4

The RF Link

In this chapter the fundamental elements of the communications satellite Radio Frequency (RF) or free space link are introduced. Basic transmission parameters, such as antenna gain, beamwidth, free-space path loss, and the basic link power equation are introduced. The concept of system noise and how it is quantified on the RF link is then developed, and parameters such as noise power, noise temperature, noise figure, and figure of merit are defined. The carrier-to-noise ratio and related parameters used to define communications link design and performance are developed, based on the basic link and system noise parameters introduced earlier.

4.1 Transmission Fundamentals

The RF (or free space) segment of the satellite communications link is a critical element that impacts the design and performance of communications over the satellite. The basic communications link, shown in Figure 4.1, identifies the basic parameters of the link.

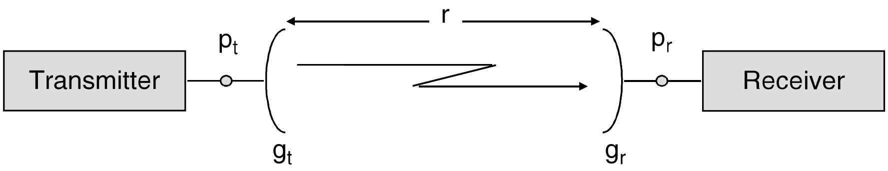

Figure 4.1 Basic communications link

The parameters of the link are defined as: p_t = transmitted power (watts); p_r = received power (watts); g_t = transmit antenna gain; g_r = receive antenna gain; and r = path distance (meters).

An electromagnetic wave, referred to as a ***radiowave*** at radio frequencies, is nominally defined in the range of ~100 MHz to 100+ GHz. The radiowave is characterized by variations of its electric and magnetic fields. The oscillating motion of the field intensities vibrating at a particular point in space at a frequency f excites similar vibrations at neighboring points, and the radiowave is said to travel or to ***propagate***. The wavelength, λ, of the radiowave is the

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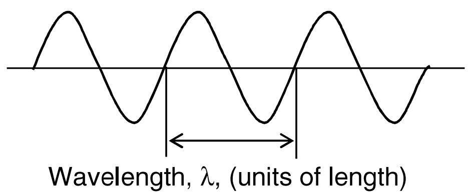


Figure 4.2 Definition of wavelength

spatial separation of two successive oscillations, which is the distance the wave travels during one cycle of oscillation (Figure 4.2).

The frequency and wavelength in free space are related by

$$\lambda = \frac{c}{f} \tag{4.1}$$

where c is the phase velocity of light in a vacuum.

With $c = 3 \times 10^8$ m/s, the free space wavelength for the frequency in GHz can be expressed as

$$\lambda(\mathrm{cm}) = \frac{30}{f(\mathrm{GHz})} \quad \text{or} \quad \lambda(\mathrm{m}) = \frac{0.3}{f(\mathrm{GHz})} \tag{4.2}$$

Table 4.1 provides examples of wavelengths for some typical communications frequencies.

Table 4.1 Wavelength and frequency

λ (cm)	f (GHz)
15	2
2.5	12
1.5	20
1	30
0.39	76

Consider a radiowave propagating in free space from a point source P of power p_t watts. The wave is isotropic in space, i.e., spherically radiating from the point source P, as shown in Figure 4.3.

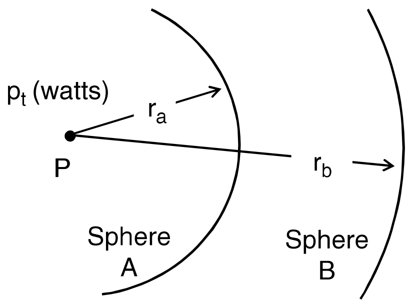


Figure 4.3 Inverse square law of radiation

The power flux density (or power density), over the surface of a sphere of radius r_a from the point P, is given by

$$(\mathrm{pfd})_A = \frac{p_t}{4\pi r_a^2}, \ \text{watts/m}^2 \tag{4.3}$$

Similarly, at the surface B, the density over a sphere of radius r_b is given by

$$(\mathrm{pfd})_B = \frac{p_t}{4\pi r_b^2}, \ \text{watts/m}^2 \tag{4.4}$$

The ratio of power densities is given by

$$\frac{(\mathrm{pfd})_A}{(\mathrm{pfd})_B} = \frac{r_b^2}{r_a^2} \tag{4.5}$$

where $(\mathrm{pfd})_B < (\mathrm{pfd})_A$. This relationship demonstrates the well-known ***inverse square law of radiation***: the power density of a radiowave propagating from a source is inversely proportional to the square of the distance from the source.

4.1.1 *Effective Isotropic Radiated Power*

An important parameter in the evaluation of the RF link is the ***effective isotropic radiated power***, eirp. The eirp, using the parameters introduced in Figure 4.1, is defined as

$$\begin{gathered} \mathrm{eirp} \equiv p_t\, g_t \\ \text{or, in db,} \\ \mathrm{EIRP} = P_t + G_t \end{gathered} \tag{4.6}$$

The eirp serves as a single parameter 'figure of merit' for the transmit portion of the communications link.[1]

4.1.2 *Power Flux Density*

The power density, usually expressed in watts/m^2, at the distance r from the transmit antenna with a gain g_t, is defined as the ***power flux density*** $(\mathrm{pfd})_r$ (see Figure 4.4).

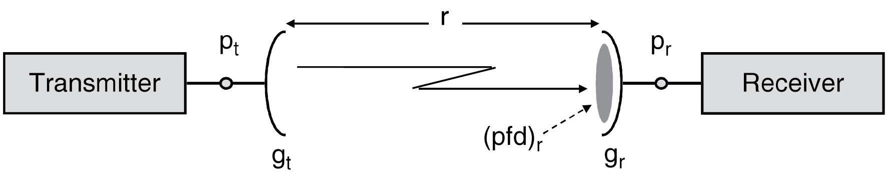


Figure 4.4 Power flux density

[1] The format followed in this book is to use a lower case designation for the *numerical* value of a parameter, and an upper case designation for the *decibel (dB)* value of that same parameter. Every effort is made to maintain this designation throughout the book, however occasionally, where strong precedent or common use indicates otherwise, we may have to deviate from this format.

The $(\mathrm{pfd})_r$ is therefore

$$(\mathrm{pfd})_r = \frac{p_t\, g_t}{4\pi r^2}\ \mathrm{w/m^2} \tag{4.7}$$

Or, in terms of the eirp,

$$(\mathrm{pfd})_r = \frac{\mathrm{eirp}}{4\pi r^2}\ \mathrm{w/m^2} \tag{4.8}$$

The power flux density expressed in dB, will be

$$\begin{aligned}(\mathrm{PFD})_r &= 10\log\left(\frac{p_t\, g_t}{4\pi r^2}\right)\\ &= 10\log(p_t) + 10\log(g_t) - 20\ \log(r) - 10\log(4\pi)\end{aligned}$$

With r in meters,

$$\begin{aligned}(\mathrm{PFD})_r &= P_t + G_t - 20\log(r) - 10.99\\ &\text{or}\\ (\mathrm{PFD})_r &= \mathrm{EIRP} - 20\log(r) - 10.99\end{aligned} \tag{4.9}$$

where P_t, G_t, and EIRP are the transmit power, transmit antenna gain, and effective radiated power, all expressed in dB.

The (pfd) is an important parameter in the evaluation of power requirements and interference levels for satellite communications networks.

4.1.3 Antenna Gain

Isotropic power radiation is usually not effective for satellite communications links, because the power density levels will be low for most applications (there are some exceptions, such as for mobile satellite networks, which will be discussed in Chapter 9). Some directivity (gain) is desirable for both the transmit and receive antennas. Also, physical antennas are not perfect receptors/emitters, and this must be taken into account in defining the antenna gain.

