Satellite Space Link
Link-power Budget





Satellite System Parameters

1. Effective Isotropic Radiated Power (EIRP)

- A key parameter in link budget is the equivalent/Effective isotropic radiated power:

$$[EIRP]=[Ps]+[G] \quad dBW$$

[Ps]- the power at the antenna input (dBW)

[G] – Antenna Gain (dB)

Satellite System Parameters

1. Effective Isotropic Radiated Power (EIRP)

- For Parabolic Antennas with efficiency η=0.55-0.73 , the gain can be approximated by:

$$G=\eta(10.472\, fD)^2$$

Where f – the operating frequency in GHz

D – Ant. Diameter in m

EIRP Example

A Sat. downlink at 12 GHz operates with a transmit power (Pt) of 6W and an antenna diameter of 3 m and efficiency 0.55. Calculate EIRP

Sol.

$G=\eta(10.472fD)^2=0.55x(10.472x12x3)^2=78.168$

$[G]=10\ \mathrm{Log}(78.168)=48.9\ \mathrm{dB}$

$[EIRP]=10\log 6+48.9= 56.7\ \mathrm{dBW}$

Satellite System Parameters

2. Free Space Path Loss (Lp)

- Lp is the loss incurred by an electromagnetic wave as it propagates in a straight line through vacuum with no absorption or reflection of energy from nearby objects
- Lp is frequency dependent (wavelength λ) and increases with distance *r* :

$$\boxed{\mathrm{L_P} = \left(\frac{4\pi\, r}{\lambda}\right)^2 = \left(\frac{4\pi\, f\, r}{c}\right)^2}$$

Satellite System Parameters

- **Lp in dB:**

$$[\mathrm{L_P}] = 10\,Log\left(\frac{4\pi fr}{c}\right)^2 = 20\,Log\left(\frac{4\pi fr}{c}\right)$$

$$[\mathrm{L_P}] = 20\,Log\left(\frac{4\pi}{c}\right) + 20\,Log(f) + 20\,Log(r)$$

- **With c=3x10^8 m/s, *f* in GHz and *r* in Km, Lp in dB:**

$$[\mathrm{L_P}] = 92.4 + 20\,Log(f_{GHz}) + 20\,Log(r_{Km})$$

EIRP Example

Find Lp for an uplink operating at 6 GHz with a distance r=42000Km. If the ES EIRP is 120 dBW, what will be the RX power in dBm.

Sol.

$[L_p]=92.4+20\,\mathrm{Log}(42000)+20\,\mathrm{Log}(6)$

$[L_p]=200.4$ dB

$[P_{RX}]=120-200.4=-80.4$ dBW$=-110.4$ dBm

Satellite System Parameters

3. Additional Atmospheric and Ionospheric Losses (Lu/Ld)

Atmospheric gases result in losses by absorption. These losses usually amount to a fraction of a dB[AA].

Also, the ionosphere introduces a depolarization loss [PL]

Satellite System Parameters

4. Feeder and Branching Losses (L_{bf})

Losses will occur in the connection between waveguides, filters couplers and Branching units

5. Antenna Misalignment Losses (AML)

Loss that occurs as a result of having the ES and Sat. antennas being off-axis. For ES, this loss is called antenna pointing loss.

