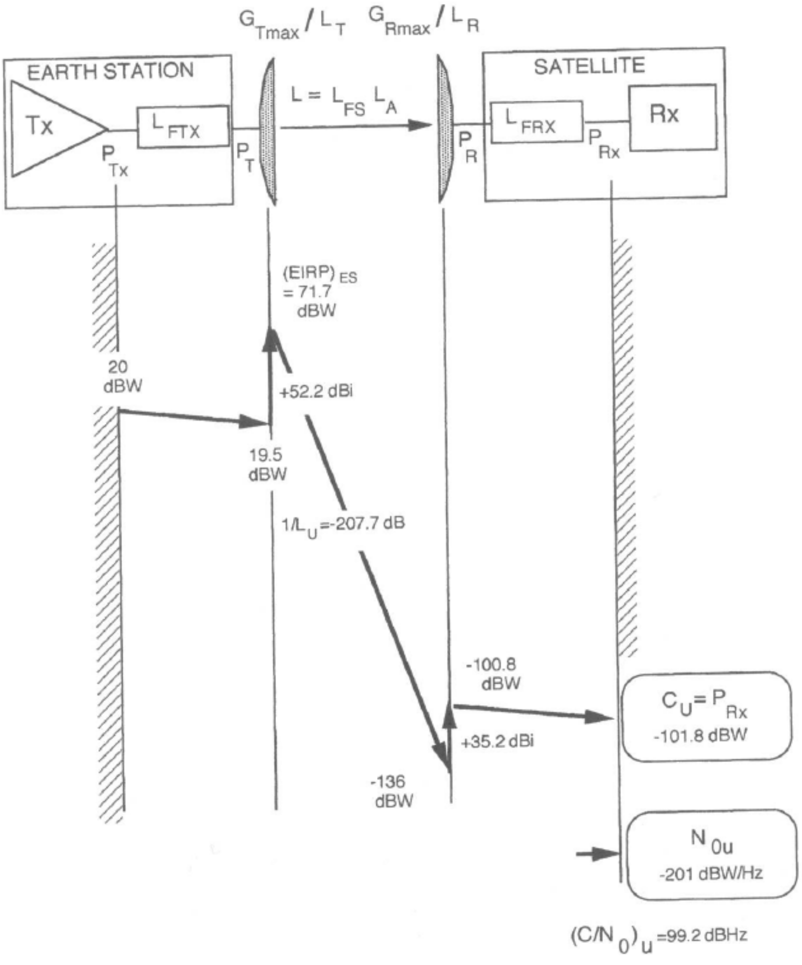
$$= \underbrace{60 + 438}_{498} + \frac{289}{1000} + \frac{2610}{1000 \times \frac{1}{2}} + \cdots = 509.3\,[\mathrm{K}] \tag{26}$$

Outline

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 [dBi]	36.9 [dBi]
Receiver antenna gain	37.9 [dBi]	52.6 [dBi]
Receiver noise figure	8 [dB]	3 [dB]
Receiver antenna temperature	290 [K]	50 [K]
Free space path loss (30^0 elevation)	207.2 [dB]	205.8 [dB]

Clear sky downlink performance [2]



For further reading

- L. Ippolito.
  Satellite Communications Systems Engineering: Atmospheric Effects, Satellite Link Design and System Performance. Wiley, 2008.
- G. Maral, M. Bousquet.
  Satellite Communications Systems: Systems, Techniques and Technology. Wiley, 2002.
- J. Gibsons.
  The Communications Handbook. CRC Press, 1997.
- Wikipedia.
  `http://wikipedia.org`