Impact of G/T, SFD and EIRP on System Design

(or All you wanted to know about Link Budgets that is not in text books)

by: Hector Velasco

In this paper we will not discuss in detail link formulas which are extensively described in the telecommunications literature.

G/T

The G/T of the satellite is the "figure of merit" and gives you an idea of the ratio between the input gain and the noise that is added to the signal. The bigger the G/T ratio the more gain and the less noise is added to the signal. If the G/T is large, the resulting C/N in the uplink that can be achieved will be higher with the same uplink power.

SFD and FCA

The SFD is the Saturated Flux Density and is a measure for the sensitivity of the input of the transponder. A lower SFD (more negative) value makes the input of the transponder more sensitive and requires less uplink power from the uplink station.

Satellite transponders have a variable attenuator commonly called Flux Control Attenuator or padding These changes are made via TT&C commands from ground. The attenuation is set in steps and used to set the incident flux density necessary to saturate the transponder. When the padding or attenuation is reduced, the satellite operator is configuring the transponder to be more sensitive or increasing its gain. Increasing the sensitivity in the transponder allows the introduction of more noise into the system, due to the higher sensitivity.

However when increasing the gain of the transponder (by lowering the SFD), the noise added to the signal increases so the resulting C/N in the uplink will be lower. So a trade off needs to be made between required uplink power (size and cost of the BUC) and the resulting performance of the link (needed satellite bandwidth and related cost).

For big earth stations like for example DTH or IP trunking uplinks, the SFD is typically increased (made less negative) or less sensitive and uplink power is increased. This comes at a certain cost for the earth station HPA but has a positive impact on uplink C/N which increases the overall efficiency of the whole network. This reflects in the need of smaller size antennas on the downlink which may have a significant and positive impact on the overall project cost.

On the other hand in a network of two-way VSATs, the SFD can be particularly important because it determines the requirement for VSAT transmit power which determines the type, and therefore the cost, of the required solid state power amplifier on the VSAT antenna, therefore in this case you may want to decrease (more negative, more sensitive) the SFD, so less power is needed.

	FCA (attenuation)	
	More attenuation	Less attenuation
SFD	Increase (less sensitive)	Lower (more sensitive)
Transponder Gain	Decrease	Increase
UL power	More UL power req	Less UL power req
Rx terminal	larger	smaller
U/L C/N	Higher	Lower

Table shows trades when modifying FCA settings.

The saturation flux density is a measure of the power density required at the input of the satellite (right before the receiving antenna) in order to deliver the maximum EIRP from the amplifier in the output, considering the backoffs set by the satellite operator.

It can be specified independent of the position where you are in the coverage area, as it is transponder specific, in some cases it is given as a range where it is made to depend on the G/T of the satellite in the direction of your station. For example: -127.5 to -137.5 dB/K at the -3 dB/K G/T contour.

Some other operators actually provide contours of the SFD. SFD is used as a reference point to determine the input backoff, as the difference between the saturation density and the operational flux density (that achieved by the carrier you are activating and which depends on the EIRP of the earth station) is the input backoff.

If you know the input backoff, there are two ways to determine the output backoff : either the operator tells you the operational difference between input and output backoff (delta) so that OBO = IBO - DELTA, or they give you a functional form to approximate OBO based on IBO, such as OBO = 0.9IBO + 4 or something like that.

Once you know OBO, then the EIRP per carrier of the downlink is EIRP at saturation - OBO.

$$EIRP_{DL} = EIRP_{sat} - OBO$$

You need the EIRP of the earth station to determine the operational flux density and therefore the determine IBO and then OBO and then downlink satellite EIRP.

Now, C/No of the uplink is calculated based on the EIRP of the earth station.