Consider first a lossless (ideal) antenna with a physical aperture area of A (m^2). The gain of the ideal antenna with a physical aperture area A is defined as

$$g_{\mathrm{ideal}} \equiv \frac{4\pi A}{\lambda^2} \tag{4.10}$$

where λ is the wavelength of the radiowave.

Physical antennas are not ideal – some energy is reflected away by the structure, some energy is absorbed by lossy components (feeds, struts, subreflectors). To account for this, an ***effective aperture***, A_e, is defined in terms of an ***aperture efficiency***, η_A, such that

$$A_e = \eta_A A \tag{4.11}$$

Then, defining the 'real' or physical antenna gain as g,

$$g_{\mathrm{real}} \equiv g = \frac{4\pi A_e}{\lambda^2} \tag{4.12}$$

Or,

$$g = \eta_A \frac{4\pi A}{\lambda^2} \tag{4.13}$$

Antenna gain in dB for satellite applications is usually expressed as the dB value above the gain of an isotropic radiator, written as 'dBi'. Therefore, from Equation (4.13),

$$G = 10\ \log\left[\eta_A \frac{4\pi A}{\lambda^2}\right],\ \mathrm{dBi} \tag{4.14}$$

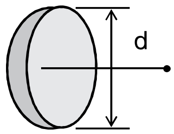
Note also that the effective aperture can be expressed as

$$A_e = \frac{g\lambda^2}{4\ \pi} \tag{4.15}$$

The aperture efficiency for a circular parabolic antenna typically runs about 0.55 (55 %), while values of 70 % and higher are available for high performance antenna systems.

4.1.3.1 Circular Parabolic Reflector Antenna

The circular parabolic reflector is the most common type of antenna used for satellite earth station and spacecraft antennas. It is easy to construct, and has good gain and beamwidth characteristics for a large range of applications. The physical area of the aperture of a circular parabolic aperture is given by



$$A = \frac{\pi d^2}{4} \tag{4.16}$$

where d is the physical diameter of the antenna.

From the antenna gain Equation (4.13),

$$g = \eta_A \frac{4\pi A}{\lambda^2} = \eta_A \frac{4\pi}{\lambda^2}\left(\frac{\pi d^2}{4}\right)$$

or

$$g = \eta_A \left(\frac{\pi d}{\lambda}\right)^2 \tag{4.17}$$

Expressed in dB form,

$$G = 10 \log\left[\eta_A \left(\frac{\pi d}{\lambda}\right)^2\right] \quad \mathrm{dBi} \tag{4.18}$$

For the antenna diameter d given in meters, and the frequency f in GHz,

$$g = \eta_A\ (10.472\ f\ \ d)^2$$

$$g = 109.66\ f^2\ d^2\ \eta_A$$

Or, in dBi

$$G = 10\ \log(109.66\ f^2\ d^2\ \eta_A) \tag{4.19}$$

Table 4.2 presents some representative values of antenna gain for various antenna diameters and frequencies. An antenna efficiency of 0.55 is assumed for all the cases.

Table 4.2 Antenna gain, diameter, and frequency dependence

Dia. d (meters)	Freq. f (GHz)	Gain G (dBi)
1	12	39
3	12	49
6	12	55
10	12	59

Dia. d (meters)	Freq. f (GHz)	Gain G (dBi)
1	24	45
3	24	55
6	24	61
10	24	65

Note that as the antenna diameter is doubled, the gain increases by 6 dBi, and as the frequency is doubled, the gain also increases by 6 dBi.

4.1.3.2 Beamwidth

Figure 4.5 shows a typical directional antenna pattern for a circular parabolic reflector antenna, along with several parameters used to define the antenna performance. The ***boresight*** direction refers to the direction of maximum gain, for which the value g is determined from the above equations. The 1/2 ***power beamwidth*** (sometimes referred to as the '3 dB beamwidth') is the contained conical angle θ for which the gain has dropped to 1/2 the value at boresight, i.e., the power is 3 dB down from the boresight gain value.

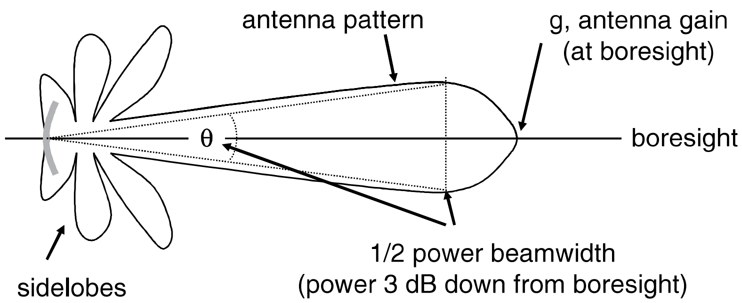


Figure 4.5 Antenna beamwidth

The antenna pattern shows the gain as a function of the distance from the boresight direction. Most antennas have ***sidelobes***, or regions where the gain may increase due to physical structure elements or the characteristics of the antenna design. It is also possible that some energy may be present behind the physical antenna reflector. Sidelobes are a concern as a possible source for noise and interference, particularly for satellite ground antennas located near to other antennas or sources of power in the same frequency band as the satellite link.

The antenna beamwidth for a parabolic reflector antenna can be approximately determined from the following simple relationship,

$$\theta \cong 75\frac{\lambda}{d} = \frac{22.5}{d\,f} \tag{4.20}$$

where θ is the 1/2 power beamwidth in degrees, d is the antenna diameter in meters, and f is the frequency in GHz.

Table 4.3 lists some representative antenna beamwidths for a range of frequencies and diameters used in satellite links, along with antenna gain values.

Table 4.3 Antenna beamwidth for the circular parabolic reflector antenna

f (GHz)	d (m)	G (dBi)	θ (°)
6	3	43	1.25
	4.5	46	0.83
12	1	39	1.88
	2.4	47	0.78
	4.5	53	0.42
30	0.5	41	1.50
	2.4	55	0.31
	4.5	60	0.17

θ (°)	G (dBi)
1	44.85
0.1	64.85

$(\eta_A = 0.55)$

Antenna beamwidths for satellite links tend to be very small, in most cases much less than 1°, requiring careful antenna pointing and control to maintain the link.

4.1.4 *Free-Space Path Loss*

Consider now a receiver with an antenna of gain g_r located a distance r from a transmitter of p_t watts and antenna gain g_t, as shown in Figure 4.4. The power p_r intercepted by the receiving antenna will be

$$p_r = (pfd)_r A_e = \frac{p_t g_t}{4\pi_{r^2}} A_e, \text{ watts} \tag{4.21}$$

where $(pfd)_r$ is the power flux density at the receiver and A_e is the effective area of the receiver antenna, in square meters. Replacing A_e with the representation from Equation (4.15),

$$p_r = \frac{p_t g_t}{4\pi d^2} \frac{g_r \lambda^2}{4\pi} \tag{4.22}$$

A rearranging of terms describes the interrelationship of several parameters used in link analysis:

$$p_r = \underbrace{\left[\frac{p_t g_t}{4\pi r^2}\right]}_{\Uparrow} g_r \underbrace{\left[\frac{\lambda^2}{4\ \pi}\right]}_{\Uparrow} \tag{4.23}$$

Power Flux Density	**Spreading Loss**
(pfd)	s
in w/m^2	in m^2

The first bracketed term is the power flux density defined earlier. The second bracketed term is the ***spreading loss***, s, a function of wavelength, or frequency, only. It can be found as

$$s = \frac{\lambda^2}{4\pi} = \frac{0.00716}{f^2}$$
$$S(dB) = -20\log(f) - 21.45 \tag{4.24}$$

where the frequency is specified in GHz. Some representative values for S are −44.37 dB at 14 GHz, −47.47 at 20 GHz, and −50.99 at 30 GHz.

