Satellite Link Budgets

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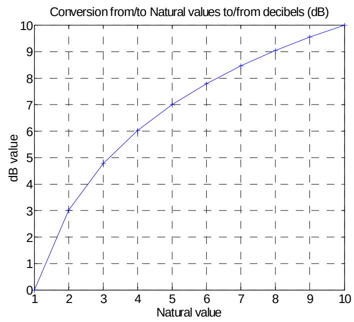
Outline

- **Link parameters**
  - Decibel
  - Performance specifications
  - Satellite specificities
- **Point-to-point link budget**
  - Power
  - Losses
  - Noise
- **Satellite link budget**
  - Uplink&Downlink
  - Interferences
  - Overall link

Decibel (dB)

$$X_{dB} = 10\log_{10} X \quad \Leftrightarrow \quad X = 10^{X_{dB}/10}$$

Ratio	Value in dB
1	0dB
10	10dB
1.02	0.1dB
1.26	1dB
2	3dB
3	4.77dB
π	4.97dB
4=2*2	6dB
5=10/2	7dB
6=2*3	7.77dB
7	8.45dB



- Use for a ratio (dB) or any unit (dBW, dBW/m², dBJ, dBK, dBK⁻¹)
- Easy handling of small numbers (1µW ⇔ -60dBW ⇔ -30dBm)
- Additive operations due to logarithms

Theoretical Performances

- Spectral efficiency

  $\eta = \frac{R_b}{B_N} (b/s/Hz)$ R_b bit rate, B_N noise bandwidth

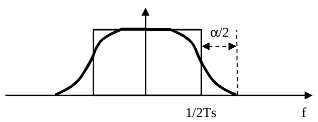
- Nyquist sampling theorem (one sample per symbol)

  $B_W = R_s (Hz)$ B_W Nyquist bandwidth, R_s symbol rate

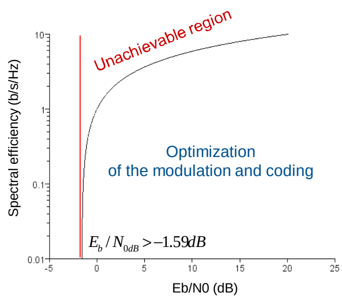
- Shannon channel capacity (maximum data rate)

$$R_b = B_W \log_2\left(1+\frac{C}{N}\right) = B_W \log_2\left(1+\eta\frac{E_b}{N_0}\right)(b/s)$$

Nyquist filter

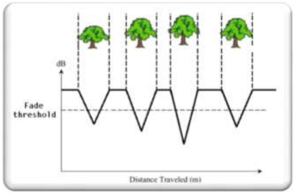


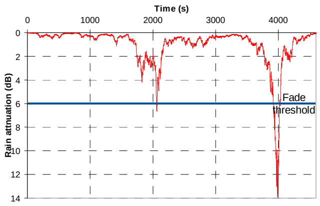
$$B_N = B_W \Rightarrow \eta = \frac{R_b}{R_s} \Rightarrow E_b/N_0 = \frac{2^\eta - 1}{\eta}$$



Link Performances

- **Link availability (100-P)% or average annual time outage P%**





Availability (100-P)%	Outage (per year)
90%	876h
99%	87.6h
99.9%	8.76h
99.99%	53min

  - Measured carrier to noise ratio at demodulator input (C/N)

- **Specification**
  - Analog systems: signal to noise ratio at demodulator output (S/N)

$$S/N_{dB} = C/N_{dB} + 10\log_{10}\left(1.5\frac{\Delta_{pp}^2 B_N}{b_V^3}\right) + 2.2dB$$

Δ_{pp} peak-to-peak deviation e.g. Δ_{pp}=17.74MHz/V
B_N receiver bandwidth e.g. B_N=25Mhz
b_V video bandwidth e.g. b_V=5MHz
e.g. C/N_{dB}=21dB (clear sky) ⇒ S/N_{dB}=43dB

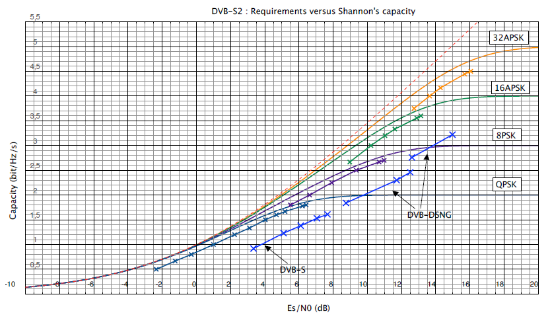
  - Digital systems: Bit Error Rate (BER) function of energy per bit to noise density ratio (E_b/N_0)

$$BER_{BPSK/QPSK} = \frac{1}{2}erfc\left(\sqrt{\frac{E_b}{N_0}}\right) = Q\left(\sqrt{\frac{2E_b}{N_0}}\right)$$

