Satellite Communications

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Outline

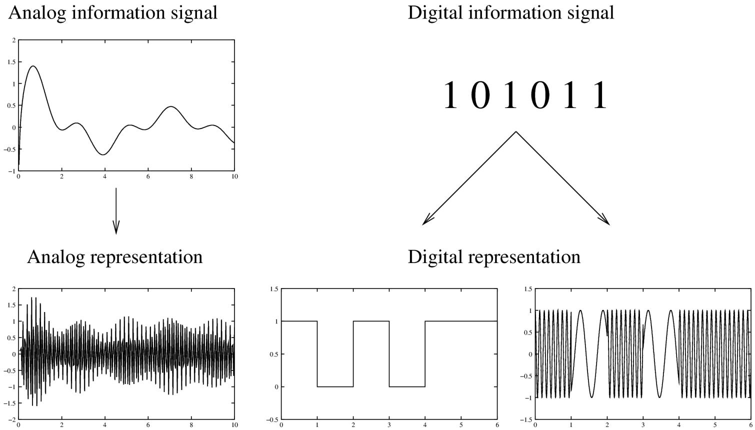
1. Signal processing elements
   - What do we transmit? Information!
   - Source coding
   - Modulation
   - Multiplexing
2. Propagation and radio communications
   - Background
   - Radiowave propagation
   - Examples of antennas
3. Engineering
   - Noise
   - Link budget

Outline

Main types of satellite

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

Analog and digital signals



Characterization

Analog signal	Digital signal
Bandwidth [Hz]	Bit rate [bit/s]
Signal to Noise ratio (S/N)	Bit error rate (BER)
Bandwidth of the underlying channel [Hz]	

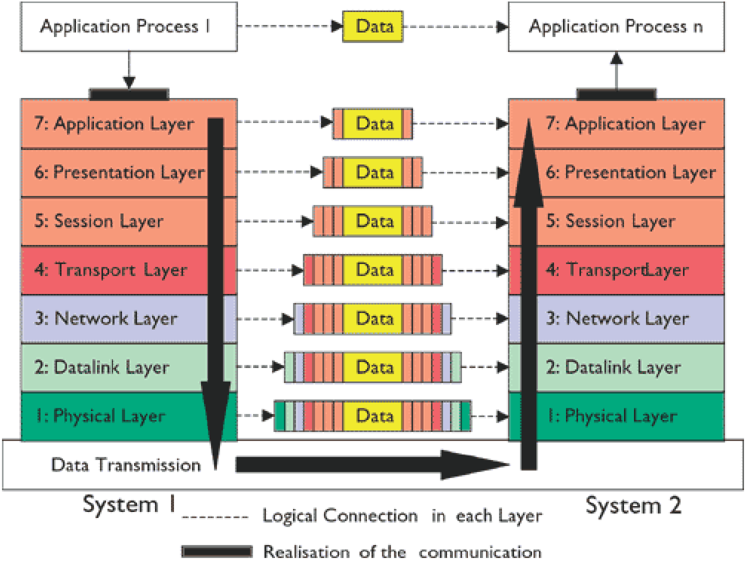
Going digital because:

- possibility to regenerate a digital signal
- better bandwidth usage
  - analog PAL television signal: bandwidth of $8\,[MHz]$
  - digital television, PAL quality $\sim 5\,[Mb/s]$
    - With a 64-QAM modulation, whose spectral efficiency is $6\,b/s$ per Hz. $8\,[MHz]$ allows for $48\,[Mb/s]$.
    - Therefore, there is room for 10 digital television instead of one analog channel.

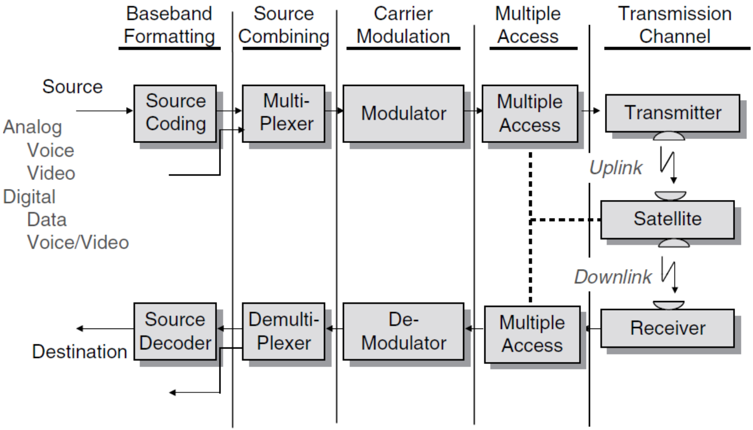
Data streams

Types of data	Characteristics
Control data	Must be very reliable
Measurements	Accurate signals with constant monitoring
Remote sensing	High volume of downstream data
Localization data	Accurate time reference (synchronization)
Broadcasting	Television channels
Payload	Unicast communication for mobile ground station

Data encapsulation: OSI model



Elements of a communication channel



Outline

Theorem

[Shannon] *The capacity of an Additive White Gaussian Noise (AWGN) channel is*

$$C = W \log_2 \left(1 + \frac{S}{N}\right) \tag{1}$$

where W *is the bandwidth occupied by the signal,* S *is the signal power and* $N = WN_0$ *is the Gaussian noise variance.*

Let R be the bit rate and E_b the energy per bit (in joules), we have $S = E_b R$, and

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

The ratio $\frac{R}{W}$ is the *spectral efficiency* expressed in $[b/s]$ per $[Hz]$.

