Satellite Communications

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Postgraduate Course in Radio Communications

Contents

Introduction I

- Satellite communications systems exist because earth is a sphere.
  - Radio waves travel in straight lines at the microwave frequencies used for wideband communications
  - -> repeater is needed to convey signals very long distances
- Satellites are important in: voice communications, video & radio transmission, navigation (GPS), remote sensing (maps, weather satellites) etc.
- A majority of communication satellites are in geostationary earth orbit an altitude of 35 786 km
  - Satellite in ”fixed place”
  - typical path length from earth station to to a GEO satellite is 38 500 km
- Satellite systems operate in the microwave and millimeter wave frequency bands, using frequencies between 1 and 50 GHz
  - Above 10 GHz rain causes significant attenuation of the signal
- For the first 20 years of satellite communications analog signals were widely used (FM with most links)

History of Satellite Communications – Some Milestones

- Satellite communications began in October 1957 with the launch by the USSR a small satellite called Sputnik 1 (4.10.1957)
  - Beacon transmitter, no communications capability
- 3.11.1957 Sputnik 2 with Laika
- 12.4.1961 Vostok 1 with Juri Gagarin
- First true communication satellites (Telstar I & II) were launched in July 1962 & May 1963
- 10/1964 Syncom 2: First GEO satellite, 7.4/1.8 GHz (one TV-channel or several 2-way telephone connections
- 1987 TVSAT: First DBS-satellite (Direct Broadcast Satellite, Television-broadcasts directly to home)

Satellite communications - Organizations

- International Telecommunications Satellite Organization (ITSO), previously known by the acronym, “INTELSAT,”
  - global cooperation in satellite communications
- Europe: The European Space Agency (ESA)
  - ESA is responsible for performing R&D and developing new technology for European space industries for the field of satellite communications
- National organizations:
  - National Aeronautics and Space Administration (NASA)
  - Japan Aerospace Exploration Agency
  - China National Space Administration (CNSA)
  - etc. etc.

Satellite orbits [5]

- GEostationary Orbit (GEO) satellites, i.e. satellites that are stationary with respect to a fixed point on the earth
  - + good coverage: Theoretically, only three GEO satellites are sufficient to serve all the earth.
  - + the simplest space configuration and simple space control system
  - + no need for tracking system at the earth stations
  - + no variation of propagation delay and elevation angle
  - + negligible Doppler effects
  - - problematic links feasibility due to the long satellite-user distance (prohibitive power levels and/or too large on-board antennas could be required if low power hand-held user terminals are considered)
  - - high propagation delays for interactive services and mobile-to-mobile communications (higher than 400 ms recommended by CCITT in case of double hop communications)
  - - low minimum elevation angles at high latitudes (i.e. polar regions cannot be covered).
- Non-GeoStationary Orbit (NGSO) satellites, that are moving with respect to a point on the earth
  - + excellent links feasibility, due to the low orbit altitude
  - + low propagation delays
  - - a satellite constellation is necessary to serve all the earth and the constellation size increases if the satellite altitude decreases)
  - - high system costs

Satellite Orbits

- Highly Elliptical Orbit (HEO)
  - \+ high elevation angles (55-60°) for European coverage, due to the orbital location of the apogee;
  - \+ possibility of tailoring the system to cover specific regions of the earth with a limited number of satellites.
  - \- problematic links feasibility (even higher than in the GEO case) due to the considerable altitude of the satellites
  - \- big on-board antennas (6 meters or more) required
  - \- HEO satellites are not suitable for a global coverage;
- LOOPUS (quasi-geostationary Loops in Orbit Occupied Permanently by Unstationary Satellites) is a HEO orbit characterized by an apogee altitude of 39,700 km and a perigee altitude of 1,250 km, with orbital plane inclination of 63.4°.