Rearranging Equation (4.22) in a slightly different form,

$$p_r = p_t\, g_t\, g_r \left[\left(\frac{\lambda}{4\pi r}\right)^2\right] \tag{4.25}$$

The term in brackets accounts for the inverse square loss. The term is usually used in its reciprocal form as the ***free space path loss***, l_{FS}, i.e.,

$$l_{FS} = \left(\frac{4\pi r}{\lambda}\right)^2 \tag{4.26}$$

Or, expressed in dB,

$$L_{FS}(dB) = 20\log\left(\frac{2\pi r}{\lambda}\right) \tag{4.27}$$

The term is inverted for 'engineering convenience' to maintain L_{FS} (dB) as a positive quantity, that is ($l_{FS} > 1$).

Free space path loss is present for all radiowaves propagating in free space or in regions whose characteristics approximate the uniformity of free space, such as the earth's atmosphere.

The dB expression for free space path loss can be simplified for specific units used in link calculations. Re-expressing Equation (4.26) in terms of frequency,

$$l_{FS} = \left(\frac{4\pi r}{\lambda}\right)^2 = \left(\frac{4\pi r f}{c}\right)^2$$

For the range r in ***meters***, and the frequency f in ***GHz***,

$$l_{FS} = \left(\frac{4\pi r\ (f \times 10^9)}{(3 \times 10^8)}\right)^2 = \left(\frac{40\ \pi}{3} r\, f\right)^2$$

$$L_{FS}(dB) = 20\log(f) + 20\log(r) + 20\log\left(\frac{40\ \pi}{3}\right) \tag{4.28}$$

$$L_{FS}(dB) = 20\log(f) + 20\log(r) + 32.44$$

For the range r in ***km***,

$$L_{FS}(dB) = 20\ \log(f) + 20\ \log(r) + 92.44 \tag{4.29}$$

Table 4.4 lists some path losses for a range of satellite link frequencies and representative GSO and non-GSO orbit ranges. Values near to 200 dB for GSO and 150 dB for non-GSO are to be expected and must be accounted for in any link design.

Table 4.4 Representative free space path losses for satellite links

GSO Orbit

r (km)	f (GHz)	L_{FS} (dB)
35 900	6	199
	12	205
	20	209
	30	213
	44	216

NON-GSO Orbits

r (km)	f (GHz)	L_{FS} (dB)
100	2	138
	6	148
	12	154
	24	160
1000	2	158
	6	168
	12	174
	24	181

4.1.5 Basic Link Equation for Received Power

We now have all the elements necessary to define the basic link equation for determining the received power at the receiver antenna terminals for a satellite communications link. We refer again to the basic communications link (Figure 4.1, repeated here as Figure 4.6).

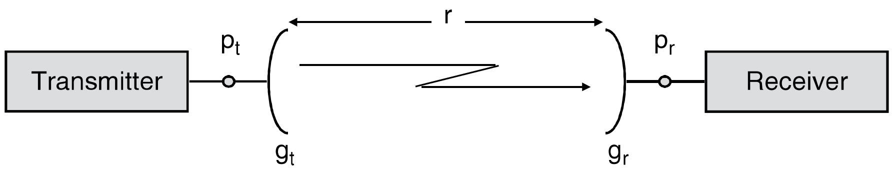


Figure 4.6 Basic communications link

The parameters of the link are defined as: p_t = transmitted power (watts); p_r = received power (watts); g_t = transmit antenna gain; g_r = receive antenna gain; and r = path distance (meters or km).

The receiver power at the receive antenna terminals, p_r, is given as

$$\begin{aligned} p_r &= p_t\, g_t \left(\frac{1}{l_{FS}}\right) g_r \\ &= \text{eirp}\left(\frac{1}{l_{FS}}\right) g_r \end{aligned} \tag{4.30}$$

Or, expressed in dB,

$$P_r(\text{dB}) = \text{EIRP} + G_r - L_{FS} \tag{4.31}$$

This result gives the basic link equation, sometimes referred to as the ***Link Power Budget Equation***, for a satellite communications link, and is the design equation from which satellite design and performance evaluations proceed.

4.1.5.1 Sample Calculation for Ku-Band Link

In this section we present a sample calculation for the received power for a representative satellite link operating in the Ku-band. Consider a satellite uplink with the parameters shown in Figure 4.7.

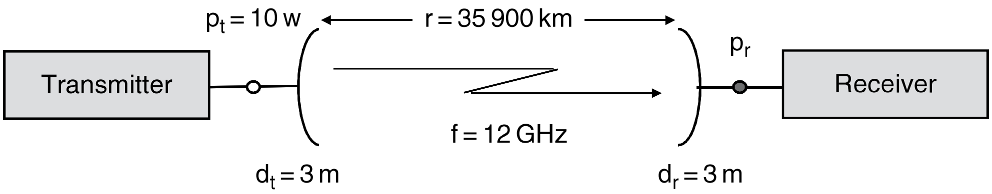


Figure 4.7 Ku-band link parameters

The transmit power is 10 watts, and both the transmit and receive parabolic antennas have a diameter of 3 m. The antenna efficiency is 55 % for both antennas. The satellite is in a GSO location, with a range of 35 900 km. The frequency of operation is 12 GHz. These are typical parameters for a moderate rate private network VSAT uplink terminal. Determine the received power, p_r, and the power flux density, $(pfd)_r$, for the link.

First the antenna gains are determined (Equation (4.19)):

$$G = 10\log(109.66\,f^2\,d^2\,\eta_A)$$

$$G_t = G_r = 10\log(109.66 \times (12)^2 \times (3)^2 \times 0.55) = 48.93\,\text{dBi}$$

The effective radiated power, in db, is found as (Equation (4.1.1))

$$\begin{aligned} EIRP &= P_t + G_t \\ &= 10\log(10) + 48.93 \\ &= 10 + 48.93 = 58.93\,\text{dBw} \end{aligned}$$

The free space path loss, in dB is (Equation (4.28))

$$\begin{aligned} L_{FS} &= 20\log(f) + 20\log(r) + 32.44 \\ &= 20\log(12) + 20\log(3.59 \times 10^7) + 32.44 \\ &= 21.58 + 151.08 + 32.44 = 205.1\,\text{dB} \end{aligned}$$

The received power, in db, is then found from the link power budget equation (Equation (4.31)):

$$\begin{aligned} P_r(\text{dB}) &= EIRP + G_r - L_{FS} \\ &= 58.93 + 48.93 - 205.1 \\ &= -97.24\,\text{dBw} \end{aligned}$$

The received power in watts can be found from the above result:

$$p_r = 10^{\frac{-97.24}{10}} = 1.89 \times 10^{-10}\,\text{watts}$$

The power flux density, in dB, is then determined from Equation (4.9):

$$
\begin{aligned}
(\mathrm{PFD})_r &= \mathrm{EIRP} - 20\log(r) - 10.99 \\
&= 58.93 - 20\log(3.59 \times 10^7) - 10.99 \\
&= 58.93 - 151.08 - 10.99 \\
&= -103.14\ \mathrm{dB(w/m^2)}
\end{aligned}
$$

Note that the received power is very, very low, and this is an important consideration in designing links for adequate performance when noise is introduced in the link, as we will see in later sections.

4.2 System Noise

Undesired power or signals (noise) can be introduced into the satellite link at all locations along the signal path, from the transmitter through final signal detection and demodulation. There are many sources of noise in the communications system. Each amplifier in the receiver system will produce noise power in the information bandwidth, and must be accounted for in a link performance calculation. Other sources include mixers, upconverters, downconverters, switches, combiners, and multiplexers. The system noise produced by these hardware elements is additive to the noise produced in the radiowave transmission path by atmospheric conditions.