To estimate C/No you can use the SFD as a reference point as follows (from Maral's VSAT networks book)

Reference C/No, uplink at saturation

$C/No\ u,sat = SFD - G_{1m2} - Losses + G/T$ *of the satellite in your direction + 228.6 (boltzmann constant)*

The gain of a reference 1m^2 antenna is the tool used to convert from a flux density to effective power captured per m2,

$$G_{1m}{}^2 = 10Log10(4\pi) + 20LOG(F/c)$$

continuing:
at this moment we have the C/No that would be achieved if I had saturated the satellite, but this is not what we want. We want the C/N produced by your carrier, at an EIRP much less in the typical case than the required to saturate.

OFD is the operational flux density of your carrier, is estimated based on the EIRP as follows

$$OFD = EIRP + G_{1m}{}^2 - Losses$$

since you now know OFD, you can calculate the input backoff:

$$IBO = ABS\ (\ SFD - OFD\ )$$

and then

$$C/No,UL = C/No,\ UL,\ saturation - IBO$$

note that I force IBO to be positive. it can be negative or positive depending on how the parameters are defined and specified by the operator. normally you will have an SFD less negative than the OFD so it will be negative. but just remember the concept, IBO is the difference in power from your point and the saturation point. since it represents how much less power you have, i subtract it from the saturation C/N to take me to my operating point. Of course there are other ways to calculate C/No uplink, without considering SFD, just change SFD from the first equation to OFD and that would be it.

In a simple approach,

$$C/N_{o,u} = EIRP + G/T - Losses - Boltzmann's\ K$$

But in any case you need the SFD and the OFD to estimate IBO and then link the IBO to the OBO to find the downlink EIRP. Without that, you wouldn't be able to have the uplink and the downlink tied up, unless you knew the OBO already, so you can calculate the downlink based on the saturation EIRP from the satellite, and subtract the OBO.

EIRP

On the downlink the EIRP of the satellite determines how much power can be sent back down to the receiving stations. The bigger this EIRP, the smaller the antennas can be in order to achieve the same link. This is important in for example DTH networks where the need for reasonable size receive antennas (due to the large number of subscribers) is the dominant factor.

As ever, a link budget is not only a technical exercise but a cost exercise too. The cost and application will determine the used G/T, SFD and EIRP.

In this case, as you assign services to the transponder, you may find out that you have power available but run out of bandwidth (**bandwidth limited case**) or bandwidth available but run out of power (**power limited case**).

C/T

C/T is converted into carrier-to-noise ratio (C/N) by taking into account the bandwidth of the RF signal that the link supports. The following formula is expressed in dB:

$$C/N = C/T - 10\log(k) - 10\log(B)$$

Another parameter is C/T (C-to-T), which is the uplink saturated carrier to noise temperature ratio, and is a fundamental design parameter in a satellite transponder. It is related to SFD and G/T by the following equation :

$$C/T = SFD + G/T + 10\log(\lambda^2 /4\pi)$$

Where :

C/T = Saturated Carrier-to-noise temperature ratio (dBW/K)

SFD = Saturated Flux Density (dBW/m^2)

G/T = Receive Gain-to-noise-temperature ratio in (dB/K)

$\lambda^2 /4\pi$ = Isotropic area conversion factor (m^2)

Example 1 :

I got a task to design the ground station antenna. I need at least to figure out G/T of the station. I looked at different link budget analysis, but could not find out how to calclate G/T of the antenna, or at least how to assume this value. Usually G/T is given, but I have the inverse task - to find G/T when everything else (well, almost everything) is provided. Satellite and channel parameters are given below:

Orbital altitude: 36 000 km
Inclination, Position: 0º, 30 º W
DL frequency: 20 GHz
UL frequency: 30 GHz
Polarization: UL: RHCP , DL: LHCP
Bandwidth, 3 channels: 143 MHz
Modulation: QPSK
Minimum satellite EIRP: 54 dBW

Minimum SFD from satellite at ground stations: -100 dBW/m2
Maximum SFD from satellite at ground stations: -80 dBW/m2
Minimum satellite G/T: 6.7 dB/K

In general, the minimum value of earth station G/T is the difference between the received carrier power density and the required carrier/thermal noise ratio. It is a very simple computation but you need to know the satellite EIRP per carrier as well as the occupied bandwidth and the required receive carrier/noise ratio based upon the bit error rate desired.