Satellite orbits: LEO, MEO, GEO

- LEO = Low Earth Orbit satellites, providing mainly mobile data services.
- MEO = Medium Earth Orbit satellites, again providing mobile telephony services.
- GEO = Geostationary Earth Orbit Satellites, major existing telecommunications and broadcasting satellites fall into this category

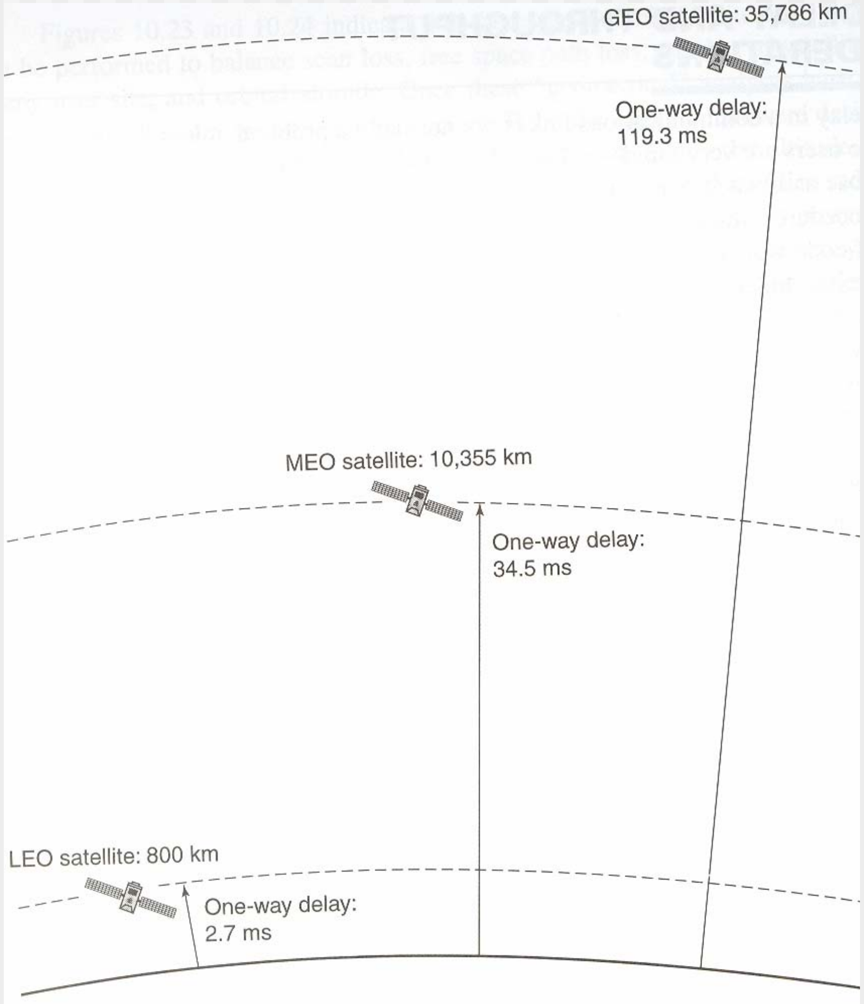

Figure 1. Satellite orbits [1]

Satellites - Satellite subsystems

- Attitude and Orbit Control System
  - rocket motors to move satellite back to the correct orbit
  - keep antennas point toward to earth
- Telemetry, tracking, command and monitoring
  - telemetry system monitor satellite health, tracking system is located at the earth station and provides information about elevation and azimuth angles of the satellite
- Power system
  - electrical power from solar cells
- Communication subsystem
  - major component of communications satellites, one or more antennas and a set of receivers and transmitters (transponders)
    - the linear or bent pipe transponders; amplifiers the received signal and retransmits it a different, usually lower frequency
    - baseband processing transporters; used with digital signals, converts the received signal to baseband, process it, and then retransmits a digital signal

System Noise Temperature and G/T ratio

- Noise temperature is a useful concept in communications receivers since it provides a way of determine how much thermal noise is generated by active and passive devices in the receiving system
- At microwave frequencies, a black body with physical temperature T_p (kelvins) generates electrical noise over a wide bandwidth.
- The noise power: $P_n = kT_pB_n$ watts

where

k is Boltzmann's constant (-228.6 dBW/K/Hz)

T_p physical temperature of source in kelvin degrees

B_n is the noise Bandwith in herz

P_n is the available noise power in watts

G/T ratio

- The sensitivity of a radio telescope is a function of many factors including antenna gain (G) and system noise temperature (T)
- T_s is the total system noise temperature (in degrees Kelvin) and is equal to the sum of the noise generated in the receiving system (T_r) and the noise delivered from the antenna (T_a) when the antenna is looking at a region of the sky free of strong sources. T_a includes the galactic background temperature as well as additional noise picked up by the antenna side lobes viewing the earth at ambient temperature.
- The receiving system temperature (T_r) is related to the system noise factor (FN) by:

  $$T_r = (NF - 1)*T_0 \qquad (1)$$

  where the noise factor (NF) is systems noise figure:

  $$NF = (S/N)in / (S/N)out$$

  and T_0 is the reference temperature used to calculate the standard noise figure (usually 290 K)