Noise that is introduced into the communications system at the ***receiver front end*** is the most significant, however, because that is where the desired signal level is the lowest. The shaded portions of Figure 4.8 indicate the receiver front-end area in the satellite link to which we are referring.

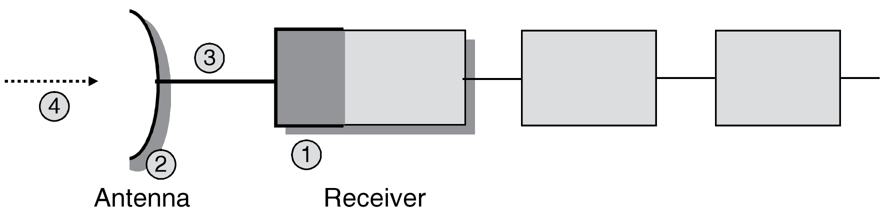


Figure 4.8 Receiver front end

The four sources of noise in the front-end area are: 1) the receiver front end; 2) the receiver antenna; 3) the connecting elements between them; and 4) noise entering from the free space path, often referred to as ***radio noise***[2]. The receiver antenna, receiver front end, and the connecting elements between them (consisting of both active and passive components) are the subsystems that must be designed to minimize the effects of noise on the performance of the satellite link. Both the ground terminal antenna/receiver (downlink) and the satellite

[2] The hardware component sources of noise (items 1, 2, and 3 above) are discussed further here; radio noise (item 4) will be fully addressed in Chapter 6.

antenna/receiver (uplink) are possible sources of noise degradation. The received carrier power at the receive antenna terminals, p_r, as we saw in the previous section, is very low (picowatts), therefore very little noise introduced into the system at that point is needed to degrade the performance.

The major contributor of noise at radio frequencies is ***thermal noise***, caused by the thermal motion of electrons in the devices of the receiver (both the active and passive devices). The noise introduced by each device in the system is quantified by the introduction of an ***equivalent noise temperature***. The equivalent (or excess) noise temperature, t_e, is defined as the temperature of a passive resistor producing a noise power per unit bandwidth that is equal to that produced by the device.

Typical equivalent noise temperatures for receiver system front-end elements found in satellite communications systems are:

- low noise receiver (C, Ku, ka band); 100 to 500 K;
- 1 dB line loss; 60 K;
- 3 dB line loss; 133 K;
- cooled parametric amplifier (paramp), used for example in the NASA Deep Space Network; 15 to 30 K.

The ***noise power***, n_N, is defined by the Nyquist formula as

$$n_N = k\, t_e\, b_N \text{ watts} \tag{4.32}$$

where:

k = Boltzmann's Constant
$= 1.39 \times 10^{-23}$ Joules/K
$= -198$ dBm/K/Hz
$= -228.6$ dBw/K/Hz
t_e = equivalent noise temperature of the noise source, in K
b_N = noise bandwidth, in Hz

The noise bandwidth is the RF bandwidth of the information-bearing signal – usually it is the filtered bandwidth of the final detector/demodulator of the link. The noise bandwidth must be considered for both analog and digital-based signal formats.

The Nyquist result shows that n_N is independent of the frequency, i.e., the noise power is uniformly distributed across the bandwidth. For higher frequencies, above the radio communications spectrum, ***quantum noise*** rather than thermal noise will dominate and the quantum formula for noise power must be used. The transition frequency between thermal and quantum noise occurs when

$$f \approx 21 t_e \tag{4.33}$$

where f is in GHz and t_e is in K. Thermal noise dominates below this frequency, quantum noise above.

Table 4.5 lists the transition frequency for the range of effective noise temperatures experienced in satellite radio communications systems. Except for very low noise systems, where

t_e is less than about 5 K, thermal noise will dominate radio communications systems and the satellite links we are concerned with here.

Table 4.5 Transition frequency, thermal versus quantum noise

t_e (K)	f (GHz)
100	2100
10	210
4.8	100

Since thermal noise is independent of the frequency of operation, it is often useful to express the noise power as a ***noise power density*** (or ***noise power spectral density***), n_o, of the form

$$n_o = \frac{n_N}{b_N} = \frac{k\ t_e\ b_N}{b_N}$$

or

$$n_o = k\ t_e\ (\text{watts/Hz}) \tag{4.34}$$

The noise power density is usually the parameter of choice in the evaluation of system noise power in satellite link communications systems.

4.2.1 Noise Figure

Another convenient way of quantifying the noise produced by an amplifier or other device in the communications signal path is the ***noise figure***, nf. The noise figure is defined by considering the ratio of the desired signal power to noise power ratio at the input of the device, to the signal power to noise power ratio at the output of the device (see Figure 4.9).

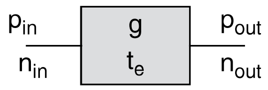


Figure 4.9 Noise figure of device

Consider a device with a gain, g, and an effective noise figure, t_e, as shown in Figure 4.9. The noise figure of the device is then, from the definition,

$$nf \equiv \frac{\dfrac{p_{in}}{n_{in}}}{\dfrac{p_{out}}{n_{out}}}$$

Or, in terms of the device parameters,

$$nf \equiv \frac{\dfrac{p_{in}}{n_{in}}}{\dfrac{p_{out}}{n_{out}}} = \frac{\dfrac{p_{in}}{k\ t_o\ b}}{\dfrac{g\ p_{in}}{g\ k\ (t_o + t_e) b}}$$

where t_o is the input reference temperature, usually set at 290 K, and b is the noise bandwidth. Then, simplifying terms

$$nf = \frac{t_o + t_e}{t_o} = \left(1 + \frac{t_e}{t_o}\right) \tag{4.35}$$

The noise figure expressed in dB is

$$NF = 10 \ \log\left(1 + \frac{t_e}{t_o}\right) \ dB \tag{4.36}$$

The term in brackets, $\left(1 + \frac{t_e}{t_o}\right)$, is sometimes referred to as the ***noise factor***, when expressed as a numerical value.

The noise out, n_{out}, of the device, in terms of the noise figure, is

$$\begin{aligned} n_{out} &= g\ k(t_o + t_e)b = g\ k\ t_o \left(1 + \frac{t_e}{t_o}\right) b \\ &= nf\ g\ k\ t_o\ b \\ &= nf\ g\ n_{in} \end{aligned}$$

Note also that

$$\begin{aligned} n_{out} &= g\ k\ t_o\ b + g\ k\ t_e\ b \\ &= g\ k\ t_o\ b + g\ k \left(\frac{t_e}{t_o}\right) t_o\ b \\ &= \underbrace{g\ k\ t_o\ b}_{\Uparrow\ \textbf{Input noise Contribution}} + \underbrace{(nf - 1) g\ k\ t_o\ b}_{\Uparrow\ \textbf{Device noise Contribution}} \end{aligned} \tag{4.37}$$

This result shows that the noise figure quantifies the noise introduced into the signal path by the device, which is directly added to the noise already present at the device input.

Finally, the effective noise temperature can be expressed in terms of the noise figure by inverting Equation (4.35):

$$t_e = t_o(nf - 1) \tag{4.38}$$

Or, with the noise figure expressed in dB,

$$t_e = t_o \left(10^{\frac{NF}{10}} - 1\right] \tag{4.39}$$

This result provides the equivalent noise temperature for a device with a noise figure of NF dB.

Table 4.6 lists noise figure and the equivalent effective noise temperature for the range of values expected in a satellite communications link.

A typical low noise amplifier at C-band would have noise figures in the 1 to 2 dB range, Ku-band 1.5 to 3 dB, and Ka band 3 to 5 dB. Noise figures of 10 to 20 dB are not unusual to find in a communications link, particularly in the high power portion of the circuit. It is usually essential, however, to keep the components in the receiver front-end area to noise figures in the low single digits to maintain viable link performance.

