4 Communication Subsystems

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4.1 Introduction

The communications subsystem is perhaps the most vital aspect of the operation of a spacecraft. The communications system provides the only link between an operational vehicle and the ground control station or other satellites. Examples of communicated data can include scientific research, telemetry, payload results, or relayed information from other spacecraft. This subsystem plays a crucial role in the proper functioning of the space system.

The purpose of this characterization is to describe the major elements of a communications subsystem and to provide the equations for preliminary sizing of the major components. The particular vocabulary associated with this area of design will be outlined, along with the basic tenets of the design of a communications system. In addition, some operational examples will be provided to clarify the topic.

4.2 Communication Subsystem Characterization

The communications subsystem can be broadly defined as the system which allows data transfer to and from extravehicular sources. However, the mission requirements of particular vehicles lead the design process to create variations in the communications subsystem that can satisfy this broad definition. Regardless of the goals dictated by specific mission requirements, the common goal of any communications system is to provide the best signal in terms of power, accuracy, reliability, and security, with constraints on mass, size and ultimately costs. Table 4.2.1 [Wertz, 331] outlines the general functions of a communications subsystem and some of the specific tasks that aid in the accomplishment of those general functions. Table 4.2.2 [Wertz, 332] details the subsystem requirements and some available options to satisfy them. Some of the terms in this table will be described in later sections. Table 4.2.3 [Wertz, 334] defines some of the constraints the communications system experiences and those it places on the other spacecraft subsystems.

Broad Functions	Specific Functions
• Receive signals - From Earth - From another satellite	• Carrier tracking - 2-way coherent communication (downlik is a ratio of the uplink) - 2-way noncherent communication - 1-way communicaiton
	• COmmand reception and detection - Acquire and track uplink carrier - Demondulate carrier and subcarrier - Derive bit timing and detect data bits - Resolve data-phase ambiguity if it exists - Forwar command data, clock, and in-lock indicator to the subsystem for command and data handling
	• Telemetry modulation and transmission - Receive telemetry data streams from the command and data handling sybsystem or data storage sbsystem - Modulate downlik subcarrier and carrier with mission or science telemetry - Transmit composite signal to Earth or relay satellite
	• Ranging - Detect and retransmit ranging pseudorandom code or ranging tone signals - Retransmit either phase coherently or noncoherently
	• Subsystem Operations - Receive commands from the subsustem for command and data handling - Provide health ans status telemetry to the C&DH subsystem - Perform antenna pointing for any antenna requiring beam steering - Perform mission sequence operations per stored software sequence - Autonomously select omni antenna when spacecraft attitude is lost - Automously detect falts and recover communications using stored software sequence

Table 4.2.1 Communications System Primary Functions [Wertz, 331]

Requirement	Option	Comment
Data Rates - Command - Health and status telemetry - Mission/ science	1000 bps typical, 8 to 64 bps deep space 2400 bps is common - Low = 10 - 1000 bps - Medium = 1- 100 kbps - High = 100 kbps to Gbps	8-2000 bps for command 40-10,000 bps for health and status Mission dependent for mission/ science - some experiments - real-time imaging
Data Volume	Record data and transmit during longer windows	Data rate x transmission duration - Shorter duration increases data rate - May require data compression techniques
Data Storage	Tape recorders 75 x 10^9 bits Solid state recorders 128 x 10^6 bits Bubble memory 128 x 10^6 bits	Policy may dictate all data to be stored that is not immed. transmitted Mission may require that data be stored them played back later
Frequency	Used existing assigned frequencies and channels Used systems that are compatible to the existing system	Policy set by FCC, ITU, & NTIA Refer to the frequency atmospheric absorption charts
Bandwidths	Use C.E. Channon's theorem to calculate channel capacity See Chapter 13, Equation 13-24	Primary driver is data rate Secondary driver modulation scheme
S/C power	Use larger antennas/higher efficiency amplifiers Reconsider data requirements	S/C power may limit size of communications system transmitter
S/C mass	Use TWTAs for higher rf power output too reduce antenna size, reconsider data requirements	S/C communications system mass allocation may limit size or antennas
Beamwidth	See Tables 13-13, 13-14, and 13-15 for various antenna types, beam shapes, and beamwidths	Ground coverage area rqmts or the radiation footprint on the ground Antenna gain null requirements Antenna pointing error
EIRP (Effective Isotropic Radiated Power)	For a constant EIRP: As antenna size (gain) is increased, the transmitter power requirement decreases	EIRP = transmitted power x antenna gain - From end losses Min EIRP required EIRP = space loss + atmospheric loss + antenna pointing loss - receiver antenna gain - receiver sensitivity
G/T [Receiver antenna gain (dB)/recvr sys noise temp (K)]	See Table 13-9 for various communication system temperatures and G/Ts	G/T is the sensitivity of the receiving station and common Figure of Merit for an existing satellite link, a ground station can only very its antenna gain and sys noise temp to improve the sys signal-to-noise ratio

Table 4.2.2 Communications Subsystem Requirements [Wertz, 332]

Subsystem	Constraint or Requirement	Subsystem	Constraint or Requirement
Guidance, navigation, and control	- Spacecraft pointing and attitiude knowledge for fixed antennas - Antenna pointing requirements for gimballed antennas - Uncertanity for attitude and pointing knowledge estimates - Pointing requirements of the lesser of 1/10 of antenna beamwidth or 0.3 deg - Closed-loop pointing requirements (i.e. crosslinks)	Structure/ thermal	- Heat sinks for traveling wave tube amplifiers - Heat dissipation of all active boxes - Size of space radiator and thermal control louvers - Location of communications electronics and antennas - A clear field of view and movement for all gimballed antennas - Reducing the temperature uncertainty on non-oven-controlled crystals to reduce frequency uncertainty
Command and data handling	- Command and telemetry data rates - Clock, bit sync, and timing requiremets - 2-way comm. requirements - Autonomous falt detection and recovery requirements - Comm. subsystem command and telemetry interface - Onbaord storeage and processing	Payload	- Data rates for mission or science telemetry - Data volume for mission or science telemetry - Requirements for storing mission data - rf/EMC interface requirements - Special requirements for modulation, coding, and decoding
Power	- Amount and quality of power, incliding requirements for duty cycle, average, and peak power - Distribution requirements	Propulsion	- None

Table 4.2.3 Communications Design Interface [Wertz,334]

Figure 4.1 is first cut look at the input and output (interfaces) involved in communications subsystem design. In this figure, the interface is divided between design and operation to clarify the interactions and where they become most important.

There are numerous general types of communication subsystems that describe the operational systems in current spacecraft. Three major categories of communications systems are used when characterizing a mission. These are 1) Near Earth Communication; 2) Long Range Data Relay; and 3) Telecommunications. That is, on a specific vehicle, the communications subsystem fits into one of these three categories with respect to its primary mission and its general configuration. In each category there are many options that satisfy the requirements.