G/T ratio II – Practical case [6]

- The principle behind determination of G/T is to measure the increase in noise power which occurs when the antenna is pointed first at a region of cold sky and then moved to a strong source of known flux density - usually the sun. This ratio of received power is known as the Y-factor.

  $$Y = P_{sun} / P_{cold}\ sky$$

- The following equation shows the relationship between G/T, the measured Y-factor, and the value of solar flux (F) at the observing frequency:

  $$G/T = (Y - 1) * 8 * pi * k * L / (F * L_{am}\hat{}2)$$

  where
  Y = sun noise rise expressed as a ratio (not dB)
  k = Boltzmann's constant (1.38 *10^-23 joules/deg K)
  L = beam size correction factor
  L_{am} = wavelength in meters (at the operating frequency f_o)
  F = solar flux at f_o in watts / meter^2 / Hz

- If the dish has a beamwidth larger than 2 or 3 degrees the L can be set L=1 and forget about next equation.

  $$L = 1 + 0.38 (W_s / Wa)\hat{}2$$

  where:
  W_s = diameter of the radio sun in degrees at fo
  W_a = antenna 3 dB beamwidth at f_o

G/T ratio III

- The diameter of the radio sun (W_s) is frequency dependent. You can assume a value of 0.5 degrees for frequencies above 3000 MHz, 0.6 degrees for 1420 MHz, and 0.7 degrees for 400 MHz.
- USAF Space Command runs a worldwide solar radio monitoring network with stations in Massachusetts, Hawaii, Australia, and Italy. These stations measure solar flux density (F) at 245, 410, 610, 1415, 2695, 4995, 8800, and 15400 MHz. If you are operating near one of these eight "standard" frequencies then you can use the reported flux density.
  - When operating between two given frequencies then interpolate between flux densities at the lower and higher frequencies. The best interpolation scheme is to graph the flux density at several frequencies and use a curve fitting routine to determine the flux density at your operating frequency.
  - The solar flux density obtained from the USAF must be multiplied by 10^-22 in order to get the units correct for use in equation (4). In other words, if the 1415 MHz solar flux density is 98 *10^-22 watts/meter^2/Hz, the operator may simply state "the solar flux at 1415 Mhz is 98".

Satellite Link Design

- The four factors related to satellite system design:
  1. The weight of satellite
  2. The choice frequency band
  3. Atmospheric propagation effects
  4. Multiple access technique
- The major frequency bands are 6/4 GHz, 14/11 GHz and 30/20 GHz (Uplink/Downlink)
- At geostationary orbit there is already satellites using both 6/4 and 14/11 GHz every 2˚(minimum space to avoid interference from uplink earth stations) -> Additional satellites higher BW
- Low earth orbit (LEO) & medium earth orbit (MEO) satellite systems are closer and produces stronger signals but earth terminals need omni directional antennas
- The design of any satellite communication is based on
  - meeting of minimum C/N ratio for a specific percentage of time
  - carrying the maximum revenue earning traffic at minimum cost

Link budgets

- C/N ratio calculation is simplified by the use of link budgets
- evaluation the received power and noise power in radio link
- the link budget must be calculated for individual transponder and for each link
- When a bent pipe transponder is used the uplink and down link C/N rations must be combined to give an overall C/N

Satellite Link Design – Example of Satellite Link Budget

Table 1 C-band GEO Satellite link budget in clear air. [1]