E_b/N_0=C/N/η
η spectral efficiency e.g. η=2 in QPSK
e.g. C/N_{dB}=12dB (clear sky) ⇒ BER=3.10^{-5}

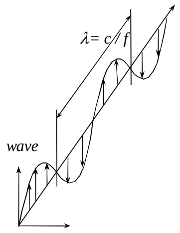
Example of Link Performances

DVB-S	η	E_s/N_{0dB}
QPSK1/2	0,92	3,35
QPSK2/3	1,23	5,10
QPSK3/4	1,38	6,11
QPSK5/6	1,54	7,06
QPSK7/8	1,61	7,68

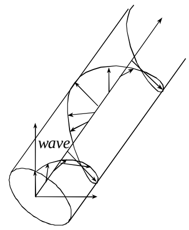


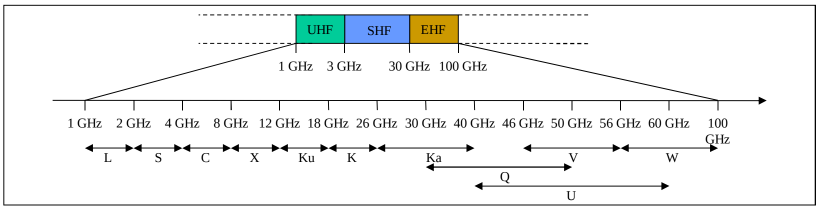
DVB-S2 (Extract)	η	E_s/N_{0dB}
QPSK 1/4	0,49	-2,35
QPSK 1/3	0,66	-1,24
QPSK 2/5	0,79	-0,30
QPSK 1/2	0,99	1,00
QPSK 3/5	1,19	2,23
QPSK 2/3	1,32	3,10
QPSK 3/4	1,49	4,03
QPSK 5/6	1,65	5,18
QPSK 8/9	1,77	6,20
8PSK 3/5	1,78	5,50
8PSK 2/3	1,98	6,62
8PSK 3/4	2,23	7,91
8PSK 5/6	2,48	9,35
8PSK 8/9	2,65	10,69
16APSK 2/3	2,64	8,97
16APSK 3/4	2,97	10,21
16APSK 5/6	3,30	11,61
16APSK 8/9	3,52	12,89
32APSK 3/4	3,70	12,73
32APSK 5/6	4,12	14,28
32APSK 9/10	4,45	16,05

Satellite Frequencies



Wave length λ = c / f
Light speed c = 299 792 458 m/s
Linear (horizontal or vertical) / Circular (left or right)





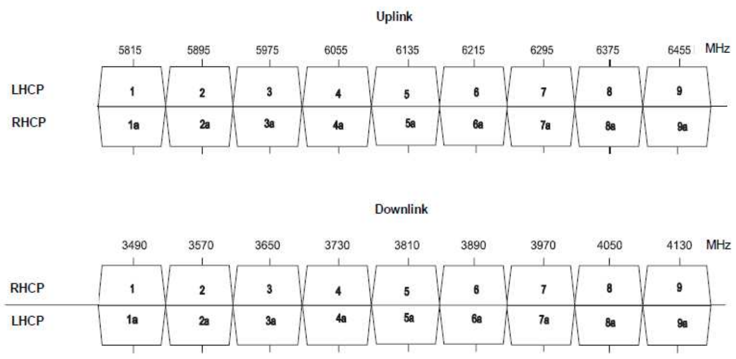
L	1.6GHz↑ - 1.5GHz↓	~30Mhz	Global Positioning System (GPS), Inmarsat/Iridium/Globastar(↑) terminals
S	2.1GHz↑ - 2.3GHz↓	~30Mhz	Radio broadcasting, Globastar(↓) terminals
C	6GHz↑ - 4GHz↓	~0.5Ghz	DTH (Direct-to-Home), Very Small Aperture Terminal (VSAT), Inmarsat/Globalstar feeders
Ku	14GHz↑ - 12GHz↓	~1Ghz	DTH, VSAT, interactivity
Ka	30GHz↑ - 20GHz↓	~3Ghz	Iridium feeders, New DTH, interactivity

Example of Satellite Frequencies

<u>Yamal 202 RKK Energiya USP Bus (2003)</u>

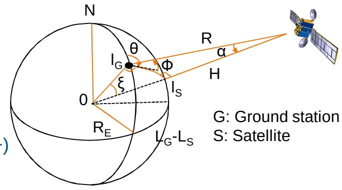
C band

- **18 active transponders in dual circular polarization**
  - Receive frequency band 5.775-6.495 GHz
  - Transmit frequency band 3.45-4.17 GHz
  - Transponder bandwidth 72MHz
  - Separation between adjacent transponders 80MHz