6. Polarization Misalignment Losses (PL)

Loss that occurs as a result of having polarization misalignment

Antenna Misalignments

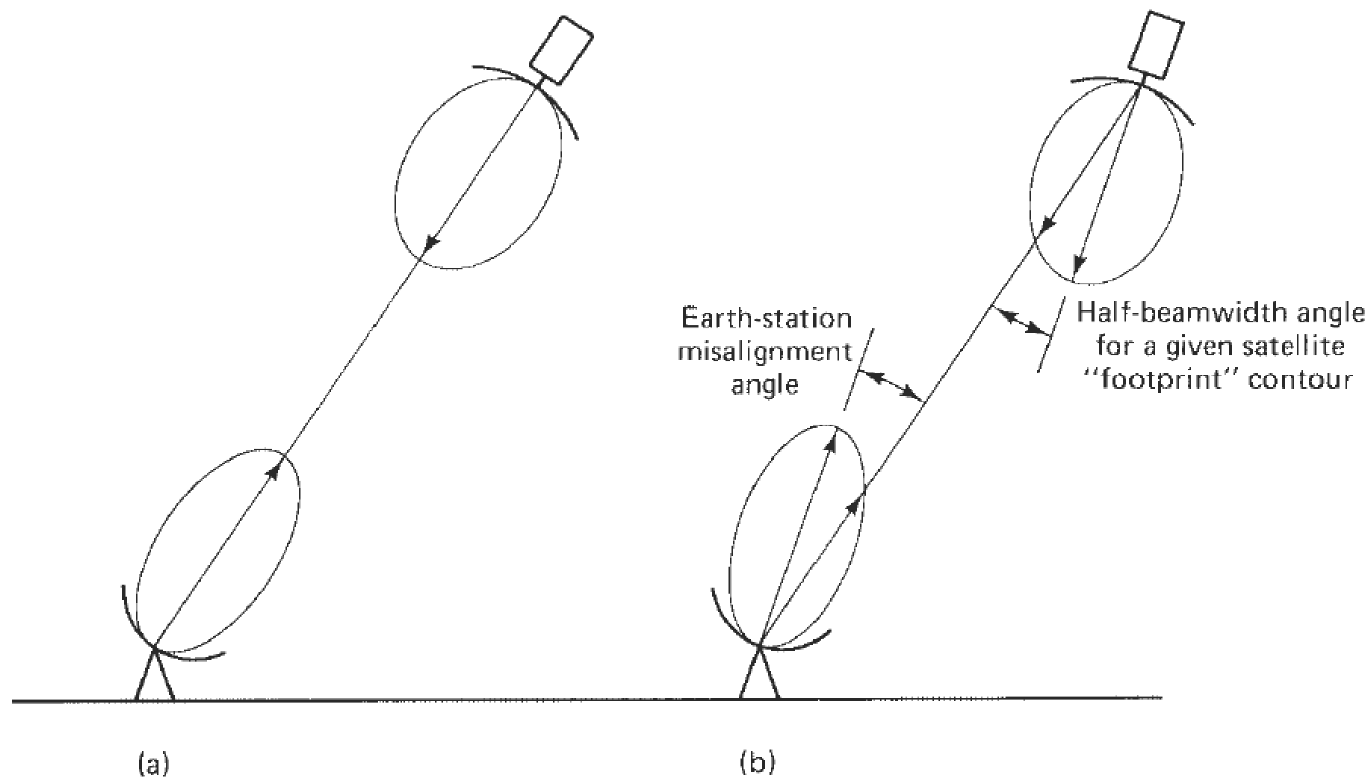


Figure 12.1 (*a*) Satellite and earth-station antennas aligned for maximum gain; (*b*) earth station situated on a given satellite "footprint," and earth-station antenna misaligned.

Example: TelSat Canada Design

TABLE 12.1 Atmospheric Absorption Loss and Satellite Pointing Loss for Cities and Communities in the Province of Ontario

	Atmospheric Absorption	Satellite antenna pointing loss, dB	
Location	dB, summer	1/4 Canada coverage	1/2 Canada coverage
Cat Lake	0.2	0.5	0.5
Fort Severn	0.2	0.9	0.9
Geraldton	0.2	0.2	0.1
Kingston	0.2	0.5	0.4
London	0.2	0.3	0.6
North Bay	0.2	0.3	0.2
Ogoki	0.2	0.4	0.3
Ottawa	0.2	0.6	0.2
Sault Ste. Marie	0.2	0.1	0.3
Sioux Lookout	0.2	0.4	0.3
Sudbury	0.2	0.3	0.2
Thunder Bay	0.2	0.3	0.2
Timmins	0.2	0.5	0.2
Toronto	0.2	0.3	0.4
Windsor	0.2	0.5	0.8

SOURCE: *Telesat Canada Design Workbook.*

Satellite System Parameters

7. Back-off Loss ($L_{bo}=[BO]_i/[BO]_o$)

HPAs used in ES transmitters and TWTs used in Sat. transponders are nonlinear devices: their gain (output-input) is dependent on the input signal.