Table 4.6 Noise figure and effective noise temperature

NF(dB)	t_e (K)
1	75
4	438
6	865
10	2610
20	28 710

t_e (K)	NF(dB)
30	0.4
100	1.3
290	3
1000	6.5
10 000	15.5

4.2.2 Noise Temperature

In this section we develop procedures to determine the equivalent noise temperature for specific elements of interest in the communications circuit. Three types of devices will be discussed: active devices, passive devices, and the receiver antenna system. Finally, the process of combining all relevant noise temperatures to determine a system noise temperature will be developed.

4.2.2.1 Active Devices

Active devices in the communications system are amplifiers and other components that increase the signal level, i.e., they provide an output power that is greater than the input power ($g > 1,\ G > 0$ dB). Examples of other active devices in addition to the amplifier include upconverters, downconverters, mixers, active filters, modulators, demodulators, and some forms of active combiners and multiplexers.

Amplifiers and other active devices can be represented by an ***equivalent noise circuit*** to best determine the noise contributions to the link. Figure 4.10 shows the equivalent noise circuit for an active device with a gain g and noise figure NF (dB). Note that this equivalent circuit is only used for evaluation of the noise contribution of the device – it is not necessarily the equivalent circuit applicable to analysis of the information-bearing portion of the signal transmission through the device.

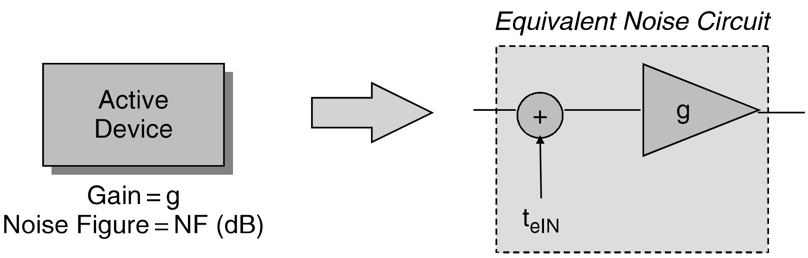


Figure 4.10 Equivalent noise circuit for an active device

The equivalent circuit consists of an ideal amplifier of gain g and an additive noise source t_{eIN} at the input to the ideal amplifier, through an ideal (noiseless) summer. We found in the previous section (Equation (4.38)) that the noise contribution of a device with gain g can be represented as t_0 (nf − 1), where nf is the noise figure, and t_0 is the input reference temperature. Therefore,

$$t_{eIN} = 290(nf - 1) \tag{4.40}$$

where the input reference temperature is set at 290 K.

Expressing the noise figure in terms of the equivalent noise temperature of the device, t_e, (Equation (4.35)), we see that the equivalent noise circuit additive noise source for the active device is, not surprisingly, equal to the device equivalent noise temperature:

$$t_{eIN} = 290\left(\left(1 + \frac{t_e}{290}\right) - 1\right) = t_e \tag{4.41}$$

The noise source, in terms of the NF the active device in (dB), is then

$$t_{eIN} = 290\left(10^{\frac{NF}{10}} - 1\right) \tag{4.42}$$

The equivalent noise circuit of Figure 4.10, along with the input noise contribution of Equations (4.41 or 4.42), can be used to represent each active device in the communications path, for the purpose of determining the noise contributions to the system.

4.2.2.2 Passive Devices

Waveguides, cable runs, diplexers, filters, and switches are examples of passive or absorptive devices that reduce the level of the power passing through the device (i.e., $g < 1$, $G < 0$ dB). A passive device is defined by the ***loss factor***, ℓ:

$$\ell = \frac{p_{in}}{p_{out}} \tag{4.43}$$

where p_{in} and p_{out} are the powers into and out of the device, respectively.

The loss of the device, in dB, is

$$A(dB) = 10\log(\ell) \tag{4.44}$$

Figure 4.11 shows the equivalent noise circuit for a passive device with a loss of A dB. Note that again this equivalent circuit is only used for evaluation of the noise contribution of the device – it is not necessarily the equivalent circuit applicable to analysis of the information-bearing portion of the signal transmission through the device.

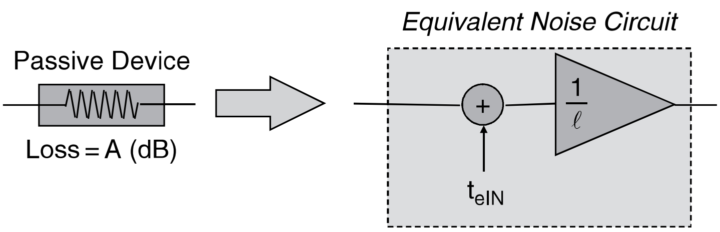


Figure 4.11 Equivalent noise circuit for a passive device

The equivalent circuit consists of an ideal amplifier of gain $\frac{1}{\ell}$ and an additive noise source t_{eIN} at the input to the ideal amplifier, through an ideal (noiseless) summer. The input noise contribution of the passive device will be

$$
\begin{aligned}
t_{eIN} &= 290(l - 1) \\
&= 290\left(10^{\frac{A(dB)}{10}} - 1\right)
\end{aligned}
\tag{4.45}
$$

The 'gain' of the ideal amplifier, in terms of the loss, is

$$
\frac{1}{\ell} = \frac{1}{10^{\frac{A(dB)}{10}}} = 10^{-\frac{A(dB)}{10}} \tag{4.46}
$$

The equivalent noise circuit of Figure 4.11, along with the input noise contribution given by Equation (4.45) and an ideal 'gain' given by Equation (4.46), can be used to represent each passive device with a loss of A(dB) in the communications path, for the purpose of determining the noise contribution to the system.

4.2.2.3 Receiver Antenna Noise

Noise can be introduced into the system at the receiver antenna in two possible ways: from the physical antenna structure itself, in the form of ***antenna losses***, and from the radio path, usually referred to as ***radio noise*** or ***sky noise*** (see Figure 4.12).

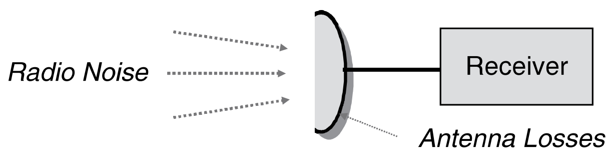


Figure 4.12 Sources of receiver antenna noise

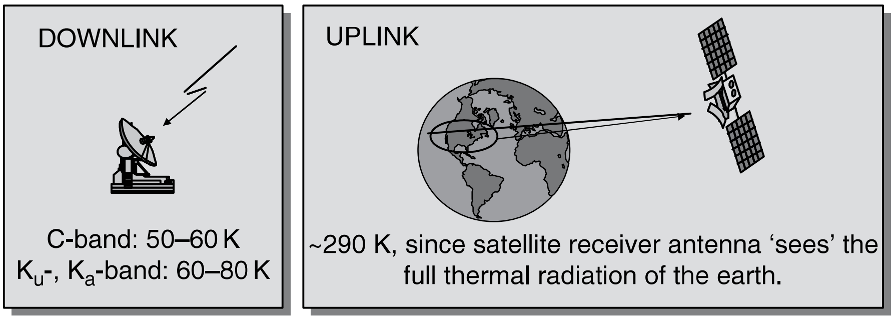
Antenna losses are absorptive losses produced by the physical structure (main reflector, sub-reflector, struts, etc.), which effectively reduce the power level of the radiowave. Antenna losses are usually specified by an equivalent noise temperature for the antenna. The equivalent antenna noise temperature is in the range of 10s of degrees K (0.5 to 1 dB loss). The antenna loss is usually included as part of the antenna aperture efficiency, η_A, and does not need to be included in link power budget calculations directly. Occasionally, however, for specialized antennas, the manufacturer may specify an antenna loss that may be elevation angle dependent, due to sidelobe losses or other physical conditions.