A bandwidth of 143 Mhz for the 3 carrier and a satellite EIRP of 54 dBw looks about right. We can demonstrate a typical calculation of a full transponder (54 Mhz BW) carrier utilizing the full transponder EIRP of 54 dBw. Maybe that will give you an idea of how to do a calculation for any carrier you want.

The Ka-band path loss is easily calculated to be 210 dB at 20 Ghz. Atmospheric losses can be very considerable at Ka and need to be factored in for worst case along with the implementation margin for link reliability, but we leave that for last!

So, 54 dBw – 210 dB path loss = -156 dBw received carrier density at earth station.
I will assume a standard modem C/N of 9.7 dB for QPSK. Convert that to C/N in dB-Hz by adding 10*Log(BW): 9.7 + 77.3 = 87 dB-Hz C/N

Now the carrier/temp is computed by adding Boltzmann’s constant:

87 + (-228.6) = -141.6 dBw/k

So the minimum required earth station G/T is: -141.6 – (-156) = 14.4 dB/k
This is a bare bones minimum which does not consider atmospheric losses, link implementation margin and intermod, among other things. It might be OK for a backyard VSAT terminal but for a reliable commercial operation you want to double that number.

Just want to clarify, when I said to double that number, I meant to increase it by 3 dB, from 14.4 to 17.4. The system noise calculations look to be in the ballpark at around 1100 K worst case, or 30 dB. If you use G/T of 14.4 dB/K that means you need 45 dBi of antenna gain which can be done with a one meter dish at Ka. To implement with a G/T of 17.4 dB/K you will need to go up to about 1.5 m dish. Not much difference in price there but you will probably want the extra margin.

With Ka band waveguide, there is always the possibility of transmit harmonics getting into the receive path, similar to Ku only worse. So (assuming you will be transmitting) you probably want transmit reject filters in the receive waveguide at front end of LNA which reduces the G/T somewhat.

As you assign services to the transponder, you may find out that you have power available but run out of bandwidth (bandwidth limited case) or bandwidth available but run out of power (power limited case).

Example 2:

The earth stations in the analysis are defined as follows:

- Uplink earth station.a typical BSS broadcast center, similar in concept to that of DIRECTV, discussed in Chapter 1. Each uplinked carrier can support a quantity of digitally compressed TV channels containing full-time video and audio programming. The modulation format in DVB-S (the satellite mode of DVB) is QPSK using concatenated coding (i.e., Reed Solomon outer code followed by a convolutional inner code). A klystron high-power amplifier (HPA) operating at 18 GHz provides RF uplink power to a 13-m transmitting antenna. Tracking and uplink power control (UPC) maintain the received power at the satellite during relative motion of the satellite and during heavy rain along this path, respectively.

- Downlink antenna --a DTH home receiving system with a 45-cm antenna, a true commercial user terminal with many features to simplify installation and use by the subscriber. Within the set-top box are the channel selection, carrier demodulation, error correction, demultiplexing, decryption, MPEG-2 decompression, and conditional access elements needed to reproduce the original programming material.

Basic link budgets for the downlink, uplink, and combined overall link are provided in Tables 3.1, 3.2, and 3.3, respectively. We have included only the top-level performance parameters of the transmit earth station, satellite repeater, and receiving user terminal. These factors provide the basic performance of the end-to-end system; that is, if the three main elements of the system function as assumed, then the service will work accordingly.

Tables 3.1 and 3.2 present the stable unfaded condition, which is normal for a GEO link with no rain on the uplink or downlink, for a satellite that is stationkept to remain within the beamwidth of the earth station and user terminal. The links operate in the Region 2 allocation for BSS: downlink between 12.2 and 12.7 GHz and the corresponding uplink between 17.7 and 18.2 GHz. The second half of Table 3.3 accounts for the amount of rain attenuation on the downlink, which would cause a threshold condition, i.e., one in which reception would be just barely acceptable. Rain on the uplink can be countered by uplink power control (this is discussed further in Chapter 4 of the Earth Satation Handbook by Bruce Elbert).