Bit/packet error rate

Assume a packet of size N and let P_e be the probability error on one bit.
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

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

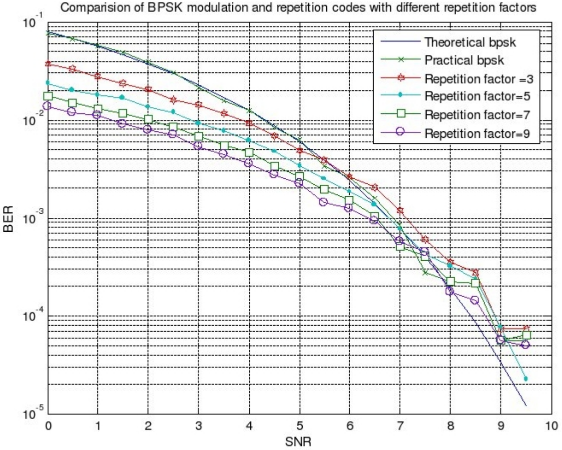
Example

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

Forward Error Coding

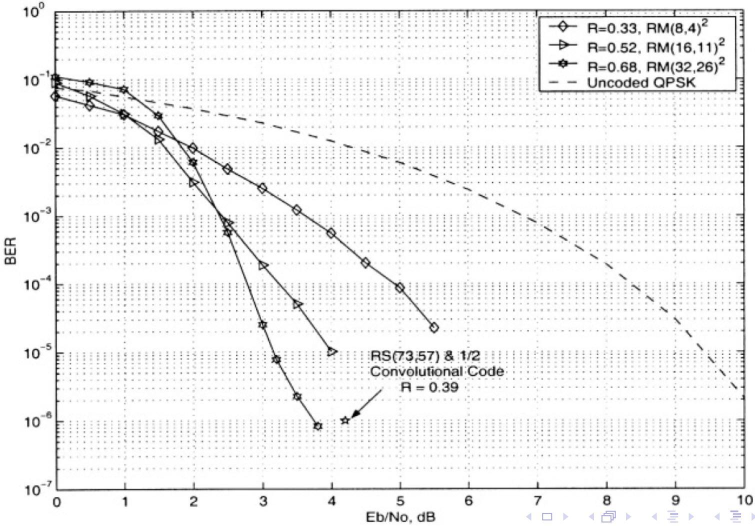
A simplistic example of Forward Error Coding (*FEC*) is to transmit each data bit 3 times, known as a (3,1) repetition code.

Triplet received	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, ...



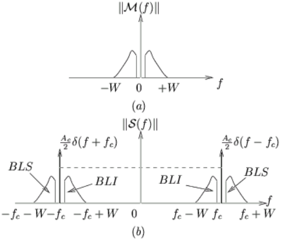
Outline

Modulation

A cosine $\cos(2\pi f_c t)$ is the *carrier*. $s(t)$ is the *modulated signal*

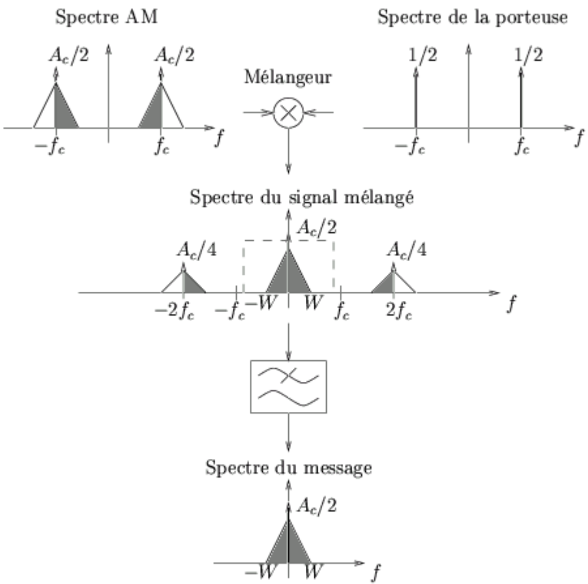
$$s(t) = A(t)\cos(2\pi f(t)t + \phi(t)) \tag{6}$$

- $A(t)$: Amplitude Modulation (AM)

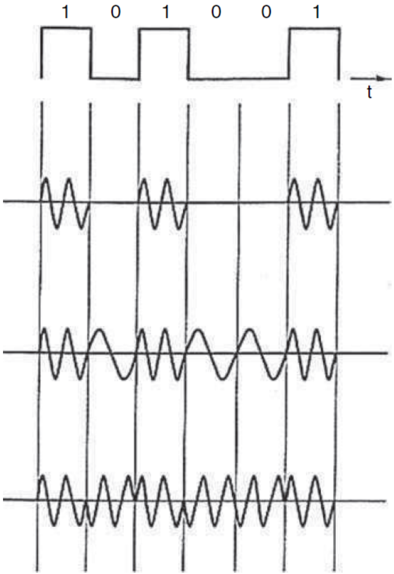


- $f(t)$: Frequency Modulation (FM)
- $\phi(t)$: Phase Modulation (PM)

Demodulation



Basic digital modulation techniques



OOK - On-Off Keying

- also called ASK, (amplitude-shift keying)
- binary signal is used to switch carrier on and off

FSK -Frequency Shift Keying

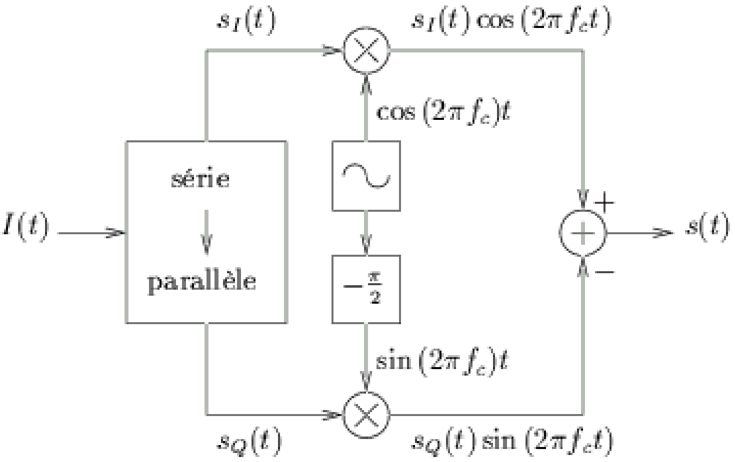
- binary signal used to FM the carrier, f_1 for a binary 1, f_2 for a binary 0

BPSK -Binary Phase Shift Keying

- polarity changes in binary signal used to produce 180° carrier phase change

It is possible to use both a cosine and a sine with a unique bandwidth.