C-band satellite parameters		
	Transponder saturated output power	20 W
	Antenna gain, on axis	20 dB
	Transponder bandwidth	36 MHz
	Downlink frequency band	3.7–4.2 GHz
Signal	FM-TV analog signal	
	FM-TV signal bandwidth	30 MHz
	Minimum permitted overall C/N in receiver	9.5 dB
Receiving C-band earth station		
	Downlink frequency	4.00 GHz
	Antenna gain, on axis, 4 GHz	49.7 dB
	Receiver IF bandwidth	27 MHz
	Receiving system noise temperature	75 K
Downlink power budget		
	P_t = Satellite transponder output power, 20 W	13.0 dBW
	B_o = Transponder output backoff	−2.0 dB
	G_t = Satellite antenna gain, on axis	20.0 dB
	G_r = Earth station antenna gain	49.7 dB
	L_p = Free space path loss at 4 GHz	−196.5 dB
	L_{ant} = Edge of beam loss for satellite antenna	−3.0 dB
	L_a = Clear air atmospheric loss	−0.2 dB
	L_m = Other losses	−0.5 dB
	P_r = Received power at earth station	−119.5 dBW
Downlink noise power budget in clear air		
	k = Boltzmann's constant	−228.6 dBW/K/Hz
	T_s = System noise temperature, 75 K	18.8 dBK
	B_n = Noise bandwidth, 27 MHz	74.3 dBHz
	N = Receiver noise power	−135.5 dBW
C/N ratio in receiver in clear air		
	$C/N = P_r - N = -119.5\text{ dBW} - (-135.5\text{ dBW}) = 16.0\text{ dB}$	

Table 2 C-band GEO Satellite link budget in rain. [1]

P_{rca}	= Received power at earth station in clear air	−119.5 dBW
A	= Rain attenuation	−1.0 dB
P_{rain}	= Received power at earth station in rain	−120.5 dBW
N_{ca}	= Receiver noise power in clear air	−135.5 dBW
ΔN_{rain}	= Increase in noise temperature due to rain	2.3 dB
N_{rain}	= Receiver noise power in rain	−133.2 dBW
C/N ratio in receiver in rain		
C/N	$= P_{rain} - N_{rain} = -120.5\text{ dBW} - (-133.2\text{ dBW})$	= 12.7 dB

Satellite Link Design – Downlink Received Power

- The calculation of carrier to noise ratio in a satellite link is based on equations for received signal power P_r and receiver noise power:

$$P_r = \mathrm{EIRP} + G_\mathrm{r} - L_\mathrm{p} - L_\mathrm{a} - L_\mathrm{ta} - L_\mathrm{ra}\,\mathrm{dBW},$$

Where:

$$\mathrm{EIRP} = 10\log_{10}(P_\mathrm{t} G_\mathrm{t})\,\mathrm{dBW}$$

$$\mathrm{G}_\mathrm{r} = 10\log_{10}(4\pi A_e/\lambda^2)\,dB$$

$$PathLoss\; L_P = 10\log_{10}\left[\left(4\pi R/\lambda\right)^2\right] = 20\log_{10}\left(4\pi R/\lambda\right)\mathrm{dB}$$

L_a = Attenuation in the athmosphere

L_ta = Losses assosiated with transmitting antenna

L_ra = Losses assosiated with receiving antenna

Satellite Link Design – Downlink Noise Power

- A receiving terminal with a system noise temperature T_sK and a noise bandwidth B_n Hz has a noise power P_n referred to the output terminals of the antenna where

$$P_n = kT_sB_n \text{ watts}$$

- The receiving system noise power is usually written in decibel units as

$$N = k + T_s + B_n \text{ dBW},$$

where

k is Boltzmann's constant (-228.6 dBW/K/Hz)