For simplicity, only one channel of communication is considered, and so we have ignored the following effects.

- Adjacent channel interference, produced by other carriers on different
- frequencies received in the same polarization;
- Cross-polarized signals transmitted to and by the same satellite on

- the same (or adjacent) frequency channels;
- Adjacent satellite interference;
- Distortion produced by group delay filters in the earth station
- and satellite repeater;
- Nonlinear distortion produced by amplifiers, namely the earth station HPA and the satellite TWTA or SSPA, as appropriate.

The downlink (Table 3.1) is straightforward, starting with the satellite repeater HPA output power of 112 watts (produced by a TWTA), and applied to the antenna after passing through output losses of 1.5 dB. The spacecraft antenna gain of 33 dBi corresponds to an area coverage footprint of a relatively large country. The resulting EIRP of 52 dBW is typical of BSS satellites serving nontropical regions, as suggested by the footprint in Figure 3.3.

Free space loss at about 205 dB is the largest single entry; however, it is fixed for the specific combination of earth station and satellite position. The receiving user terminal consists of a nominal 45-cm offset-fed reflector and circularly polarized feed and LNB combination. With about 0.2 dB of loss in the receive feed and a system noise temperature of 150K, the combination produces a receive G/T of 12.0 dB/K. The output of the LNB is a value of C/T of -141.5 dBW/K, obtained with the following simple formula:

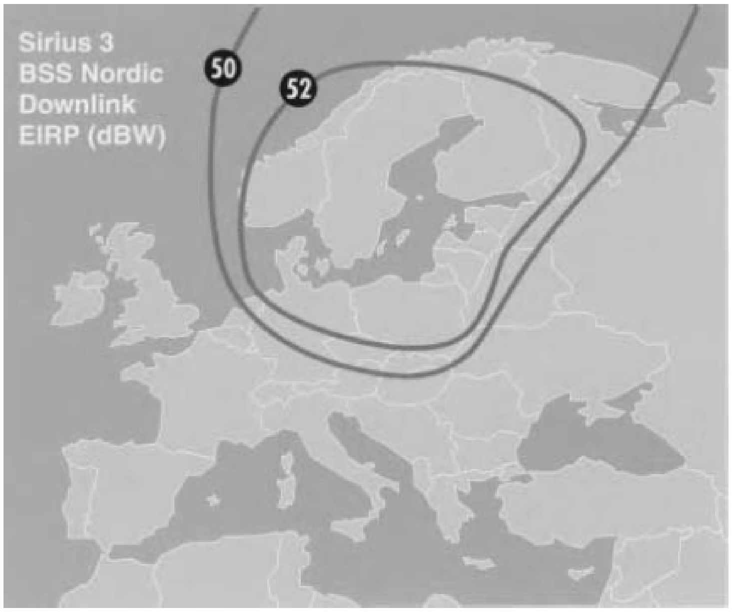
$$C/T = EIRP - A + G/T$$

where A is the sum of the path losses (assumed to be free space loss in this example). The corresponding value of C/N ratio is 12.3 dB as measured in the assumed 30 MHz of bandwidth.