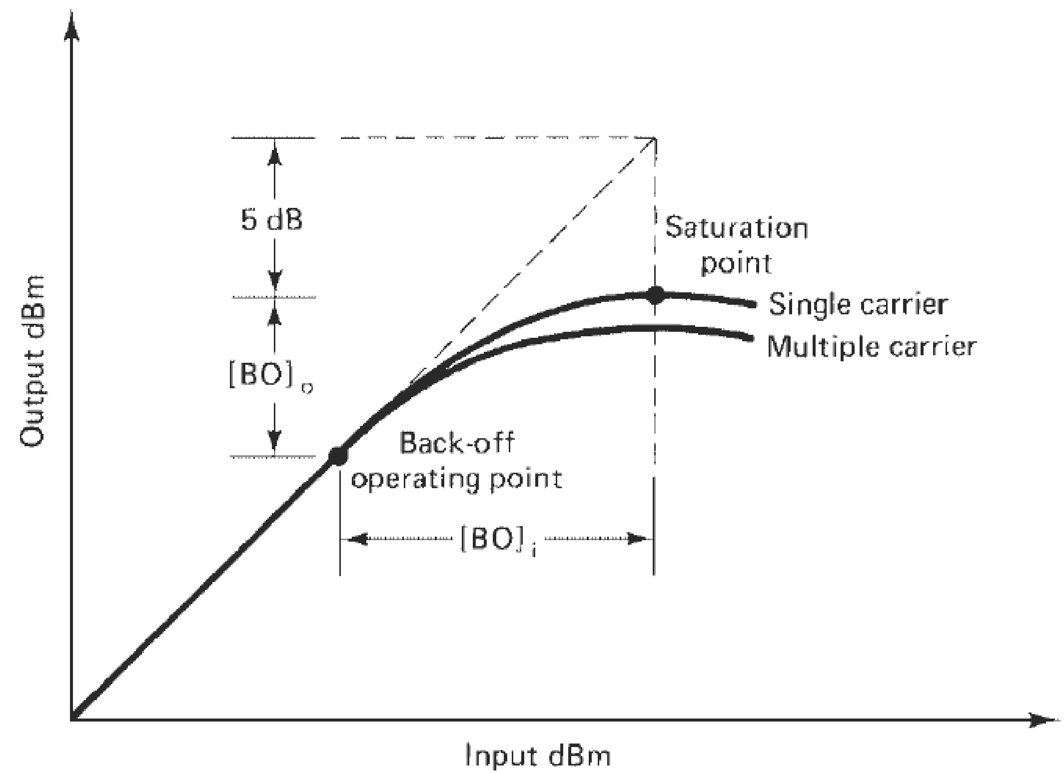


Figure 12.7 Input and output back-off relationship for the satellite traveling-wave-tube amplifier; $[BO]_i = [BO]_0 + 5$ dB.

Satellite System Noise

The RX power in a Sat. link is very small (couples of pW)→ amplification can be used to bring the signal strength up to an acceptable level.

The main source of noise is the random thermal motion of electrons + thermal-like noise from antenna radiation

The total noise power can be :

$$\boxed{P_N = KT_N B_N}$$

K-Boltzmans const. = 1.38×10^{-23} J/K

T_N-temperature of the environment (K)

B_N- Noise Bandwidth (Hz)

Satellite System Noise

Another parameter is the noise factor F:

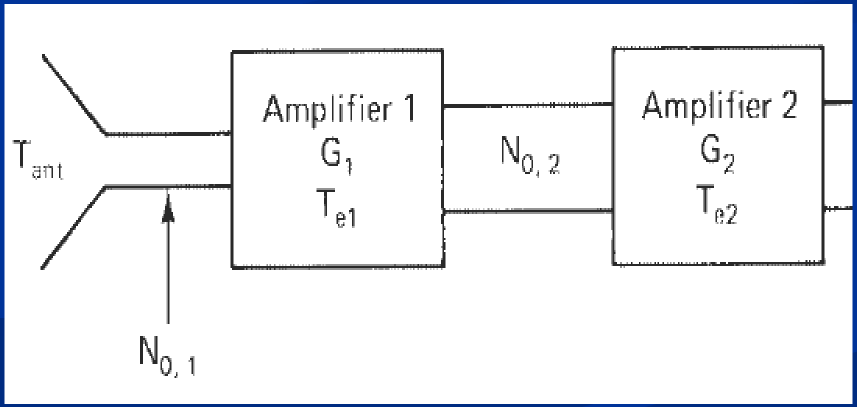
$$F = 1 + \frac{T_e}{T} \rightarrow T_e = T(F-1) \rightarrow [T_e] = 10\,\mathrm{Log}(T_e)$$

Te- Equivalent noise temperature (K)

The Noise Figure NF is:

$$[NF] = 10\,\mathrm{Log}(F)$$

For a cascaded amplifier:



$$N_{0,2} = G_1 \; K(T_{ant} + T_{e1}) + KT_{e2}$$

Satellite System Noise

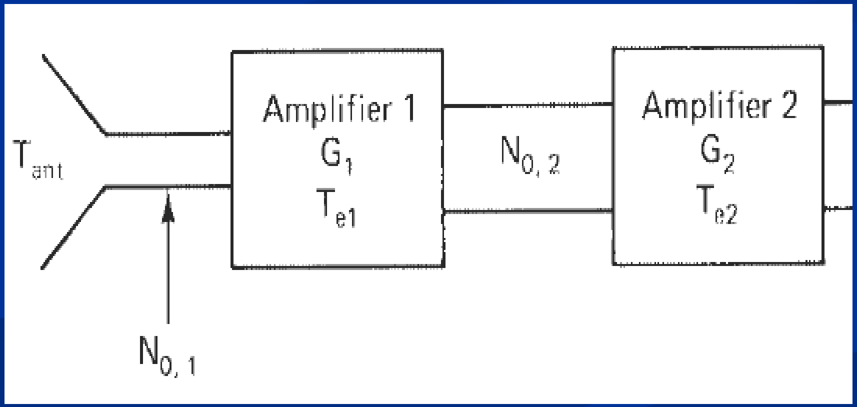
In general, for a cascaded system N is:

$$T_s = T_{ant} + T_{e1} + \frac{T_{e2}}{G_1} + \frac{T_{e3}}{G_1 G_2} + \ldots$$