Radio noise can be introduced into the transmission path from both natural and human induced sources. This noise power will add to the system noise through an increase in the antenna temperature of the receiver. For very low noise receivers, radio noise can be the limiting factor in the design and performance of the communications system.

The primary natural components present in radio noise on a satellite link are:

- Galactic noise: ~2.4 K for frequencies above about 1 GHz.
- Atmospheric constituents: any constituent that absorbs the radiowave will emit energy in the form of noise. The primary atmospheric constituents impacting satellite communications links are oxygen, water vapor, clouds, and rain (most severe for frequencies above about 10 GHz).
- Extraterrestrial sources, including the moon, sun, and planets.

Figure 4.13 summarizes some representative values for the increase in antenna temperature due to atmospheric constituents in the path, for both the downlink and the uplink.



(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

Figure 4.13 Increase in antenna temperature due to atmospheric constituents: (a) no rain; (b) rain

Radio noise for both the uplink and downlink, including specific effects and the determination of radio noise power (including the origins of the values shown in Figure 4.13), is fully discussed in the Radio Noise section of Chapter 6.

Human sources of radio noise consist of interference noise in the same information bandwidth induced from:

- communications links, both satellite and terrestrial;
- machinery;
- other electronic devices that may be in the vicinity of the ground terminal.

Often interference noise will enter the system through the sidelobes or backlobes of the ground receiver antenna. It is often difficult to quantify interference noise directly, and for most applications measurements and simulations are used to develop estimates of interference noise.

4.2.3 System Noise Temperature

The noise contributions of each device in the communications transmission path, including sky noise, will combine to produce a total ***system noise temperature***, which can be used to evaluate the overall performance of the link. The noise contributions are referenced to a common reference point for combining; usually the receiver antenna terminals, because that is where the desired signal level is the lowest, and that is where the noise will have the most impact. The process of combining the noise temperatures of a set of cascaded elements is described here.

Consider a typical satellite receiver system with the components shown in Figure 4.14(a). The receiver front end consists of the following: an antenna with a noise temperature of t_A; a low noise amplifier (LNA) with a gain of g_{LA} and noise temperature of t_{LA}; a cable with a line loss of A(dB) connecting the LNA to a downconverter (mixer) with a gain of g_{DC} and noise temperature of t_{DC}; and finally an intermediate frequency (I.F.) amplifier with a gain of g_{IF} and t_{IF}. We represent each device by its equivalent noise circuit, either active or passive, as shown in Figure 4.14(b). Note that in this example, all devices are active, except for the cable line loss.

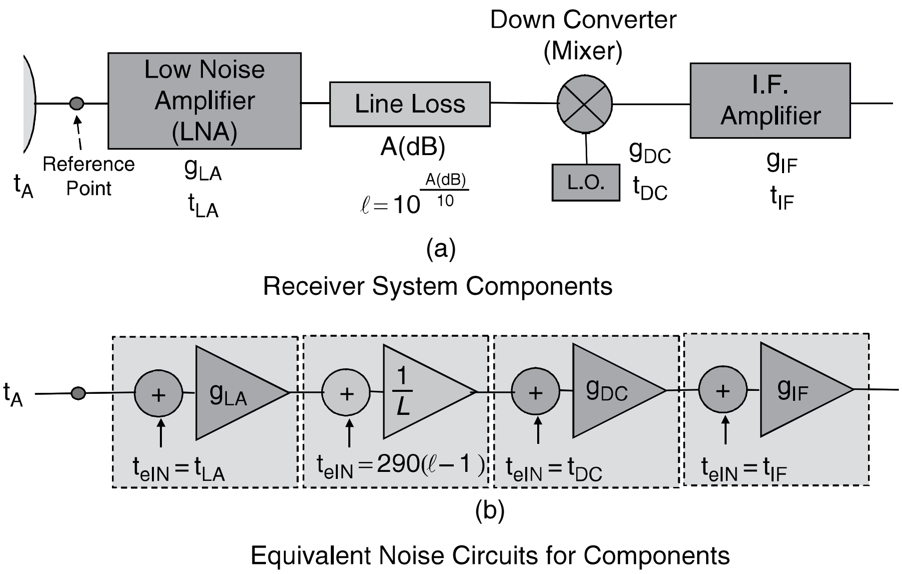


Figure 4.14 Satellite receiver system and system noise temperature

All noise temperature contributions will be summed at the reference point, indicated by the dot in Figure 4.14. We begin with the left most component, then move to the right, adding the noise temperature contribution REFERRED TO THE REFERENCE POINT, keeping track of any amplifiers in the path. The sum of the noise temperature contributions as referred to the reference point will be the system noise temperature, t_S.

The first component, the antenna, is at the reference point so it adds directly. The second component (LNA) noise contribution, t_{LA}, is also at the reference point, so it will also add directly.

The line loss noise contribution $290(\ell - 1)$ referred back to the reference point, passes through the LNA amplifier, in the reverse direction. Therefore the line loss noise contribution AT THE REFERENCE POINT will be

$$\frac{290(\ell - 1)}{g_{LA}}$$

which accounts for the gain acting on the noise power; i.e., a power of $\frac{290(\ell-1)}{g_{LA}}$ at the input to the LNA is equivalent to a power of $290(\ell - 1)$ at the output of the device.

Continuing with the rest of the devices, proceeding in a similar manner to account for all gains in the process, we get the total system noise, t_S, at the reference point

$$t_S = t_A + t_{LA} + \frac{290(\ell - 1)}{g_{LA}} + \frac{t_{DC}}{\left(\frac{1}{\ell}\right) g_{LA}} + \frac{t_{IF}}{g_{DC}\left(\frac{1}{\ell}\right) g_{LA}} \tag{4.47}$$

The system noise figure can be obtained from t_S,

$$NF_S = 10 \log\left(1 + \frac{t_S}{290}\right) \tag{4.48}$$

The system noise temperature t_S represents the noise present at the antenna terminals from all the front-end devices given in Figure 4.14. Devices further down the communications system will also contribute noise to the system, but as we shall see in the next section, they will be negligible compared to the contributions of the first few devices in the system.

4.2.3.1 Sample Calculation for System Noise Temperature

The impact of each of the components in the receiver system to the total system noise system will be observed by assuming typical values for each. Figure 4.15 presents the satellite receiver noise system introduced in the previous section with specific parameters given for each device.

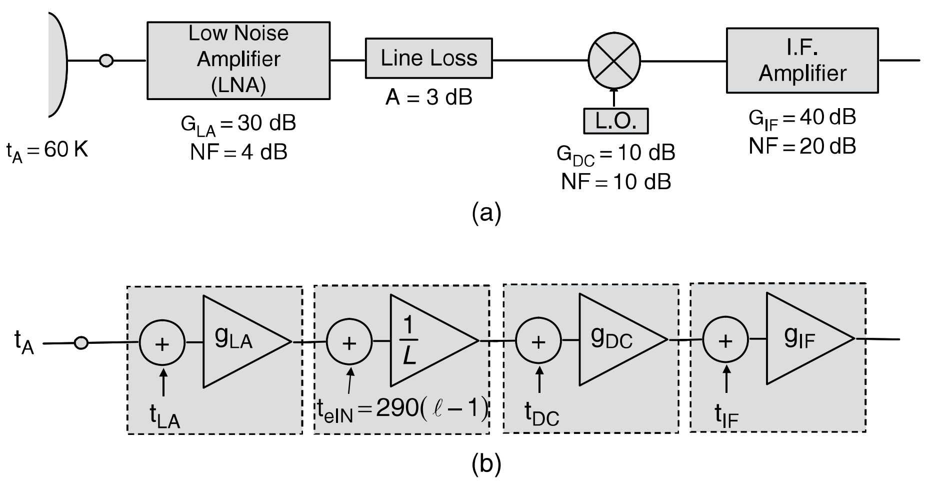


Figure 4.15 Sample calculation parameters for system noise temperature

The low noise amplifier (LNA) has a gain of 30 dB, and a noise figure of 4 dB. The LNA is connected to the downconverter through a 3 dB line loss cable. The downconverter has a gain of 10 db and a noise figure of 10 dB. Finally the signal passes to an I.F. amplifier with a gain of 40 dB, and a noise figure of 20 dB. These are typical values found in a good quality satellite receiver operating at C, Ku, or Ka band. We also assume an antenna temperature of 60 K, which is a typical value for a satellite downlink operating in dry clear weather. The equivalent noise circuit for the receiver is also shown in Figure 4.15.