$$s(t) = s_I(t)\cos(2\pi f_c t) - s_Q(t)\sin(2\pi f_c t) \tag{7}$$



Quadrature demodulation

$s(t) = s_I(t)\cos(2\pi f_c t) - s_Q(t)\sin(2\pi f_c t)$ is the modulated signal.
We want to recover $s_I(t)$

- *Step 1:* multiply by $\cos(2\pi f_c t)$

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

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

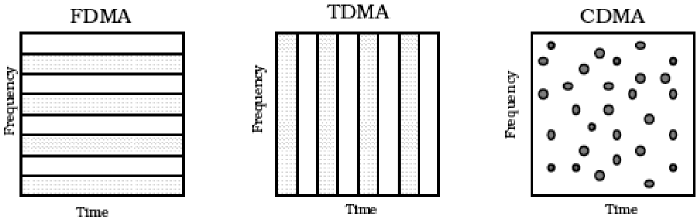
$$\frac{1}{2}s_I(t)$$

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

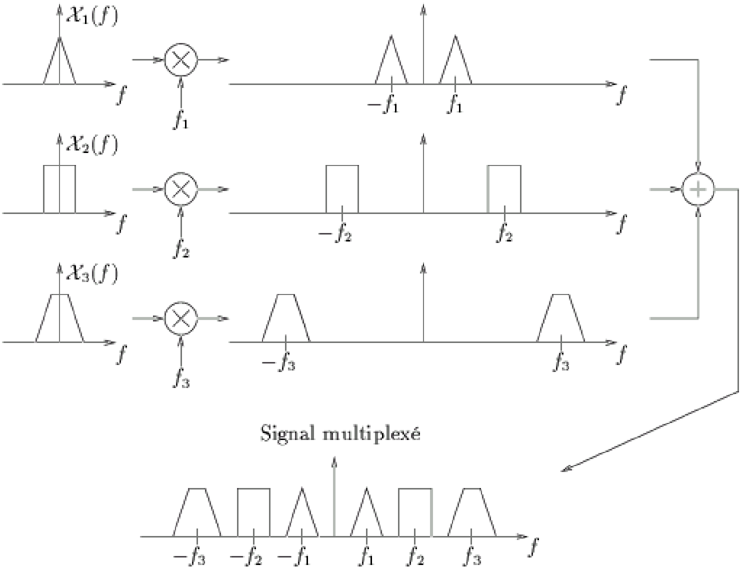
Outline

Multiplexing: combining several sources

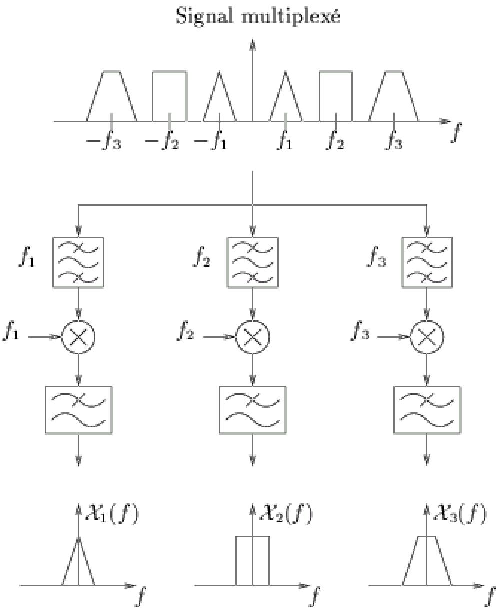
- Frequency Division Multiplexing (FDM)
- Time Division Multiplexing (TDM)
- Code Division Multiplexing (CDM)
- Space Division Multiplexing
- + combinations !



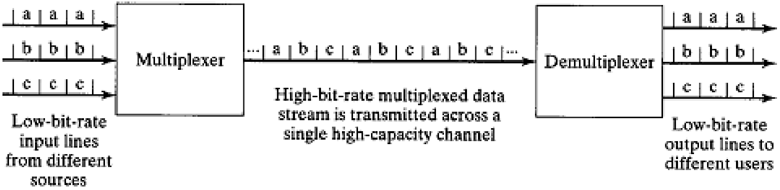
Frequency Division Multiplexing (FDM)



Demultiplexing

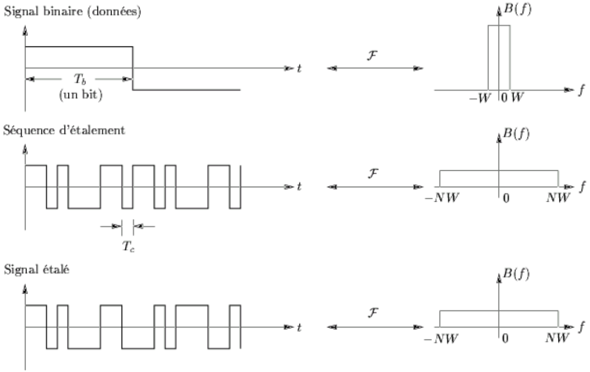


Time Division Multiplexing (TDM)



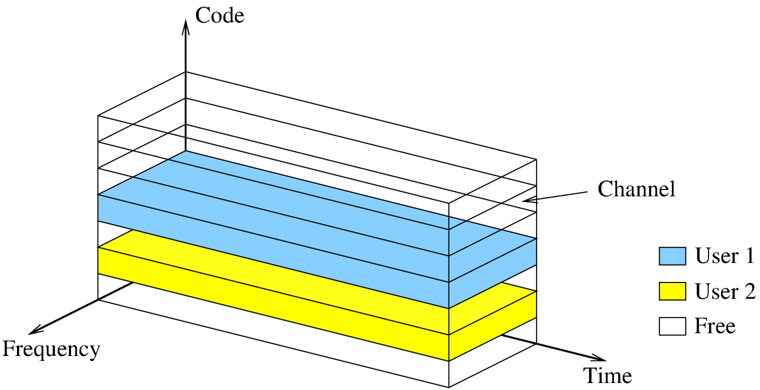
Spread spectrum for Code Division Mulplexing

Principle of spread spectrum: multiply a digital signal with a faster pseudo-random sequence.