Te- Equivalent noise temperature (K)

The Noise Figure NF is:

$$[NF] = 10\,\mathrm{Log}(F)$$



For a cascaded amplifier:

$$N_{0,2} = G_1 \; K(T_{ant} + T_{e1}) + KT_{e2}$$

Noise Example

An Ant. Has a noise temperature of 35 K and is matched into a receiver which has a noise temperature of 100K. Calculate the noise density and the noise power with a BW=36MHz.

Sol.

$$N_o = KT = (35+100) \times 1.38 \times 10^{-23} = 1.86 \times 10^{-21}\ \text{J}$$

$$P_N = KTB = 1.86 \times 10^{-21} \times 36 \times 10^{6} = 0.067\ \text{pW}$$

Noise Example

Convert NF of 4 & 4.1 dB to Te with K=300K.

<u>Sol.</u>

[NF]=4 dB → F=2.512

[NF]=4.1 → F=2.57

Te=300(2.512-1)=453.6 K

Te=300(2.57-1)=471 K

Note that a *<u>0.1 dB</u>* difference in [NF] led to a *<u>17.4^o</u>* difference in Te

Antenna Noise

- RX antennas (ES and Sat.) introduce noise into the system!!!!
- Types: 1) Self Antenna Noise
  2) Sky Noise
- Antenna Noise is also dependent on the angle of elevation
- Typical Example:
  1- ES Large C-band = 60 K
  2- ES Ku (clear sky)= 80 K
  3- Sat. ant. = 290 K (Why High?!)