T_s is the system noise temperature in dBK

B_n is the noise Bandwith of the receiver in dBHz

Satellite link design – Noise sources

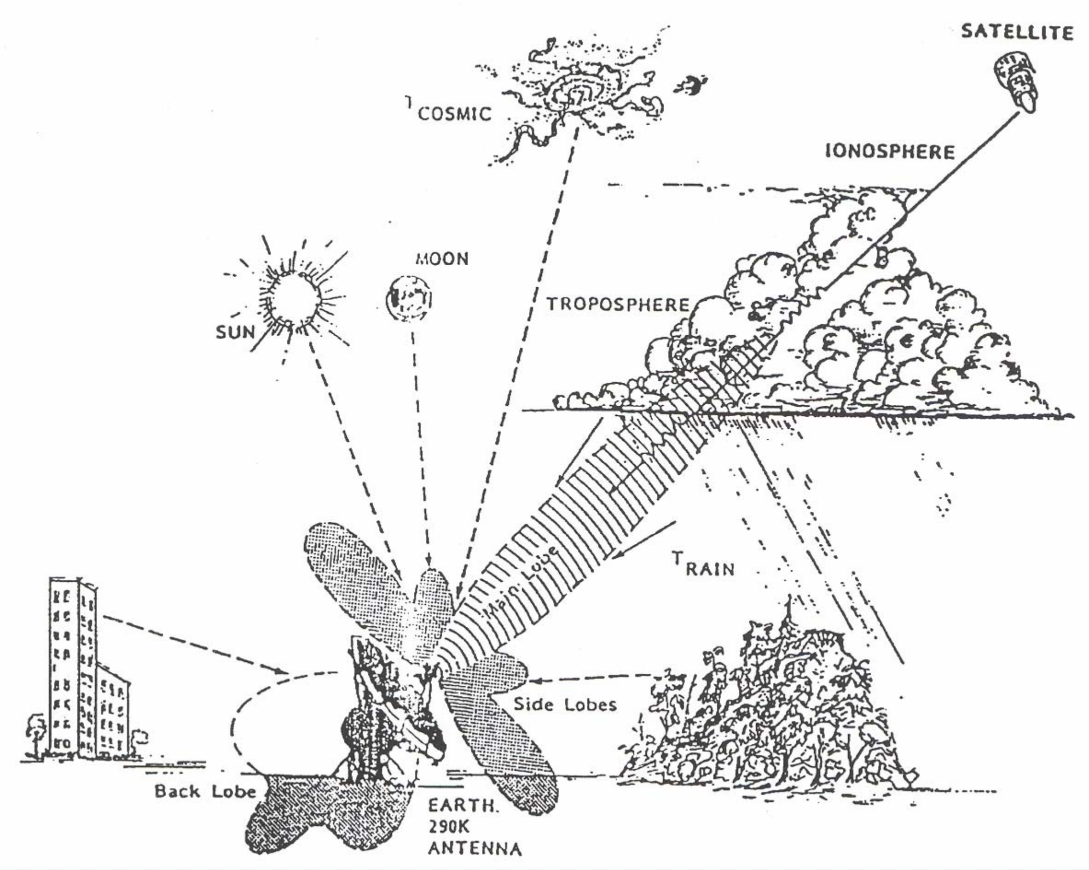

Figure 2. Sources of the antenna thermal noise [2]

Satellite link design - Uplink

- Uplink design is easier than the down link in many cases
  - earth station could use higher power transmitters
- Earth station transmitter power is set by the power level required at the input to the transporter, either
  - a specific flux density is required at the satellite
  - a specific power level is required at the input to the transporter
- analysis of the uplink requires calculation of the power level at the input to the transponder so that uplink C/N ratio can be found
- With small-diameter earth stations, a higher power earth station transmitter is required to achieve a similar satellite EIRP.
  - interference to other satellites rises due to wider beam of small antenna
- Uplink power control can be used to against uplink rain attenuation

Propagation Effects and their impact

- Many phenomena causes lead signal loss on through the earths atmosphere:
  - Atmospheric Absorption (gaseous effects)
  - Cloud Attenuation (aerosolic and ice particles)
  - Tropospheric Scintillation (refractive effects)
  - Faraday Rotation (an ionospheric effect)
  - Ionospheric Scintillation (a second ionospheric effect)
  - Rain attenuation
  - Rain and Ice Crystal Depolarization
- The rain attenuation is the most important for frequencies above 10 GHz
  - Rain models are used to estimate the amount of degradation (or fading) of the signal when passing through rain.
  - Rain attenuation models: Crane 1982 & 1985; CCIR 1983; ITU-R P.618-5(7 & 8)