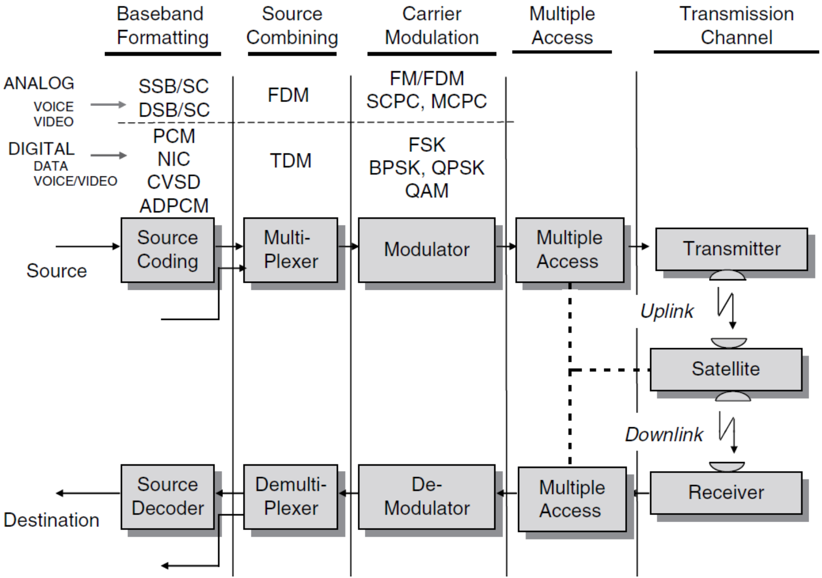


At the receiver, the pseudo-random sequence is generated and used to despread the signal.

Code Division Multiple Access

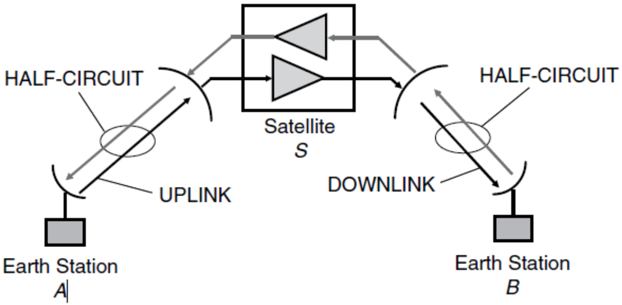


Summary


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
Multiple Access
De-Modulator
Demulti-Plexer
Source Decoder
Destination

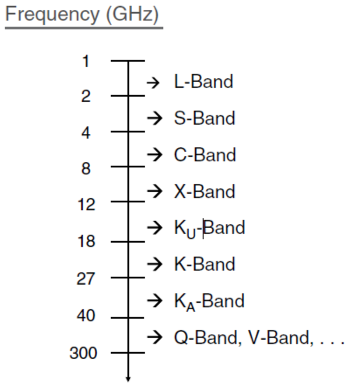
Outline

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

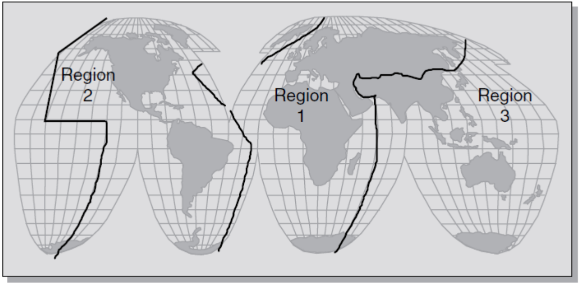
Frequency bands



But it is better to designate the carrier frequency directly

Regulatory bodies

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

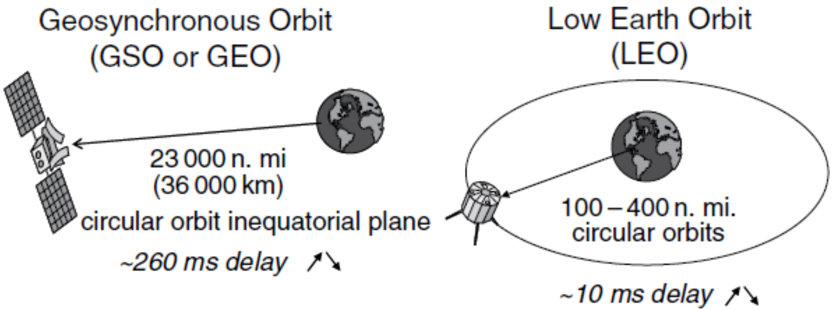


  - organizes WARC (World Administrative Radio Conference) - worldwide allocation of frequencies
- Regional body: European Conference of Postal and Telecommunications Administrations (CEPT)

Extract 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		

Orbits



Geosynchronous Orbit
(GSO or GEO)
23 000 n. mi
(36 000 km)
circular orbit inequatorial plane
~260 ms delay
Low Earth Orbit
(LEO)
100 – 400 n. mi.
circular orbits
~10 ms delay

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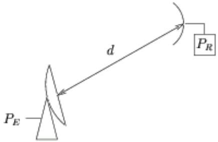
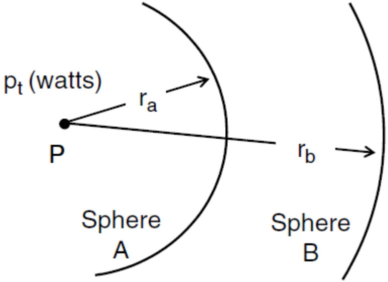
Radiowave propagation



Important parameters:

- channel characteristics
  - attenuation (distance)
  - wave polarization
  - rain mitigation
- antenna design
- power budget

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

$$S_a = \frac{P_t}{4\pi r_a^2} \quad \left[\frac{W}{m^2}\right] \tag{8}$$

Effective Isotropic Radiated Power [EIRP]

Definition

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).