Antenna Noise

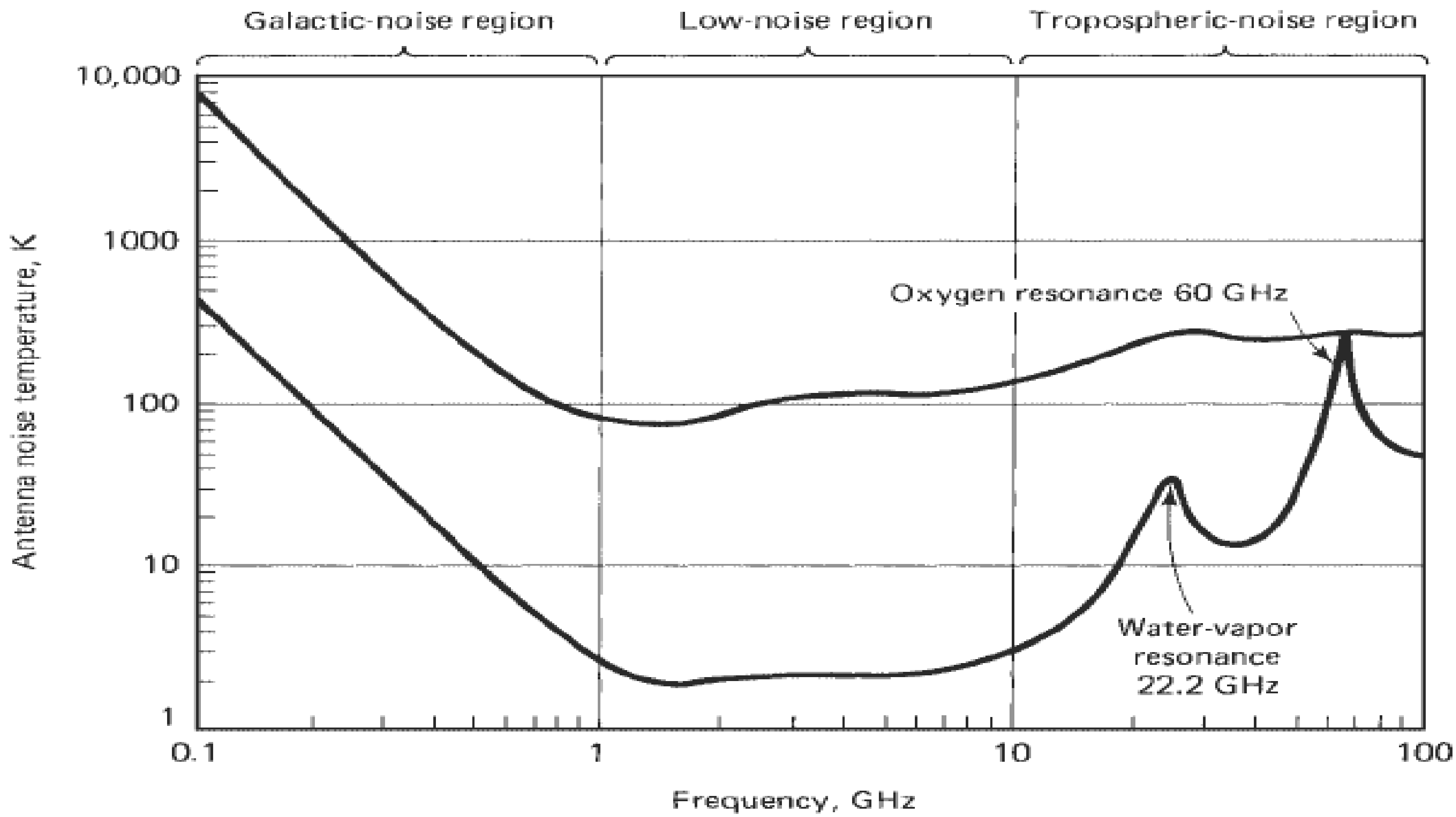
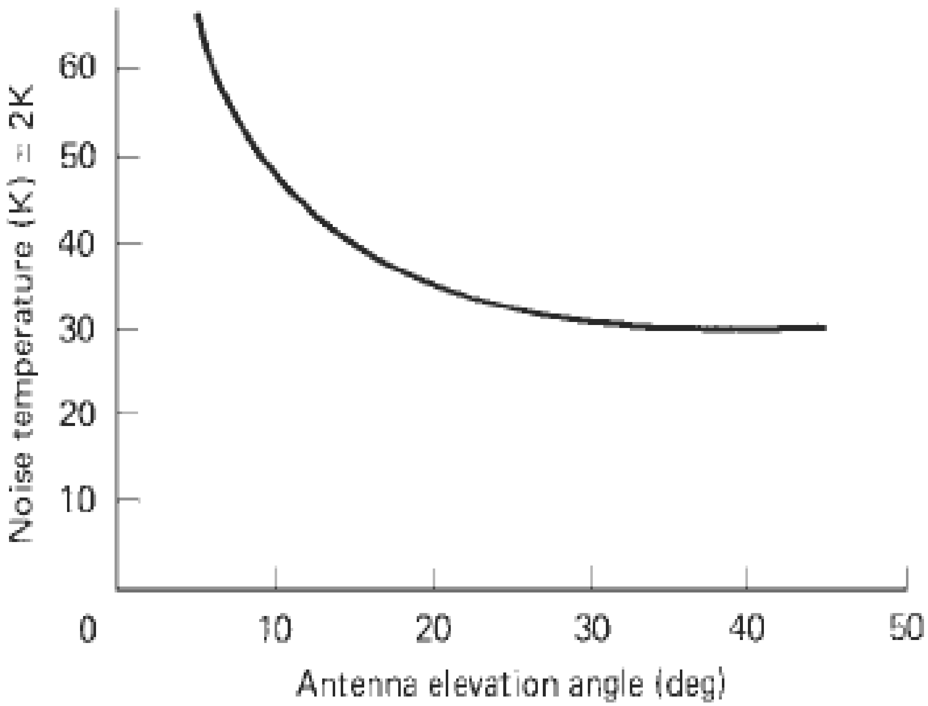


Figure 12.2 Irreducible noise temperature of an ideal, ground-based antenna. The antenna is assumed to have a very narrow beam without sidelobes or electrical losses. Below 1 GHz, the maximum values are for the beam pointed at the galactic poles. At higher frequencies, the maximum values are for the beam just above the horizon and the minimum values for zenith pointing. The low-noise region between 1 and 10 GHz is most amenable to application of special, low-noise antennas. *(From Philip F. Panter, "Communications Systems Design," McGraw-Hill Book Company, New York, 1972. With permission.)*

Antenna Noise



Operating frequency (GHz)	11.7-12.2
Polarization	Linear
Gain dB_i ± 0.2 dB at 11.95 GHz	45.0
Noise temperature (K)	
At 10° elevation	47
At 20° elevation	35
At 30° elevation	32
VSWR maximum	1.3
Isolation (dB)	35
Half-power beamwidth (deg)	0.91
Pattern envelope (PE) number	4374
Output flanges	WR-75

Figure 12.3 Antenna noise temperature as a function of elevation for 1.8-m antenna characteristics. (*Andrew Bulletin 1206; courtesy Andrew Antenna Company, Limited.*)

Rain Fading

- Rain attenuation is more serious at higher frequencies (C, Ku, Ka,….)