Propagation Effects and their impact II

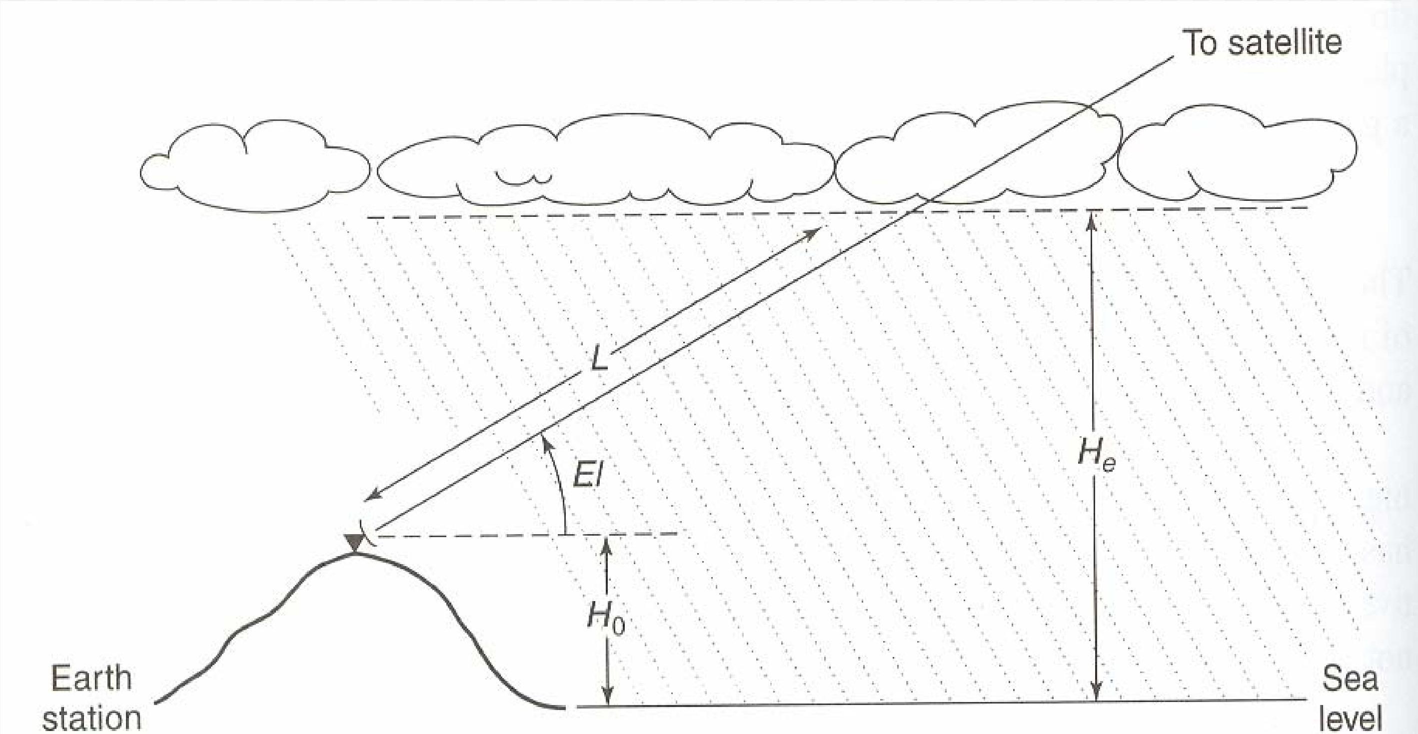

Figure 3. Geometry of satellite path through rain [1]