Therefore, at the receiver,

$$P_t = P_E G_E \tag{9}$$

Effective area

Definition

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

$$A_{eff} = \frac{P_R}{S_{eff}} \tag{10}$$

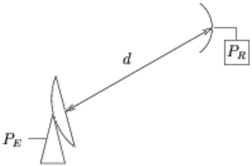
Theorem

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

$$A_{eff} = G_E \frac{\lambda^2}{4\pi} \tag{11}$$

Friis relationship

We have



$$P_R = S_{eff,R} A_{eff,R}$$
$$= \left(\frac{P_E G_E}{4\pi d^2}\right) A_{eff,R} = \left(\frac{P_E G_E}{4\pi d^2}\right)\left(\frac{\lambda^2}{4\pi}\right) G_R = P_E G_E G_R \left(\frac{\lambda}{4\pi d}\right)^2$$

Free space path loss	Friis's relationship
$L_{FS} = \left(\frac{\lambda}{4\pi d}\right)^2$	$\varepsilon = \frac{P_E}{P_R} = \left(\frac{4\pi d}{\lambda}\right)^2 \frac{1}{G_E G_R}$

Decibel as a common power unit

$$x \leftrightarrow 10\log_{10}(x)\,[dB] \tag{12}$$

$$P\,[dBm] = 10\log_{10}\frac{P\,[mW]}{1\,[mW]} \tag{13}$$

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

Are high frequencies less adequate?

In $[dB]$, Friis's relationship becomes

$$\varepsilon = 32.5 + 20\log f_{[MHz]} + 20\log d_{[km]} - G_{E\,[dB]} - G_{R\,[dB]}$$

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

but

$$A_{eff} = G_E \frac{\lambda^2}{4\pi} \tag{14}$$

$$\varepsilon = \left(\frac{4\pi d}{\lambda}\right)^2 \frac{1}{G_E G_R} = \left(\frac{4\pi d}{\lambda}\right)^2 \frac{\lambda^2}{4\pi A_E} \frac{\lambda^2}{4\pi A_R} \tag{15}$$

$$= \frac{\lambda^2 d^2}{A_E A_R} = \frac{c^2 d^2}{f^2 A_E A_R} \tag{16}$$

It all depends on the antenna gains.

Are high frequencies less adequate?

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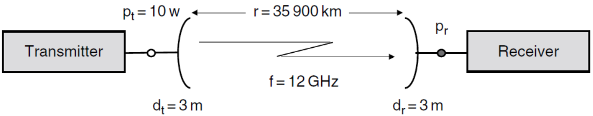
$$A_{eff} = G_E \frac{\lambda^2}{4\pi} \quad (14)$$

$$\begin{aligned} \varepsilon &= \left(\frac{4\pi d}{\lambda}\right)^2 \frac{1}{G_E G_R} = \left(\frac{4\pi d}{\lambda}\right)^2 \frac{\lambda^2}{4\pi A_E} \frac{\lambda^2}{4\pi A_R} && (15) \\ &= \frac{\lambda^2 d^2}{A_E A_R} = \frac{c^2 d^2}{f^2 A_E A_R} && (16) \end{aligned}$$

It all depends on the antenna gains.

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



Antenna gain: $48.93\,[dB]$

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

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

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

$$P_R = P_E + G_E + G_R - L_{FS} \quad (17)$$

$$= 10 + 48.93 + 48.93 - 205.1 = -97.24\,[dB] \quad (18)$$

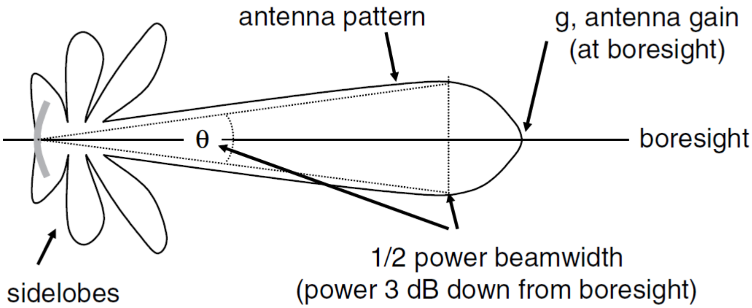
In $[W]$, the *received power* is

$$P_R = 10^{-\frac{97.24}{10}} = 1.89 \times 10^{-10}\,[W] = 189\,[pW] \quad (19)$$