4.2.1 Near Earth Communications

Many satellites in low Earth orbit utilize the communications system to maintain contact with ground control centers for the purpose of Telemetry, Tracking, & Control (TT&C) and mission data transmission. Figure 4.2.1 [Wertz, 443] illustrates some of the near-earth applications of the communications subsystem on vehicles in various stages of orbital insertion and operation.

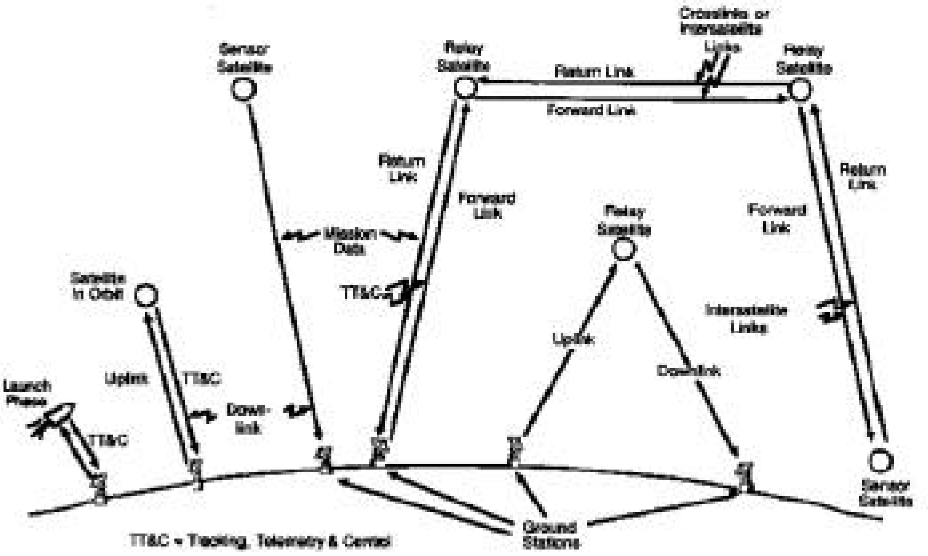


Figure 4.2.1 Near Earth Communications Architecture [Wertz, 443]

These missions typically have scientific observation or reconnaissance related payloads that are the major design drivers of the spacecraft. These systems require more design resources and thus often force constraints on the communication system. In a number of cases, the design limitations lead the vehicle to rely on relay satellites to communicate with the ground. This process reduces the percentage of total mass and power that a communications subsystem needs as opposed to directly communicating with a ground station. Figure 4.2.2 [Wertz, 447] examines some of the typical data dissemination techniques that the design process can use.

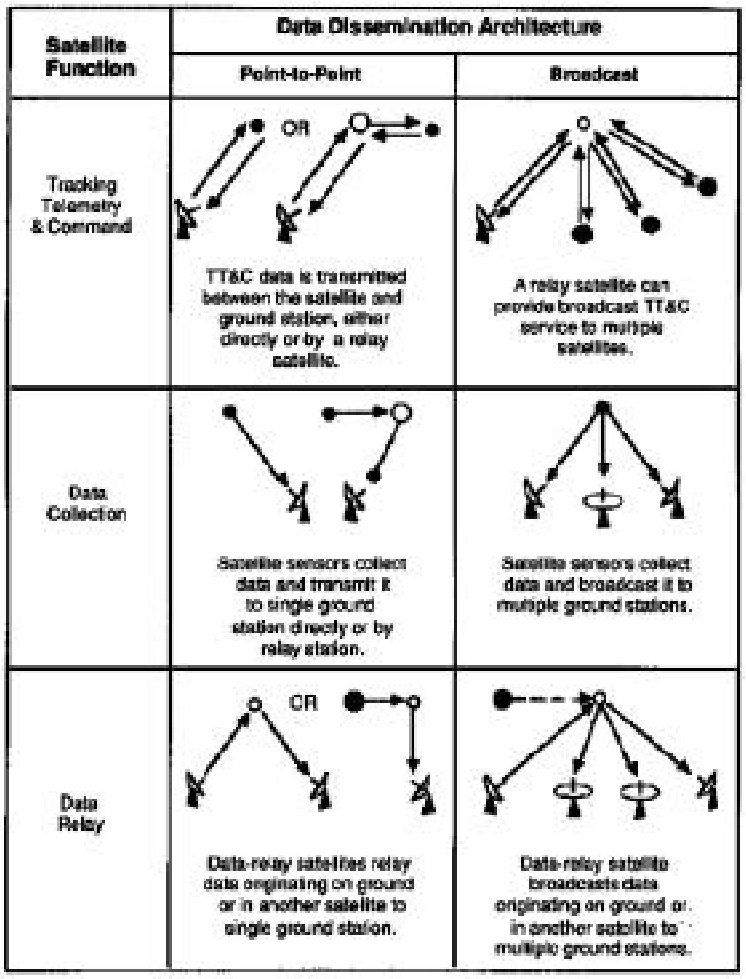


Figure 4.2.2 Data Dissemination Design Options [Wertz, 447]

Some examples of space vehicles that use communications for TT&C and mission data transmission include NOAA, Nimbus, GEOSAT, Landsat, UARS, and the Space Shuttle. In each of these spacecraft, although the communications system is critical, the emphasis is on the missions payload (i.e. mapping, sensing equipment) and thus the communication subsystem is placed into a support role. This necessitates subsystem design sacrifices when allocating limited resources (such as power and mass).

4.2.2 Long Range Data Relay

Long range spacecraft systems (typically interplanetary exploration missions) have particular communications requirements that places more emphasis on the design and resources of the communications subsystem. In these long range vehicles the communicated data is crucial for mission success where the data is typically scientific in nature and can include video images and other data intensive forms of communication.

The power that the communications system requires is a major design driver. Power saving techniques can include low frequency transmissions, non-continuous communications, and data encryption. Additionally, the antenna's selection is a key design concern in the context of accurate transmission at adequate data rates under obvious power constraints. In spite of these efforts, the communications subsystem requires more of the design resources to ensure successful data transmission over the long interplanetary distances. In overall vehicle design, then , the communications subsystem plays a more important role than in spacecraft using TT&C communications. Some examples of these long-range spacecraft are Pioneer, Voyager, Magellan and Galileo.

4.2.3 Telecommunications

The space systems in which communications plays the pivotal role is that of a telecommunications satellite. In these spacecraft, the communications payload drives the design of the other subsystems. These vehicles can be viewed as orbiting communications subsystems that possess the other subsystems as support for their mission. The communications system utilizes a significant degree of the design resources for these spacecraft. Some examples telecommunications spacecraft are TDRS, Comstar, Telstar, Syncom, and ACTS.

4.2.4 Summary

It is important when choosing a communication subsystem for a mission to first characterize that mission as a whole. This will give the designer an idea of where the emphasis of the design resources lie as well as the role of the communications subsystem itself. It is important to understand up front the constraints on the power and mass. Use Tables 4.1-4.3 along with the descriptions above to form the general characterization. Once the spacecraft has been characterized look for information on past spacecraft under the same general characterization. Heritage information is usually a good place to start.

4.3 Communication Subsystem Components

A communications subsystem, in general, is comprised of similar components regardless of the mission for which it is designed. Although some obvious exceptions exist, an examination of the primary elements of a communications system will serve to introduce the design process.