- Rain Information are available in the forms of curves and tables

TABLE 12.2 Rain Attenuation for Cities and Communities in the Province of Ontario

	Rain attenuation, dB		
Location	1%	0.5%	0.1%
Cat Lake	0.2	0.4	1.4
Fort Severn	0.0	0.1	0.4
Geraldton	0.1	0.2	0.9
Kingston	0.4	0.7	1.9
London	0.3	0.5	1.9
North Bay	0.3	0.4	1.9
Ogoki	0.1	0.2	0.9
Ottawa	0.3	0.5	1.9
Sault Ste. Marie	0.3	0.5	1.8
Sioux Lookout	0.2	0.4	1.3
Sudbury	0.3	0.6	2.0
Thunder Bay	0.2	0.3	1.3
Timmins	0.2	0.3	1.4
Toronto	0.2	0.6	1.8
Windsor	0.3	0.6	2.1

Rain Fading

- The Effective Noise Temperature of Rain:

$$T_{rain} = T_a\left(1 - \frac{1}{A}\right)$$

A- Rain attenuation

Ta- Apparent absorber temperature

- The Total Sky-noise Temperature:

$$T_{sky} = T_{CS} + T_{rain}$$

Example

Under clear sky conditions, [C/N] is 20 dB, the total effective noise is 400K. If rain attenuation exceeds 1.9 dB for 0.1 % of the time, then calculate the value below which [C/N] falls for 0.1% given Ta=280K.

Sol. :

$1.9 \rightarrow 1.55$

$T_{ant}=280(1-1/1.55)=99.2$ K

$T_s=[499.2]-[400]=0.96$ dB

$[C/N]=20-1.9-0.96=17.14$ dB

Satellite System Parameters

8. Transmit Power (Pt) and Bit Energy (Eb)

- The Energy per bit (E_b) having P_t at saturation and bit duration of T_b:

$$\boxed{E_b = P_t . T_b}$$

- In terms of the bit rate $f_b = 1/T_b$, E_b is:

$$\boxed{E_b = \frac{P_t}{f_b}}$$

Satellite System Parameters

9. Carrier-to-Noise Density Ratio (C/No)

- C/No is the average wideband carrier power-to-noise density ratio:

$$\frac{C}{N_o} = \frac{C}{KT} \Rightarrow [\frac{C}{N_o}] = [C] - [No]$$

10. Bit Energy-to-Noise Density Ratio (E_b/N_o)

- E_b/No is a convenient method to compare digital systems using different mod. Schemes!:

$$\frac{E_b}{N_o} = \frac{C/f_b}{N/B_b} = \frac{CB}{Nf_b} \Rightarrow [\frac{E_b}{N_o}] = [\frac{C}{N}] + [\frac{B}{f_b}]$$