Outline

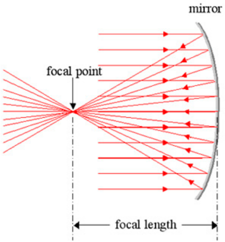
Terrestrial antennas

Beamwidth and aperture

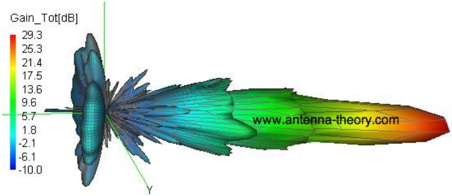


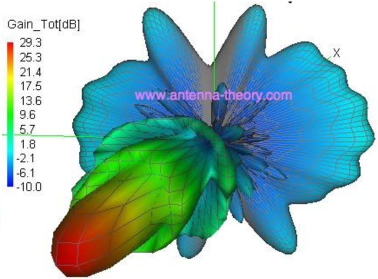
Ground station antenna

Parabolic (dish) antenna

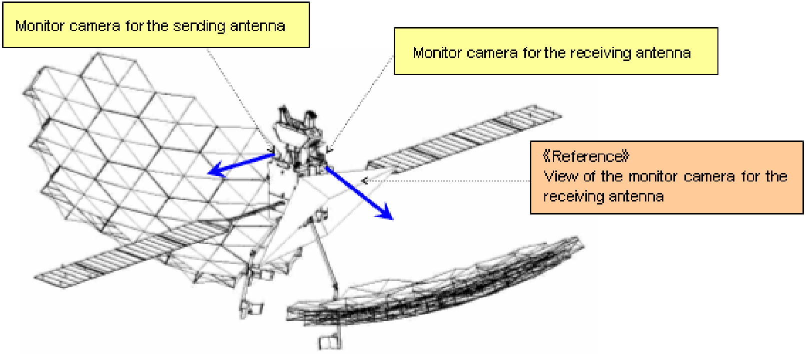


Radiation pattern

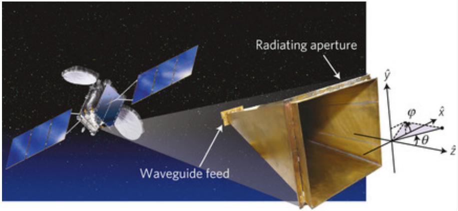


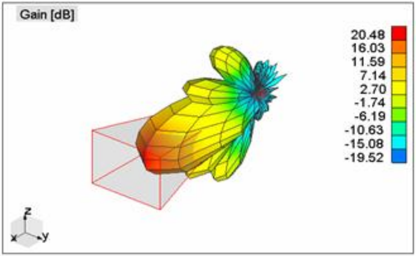


Deployable antenna

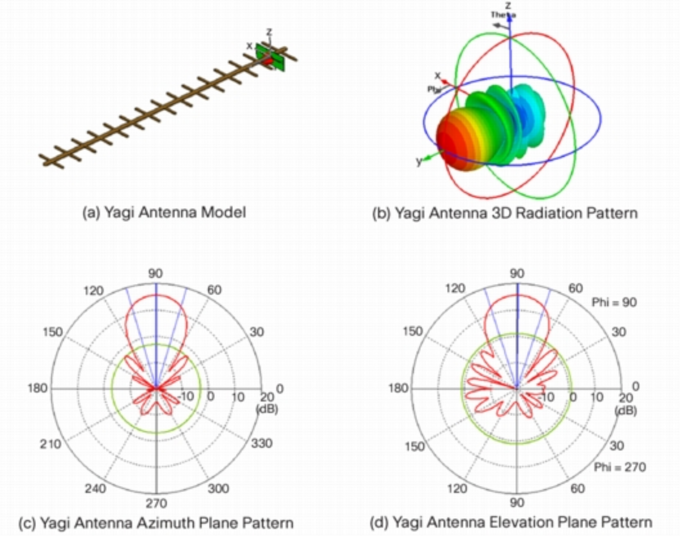


Horn antenna and waveguide feed





Yagi antenna



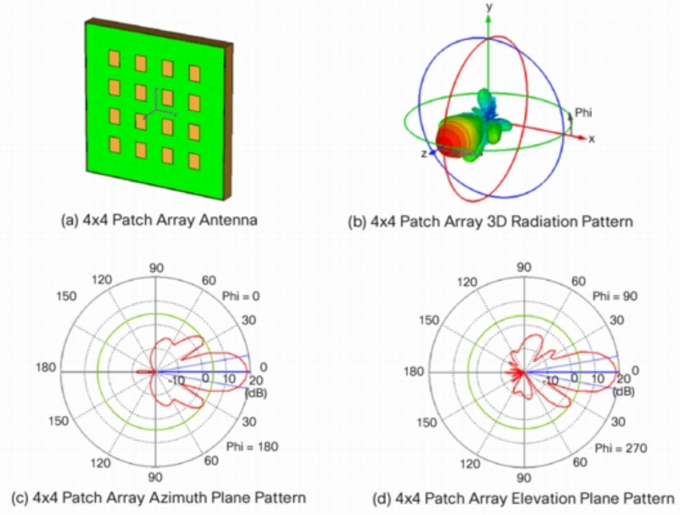
(a) Yagi Antenna Model

(b) Yagi Antenna 3D Radiation Pattern

(c) Yagi Antenna Azimuth Plane Pattern

(d) Yagi Antenna Elevation Plane Pattern

Patch array antenna



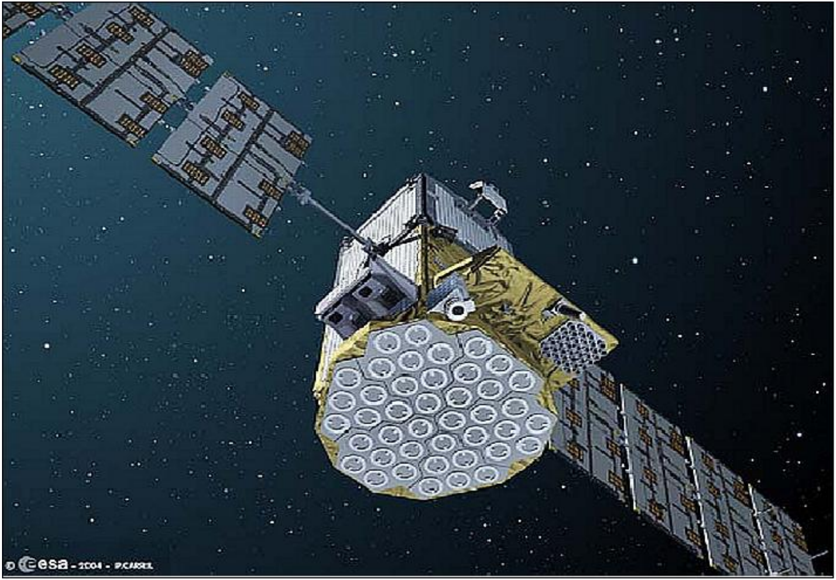
(a) 4x4 Patch Array Antenna

(b) 4x4 Patch Array 3D Radiation Pattern

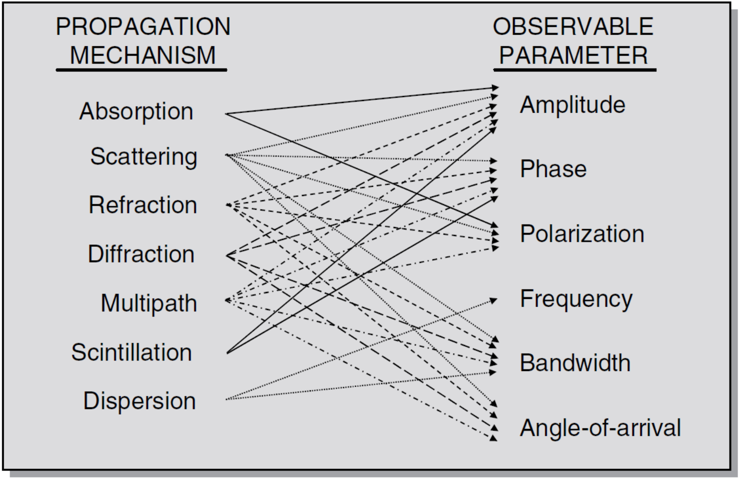
(c) 4x4 Patch Array Azimuth Plane Pattern