Some of these components include the system's antenna, transponder, amplifier, modulating / demodulating equipment, noise filters, and encryption / decryption equipment. Figure 4.3.1 [Wertz, 338] is of a generic communications subsystem and illustrates some of the component interaction.

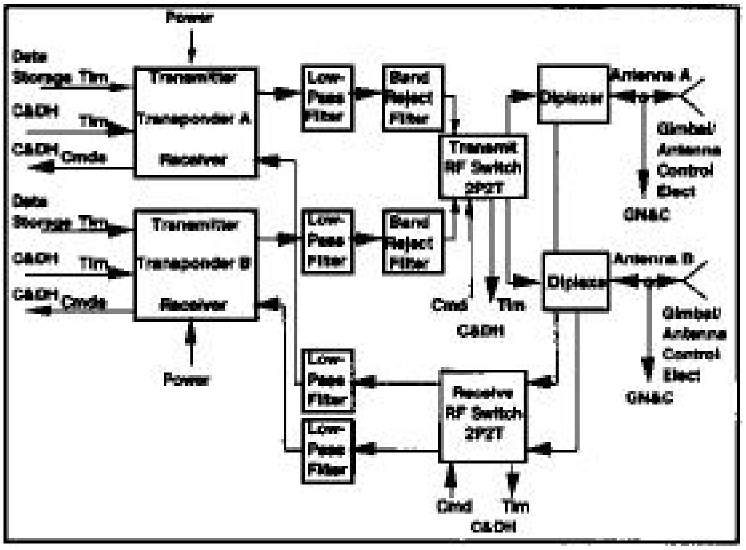


Figure 4.3.1 Generic Communications System [Wertz, 338]

4.3.1 Antennas

"The antenna converts electronic carrier signals to polarized electromagnetic fields and vice versa. A transmitting antenna is composed of a feed assembly that illuminates an aperture reflecting surface, from which the electromagnetic filed then radiates. A receiving antenna has an aperture or surface focusing an incident radiation field to a collecting feed, producing an electromagnetic signal proportional to the incident radiation." [Gagliardi, 99]

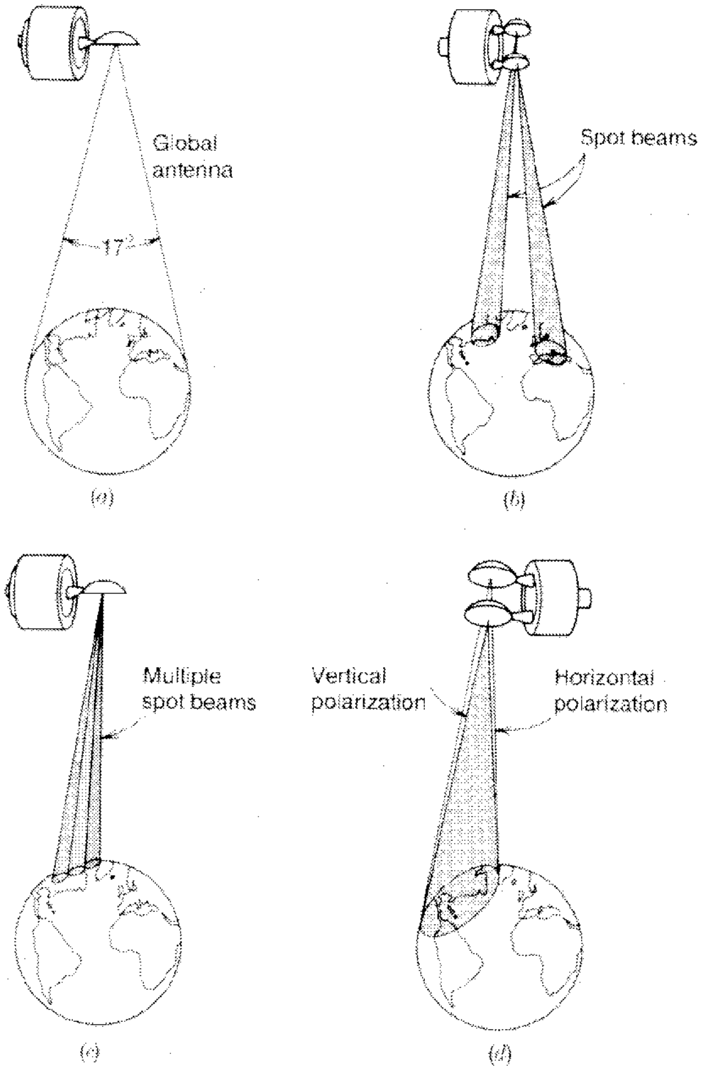
The most important parameters to consider in antenna design are its gain, its beamwidth, and its sidelobes. The first two are discussed in other sections. In simple terms the antenna's sidelobes are a measure of the gain in off-axis directions. In general, for the majority of communications purposes, antenna patterns are highly directional with high maximum gain. These gains are concentrated over a narrow beamwidth with sidelobe transmissions small enough to be neglected.

From the equations of gain and beamwidth, it is seen that the "... antenna gain is always proportional to the square of the carrier frequency and the antenna size, where the beamwidth varies inversely with frequency and size. Hence, the larger the antenna or the higher the frequency, the larger is the gain and the narrower the beamwidth. Thus, a given antenna has an increasingly more directional pattern as higher frequencies are used. At a fixed frequency, the pattern becomes more directional as the antenna is made larger." [Gagliardi, 101]

The four main types of antennas used on spacecraft are the linear dipole (or wire), horn, the antenna array and the parabolic reflector. Wire antennas are typically used at VHF and UHF to provide communications for TT&C systems. These antennas provide omni-directional coverage that are used primarily during launch and orbit insertion, when the main antennas have not been deployed or properly positioned.

"Horn antennas are used at microwave frequencies when relatively wide beams are required, as for global coverage. A horn is a flared section of a waveguide that provides an aperture several wavelengths wide and a good match between the waveguide impedance and free space. Horns are also used as feeds for reflectors, either singly or in clusters. Horns and reflectors are examples of aperture antennas that launch a wave into free space from a waveguide. It is difficult to obtain gains much greater than 23 dB or beamwidths narrower than about 10° with horn antennas. For higher gains or narrower beamwidths a reflector antenna or array must be used." [Pratt & Bostian, 80]

To provide a larger aperture than achieved with a horn antenna a reflector antenna is illuminated by one or more horns. "For maximum gain, it is necessary to generate a plane wave in the aperture of the reflector. This is achieved by choosing a reflector profile that has equal path lengths from the feed to the aperture, so that all the energy radiated by the feed and reflected by the reflector reaches the aperture with the same phase angle and creates a uniform phase front." [Pratt & Bostian, 80] The shape most often used for reflector antennas is the paraboloid. The parabolic antenna is actually a small antenna (horn) placed at the focus of the parabolic reflector. This is the most common antenna type for earth ground stations as well as for satellites. These antennas can be used to generate spot beams or radiation patterns that cover only portions of the Earth' s surface. By using multiple feedhorns radiation patterns of parabolic reflectors can be tailored to cover specific regions as shown in Figure 4.3.2 [Pratt and Bostian, 79].