Satellite System Parameters

11. Gain-to-Equivalent Noise Temperature Ratio (G/Te)

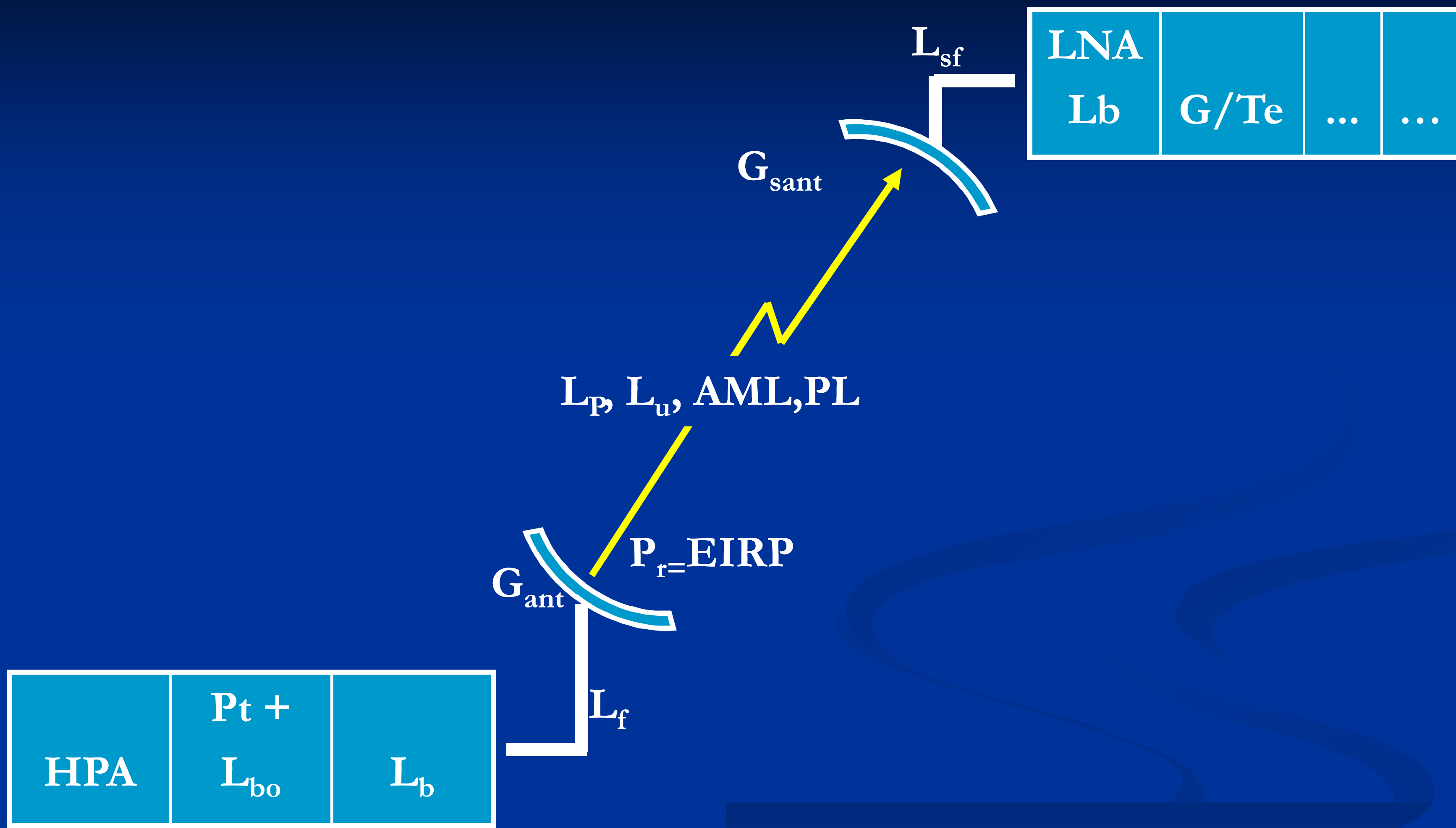
- G/Te is a figure of merit used to represent an ES or Sat. RX:

$$\frac{G}{T_e} = \frac{G_{ant} + G_{LNA}}{T_e} \Rightarrow [\frac{G}{T_e}]_{dB/K} = [G_{ant}] + [G_{LNA}] - [T_e]$$

For a transponder G_{ant}=12 dB, G_{LNA}=10 dB and Te=26 dBK, then its G/Te figure of merit:

G/Te=12+10-26=-4 dBK^{-1}

Satellite UpLink Equation



$$\frac{C}{N_o} = \frac{G_{ant} P_{in} (L_{bf} . L_{bo})_{ES} (L_p L_u) G_{sant} . G_{LNA} . (L_{bf} . L_{bo})_{sat}}{KT_e}$$

Satellite UpLink Equation

$$\frac{\mathrm{C}}{\mathrm{N_o}} = G_{ant} P_{in} (L_{bf} . L_{bo})_{ES} \left(L_p L_u \right) \left(\frac{G_{sant} . G_{LNA}}{T_e} \right) (L_{bf} . L_{bo})_{sat} \left(\frac{1}{K} \right)$$

$$(L_{bf})_{sat} = (L_{bo})_{sat} = 0$$

$$[\frac{\mathrm{C}}{\mathrm{N_o}}] = [EIRP] + [\frac{G}{T_e}] - \left([L_p] + [L_u] \right) - 10 Log(K)$$

Note: The downlink equation can be easily maniplulated from the uplink equation (by replacing ES by Sat)

Link Budget Example

Complete the link budget for a satellite system with the parameters given in table below.

Uplink	Downlink
1. ES TX output power at saturation, 2000 W	*1. Sat. TX output power at saturation, 10dB W*
2. ES back-off Loss, 3 dB	*2. Sat. back-off Loss, 0.1 dB*
3. ES branching and feeder losses, 4 dB	*3. Sat. branching and feeder losses, 0.5 dB*
4. ES antenna gain, 64 dB	*4. Sat. antenna gain, 30.8 dB*
5. Additional Uplink atmospheric Losses, 0.6 dB	*5. Additional Downlink atmospheric Losses, 0.4 dB*
6. Satellite RX (G/Te) ratio (GTR), -5.3 dbK^{-1}	*6. ES RX antenna gain, 62 dB*
7. Satellite branching and feeder Losses, 0 dB	*7. ES branching and feeder Losses, 0 dB*
8. Bit Rate, 120 Mbps	*8. ES equivalent noise temperature, 270 K*
9. Modulation Scheme, 8PSK	*9. ES G/Te, 37.7 dbK^{-1}*
10. Free Space Path Loss at 14 GHz, 206.5 dB	*10. Free Space Path Loss at 12 GHz, 205.6 dB*

Solution: Uplink

* $[EIRP]=[P_{TX}]+[G_{ant}]-[L_{bo}]-[L_{bf}]=$

  $[EIRP]= 10Log(2000)+64-3-4=90$ dBW

* Carrier density at Sat. ant.