The equivalent noise temperatures for each device are found as (Equation (4.42))

$$t_{eIN} = 290\left(10^{\frac{NF}{10}} - 1\right) \qquad t_{DC} = 290\left(10^{\frac{10}{10}} - 1\right) = 2610\,\text{K}$$

$$t_{LA} = 290\left(10^{\frac{4}{10}} - 1\right) = 438\,\text{K} \qquad t_{IF} = 290\left(10^{\frac{20}{10}} - 1\right) = 28\,710\,\text{K}$$

The equivalent noise temperature for the line loss is (Equation (4.45))

$$\begin{aligned} t_{eIN} &= 290(\ell - 1) \\ &= 290\left(10^{\frac{3}{10}} - 1\right) = 289\,\text{K} \end{aligned}$$

The numerical values for each of the gains is

$$g_{LA} = 10^{\frac{30}{10}} = 1000 \qquad g_{DC} = 10^{\frac{10}{10}} = 10$$

$$\frac{1}{\ell} = \frac{1}{10^{\frac{3}{10}}} = \frac{1}{2} \qquad g_{IF} = 10^{\frac{40}{10}} = 10\,000$$

The total system noise temperature is then found from Equation (4.47):

$$\begin{aligned} t_S &= t_A + t_{LA} + \frac{290(\ell - 1)}{g_{LA}} + \frac{t_{DC}}{\left(\frac{1}{\ell} g_{LA}\right)} + \frac{t_{IF}}{g_{DC}\left(\frac{1}{\ell}\right) g_{LA}} \\ &= 60 + 438 + \frac{289}{1000} + \frac{2610}{\left(\frac{1}{2}\right)1000} + \frac{28\,710}{10\left(\frac{1}{2}\right)1000} \\ &\qquad \text{Ant.} \quad \text{LNA} \quad \text{Line} \quad \text{D.C.} \quad \text{IFAmp.} \\ &\underbrace{= 60 + 438}_{\substack{\text{major} \\ \text{contributors}}} + 0.29 + 5.22 + 5.74 = 509.3\,\text{K} \end{aligned}$$

The results confirm that the major contributors to the system noise temperature are the first two devices, comprising the 'front end 'area of the satellite receiver. The remaining devices, even though they have very high equivalent noise temperatures, contribute very little to the system noise temperature because of the amplifier gains that reduce the values considerably. The inclusion of additional devices beyond the I.F. amplifier would show similar results, because the high I.F. amplifier gain would reduce the noise contributions of the rest of the components just as was the case for the line loss, down converter, and I.F. amplifier.

The system noise figure, NF_S, can be determined from t_s:

$$\begin{aligned} NF_S &= 10\log\left(1 + \frac{t_S}{290}\right) \\ &= 10\log\left(1 + \frac{509.3}{290}\right) \\ &= 4.40\,\text{dB} \end{aligned}$$

Note that the contribution of all the other components only added 0.4 dB to the noise figure of the LNA.

Finally the noise power density can be determined:

$$N_0 = K + T_s$$
$$= -228.6 + 10\log(509.3) = -201.5\,\text{dBw(Hz)}$$
$$n_0 = 10^{\frac{-201.5}{10}} = 7.03 \times 10^{-21}\,\text{watts}$$

Comparing this result to the received power determined in the sample calculation in Section 4.1.3.1, of $p_r = 1.89 \times 10^{-10}$ watts, we see that the noise power is significantly lower than the desired signal power, which is the desired result for a satellite receiver system with acceptable performance margin.

4.2.4 Figure of Merit

The quality or efficiency of the receiver portions of a satellite communications link is often specified by a ***figure of merit***, (usually specified as $\left(\frac{G}{T}\right)$ or ‘G over T’), defined as the ratio of receiver antenna gain to the receiver system noise temperature:

$$\begin{aligned} M = \left(\frac{G}{T}\right) &= G_r - T_s \\ &= G_r - 10\log_{10}(t_s) \end{aligned} \tag{4.49}$$

where G_r is the receiver antenna gain, in dBi, and t_s is the receiver system noise temperature, in K.

The $\left(\frac{G}{T}\right)$ is a single parameter measure of the performance of the receiver system, and is analogous to eirp as the single parameter measure of performance for the transmitter portion of the link.

$\left(\frac{G}{T}\right)$ values cover a wide range in operational satellite systems, including negative dB values. For example, consider a representative 12 GHz link with a 1 m receiver antenna, 3 dB receiver noise figure, and an antenna noise temperature of 30 K (assume no line loss and an antenna efficiency of 55 %). The gain and system noise temperatures are found as

$$G_r = 10\log(109.66 \times (12)^2 \times (1)^2 \times 0.55) = 39.4\,\text{dBi}$$
$$t_s = 30 + 290\left(10^{\frac{3}{10}} - 1\right) = 30 + 290 = 320\,\text{K}$$

The figure of merit is then determined from Equation (4.49):

$$M = G_r - T_s$$
$$= 39.4 - 10\log_{10}(320) = 14.4\,\text{db/K}$$

The figure of merit can vary with elevation angle as t_s varies. Operational satellite links can have $\left(\frac{G}{T}\right)$ values of 20 dB/K and higher and as low as -3 dB/K. The lower values are typically found in satellite receivers (uplinks) with broadbeam antennas where the gain may be lower than the system noise temperature expressed in dB.

4.3 Link Performance Parameters

The previous sections in this chapter have dealt with a description of a) parameters of interest describing the desired signal power levels on the satellite communications RF link (Section 4.1), and b) parameters of interest describing the noise power levels on the link (Section 4.2). In this section we bring together these concepts to define overall RF link performance in the presence of system noise. These results will be essential for defining satellite system design and link performance for a wide range of applications and implementations.

4.3.1 Carrier-to-Noise Ratio

The ratio of average RF carrier power, c, to the noise power, n, in the same bandwidth, is defined as the ***carrier-to-noise ratio***, $\left(\frac{c}{n}\right)$. The $\left(\frac{c}{n}\right)$ is the primary parameter of interest for defining the overall system performance in a communications system. It can be defined at any point in the link, such as at the receiver antenna terminals, or at the input to the demodulator.

The $\left(\frac{c}{n}\right)$ can be expressed in terms of the eirp, G/T, and other link parameters developed earlier. Consider the link with a transmit power p_t, transmit antenna gain g_t, and receive antenna gain g_r, as shown in Figure 4.16.