Beamwidth	Earth coverage diameter
10°	3921 miles
5.7°	2235
2.8°	1117
1.0°	392
5.7°	223

Figure 4.3.2 Typical Satellite Antenna Patterns and Coverage Zones [Pratt & Bostian, 79]

The use of phased-array antennas is gaining more interest for satellite communications. The are based on the principle that "... a pointable, focused beam can be formed by simultaneously phase shifting an electromagnetic carrier field in N separate branched, and radiating each shifted component as the output on an individual radiator (dipole, horn, etc.). The resulting radiated pattern will reinforce (phase-combine) in some directions and interfere in others, the net result being a combined beam that points in a direction determined by the phase shifts used. By properly selecting the phase shifts, the directivity of the beam can be oriented in a given direction. Hence, a phased array can theoretically produce beams in arbitrary off-axis directions. The array gain increases with the square of the number of array elements, and thus high gain is achieved with large arrays. Recent advances in ferrite phase shifters that can be installed directly inside microwave waveguides have made the phased-array antenna an easily implementable, lightweight assembly for satellite use." [Gagliardi, 106]

4.3.2 Transponders and Amplifiers

The transponder is the component of the subsystem that receives the signal and shifts its frequency for retransmission. It is the path of each channel from the receiving antenna to the transmitting antenna. Its basic functions are to isolate the neighboring RF channels and to translate and amplify the frequencies for retransmission.

Typically uplink and downlink frequencies are separated to minimize interference between transmitted and received signals. Usually a lower frequency is chosen for downlink since this requires a lower output power of the satellite. Two major types of transponders are presented as well as alternate transponder configurations.

4.3.2.1 Quasilinear Repeaters

Quasilinear repeaters describe the tendency of the satellite transponder amplifiers to exhibit a nonlinear response close to maximum power output and a more linear response at lower power levels. "This repeater receives, separates, and amplifies its assigned uplink carriers, translates the frequency to the downlink band, and amplifies the signal for retransmission on the downlink. This transponder converts from uplink to downlink band in one step and is thus sometimes known as a single-conversion type."[Pritchard and Sciulli, p. 282]

Figure 4.3.2 [Pritchard and Sciulli, p. 282] is a block diagram of a typical quasilinear repeater. Traveling wave tube amplifiers (discussed later) are usually used in construction of the final high power output stage of the transponder. In the earlier stages of the transponder, after the signals have been received, the transponder must include a filter to eliminate energy outside the operating band, a low-noise amplifier (LNA) to increase signal power and a broadband frequency converter to shift the operating band from downlink to uplink. Another set of filters then separate the operating bandwidth into individual transponder channel bands (typ 36 MHz wide). High Power Amplifiers (HPA's) are then used to amplify the band signal for each channel. Finally, out-of-band products of the amplifier nonlinearity are eliminated after passing through a band pass filter. "The outputs of several channels' HPAs are then combined in an output multiplexer... and fed to a common antenna system for transmission." [Pritchard & Sciulli, p. 282]

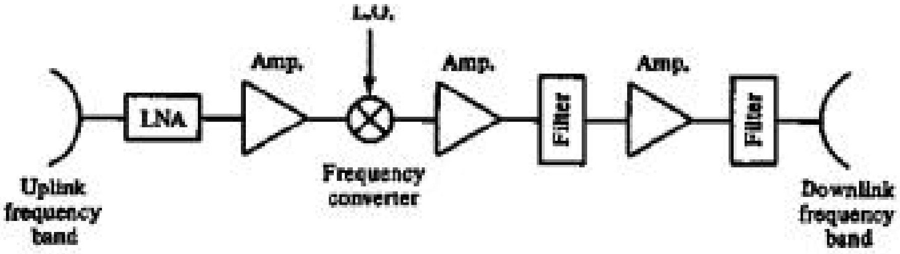


Figure 4.3.2 Quasilinear Repeater Ttransponder [Pritchard & Sciulli, 282]

4.3.2.2 Regenerative Repeaters

The regenerative repeaters yield improved performance over the quasilinear repeaters but in turn are more complex. Figure 4.3.3 [Pritchard and Sciulli, p. 286] shows a block diagram of this type of transponder. It performs the receiving and transmitting function in the same manner as the quasilinear repeater but the regenerative repeater "... contains in each transmission link a demodulator that demodulates the uplink signal to the digital baseband signal and a modulator that remodulates that signal on a downlink carrier. The demodulated signal is retimed and restored to standard form. This approach effectively isolates the uplink performance from the downlink performance, preventing the accumulation of noise and distortion over the two links."[Pritchard and Sciulli, p. 285]

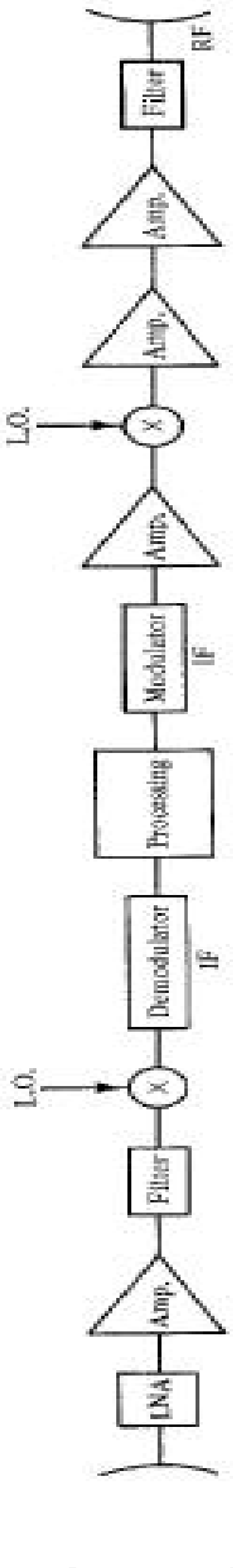


Figure 4.3.3 Regenerative Repeater [Wertz, 286]

4.3.2.3 Other Transponder Uses

1) Frequency Reuse and Transponder Gain Adjustment

   "Modern communication satellites often provide the capability to double the use of available satellite bandwidth (typ. 500 MHz) by providing dual-polarized transmit and receive antennas (discussed later) and two sets of transponders, one set for operation with each polarization." The gain of a transponder chain can be adjusted by ground command over a wide range of values. There is flexibility in the optimization of the earth station transmitter power and costs over a much wider range of earth station sizes and capacities than is possible with a fixed-gain transponder. This technique can double the capacity of the satellite system and is effective as long as the polarization isolation exceeds about 30dB (typ 33-35dB). [Pritchard and Sciulli, p. 305]

2) Cross-Band Operation

   "In some satellite applications, a transponder must interconnect stations operating in two different frequency bands. An example of such operations is the maritime satellite service operating in C-Band. Transmissions from a ship at sea to shore are received at the satellite in the 1.6 GHz band uplink and transmitted to shore in the 4 GHz band. Transmissions from shore to a ship at sea are received in 1.5 GHz band and transmitted to the ship in 1.5 GHz band. In such a case, separate transponders are always provided for each direct transmission." [Pritchard and Sciulli, p. 306]

4.3.2.4 Traveling Wave Tube Amplifiers

A traveling wave tube is a sophisticated vacuum tube which uses a narrow electron beam guided by a shaped magnetic field. Amplification is achieved by transferring energy from this beam to a microwave signal as it enters at one end and exits at the other. Because of the high voltages needed to generate and control the beam, a TWT requires a fairly complex power supply to convert the dc voltage from the spacecraft electrical system. As a matter of definition, the tube by itself is called a TWT, while the tube with its associated power supply is called a TWTA.