Satellite Geometry

- **Parameters**
  - R_E=6371km Earth radius, H satellite altitude, R distance from satellite to ground station
  - ξ central angle, Φ elevation, α nadir, Θ azimuth
  - L_S&L_G satellite & ground station longitudes (East +)
  - l_S&l_G satellite & ground station latitudes (North +)



- **Satellite distance for a given (LEO) or fixed (GEO) elevation**

$$R = R_E\left(\sqrt{\left(\left(R_E + H\right)/R_E\right)^2 - \left(\cos\varphi\right)^2} - \sin\varphi\right)$$

$$R = \sqrt{R_E^2 + \left(R_E + H\right)^2 - 2R_E\left(R_E + H\right)\cos\xi} \text{ with } \cos\xi = \cos\left(L_G - L_S\right)\cos\left(l_S\right)\cos\left(l_G\right) + \sin\left(l_S\right)\sin\left(l_G\right)$$

$$\varphi = \arctan\left(\left(\cos\xi - R_E/\left(R_E + H\right)\right)\sqrt{1 - \left(\cos\xi\right)^2}\right)$$

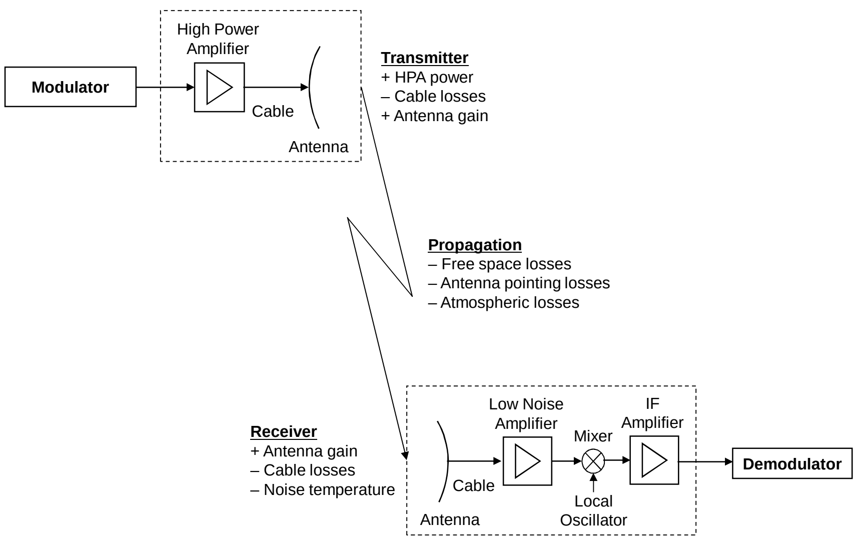
- **Satellite azimuth depending on the position of S relative to G**

$$\theta = \tilde{\theta}\left(NE\right), \pi - \tilde{\theta}\left(SE\right), 2\pi - \tilde{\theta}\left(NW\right), \pi + \tilde{\theta}\left(SW\right) \text{ for } \tilde{\theta} = \arcsin\left(\sin\left(\left|L_G - L_S\right|\right)\cos\left(l_S\right)/\sqrt{1 - \left(\cos\xi\right)^2}\right)$$

- **Coverage radius R_C and percentage of Earth P_C for a minimum elevation Φ_m**

$$R_C = R_E\sqrt{\left(1 - \cos\beta\right)/2} \quad P_C = 0.5\left(1 - \cos\beta\right) \quad \text{for } \beta = \arccos\left(\cos\varphi_m R_E/\left(R_E + H\right)\right) - \varphi_m$$

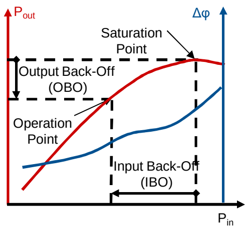
Point-to-Point Transmission



Transmitter

- **High Power Amplifier (HPA) characterized by AM/AM and AM/PM curves**
  - Solid-State Amplifiers (SSPAs)
  - Klystron-tube Power Amplifiers (KPAs) or Travelling Wave Tube Amplifiers (TWTAs)

	400W Ku SSPA GaN	400W Ku SSPA GaAs	750W Ku TWTA
Weight	30kg	80kg	37kg
Volume	29 dm³	142 dm³	74 dm³
Consumption	2.2kW	3.5kW	2.5kW
(C/I_3,Δφ) at 24dBW	(-20.67dBc,1.0° /dB)	(-19.86dBc,2.0° /dB)	(-18dBc,3.5° /dB)
(C/I_3,Δφ) at 23dBW	(-26.63dBc,0.8° /dB)	(-23.16dBc,1.5° /dB)	(-20dBc,3.0° /dB)
(C/I_3,Δφ) at 22dBW	(-31.63dBc,0.5° /dB)	(-27.50dBc,1.0° /dB)	(-22dBc,2.5° /dB)



Advantech Wireless comparison (2012)