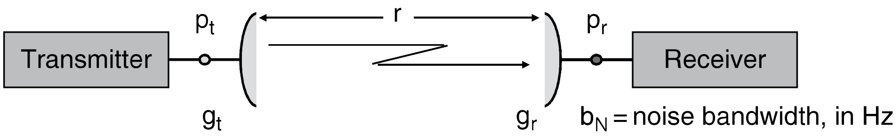


Figure 4.16 Satellite link parameters

For completeness we define the losses on the link by two components, the free space path loss, (Equation (4.26))

$$\ell_{FS} = \left(\frac{4\pi r}{\lambda}\right)^2 \tag{4.50}$$

and all other losses, ℓ_o, defined as,

$$\ell_o = \Sigma(\text{Other Losses}) \tag{4.51}$$

where the other losses could be from the free space path itself, such as rain attenuation, atmospheric attenuation, etc., or from hardware elements such as antenna feeds, line losses, etc.[3]

The power at the receiver antenna terminals, p_r, is found as

$$p_r = p_t g_t g_r \left(\frac{1}{\ell_{FS}\ell_o}\right) \tag{4.52}$$

The noise power at the receiver antenna terminals is (Equation (4.32))

$$n_r = k\ t_s\ b_N \tag{4.53}$$

The carrier-to-noise ratio at the receiver terminals is then

$$\left(\frac{c}{n}\right) = \frac{p_r}{n_r} = \frac{p_t\ g_t\ g_r \left[\frac{1}{\ell_{FS}\ \ell_o}\right]}{k\ t_s\ b_N}$$

Or

$$\frac{c}{n} = \frac{(\text{eirp})}{k\, b_N}\left(\frac{g_r}{t_s}\right)\left(\frac{1}{\ell_{FS}\ell_o}\right) \tag{4.54}$$

Expressed in dB,

$$\left(\frac{C}{N}\right) = \text{EIRP} + \left(\frac{G}{T}\right) - (L_{FS} + \Sigma\ \text{Other Losses}) - 228.6 - B_N \tag{4.55}$$

where the EIRP is in dBw, the bandwidth B_N is in dBHz, and $k = -228.6\,\text{dBw/K/Hz}$.

The $\left(\frac{C}{N}\right)$ is the single most important parameter that defines the performance of a satellite communications link. The larger the $\left(\frac{C}{N}\right)$, the better the link will perform. Typical communications links require minimum $\left(\frac{C}{N}\right)$ values of 6 to 10 dB for acceptable performance. Some modern communications systems that employ significant coding can operate at much lower values. Spread spectrum systems can operate with negative $\left(\frac{C}{N}\right)$ values and still achieve acceptable performance.

The performance of the link will be degraded in two ways: if the carrier power, c, is reduced, and/or if the noise power, n_B, increases. Both factors must be taken into account when evaluating link performance and system design.

4.3.2 Carrier-to-Noise Density

A related parameter to the carrier-to-noise ratio often used in link calculations is the ***carrier-to-noise density***, or carrier-to-noise density ratio, $\left(\frac{c}{n_o}\right)$. The carrier-to-noise density is defined in terms of noise power density, n_o, defined by Equation (4.34):

$$n_o \equiv \frac{n_N}{b_N} = \frac{k\, t_s\, b_N}{b_N} = k\, t_s$$

The two ratios are related through the noise bandwidth

$$\left(\frac{c}{n}\right) = \left(\frac{c}{n_o}\right)\frac{1}{b_N} \tag{4.56}$$

or

$$\left(\frac{c}{n_o}\right) = \left(\frac{c}{n}\right) b_N \tag{4.57}$$

In dB,

$$\begin{aligned}\left(\frac{C}{N}\right) &= \left(\frac{C}{N_o}\right) - B_N\ (\text{dB})\\ \left(\frac{C}{N_o}\right) &= \left(\frac{C}{N}\right) + B_N\ (\text{dBHz})\end{aligned} \tag{4.58}$$

The carrier-to-noise density behaves similarly to the carrier-to-noise ratio in terms of system performance. The larger the value, the better the performance. The $\left(\frac{C}{N_o}\right)$ tends to be much larger in dB value than the $\left(\frac{C}{N}\right)$ because of the large values for B_N that occur for most communications links.

4.3.3 Energy-Per-Bit to Noise Density

For digital communications systems, the bit energy, e_b, is more useful than carrier power in describing the performance of the link. The bit energy is related to the carrier power from

$$e_b = c\, T_b \tag{4.59}$$

where c is the carrier power and T_b is the bit duration in s.

The ***energy-per-bit to noise density ratio***, $\left(\frac{e_b}{n_o}\right)$, is the most frequently used parameter to describe digital communications link performance. $\left(\frac{e_b}{n_o}\right)$ is related to $\left(\frac{c}{n_o}\right)$ by

$$\left(\frac{e_b}{n_0}\right) = T_b \left(\frac{c}{n_0}\right) = \frac{1}{R_b}\left(\frac{c}{n_0}\right) \tag{4.60}$$

where R_b is the bit rate, in bits per second (bps).

This relation allows for a comparison of link performance of both analog and digital modulation techniques, and various transmission rates, for the same link system parameters.

Note also that

$$\left(\frac{e_b}{n_0}\right) = \frac{1}{R_b}\left(\frac{c}{n_0}\right) = \frac{1}{R_b}\left\{\left(\frac{c}{n}\right) b_N\right\}$$

or

$$\left(\frac{e_b}{n_0}\right) = \frac{b_N}{R_b}\left(\frac{c}{n}\right) \tag{4.61}$$

The $\left(\frac{e_b}{n_o}\right)$ will be numerically equal to the $\left(\frac{c}{n}\right)$ when the bit rate (bps) is equal to the noise bandwidth (Hz).

The $\left(\frac{e_b}{n_o}\right)$ also behaves similarly to the $\left(\frac{c}{n}\right)$ and the $\left(\frac{c}{n_o}\right)$ in terms of system performance; the larger the value, the better the performance. All three parameters can usually be considered interchangeably when evaluating satellite links, with respect to their impact on system performance.

References

1 L.J. Ippolito, Jr., *Radiowave Propagation in Satellite Communications*, Van Nostrand Reinhold Company, New York, 1986.

Problems

1. Calculate the following antenna parameters:
   (a) the gain in dBi of a 3 m parabolic reflector antenna at frequencies of 6 GHz and 14 GHz;
   (b) the gain in dBi and the effective area of a 30 m parabolic antenna at 4 GHz;
   (c) the effective area of an antenna with 46 dBi gain at 12 GHz. An efficiency factor of 0.55 can be assumed.
2. Determine the range and free space path loss for the following satellite links:
   (a) A GSO link operating at 12 GHz to a ground station with a 30° elevation angle.

(b) The service and feeder links between an Iridium satellite located at 780 km altitude and a ground location with a 70° elevation angle. The service link frequency is 1600 MHz and the feeder link frequencies are 29.2 GHz uplink and 19.5 GHz downlink.

3. A VSAT receiver consists of a 0.66 m diameter antenna, connected to a 4 dB noise figure low noise receiver (LNR) by a cable with a line loss of 1.5 dB. The LNR is connected directly to a downconverter with a 10 dB gain and 2800° K noise temperature. The I.F. amplifier following the downconverter has a noise figure of 20 dB. The LNR has a gain of 35 dB. The antenna temperature for the receiver was measured as 65° K.

(a) Calculate the system noise temperature and system noise figure at the receiver antenna terminals.

(b) The receiver operates at a frequency of 12.5 GHz. What is the G/T for the receiver, assuming a 55 % antenna efficiency?

4. The downlink transmission rate for a QPSK modulated SCPC satellite link is 60 Mbps. The E_b/N_o at the ground station receiver is 9.5 dB.

(a) Calculate the C/N_o for the link.

(b) Assuming that the uplink noise contribution to the downlink is 1.5 dB, determine the resulting BER for the link.

5. A satellite link employing BPSK modulation is required to operate with a bit error rate of no more that 1×10^{-5}. The implementation margin for the BPSK system is specified as 2 dB. Determine the E_b/N_o necessary to maintain the required performance.