4.3.3 Modulation

The purpose of modulation, in general, is to shift the information signal to a higher frequency. The modulating / demodulating equipment in the communications system serves to translate the signal from or to a signal whose carrier wave has been altered to make the transmission from of the signal more compact. Typically, the information is either amplitude or frequency modulated to allow a greater data transmission rate.

Amplitude modulation (AM) is caused by "...varying the amplitude of the RF carrier in accordance with the level of the modulating signal. In terms of the frequency spectrum, the unmodulated carrier is still present at the center frequency and sidebands are visible above and below the carrier." Since AM is very susceptible to nonlinear distortion produced in the transponders, AM is not used extensively as a direct modulation technique in satellite networks. [Elbert, 128]

"Phase and frequency modulation are used heavily in satellite communications systems because of their ability to deal with nonlinear distortion, noise and interference. In both systems, the amplitude of the carrier is held constant so that there is no change in the power level. Most nonlinear distortion is the result of amplitude variations on the carrier, and therefore PM and FM will perform better in this environment than AM." Phase modulation is produced by delaying the unmodulated carrier in time proportional to the information amplitude variations. This delay causes the phase angle change that is detected at the receiving station and converted to its original form. Frequency modulation is produced by variations of the carrier frequency proportional to the information amplitude.

4.3.4 Encryption

The encryption / decryption equipment in a communications subsystem serves to ensure that the link is secure from unauthorized reception as well as compacting the signal. Although this component is most widely used in military applications, pay television signals are currently adopting this technology to ensure that only their paying customers can unscramble the transmissions.

4.4 Design Guidelines

Once the subsystem characterization is complete and a good understanding of the equipment used is obtained design of the subsystem can proceed. It is at this point that the type, quantity and accuracy of the returned data is established.

4.4.1 Carrier Frequency Selection

One of the most important design aspects of a communications subsystem is the carrier frequency selection. This frequency defines the signal between the spacecraft and the ground receivers. All information relayed from the spacecraft is transmitted at this frequency. The frequency determines the wavelength of the signal using Wein's Law

$$f = c / \lambda$$

f = carrier frequency (1/s)
λ = signal wavelength (cm)
c = speed of light (cm/s)

Unfortunately, this important parameter is one designer's have the least control in determining. The designer can choose the desired frequency, but the actual allocation of the frequency band is regulated by the Federal Communications Commission (FCC). The FCC divides the radio frequency (RF) spectrum into several categories. Each classification embodies a specific range of frequencies. These ranges have been reserved for various purposes including military use, navigational use, domestic bands and broadcast ranges. A summary of the various bands and their reserved services is shown in Table 4.4.1 [Wertz, 474].

Frequency Band	Frequency Range (GHz)		Service	Downlink Power Flux Density Limit (dBW/m^2)
	Uplink	Downlink		
UHF	0.2 - 0.45	0.2 - 0.45	Military	-
L	1.635 - 1.66	1.535 - 1.58	Maritime/Nav	-144/4 kHz
S	2.65 - 2.69	2.5 - 2.54	Broadcase	-137/4 kHz
C	5.9 - 8.4	3.7 - 4.2	Domesti Comsat	-142/ 4 kHz
X	7.9 - 8.4	7.25 - 7.75	Militray Comsat	-142/ 4 kHz
K_u	14.0 - 14.5	12.5 - 12.75	Domestic Comsat	-138 4 kHz
K_a	27.5 - 31.0	17.7 - 19.7	Domestic Comsat	-105/ 1 kHz
SHF/EHF	43.5 - 45.5	19.7 - 20.7	Military Comsat	-
V	-60		Satellite Crosslinks	-

Table 4.4.1 Limitations on the Frequency Bands Established by the ITU [Wertz, 474]

Because of the limited space available in each band, some of the more popular bands, such as C, S, and Ku are becoming overcrowded. Consequently, it is more difficult to acquire permission to broadcast at these frequencies. Due to the number of satellites already using these bands, interference between close proximity at close frequencies is becoming a problem. Restrictions concerning signal strength and broadcast time are being paced on the users of these frequency ranges. Another factor affecting the frequency selection is the final placement of the spacecraft. For example, two satellites in close proximity cannot broadcast at similar frequencies or signal interference will occur. As a designer, these problems must be considered when choosing a frequency band. Alternative bands such as Ka offer the designer greater availability and flexibility of frequency band. Contact the International Telecommunications Union (ITU) and the FCC for specific frequency allocation.

4.4.2 Data Rate Determination

Data rate is defined by the quantity of data being relayed from the spacecraft to the ground receiver. A high data rate indicates a large quantity of data transmitted with high accuracy. A smaller data rate reflects a smaller amount of less accurate data. Two major characteristics are involved in calculating the required data rate the number of bits per sample and the sampling frequency. These factors will vary depending on the type of data transmitted and the desired accuracy of the data.

There are three primary types of data voice, video and telemetry. A spacecraft may be responsible for transmitting one or all of these data type according to the mission objectives. Each data type requires a minimum number of bits per sample. This number determines the accuracy of the data. Generally, the lower the number of bits per sample, the less accurately the word represents the data measurement. Table 4.4.2 [Wertz, 452] displays the number of bits per sample and the associated accuracy.

Number of Bits Per Sample	Maximum Quantization Error (%)	Signal Power to Quanitized Noise Power Ration* (dB)
3	6.25	18
4	3.11	24
5	1.56	30
6	0.79	36
7	0.39	42
8	0.20	48
9	0.10	54
10	0.05	60
11	0.02	66
12	0.01	72

* Assumes signal amplitudes and quantization errors are uniformaly distributed.

Table 4.4.2 Required Bits Per Sample [Wertz, 452]

The number of bits per sample and the sampling frequency also varies for each type of data. Audio data requires less accurate measurements to generate a legible signal than telemetry data. Thus, audio requires a smaller amount of bits per sample.

Telemetry data usually demands a high accuracy and therefore a larger number of bits per sample. These values can be estimated from the previous table.