(d) 4x4 Patch Array Elevation Plane Pattern

Phased array antenna

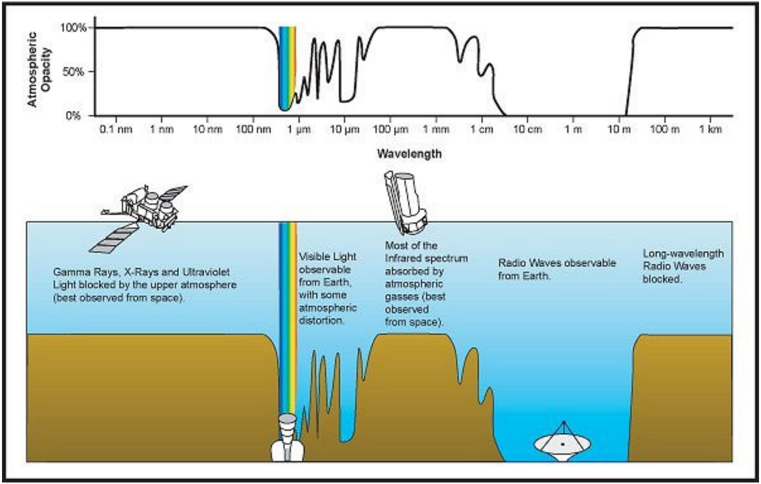


Radiowave propagation mechanisms

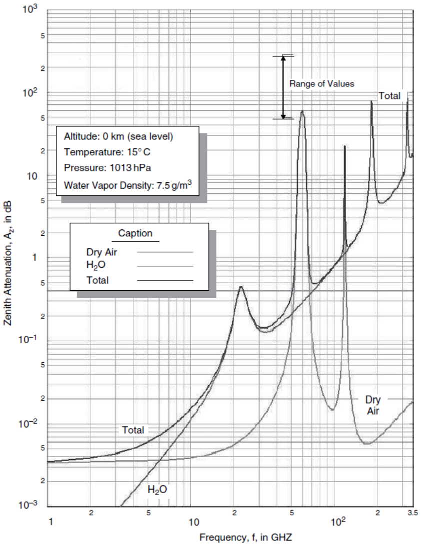


Earth atmosphere

$$\lambda\,[m] = \frac{c}{f} = \frac{3 \times 10^8\,[m/s]}{f\,[Hz]}$$

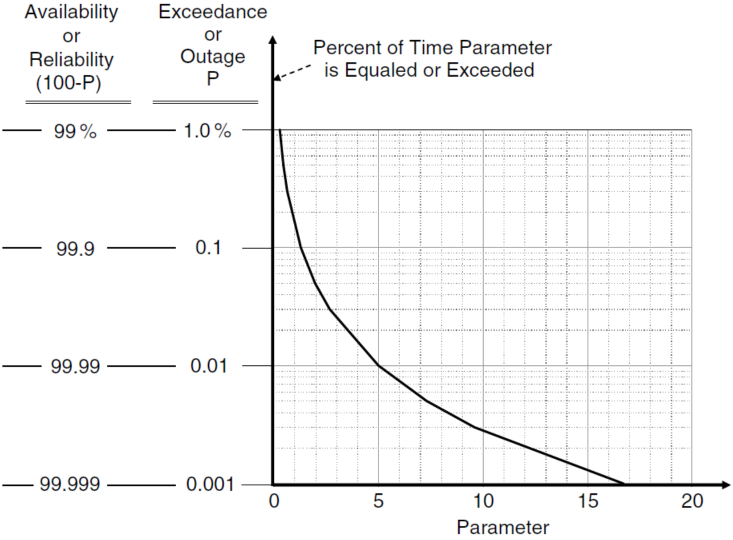


Attenuation due to atmospheric gases

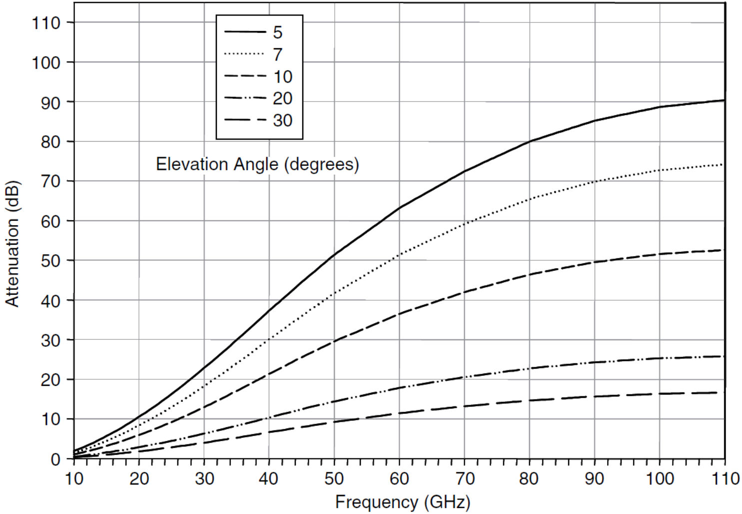


Zenith attenuation due to atmospheric gases (source: ITU-R P.676-6)

Service Level Agreement (SLA)