Table 3.1

Link Budget Example for the Downlink at 12.2 GHz (Ku-band BSS)

Link parameter	**Value**	**Units**
Transmit power (112 watts)	20.5	dBW
Transmit waveguide losses	1.5	dB
Transmit antenna gain (footprint)	33.0	dBi
Satellite EIRP (toward earth station)	52.0	dBW
Free space loss	205.5	dB
Receive antenna gain (0.45 m)	34.0	dBi
Receive waveguide loss	0.2	dB
Receive carrier power	–118.7	dBW
System noise temperature (150 K)	21.8	dBK
Earth station G/T	12.0	dB/K
Downlink C/T	–141.5	dBW/K
Boltzmann's constant	–228.6	dBW/Hz/K
Bandwidth (30 MHz)	74.8	dB Hz
Noise power	–130.8	dBW
Carrier-to-noise ratio	12.3	dB



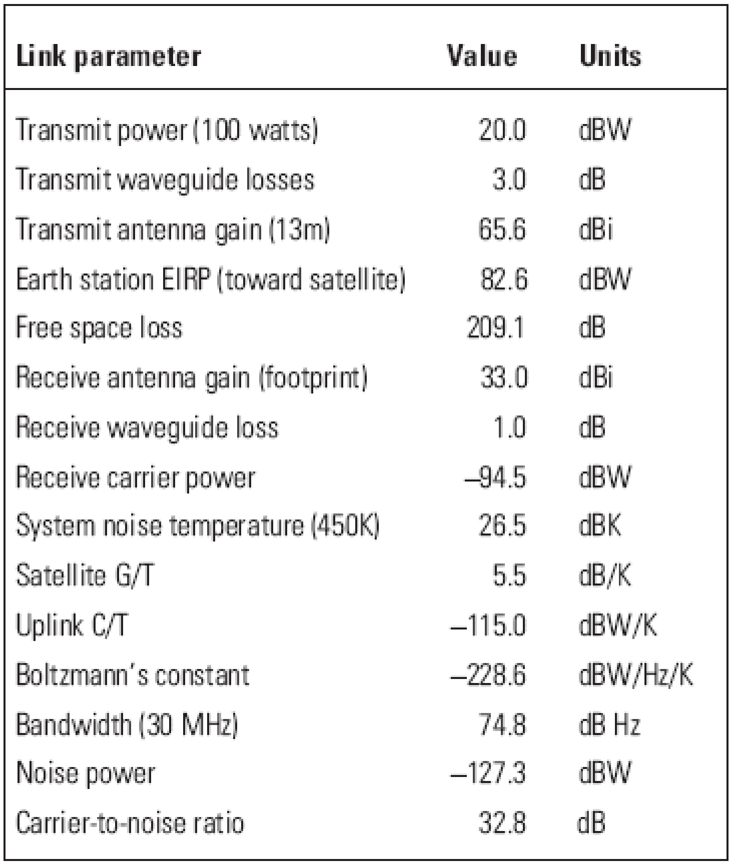
.3 Sirius 3 BSS Nordic coverage from 5.0° east longitude, indicating EIRP performance at the 52 dBW level (illustration courtesy of NSAB).

The baseband to modulated-carrier design assumed in this example is according to the DVB-S standard for Ku-band links [5]. To establish the carrier bandwidth, we assume an input information rate of 32.4 Mbps, which expands to 46.8 Mbps from Reed-Solomon encoding (188/204) and R = ¾ FEC encoding, and converted to a carrier bandwidth with a QPSK modulation factor of 1.28/2 = 0.64. We cannot determine if 12.3 dB is adequate for the downlink until the uplink and combined link are considered.

The uplink budget in Table 3.2 follows the same basic format as that described for the downlink. A difference is that the EIRP is produced by the transmitting earth station with 100 watts of HPA power.

Table 3.2

Link Budget Example for the Uplink at 18.2 GHz (Ku-band BSS)



Link parameter	Value	Units
Transmit power (100 watts)	20.0	dBW
Transmit waveguide losses	3.0	dB
Transmit antenna gain (13m)	65.6	dBi
Earth station EIRP (toward satellite)	82.6	dBW
Free space loss	209.1	dB
Receive antenna gain (footprint)	33.0	dBi
Receive waveguide loss	1.0	dB
Receive carrier power	–94.5	dBW
System noise temperature (450K)	26.5	dBK
Satellite G/T	5.5	dB/K
Uplink C/T	–115.0	dBW/K
Boltzmann's constant	–228.6	dBW/Hz/K
Bandwidth (30 MHz)	74.8	dB Hz
Noise power	–127.3	dBW
Carrier-to-noise ratio	32.8	dB