The second quantity needed to calculate the data rate is the sampling frequency. The sample rate also varies with data type. It has been shown, that the expression for the sample frequency is

$f_s > 2.2\ f_m$
f_s = sample frequency (1/s)
f_m = maximum frequency in signal spectrum (1/s)

The maximum input frequency depends on the sampled data. Voice data has a frequency range of about 3.5 kHz. Video data has a higher maximum frequency due to the complexity of the broadcast signal. The sample rate for telemetry varies with the measurement type. Measurements that change slowly, such as temperature, can be sampled at lower frequencies (once every 10 seconds), while parameters of critical importance or rapidly changing parameters are sampled at higher frequencies (10 times per second, etc.). For telemetry the sample rate is calculated by dividing the number of measurements by the sampling period.

where: $f_s = n / t$
f_s = sample rate (samples/s)
n = number of measurements (samples)
t = sampling period (s)

A summary of the three types of data, the number of bits per word and the sample rate is provided in Table 4.4.3.

After these two factors are determined, the calculation of data rate is completed by multiplying the number of bits per sample times the number of samples per second:

$R = \text{Bits} * fs$

Analog Information	Frequency (Hz)	Frequency (samples/s)	# Bits per Sample	Data Rate (bps)
Voice (PCM)	3600	8000	7	64 K*
Voice (Delta PCM)	3600	8000	6	56 K*
Color TV (Comm. qual.)	4.0 M	8.8 M	5	44 M
Color TV (brdcst qual.	4.2 M	9.25 M	10	92.5 M
Telemetry (low R)	---	10 samplse/ second	5	50
Telemetry (high R)	---	1000 samplse/ second	5	5 K

* After 1 bit per sample added for signaling and supervision

Table 4.4.3 Required Bit Rate for Analog Information Transmission

4.4.3 Defining Link Characteristics

An important output of any subsystem design process is power consumption and mass estimates, since these parameters ultimately determine the cost of the space vehicle. The steps involved in calculating these quantities for the communications subsystem are very involved. Presented below is a simplification of the link design process. Several parameters have been omitted or approximated. However, by completing the following process, rough estimates for the power can be determined. Calculate each parameter listed. Consistency of units is important.

4.4.3.1 Path Length

Path length is defined as the distance the signal has to travel from the transmitter to the receiver. This value is a function of the altitude above Earth and the look angle of the satellite antenna. Figure 4.4.4 illustrates the relationship between altitude, look angel and path length. To determine the path length, use the trigonometric relationship defined below.

where $L = h * \cos(\varphi)$
L = path length (km)
h = altitude (km)
φ =look angle

For most low earth satellites the look angle is fixed. Otherwise the path length should be calculated using the worst case scenario for the look angle. For deep space probes the look angle becomes sufficiently small such that the path length equals the spacecraft's altitude above Earth.

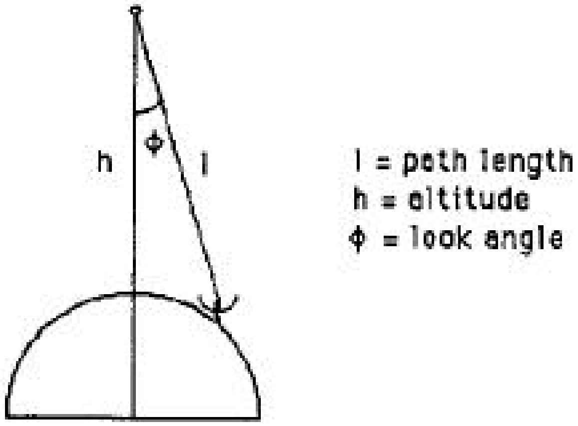


Figure 4.4.4 Look Angle of a Satellite

4.4.3.2 Beamwidth

This parameter is also a function of the mission objectives. Beamwidth is defined as the vertex angle of the antenna's cone of illumination. The communication requirements for the spacecraft often inadvertantly defines the beamwidth. For example, if full Earth coverage is specified, the beamwidth becomes dependent on the satellite altitude above Earth. To determine the beamwidth (θ) use trigonometric identities. For a satellite in geosynchronous orbit the beamwidth is approximately 18°. If full Earth coverage is not required, the relationship is still valid with the appropriate adjustments to the dimensions of the cone. A measure of the angle over which most of the gain occurs is known as the half-power beamwidth and is given by :

$$\Phi_b = \lambda / d*\mathrm{sqrt}(\eta)$$

where λ is the wavelength, d is the cross-sectional diameter, and η is the antenna efficiency.

4.4.3.3 Aperture Diameter:

Aperture diameter is a critical factor because it determines the size of the antenna needed for the mission. This value is directly related to the beamwidth. Different antenna types have different beamwidth / aperture diameter relationships. Table 4.4.4 displays the various antenna configurations and the corresponding formulas.

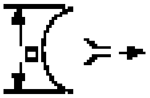
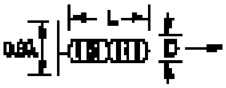
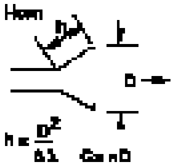
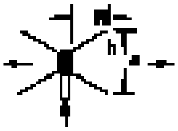
Antenna Type	Parabolic Reflector 	Helix  C = πD		Biconical Horn  Coaxial Line
Beam Shape	Conical	Conical	Conical	Toroidal
Typical Max Gain (dB)	15-65	5-20	5-20	0-5
Peek Gain (dB)	17.8 + 20 log D + 20 log f (η = 0.55)	$10.3 + 10\log\left(\frac{C^2L}{\lambda^3}\right)$ $0.8 \leq C/\lambda \leq 1.2$ (η = 0.70)	$20\log\left(\frac{C}{\lambda}\right) - 2.8$ (η = 0.52)	$5\log\left(\frac{h}{\lambda}\right) + 3.5$ $R > 2\lambda$ $a = \sqrt{ah\lambda}$
Half-Power Beamwidth (deg)	$\frac{21}{fD}$	$\frac{52}{\sqrt{C^2L/\lambda^3}}$	$\approx \frac{225}{(C/\lambda)}$	Typically 40˚ x 360˚ for gain ≥ -1 dB 70˚ x 360˚ for gain ≥ -3 dB
Peak Gain & Dimensions of 18˚ Beam at 400 MHz	G = 19.1 dB D = 2.9 m	G = 19.4 dB D: 0.19 m 0.24 m or L: 9.8 m 6.2 m	G = 19.1 dB D = 3 m h = 4 m	---

Table 4.4.4 Antenna Types for Satellite Systems [Wertz, 479]

4.4.3.4 Gain:

The gain of an antenna refers to the energy radiated or received by a particular antenna compared to the energy radiated or received by some reference antenna. The reference antenna is chosen as an isotropic radiator which radiates energy in all directions from a point source. Thus the gain of an isotropic radiator is unity.

Some antennas concentrate the energy radiated into a smaller region, or beamwidth, which increases the signal amplitude within the beamwidth. This concentration of energy in one direction provides the gain of an antenna as compared to an isotropic radiator. A reflector is used to focus or concentrate the energy into a beam, much in the same way a reflector concentrates the energy from a lightbulb in a flashlight into a light beam.