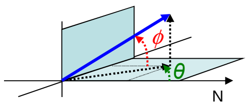
- **Cable**

f (GHz)	2	4	6	8	10	12	14	16	18	26.5
A_c (dB/m)	0.30	0.42	0.52	0.61	0.68	0.75	0.82	0.88	0.95	1.15

Sucoflex 404 – ∅ 5.5mm (2011)

Antenna

- **Geometric angles**
  - Θ azimuth (look angle in the horizontal plane from North)
  - Φ elevation (look angle above the horizontal plane)



- **Antenna gain (relative to an isotropic antenna)**
  - p(θ,Φ) transmitted power at the direction (θ,Φ)
  - p_0 total transmitted power

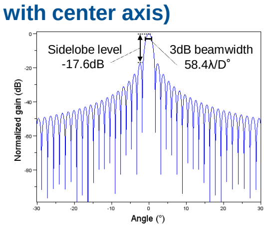
$$g(\theta,\phi)=\frac{p(\theta,\phi)}{p_0/4\pi}$$

- **Maximum antenna gain for aperture antennas (horns, reflectors)**
  - η aperture efficiency, η = 0.5…0.85 (typical)
  - A physical aperture area, D circular aperture diameter

$$g_{\max}=\eta A\frac{4\pi}{\lambda^2}\underset{\substack{circular\\aperture}}{=}\eta\left(\frac{\pi D}{\lambda}\right)^2$$

- **Antenna beamwidth for a parabolic antenna (ψ angle with center axis)**
  - Half-power beamwidth $\theta_{3dB}=k\dfrac{\lambda}{D}(°),\, k=50\ldots70\ (typical)$
  - Model with $J_1(x)$ 1st kind Bessel function (~x/2 for x small)

$$g(\psi)=g_{\max}\left(2\frac{J_1(\pi D\sin\psi/\lambda)}{(\pi D\sin\psi/\lambda)}\right)^2$$



➲ **Inverse roles of D and λ on gain and beamwidth**

Tx Antenna: Power & Flux Density

- **Effective Isotropic Radiated Power (EIRP)**

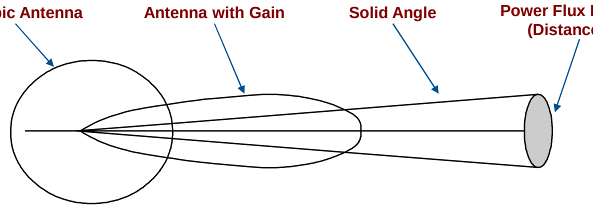
  $$eirp = p_{Tx} g_{Tx} (W) \quad \text{with } p_{Tx} = p_{HPA} l_c (W) \text{ and } l_c = a_c d_c (W)$$

  - p_{Tx}, g_{Tx} transmit antenna power, gain
  - p_{HPA} HPA power
  - l_c, a_c, d_c cable losses, attenuation per meter, length

- **Power Flux Density (PFD)**

  $$\varphi = \frac{eirp}{4\pi R^2} \left(W/m^2\right)$$

  - Power density at distance R for a spherical shell of surface $4\pi R^2$ in a lossless medium



Rx Antenna: Free Space & Losses

- **Aperture antenna**

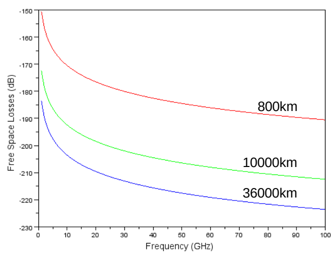
  $$p_{Rx} = \varphi \eta A (W)$$

  - P_{Rx} receive antenna power

- **Friis transmission formula**

  $$p_{Rx} = p_{Tx} g_{Tx} g_{Rx} \left(\frac{\lambda}{4\pi R}\right)^2 (W) \text{ with } l_{FS} = \left(\frac{4\pi R}{\lambda}\right)^2$$

  - G_{Rx} receive antenna gain
  - L_{FS} free space losses



- **Real transmission formula**

  $$C = \frac{p_{Tx} g_{Tx} g_{Rx}}{l_{FS} l_{Pt} l_{Atm}} (W) \Leftrightarrow C_{dB} = P_{Tx} + G_{Tx} + G_{Rx} - L_{FS} - L_{Pt} - L_{Atm} (dBW)$$

  - L_{Pt} pointing losses with $\theta_{\Delta i}$ off-boresight angles and θ_{3dB} half-power beamwidth in degrees

    $$L_{Pt} = 12 \sum_i \left(\frac{\theta_{\Delta i}^2}{\theta_{3dB}^2}\right)$$

  - L_{Atm} atmospheric losses ITU-R P.618-10 (10/09)