A considerable reserve of uplink power is available from a backed-off klystron-power amplifier (KPA), typically 10 to 15 dB, so that heavy rain on the uplink can be overcome. In addition, the link can obtain greater margin against rain through repeater AGC or limiting in front of the TWTA. The nominal earth station EIRP of approximately 80 dBW, considerably greater than that of the satellite, benefits from the use of a large-diameter antenna (13m), which is continually directed toward the satellite. Satellite G/T, on the other hand, is low (5.5 dB/K) under the assumption that there is a broad coverage footprint to allow access from across the same region as the downlink.

The nominal value of C/N obtain in the uplink is 32.8 dB, considerably greater than the downlink value, causing the uplink to have little effect on overall link and system performance. The reason for this approach is that the uplink is serving a community of literally millions of downlink antennas that are installed and maintained by nontechnical subscribers. Our objective, as service provider, is to assure the highest quality of service using those elements that are under our direct control. The high uplink C/N can be maintained during heavy rain up to the point where our uplink power margin is exhausted (i.e., about 10 dB of attenuation). From that point, the repeater AGC takes over by maintaining constant drive to the TWTA as higher rain attenuation reduces the input power. The uplink C/N will now decline with this loss of input, thus degrading the overall performance. This is another reason that a high value of clear weather uplink C/N is desired.

Figure 3.4, which is the cumulative distribution of attenuation at 20.2 GHz at Clarksburg, Maryland, provides some measure of the amount of uplink margin needed for an 18-GHz uplink. For example, one might expect that for this location, about 14 dB of uplink margin will deliver 99.9% availability in most years.

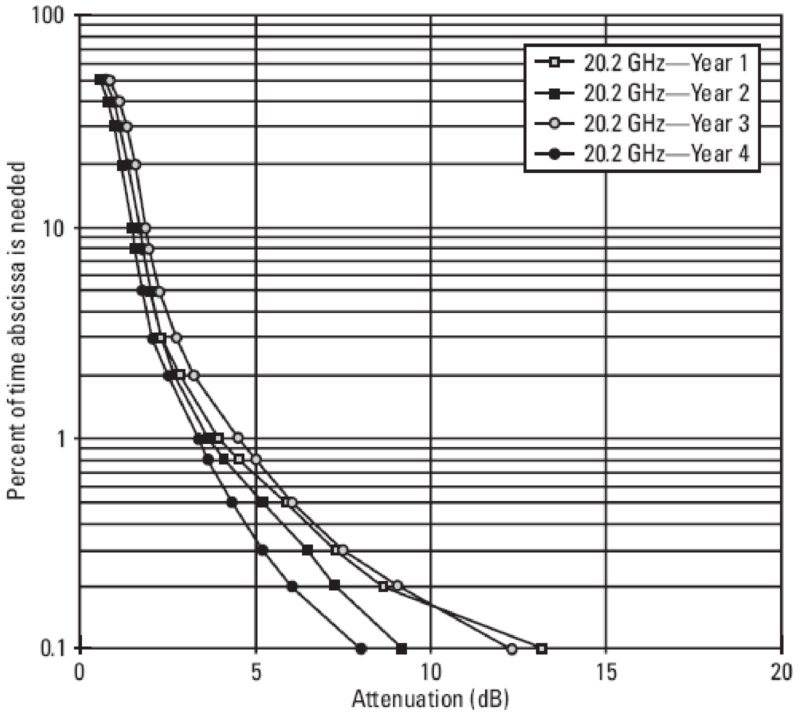
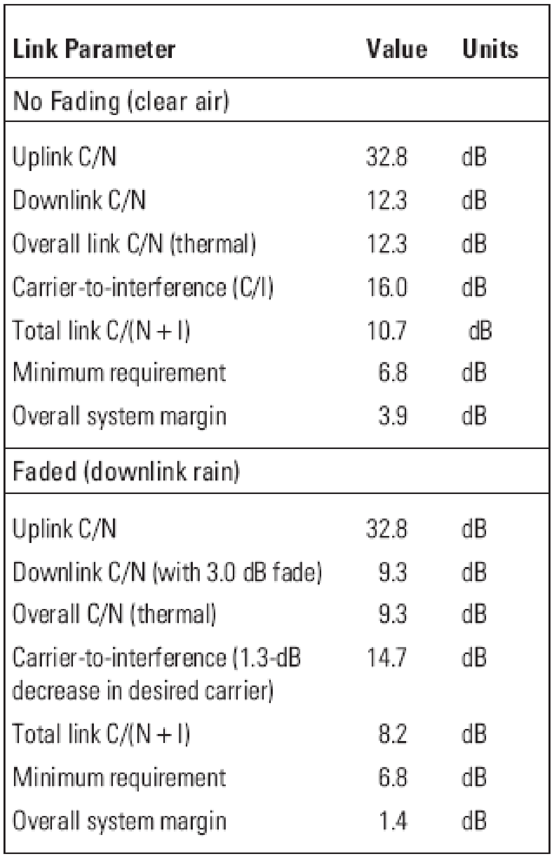