The gain is usually defined in the direction of maximum signal strength. The maximum gain would occur at the center of the signal. As stated previously the beamwidth specifies the angle in degrees from one side of the beam to the other. The following expression provides the gain relationship

$$G = \frac{\eta 4 \Pi A}{\lambda^2}$$

Where: G = antenna gain (dB)
A = antenna aperture xsectional area (cm^2)
η = antenna efficiency (typ. .55 - .70)
λ = signal wavelength

Figure 4.4.5 [Wertz, 481] shows the relationship between high- and low-gain and beamwidth. It is seen that the larger the antenna the higher the gain and the narrower the beamwidth. Typically high-gain antennas are used to support high data rates with low transmitter power.

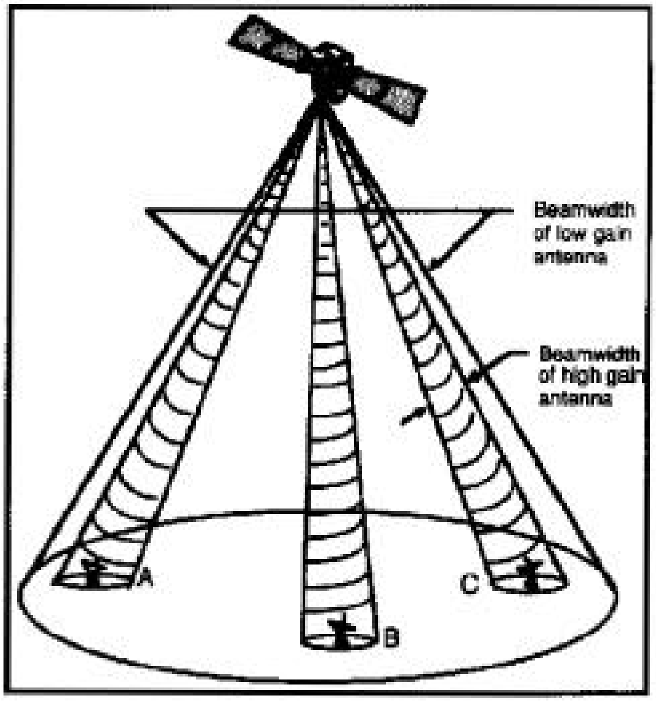


Figure 4.4.5 High Gain vs. Low Gain Coverage [Wertz, 481]

4.4.3.5 Signal-to -Noise Ratio

In order for data to be transferred effectively, the receiver must be able to differentiate between the actual signal and the signal noise. This quantity is represented for calculation purposes as the ratio of the received power over the noise spectral density (Eb / No) or the signal-to -noise ratio (SNR). The higher the SNR, the better the quality of the received signal. From a design standpoint, the SNR can be predetermined by specifying the desired Bit Error Rate (BER). The BER represents the probability of receiving erroneous bits in the signal. For highly accurate or sensitive data a BER of 10^{-6} (1 error per million bits) is not uncommon. Once the BER is chosen, Figure 4.4.6 [Wertz, 469] provides the BER/SNR relationships. The various curves differentiate between modulation schemes used in data reduction software. An additional quantity (1 to 3 dB) must be added to the final SNR value for error correction. (Note that the units of the SNR are dB.)

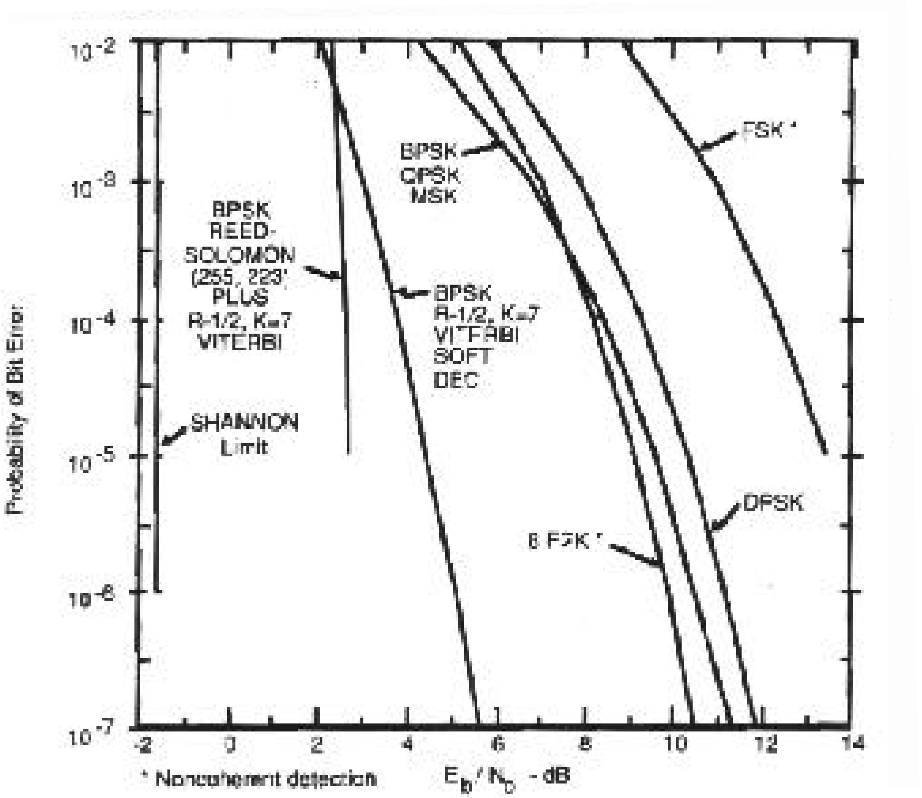


Figure 4.4.6 Bit Error Probablility as a Functional of Eb/No [Wertz, 469]

4.4.3.6 Line Loss

Line loss accounts for the transmitter to antenna reduction in power. This value is usually between -1 and -3 dB [Wertz,476]. This is sufficient for rough estimates.

4.4.3.7 Space Loss

Space loss represents the loss of power due to signal path length. This loss can be estimated from the following equation [Wertz, 463]:

$$L_s = \left(\frac{c}{4\pi S f}\right)^2$$

where L_S = space loss (unitless or dB)
c = speed of light
S = path length between transmitter & receiver (cm)
f = frequency of transmitted signal (1/s)

4.4.3.8 Antenna Loss

Another reduction in the effective transmitter power is due to antenna loss. The most prominent cause of this loss is due to rain attenuation. The amount of antenna loss is approximated by the attenuation value. Figure 4.4.7 [Wertz, 473] provides the means to determine antenna loss given the signal frequency.