Annual cumulative attenuation

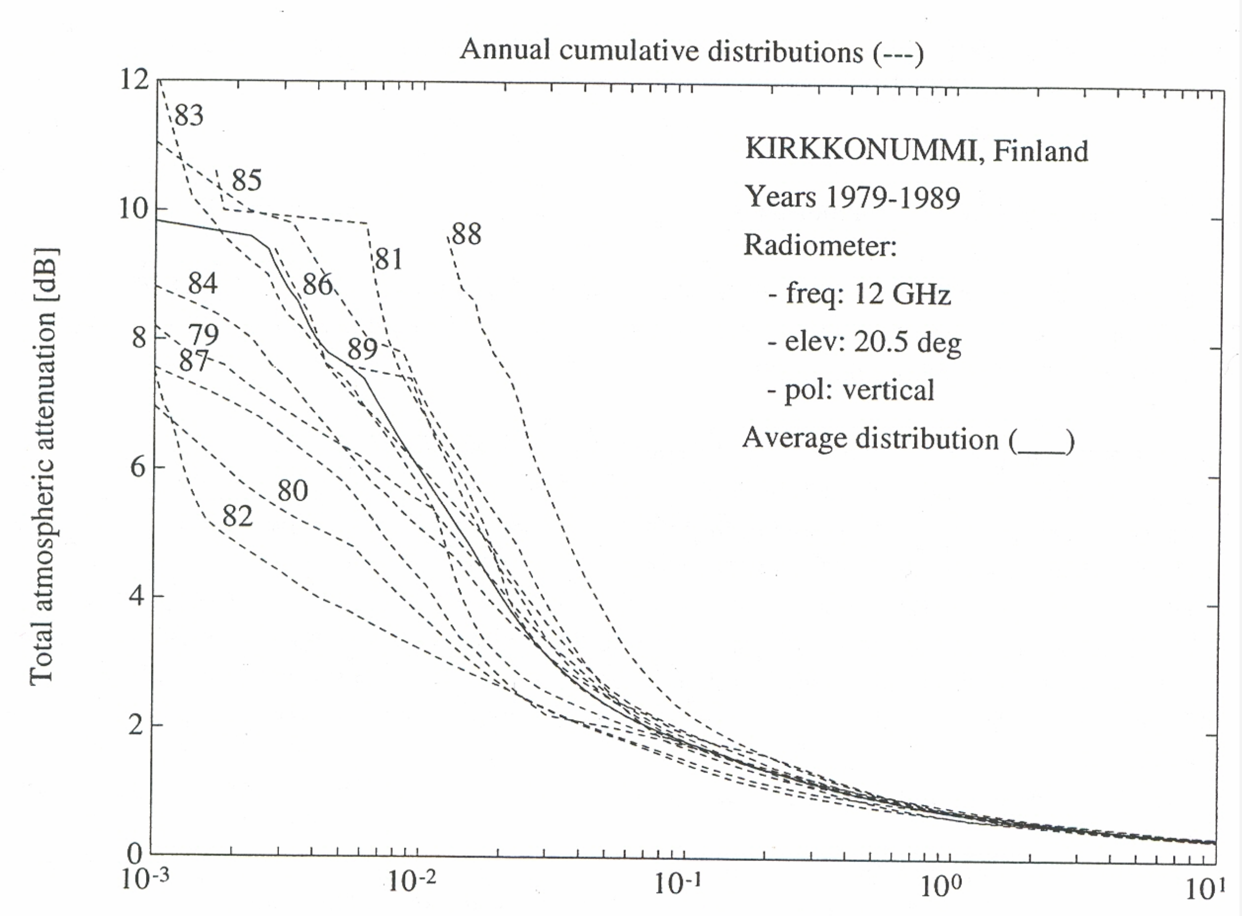

Figure 4. Annual cumulative attenuation distributions measured in Metsähovi, Kirkkonummi

Case DVB-S: Broadcast Satellites

- DVB-S (Digital Video Broadcasting)
  - Geosynchronous orbit
  - DVB-S uses QPSK modulation
- Satellite locations are specified as degree of longitude:
  - ASTRA 1 = 6 satellites: 19.2°E
  - Hot Bird = 5 satellites: 13°E
  - Thor: 0.8°W
- DVB-S2 is a newer specification of the standard, ratified by ETSI in March 2005.
  - Adaptive coding to optimize the use of satellite transponders.
  - 4 modulation modes: QPSK, 8PSK (used in non-linear transponders near to saturation); 16APSK and 32APSK
  - video codec has also been changed from MPEG-2 to H.264 (a.k.a. MPEG-4 Part 10)