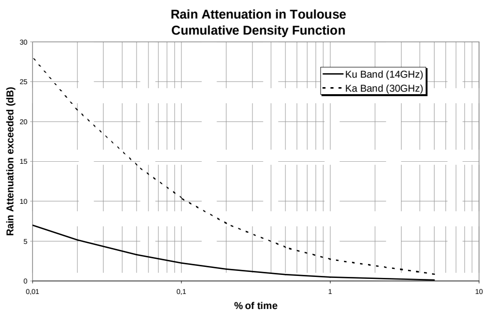
Atmospheric Losses

- **Atmospheric gas attenuation ITU-R P.676-9 (02/12)**
- **Precipitation attenuation and depolarization ITU-R P.618-10 (10/09)**
  - Rain height ITU-R P.839-3 (02/01)
  - Maps of rainfall rate ITU-R P.837-6 (02/12)
  - Specific attenuation model for rain ITU-R P.838-3 (03/05)
  - Comparison with measures ITU-R P.678-1 (03/92)
  - Conversion of annual statistics to worst-month statistics ITU-R P.841-4 (03/05)
- **Clouds and fog attenuation ITU-R P.840-5 (02/12)**
- **Tropospheric scintillation ITU-R P.618-10 (10/09)**
  - Radio refractive index ITU-R P.453-10 (02/12)
- **Total attenuation ITU-R P.618-10 (10/09)**

$$L_{Atm}(p) = L_G + \sqrt{\left(L_R(p) + L_C(p)\right)^2 + L_S(p)^2}$$

  - L_G gases attenuation
  - L_R,L_C, L_S rain, cloud, scintillation exceeded attenuations for p% of time

Example of Atmospheric Losses



Atmospheric losses in Toulouse
(0.01% of time, 30° of elevation)

Frequency (GHz)	2	4	12	20
Atmospheric Gas Attenuation (dB)	0,07	0,08	0,12	0,46
Rain Attenuation (dB)	0,02	0,14	7,61	20,04
Clouds Attenuation (dB)	0,01	0,03	0,24	0,65
Scintillation (dB)	0,18	0,27	0,46	0,58
Total Attenuation (dB)	0,26	0,39	7,98	21,16

Component Noise Temperature

- **Power due to thermal noise**

  $N = kT_{Eq}B$

  - k = 1.379 10-23 W/K/Hz Boltzmann's constant (-228.6dBW/Hz/K)
  - T_{Eq} equivalent noise temperature (of a passive resistor giving same noise power per bandwidth)
- **Noise power spectral density**

  $N_0 = N/B = kT_{Eq}$
- **Lossy element noise temperature (output, input)**

  $T_{output} = T_0(1-1/l_e) \Leftrightarrow T_{input} = T_0(l_e - 1)$

  - l_e losses at T_0 noise temperature (290K)
- **Active device noise temperature (input)**

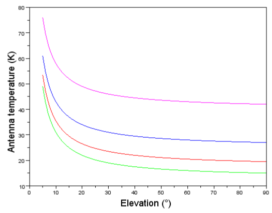
  $T_{input} = T_0(nf_d - 1)$

  - nf_d noise figure (input over output signal to noise ratios)
- **Example of ground antenna noise temperature**

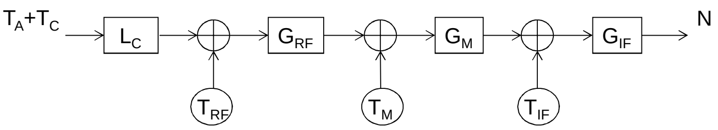
  $T_{Aground} = 15 + 30/D + 180/\phi(K)$

  - D, Φ ground station diameter (m) and elevation (°)

L (dB)	0.5	1	2	3
T_o (K)	32	60	107	145
T_i (K)	35	75	170	289



System Noise Temperature



$$N = g_{IF}kT_{IF}B + g_{IF}g_M kT_M B + g_{IF}g_M g_{RF}k((T_A+T_C)/l_C + T_{RF})B$$

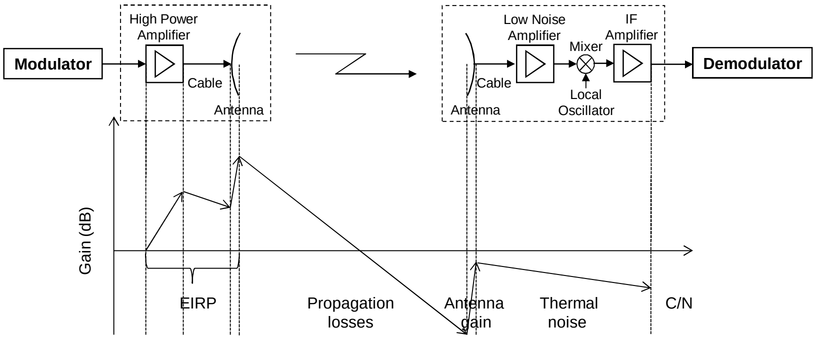
$$N = g_{IF}g_M g_{RF}kT_{Eq}B \quad \text{with} \quad T_{Eq} = (T_A+T_C)/l_C + T_{RF} + \frac{T_M}{g_{RF}} + \frac{T_{IF}}{g_M g_{RF}}$$