Figure 3.4 Cumulative distribution of attenuation at 20.2 GHz as measured at Clarksburg, Maryland, over a four-year period (illustration courtesy of ACTS Propagation Workshop).

The combined performance of this BSS link example is presented in Table 3.3, which assumes a bent-pipe type of repeater (i.e., one that allows uplink noise to pass through to the downlink). After converting C/N values to true ratios (i.e., $10^{(C/N)/10}$), we obtain the combined C/N as follows:

Table 3.3
Combined Downlink and Uplink Example, Ku-band BSS, Clear Air and Downlink Rain Conditions



Link Parameter	Value	Units
No Fading (clear air)		
Uplink C/N	32.8	dB
Downlink C/N	12.3	dB
Overall link C/N (thermal)	12.3	dB
Carrier-to-interference (C/I)	16.0	dB
Total link C/(N + I)	10.7	dB
Minimum requirement	6.8	dB
Overall system margin	3.9	dB
Faded (downlink rain)		
Uplink C/N	32.8	dB
Downlink C/N (with 3.0 dB fade)	9.3	dB
Overall C/N (thermal)	9.3	dB
Carrier-to-interference (1.3-dB decrease in desired carrier)	14.7	dB
Total link C/(N + I)	8.2	dB
Minimum requirement	6.8	dB
Overall system margin	1.4	dB

$$C/N_{th} = [N_u/C + N_d/C]^{-1}$$

where C/N_{th} is the combined C/N for the thermal noise (i.e., the receiver noise produced in the user terminal and satellite front end), N_u/C is the inverse of the true ratio of the uplink C/N (Table 3.2), and N_d/C is the inverse of the true ratio of the downlink C/N (Table 3.1).

This formula can be extended to account for interference entries from adjacent channels (ACI), cross-polarization (XPOL), adjacent satellites (ASI) and terrestrial interference (TI) sources (an example follows):

$$C/N_{tot} = [N_{th}/C + N_{aci}/C + N_{xpol}/C + N_{asi}/C + N_{ti}/C+\ldots]^{-1}$$

Of course, we must convert back to dB as a final step in this calculation.

For the BSS link in question, Table 3.3 evaluates first the combined (thermal) C/N for the unfaded (clear air) condition, which will persist for the majority of the time in all but the rainiest climates in the world. We have assumed C/I = 16 dB as an allocation for all RF interference. The clear air C/(N + I) of 10.7 dB is then compared to the minimum requirement for our user terminal receiver, assumed to be a QPSK demodulator with R = 3/4 forward error correction as used in the DVB standard (reviewed later in this chapter). For this type of device, the standard allows 6.8 dB for satisfactory operation; less than this value can produce reception difficulties such as dropouts and loss of sync. Our overall system margin is 3.9 dB to take account of rain attenuation on the downlink and other effects (e.g., additional interference, antenna mispointing, and the like).