CASE DVB-S : Error correction

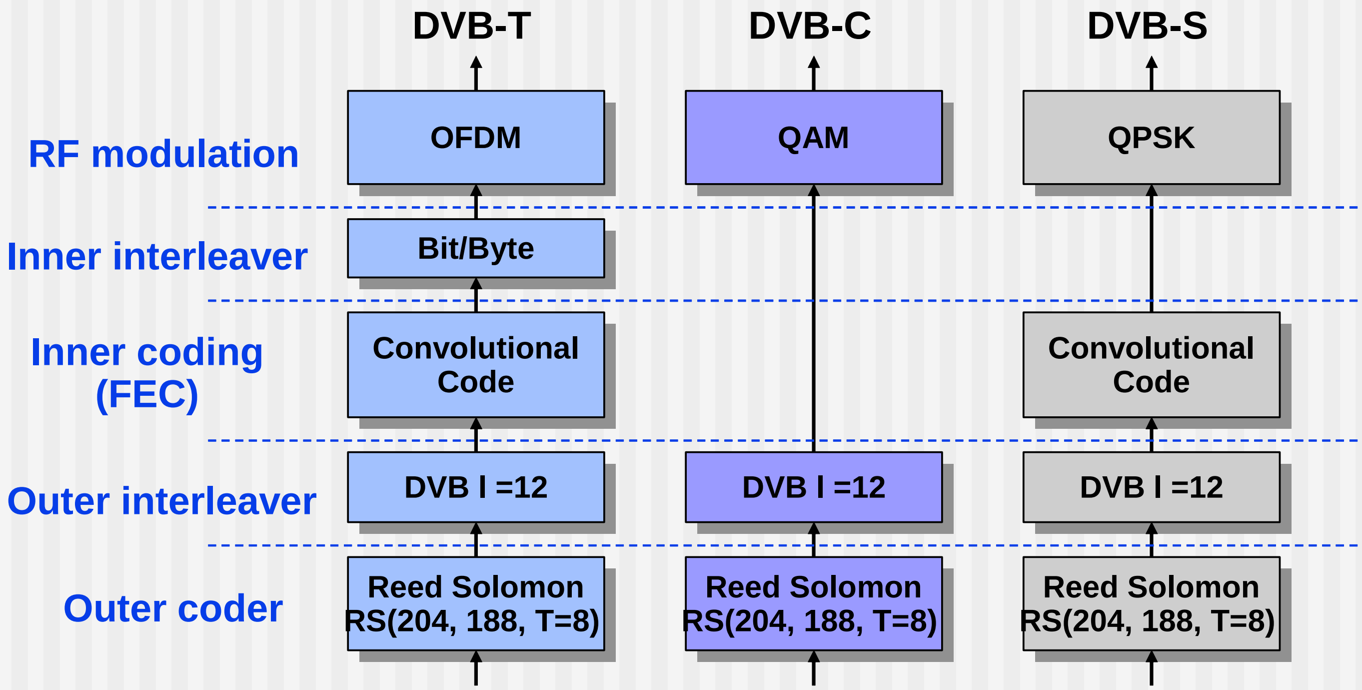

Figure 5. Error correction in DVB systems. At the receiving side in the typical bit error ratio after QPSK demodulation is $10^{-1}...10^{-2}$, after inner decoding 10^{-4} and after outer decoder 10^{-11}. [3] & [4]

CASE DVB-S : Error correction

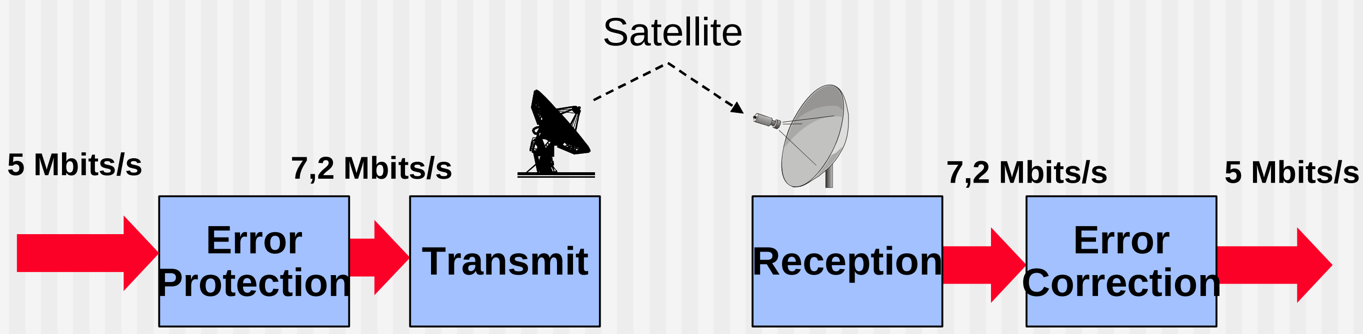

Figure 6. Error correction example, Satellite broadcast.

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Homework

1. An earth station antenna has diameter of 25 m, has an overall efficiency of 72 % and is used to receive signal at 4100 MHz. At this frequency the system noise temperature is 80 K when the antenna points at the satellite at the elevation angle of 28^o
   What is earth station G/T ratio under these conditions?