- **Good Low Noise Amplifier (LNA)**
  - Highest gain g_{RF} possible
  - Lowest temperature T_{RF} or noise figure NF_{RF} possible

  $$T_{Eq} \approx \frac{T_A}{l_C} + T_0\left(1 - \frac{1}{l_C}\right) + T_0(nf_{RF} - 1)$$
- **Antenna noise temperature**
  - Pointing at Sun ($12000f^{-0.75}$K), Moon (200-300K), Earth (290K), cosmic background (T_S=2.7K)
  - On ground with clear sky L_G (T_G=280K) or exceeded attenuation L_{Atm} (T_R=260K)

$$T_{Aclear} = \frac{T_S}{l_G} + T_G\left(1 - \frac{1}{l_G}\right) + T_{Aground} \qquad T_{Aexceeded} = \frac{T_S}{l_{Atm}} + T_R\left(1 - \frac{1}{l_{Atm}}\right) + T_{Aground}$$

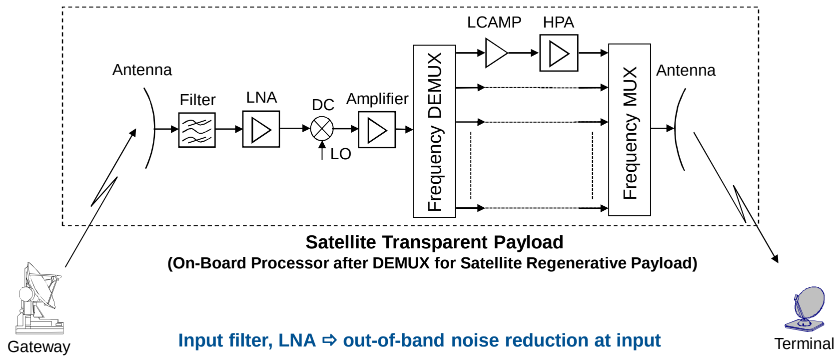
Point-to-Point Link Budget



$$C/N = \frac{p_{Tx} g_{Tx} g_{Rx}}{l_{FS} l_{Pt} l_{Atm} k T_{Eq} B} \Leftrightarrow (C/N_0)_{dBHz} = EIRP_{Tx} - L_{propagation} + (G/T)_{Rx} + 228.6$$

Transmitter Tx ⇨ p_{Tx} radiated power, g_{Tx} antenna gain
Propagation ⇨ l_{FS} free space losses, l_{Pt} pointing losses, l_{Atm} atmospheric losses
Receiver Rx ⇨ g_{Rx} antenna gain, T_{Eq} equivalent noise temperature, k Boltzmann's constant, B noise bandwidth

Satellite Transmission



Satellite Transparent Payload
(On-Board Processor after DEMUX for Satellite Regenerative Payload)

Input filter, LNA ⇨ out-of-band noise reduction at input

DC down converter, IF Amplifier ⇨ from uplink frequency to intermediate or downlink frequency

Frequency demultiplexer ⇨ 1 sub-band per transponder (e.g. 40MHz for 36MHz bandwidth)

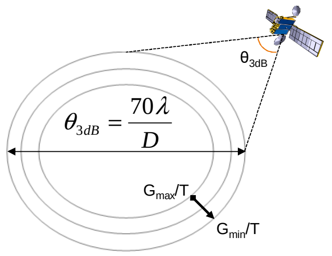
UC up converter ⇨ from intermediate frequency to downlink frequency

HPA ⇨ gain adjusted by a channel amplifier located before the TWTA

Output filter ⇨ background noise reduction at output

Frequency demultiplexer ⇨ 1 signal to the antenna

Satellite Uplink



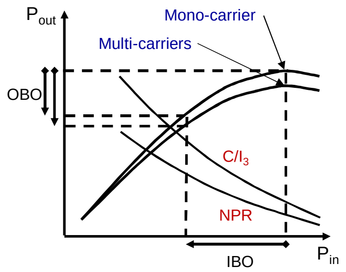
Satellite beam (G/T or SFD in Rx)

$$G_{Sat} = 10\log_{10}\eta\left(70\pi/\theta_{3dB}\right)^2$$

<u>Satellite transponder</u>
-**Saturation Flux Density (SFD)**
Power flux density for IBO=0
-**Operation Flux Density (OFD)**
Power flux density for IBO=OFD-SFD
-**Coverage variations**
Constant SFD+G/T