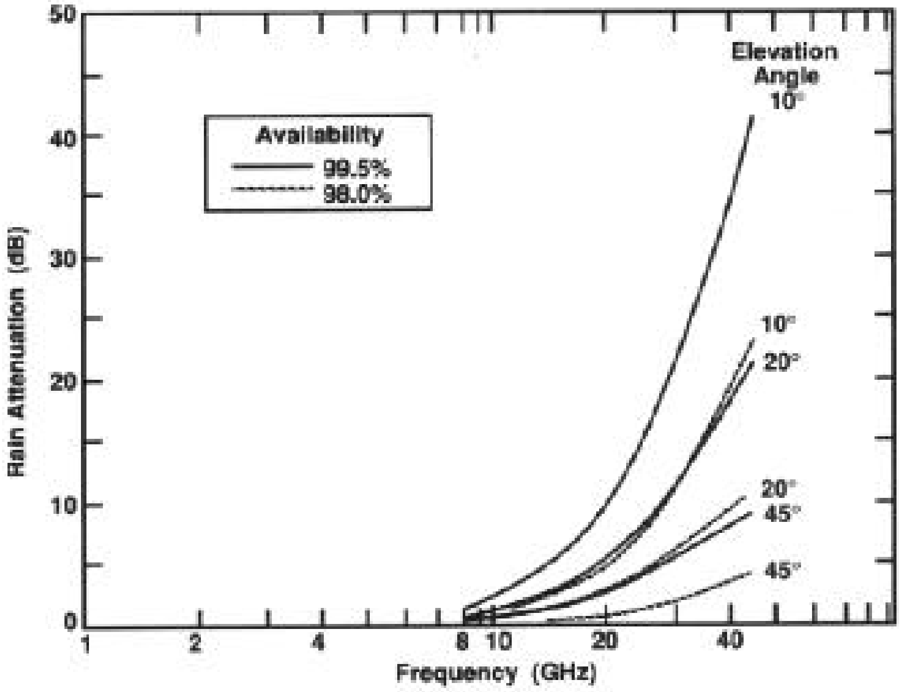


Figure 4.4.7 Rain Attenuation Predicted by the Crane Model [Wertz, 473]

4.4.3.9 Noise Temperature

The system noise contributes to the overall degradation of the signal. System noise embodies antenna noise, line noise and receiver noise. The noise temperature quantifies these effects into a number representing the energy lost as heat. Table 4.4.2 [Wertz, 466] displays typical noise temperature for various frequencies and signal paths.

Noise Temperature	Frequency (GHz)					
	Downlink			Crosslink	Uplink	
	0.2	2-12	20	60	0.2-20	40
Antenna Noise (K)	150	25	100	20	290	290
Line Loss (dB)	0.5	0.5	0.5	0.5	0.5	0.5
Line Loss Noise (K)	35	35	35	35	35	35
Receiver Noise Figure (dB)	2.0	4.0	4.5	8.0	6.0	7.5
Receiver Noise (K)	190	492	592	1728	1295	1930
System Noise (K)	375	552	727	1783	1295	1830
System Noise (db-K)	25.7	27.4	28.6	32.5	31.1	32.6

Table 4.4.2 Typical System Noise Temperatures in Satellite Communication Links [Wertz, 466]

4.4.3.10 Receiver Gain

The receiver gain is calculated the same way as the transmitting antenna gain. The value for the wavelength remains constant. However, the aperture diameter will be taken from the receiving antenna dimensions. The antenna efficiency will tend to increase (up to .85) because of the higher quality of the ground antennas.

4.4.4 Power

All of these factors are necessary to determine the power needed by the transmitter. The equation for power is given by [Wertz, 461]

$$P= E_b/N_o - L_l - G_t - L_s - L_a - G_r - 228.6 + 10\log_{10}Ts + 10\log_{10}R$$

Where P = transmitted power (dBW)
E_b/N_o = signal-to-noise ratio (dB)
L_l = line loss (dB)
G_t = transmitting antenna gain (dB)
L_s = space loss (dB)
L_a = attenuation loss (dB)
G_r = receiving antenna gain (dB)
T_s = system noise temperature (K)
R = data rate (bps)

To convert a quantity into decibles (dB) use the following relationship"

$$A(dB) = 10\log_{10}(A)$$

This power represents the transmitter radiated power. The type of transmitter chosen determines the amount of input power needed to provide the desired radiated output power. The two types of transmitters currently used are the TWTA and a solid state amplifier. The TWTA requires less input power than the solid state amplifier, but it tends to be more massive and less reliable. Figure 4.4.8 [Wertz, 483] allows the designer to estimate the required input power and the mass of the transmitter based on the radiated power. The power efficiency reflects the ratio of output power over input power for the transmitter.

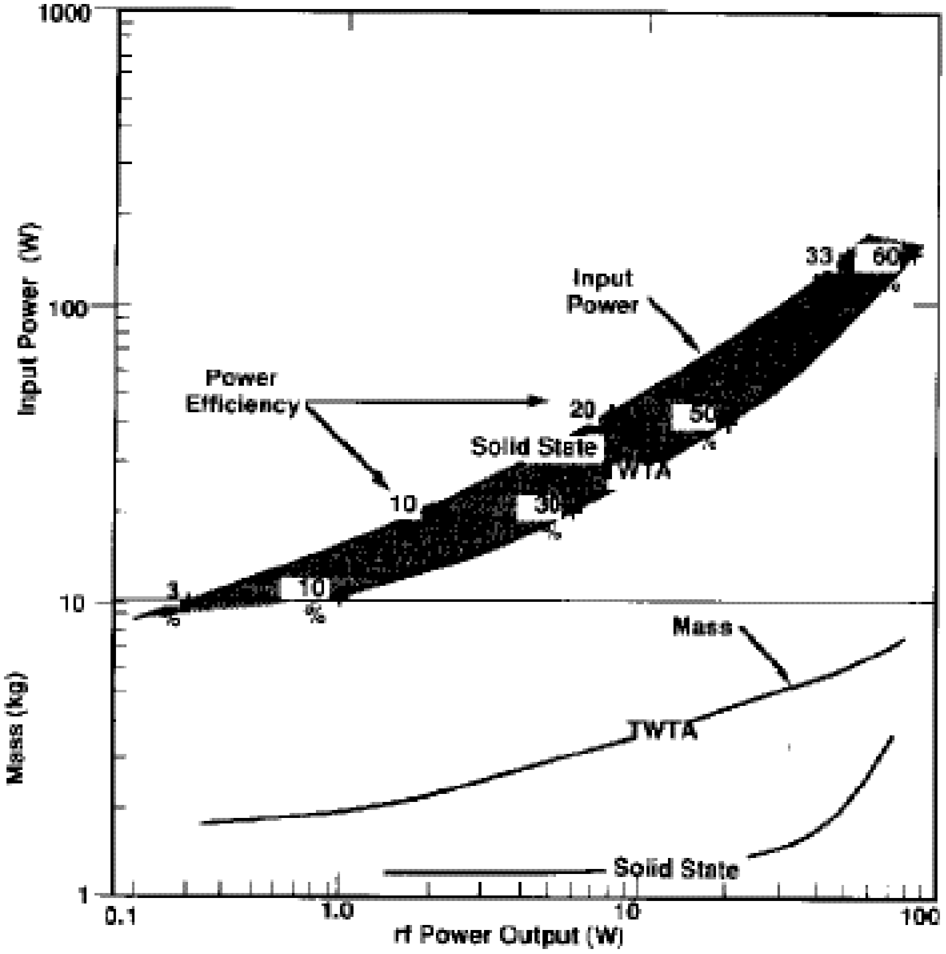


Figure 4.4.8 Satellite Transmitter Power and Mass vs. RF Power Output [Wertz, 483]

4.5 References

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