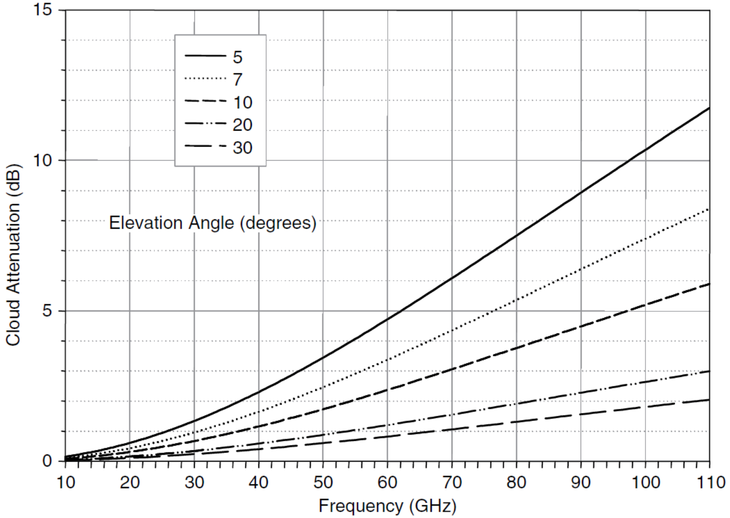
Rain attenuation



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°

Outline

Noise

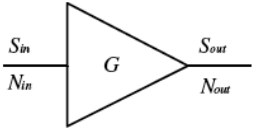
The *noise power* P_N is given by the Nyquist formula:

$$P_N = k_B T W \tag{20}$$

where

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

Two-port device



Definitions

Noise Factor (F):

$$F = \frac{\left(\frac{S}{N}\right)_{\text{in}}}{\left(\frac{S}{N}\right)_{\text{out}}} > 1 \quad (21)$$

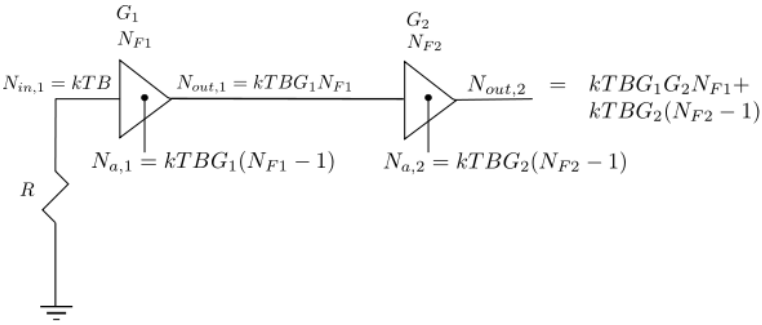
Noise Figure (NF):

$$\text{NF} = 10 \log_{10} F \quad (22)$$

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

$$T_e = T_0(F - 1) \quad (23)$$

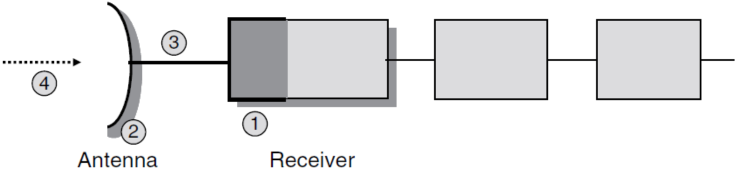
Noise factor of cascaded stages



$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \cdots = F_1 + \sum_{i=2}^{n} \frac{F_i - 1}{\prod_{j=1}^{i-1} G_j} \quad (24)$$

$$T_e = T_{e1} + \frac{T_{e2}}{G_1} + \frac{T_{e3}}{G_1 G_2} + \cdots = T_{e1} + \sum_{i=2}^{n} \frac{T_{ei}}{\prod_{j=1}^{i-1} G_j} \quad (25)$$

Receiver front end



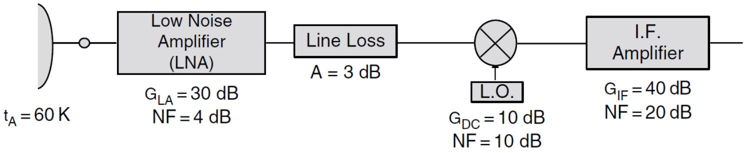
Rule of thumb: highest gain and best noise figure first.

Then

$$NF = NF_1 + \frac{NF_2 - 1}{G_1} + \frac{NF_3 - 1}{G_1 G_2} + \cdots \simeq NF_1 + \frac{NF_2 - 1}{G_1} \tag{26}$$

$$T_e = T_{e1} + \frac{T_{e2}}{G_1} + \frac{T_{e3}}{G_1 G_2} + \cdots \simeq T_{e1} + \frac{T_{e2}}{G_1} \tag{27}$$

Calculation of noise budget [1]



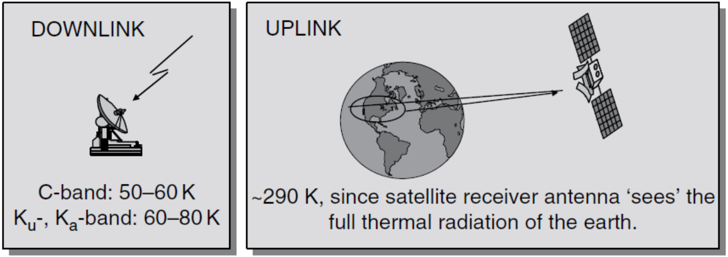
- Low Noise Amplifier: $T_{LA} = 290 \times (10^{\frac{4}{10}} - 1) = 438\,[K]$
- Line. For a passive two-part, $F = A$.
  - $T_{Line} = 290 \times (10^{\frac{3}{10}} - 1) = 289\,[K]$,
  - $G_{Line} = \frac{1}{2}$

The effective noise temperature, including the antenna noise, is

$$T_e = t_A + T_{e1} + \frac{T_{e2}}{G_1} + \frac{T_{e3}}{G_1\,G_2} + \cdots \quad (28)$$

$$= \underbrace{60 + 438}_{} + \frac{289}{1000} + \frac{2610}{1000 \times \frac{1}{2}} + \cdots = 509.3\,[K] \quad (29)$$

Representative 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

Link budget: typical parameters 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° elevation)	$207.2\,[dB]$	$205.8\,[dB]$

For further reading

L. Ippolite.
Satellite Communications Systems Engineering: Atmospheric Effects, Satellite Link Design and System Performance. Wiley, 2008.

J. Gibsons.
The Communications Handbook. CRC Press, 1997.

Wikipedia.
`http://wikipedia.org`