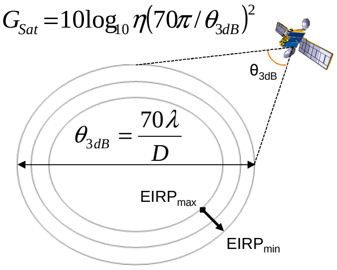
- **Ground station EIRP for a satellite transponder at saturation**
  - Clear sky
    $EIRP_G = SFD + 10\log_{10}\left(4\pi R^2\right)$
  - Atmospheric losses with Uplink Power Control (UPC)
    $EIRP_G = SFD + 10\log_{10}\left(4\pi R^2\right) + L_{Atm} + L_{Pt}$
- **Estimation of the atmospheric and pointing losses**
  - Satellite unmodulated and temperature-stabilized beacon to use with narrow bandwidth filter
  - Satellite telemetry beacons to use with large bandwidth filter to minimize level variations

Satellite Downlink



TWTA gain and inter-modulations

$$G_{Sat} = 10\log_{10}\eta\left(70\pi/\theta_{3dB}\right)^2$$

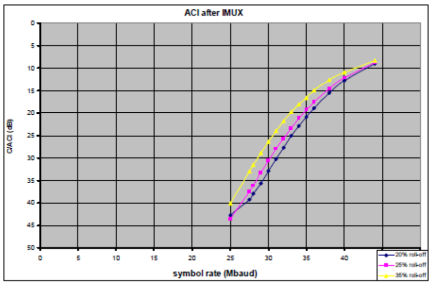


Satellite beam (EIRP in Tx)

- **Transponder gain adjustment**
  - Fixed Gain Mode (FGM), gain steps at fixed SFD+G/T (multiple transmission sites)
    ⇨ Ground station UPC required to keep the same operation point
  - Automatic Level Control (ALC), gain steps at fixed IBO (single transmission site)
    ⇨ Uplink fading compensation at the cost of the uplink C/N degradation (possibly with UPC)
- **Intermodulation noise C/I_{IM}**
  - Upper bound ⇨ 3rd order inter-modulations (C/I_3) ⇨ Mono-carrier, Small number of carriers
  - Lower bound ⇨ Noise Power Ratio (NPR) ⇨ Multi-carriers

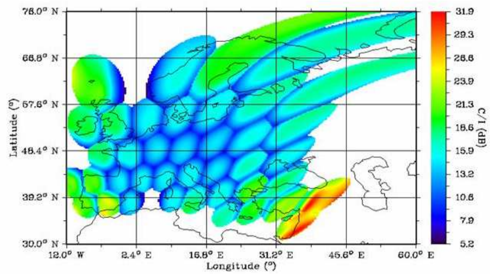
Example of Internal System Interferences

Ku band



Newtec measures (2008)
- -Bandwidth 36MHz
- -Spacing 39MHz
- ⇨Adjacent Channel Interference

Ka band



CNES simulations (2005)
- -4 colors
- -40 spots
- ⇨User Downlink Interference

(Link budget necessary for uplink)

Example of Adjacent System Interferences

Ka band

DirectTV 10 Boeing BSS702 (2007)

- Ground station off-axis EIRP compliance

Max TX power = 5.6 dBW/36 MHz = -23.9 dBW/40 kHz

Feeder-link antenna conforms to §25.209

Degrees off-axis	§25.209 Allowable Antenna Gain, dB	Max DIRECTV 10 Feeder-Link EIRP, dBW/40 kHz	§25.138 Allowable Off-Axis EIRP, dBW/40 kHz	Margin, dB
2.0	21.5	-2.4	11.0	13.4
4.0	13.9	-10.0	3.4	13.4
6.0	9.5	-14.4	-1.0	13.4
8.0	6.4	-17.5	-2.6	14.9

Ground station (Los Angeles)
- Transmit power 7.6dBW $+L_{Atm}$ *in case of rain*
- Transmit losses 2dB
- Ground antenna gain 66.3dB

$$EIRP_{LA} = 71.9dBW$$

- Uplink Adjacent Satellite Interference Analysis

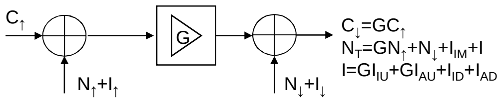
Orbital Separation, deg.	Allowable EIRP in 40 kHz, dBW	Allowable EIRP in xpndr BW, dBW	Wanted EIRP, dBW*	Delta Ant. Gain, dB	C/I, dB
2.0	11.0	40.5	71.4	0.0	30.9
4.0	3.4	33.0	71.4	0.0	38.4
6.0	-1.0	28.6	71.4	0.0	42.8
8.0	-2.6	26.9	71.4	0.0	44.5
Aggregate					26.8 **