  $[C']=[EIRP]-[Lp]-[Lu]=90-206.5-0.6=-117.1$ dBW.

* C/No at Sat.:

$C/No=C/KTe=(C/Te).(1/K) \rightarrow C/Te=C'.(G/Te)$

$\rightarrow C/No=C'.(G/Te).(1/K)$

$\rightarrow [C/No]=[C']+[G/Te]-10log(1/1.38x10^{-23})=$

$\rightarrow [C/No]=-117.1-5.3-(-228.6)=106.2$

Solution: Uplink

* $Eb/No=(C/f\,b)/No=(C/No)\,.\,(1/f\,b)$

→ $[Eb/No]=[C/No]-10Log(f\,b)$

→ $[Eb/No]=106.2 - 10\,Log(120x10^6)=25.4$ dB

* C/N for a minimum bandwidth

$C/N=(Eb.\,f\,b)/(No.B)=(Eb/No)/(B/f\,b)$

→ $[C/N]=[Eb/No]-[B/f\,b]$

→ $[C/N] = 25.4- 10\,Log[(40x10^6)/(120x10^6)]=30.2$ dB

Solution: Downlink

* $[EIRP]_{sat}=[P_{TX}]+[G_{ant}]-[L_{bo}]-[L_{bf}]=$

  $[EIRP]= 10+30.8-0.1-0.5=40.2$ dBW

* Carrier density at ES ant.

  $[C']=[EIRP]-[Lp]-[Lu]=40.2 -205.6-0.4=-165.8$ dBW.

* C/No at ES:

$C/No=C/KTe=(C/Te).(1/K) \rightarrow C/Te=C'.(G/Te)$

$\rightarrow C/No=C'.(G/Te).(1/K)$

$\rightarrow [C/No]=[C']+[G/Te]-10\log(1/1.38\times10^{-23})=$

$\rightarrow [C/No]= -165.8 + 37.7 +228.6=100.5$ dB

Solution: Downlink

* $Eb/No=(C/f\,b)/No=(C/No)\,.\,(1/f\,b)$

→ $[Eb/No]=[C/No]-10Log(f\,b)$

→ $[Eb/No]=100.5 - 10\,Log(120x10^6)=19.7$ dB

* C/N for a minimum bandwidth

$C/N=(Eb.\,f\,b)/(No.B)=(Eb/No)/(B/f\,b)$

→ $[C/N]=[Eb/No]-[B/f\,b]$

→ $[C/N] = 19.7 - 10\,Log[1/3]=24.5$ dB

Solution: Combined Link Budget

* The overall energy of bit-to-noise density ratio:

→ $[Eb/No]_{overall} = A/B$

$A = (Eb/No)_{up} . (Eb/No)_{down}$

$B = (Eb/No)_{up} + (Eb/No)_{down}$

→ $A = (346.7).(93.3)$ & $B = 346.7 + 93.3$

$(Eb/No)_{overall} = A/B = 73.5$

$[Eb/No]_{overall} = 10 \text{ Log}(73.5) = 18.7 \text{ dB}$

Uplink	Downlink
1. ES TX output power at saturation, 2000 W	1. Sat. TX output power at saturation, 10 W
2. ES back-off Loss, 3 dB	2. Sat. back-off Loss, 0.1 dB
3. ES branching and feeder losses, 4 dB	3. Sat. branching and feeder losses, 0.5 dB
4. ES antenna gain, 64 dB	4. Sat. antenna gain, 30.8 dB
5. Additional Uplink atmospheric Losses, 0.6 dB	5. Additional Downlink atmospheric Losses, 0.4 dB
6. Satellite RX (G/Te) ratio (GTR), -5.3 dbK-1	6. ES RX antenna gain , 62 dB 37.7
7. Satellite branching and feeder Losses, 0dB	7. ES branching and feeder Losses, 0dB
8. Bit Rate, 120 Mbps	8. ES equivalent noise temperature, 270 K
9. Modulation Scheme, 8PSK	9. ES G/Te, 37.7 dbK-1
10. Free Space Path Loss at 14 GHz, 206.5 dB	10. Free Space Path Loss at 12 GHz, 205.6 dB

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