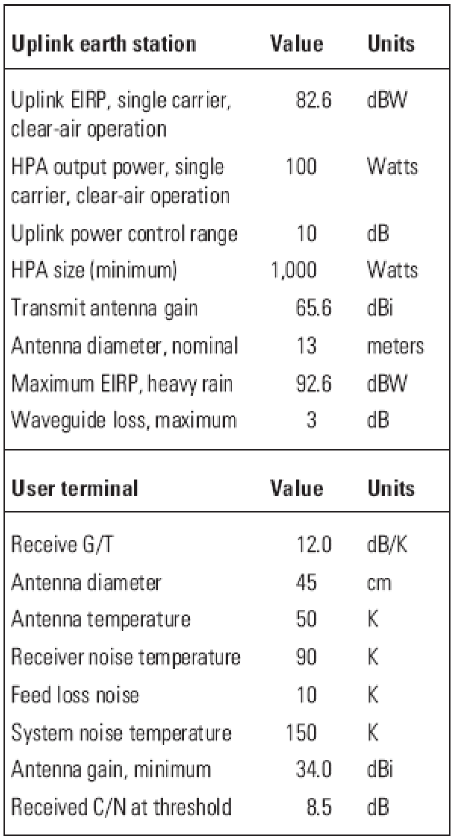
A condition with 3 dB reduction of C/N due to rain fade is shown at the bottom of Table 3.3. Due to the fact the rain produces both attenuation and an increase in downlink noise due to absorption, the actual rain loss is about 1.3 dB. Adjacent satellite interference is assumed to follow a different path and not be attenuated; therefore, C/N_{asi} is reduced by the amount of rain attenuation (e.g., 1.3 dB). The remaining 1.7 dB of fade is that produced by the increase in system noise temperature, calculated according to:

$$\Delta T=(\ell-1/\ell)270$$

where ℓ is the rain absorption as a ratio greater than 1 (e.g., 1.35 in this example). The downlink noise power increases by a factor equal to $[T + \Delta T]/T$, which is [150 + 70]/150 = 1.47, or 1.7 dB.

We see that the C/N_{tot} has decreased to 8.2, resulting in a system margin of 1.4 dB. This particular amount of fade is typical of what one would expect in a temperate climate such as western Europe (the last entry in Table 3.3) or the northeastern United States. Having an extra 1.4 dB of margin provides that much more confidence in a system that will adequately serve the customer base. From the uplink and downlink budgets, we can identify the key characteristics of the transmitting earth station and receiving user terminal (Table 3.4).This example should demonstrate the simplicity with which GEO links can be analyzed and understood. The ground segment design is quite stable, because for most applications antenna tracking is not required. From these tables, we can determine the primary performance requirements for the earth stations and user terminals.

Table 3.4
Primary RF Performance Requirements for the Earth Station and User Terminal Used in the Link Budget Example



Uplink earth station	**Value**	**Units**
Uplink EIRP, single carrier, clear-air operation	82.6	dBW
HPA output power, single carrier, clear-air operation	100	Watts
Uplink power control range	10	dB
HPA size (minimum)	1,000	Watts
Transmit antenna gain	65.6	dBi
Antenna diameter, nominal	13	meters
Maximum EIRP, heavy rain	92.6	dBW
Waveguide loss, maximum	3	dB
User terminal	**Value**	**Units**
Receive G/T	12.0	dB/K
Antenna diameter	45	cm
Antenna temperature	50	K
Receiver noise temperature	90	K
Feed loss noise	10	K
System noise temperature	150	K
Antenna gain, minimum	34.0	dBi
Received C/N at threshold	8.5	dB