(*) Pointing losses of 0.5dB
(**) West and East degrees

- Downlink Adjacent Satellite Interference Analysis

Orbital Separation, deg.	Rcv. antenna off-axis disc., dB	Delta EIRP, dB	Clear Sky S/E C/I, dB	Two Sat. C/I, dB
2.0	20.0	-5.2	14.8	11.8
4.0	26.9	-5.2	21.7	18.7
6.0	31.3	-5.2	26.1	23.1
8.0	34.4	-5.2	29.2	26.2
Aggregate				10.6

Satellite Overall Link



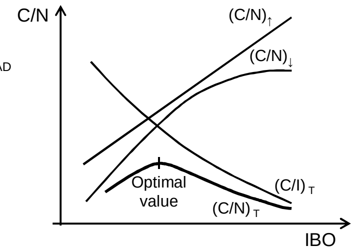
$$(C/N)_T = \left((C/N)_\uparrow^{-1} + (C/N)_\downarrow^{-1} + (C/I)^{-1}\right)^{-1}$$

NB: Independent uplink and downlink if on-board processing

(useful for symmetrical links requiring single hop)

$$C/I_{dB} = C/N_{dB} \Rightarrow C/(N+I)_{dB} = C/N_{dB} - 3dB$$

$$C/I_{dB} = C/N_{dB} + 10dB \Rightarrow C/(N+I)_{dB} = C/N_{dB} - 0.5dB$$

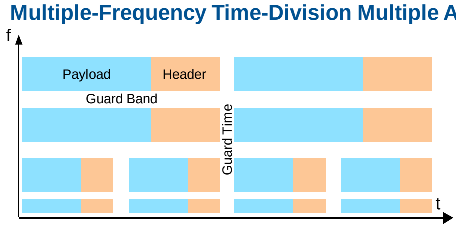


Optimal operation point

- **Internal system interferences (polarization reuse, multi-beam frequency reuse)**
  - Interferences due to the satellite reception antennas (C/I_{IU})
  - Interferences due to the satellite transmission antennas (C/I_{ID})
- **Adjacent system interferences**
  - Interferences due to other ground stations (C/I_{AU})
  - Interferences due to other satellites (C/I_{AD})

Multiple Access Links

- **Multiple-Frequency Time-Division Multiple Access (MF-TDMA)**



Burst Plan in Time and Frequency

- B_U useful bandwidth
- B_T total bandwidth
- N_U number of useful bits per frame
- N_T total number of bits per frame (with transmission during guard time)

$$\text{MF-TDMA efficiency} \Rightarrow \eta_{MF-TDMA} = \frac{N_U}{N_T}\frac{B_U}{B_T}$$

- **Multiple-Frequency Code-Division Multiple Access (MF-CDMA)**
  - R_c chip rate of the spreading sequence

    $E_b/N_0 = \gamma C/N$ with a processing gain $\gamma = R_c / R_b$
  - L_{MU} losses due to multi-user load η_{MU}

    $L_{MU} = 10\log_{10}\left(1/(1-\eta_{MU})\right)$

Mobile Satellite System Links

- **Mobile channel**
  - Three state propagation conditions ⇨ Clear line of site (LOS), Shadowing, Blockage
  - Reflection (smooth surface), Diffraction (sharp edge), Scattering (rough surface) ⇨ Multipath
  - Data bandwidth compared to path length ⇨ Narrowband fading (kHz), Wideband fading (MHz)
- **Friis transmission formula for a mobile link**

  $p_{Rx} = p_{Tx} g_{Tx} g_{Rx} g(R) x_S \alpha_M^2 (W) \text{ with } g(R) = kR^{-n}$
  - g(R) path loss factor (free space losses, two ray path losses)
  - x_S Gaussian random shadow fading (trees on roadway or buildings in urban area)
  - α_M Rice/Rayleigh distributed multipath fading (mountains or trees without shadowing)

    ⇨ Fade depth exceeded for a percentage of time cumulating the three states

    Maritime/Land/Aeronautical channel ITU-R P.680-3 (10/99) / 681-7 (10/09) / 682-3 (02/12)
- **Wideband channel**
  - Signal spectrum distortion and error floor due to delay spread
  - Mitigation techniques ⇨ diversity to reduce deep fades, directional antennas to reduce far-out echoes, equalizers to use energy in delayed taps, narrow bandwidth carrier multiplexing

Satellite Link Budget Methodology

- **Link constraints**
  - Satellite cost per bandwidth, frequency band, SFD, G/T, EIRP
  - User subscription, data rate, availability, C/N
- **Possible ground stations**
  - Transmission ground stations EIRP, UPC
  - Reception ground stations G/T
- **Satellite operation point**
  - Link budget on the uplink and satellite IBO
  - Satellite OBO and link budget on the downlink
- **Interferences**
  - Internal system interferences
  - Adjacent system interferences
- **System selection**
  - Margins for the overall link budget
  - System redesign to converge on positive margins

http://logiciels.cnes.fr/PROPA/fr/logiciel.htm