Satellite Communications Link Budget Analysis

by

Mr. Siripong Phanumphai

A Final Report of the Three-Credit Course
CE 6998 Project

Submitted in Partial Fulfillment
of the Requirements for the Degree of
Master of Science
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Project Title	Satellite Communication Link Budget Analysis
Name	Mr. Siripong Phanumphai
Project Advisor	Dr. Chamnong Jungthirapanich
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The Graduate School of Assumption University has approved this final report of the three-credit course, CE 6998 PROJECT, submitted in partial fulfillment of the requirements for the degree of Master of Science in Computer and Engineering Management.

Approval Committee:

(Dr. Chamnong Jungthirapanich)
Advisor and Program Coordinator

(Prof. Dr. Srisakdi Charmonman)
Chairman

(Assoc. Prof. Somchai Thayarnyong)
CHE Representative

November 2006

ABSTRACT

Link Budget is a generic term that is used to describe a series of mathematical calculations designed to model the performance of a communications link. In a typical simplex (one-way) satellite link, there are two link budget calculations: one link from the transmitting ground station to the satellite, and one link from the spacecraft to the receiving ground station. Many link budget analysis tools are available which include: Link budget model, uplink and downlink, satellite receiver, power flux density, positional data model, earth terminal to satellite slant range, earth terminal antenna elevation and azimuth, uplink and downlink doppler frequency shift, benign atmosphere attenuation, clear air attenuation, rain fall attenuation, atmospheric signal scintillation, modulation and channel encoding, noise equivalent bandwidth, modulation spectral efficiency, demodulator implementation loss, probability of detection of error, convolution channel coding gain, earth terminal model, antenna model, receive system model, transmit system model, satellite model, uplink signal power, downlink signal power, transponder signal and noise power sharing, transponder uplink power flux.

A link budget calculation for a spacecraft to ground station link requires the following input items: Earth station latitude, earth station longitude, spacecraft longitude, downlink frequency, antenna gain, antenna noise temperature, low noise amplifier, ortho mode transfer (OMT) loss, effective isotropic radiated power (EIRP), intermediate frequency received bandwidth, transmit data rate, link margin.

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Much of the information in this project has to be obtained from publications, text books, advanced coursework materials, and online resources for more up-to-date information. These sources are acknowledged in the project references. The advanced coursework was held at BBC Training & Development in the UK. I would then like to express my regards to my Satellite Communications professor there.

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I. INTRODUCTION

1.1 Background of the Project

The first step in designing a satellite network is performance of a satellite link budget analysis. The link budget will determine what size of antenna to use, power requirements, link availability and bit error rate, and in general, the overall customer satisfaction with your work. Satellite links which use microwave frequency bands are usually line of sight paths and are therefore essentially governed by free space propagation; the signal tends to get weaker as it travels through space simply because it spreads out. Real life propagation in clear sky conditions is almost the same except for a small loss due to the atmosphere.

The overall design of a complete satellite communications system involves many complex trade-offs to obtain a cost-effective solution. There are key parameters which influence various design decisions – the process of link budget analysis and link design.

General uses of satellites may include program contribution, program distribution, program feeds to cable head ends, direct-to-home broadcasting (DTH), international telephone traffic, business communications, mobile communications (land, sea, air), military/naval communications, earth resources /weather / space research, and monitoring (other nations satellite broadcasts). However, there are a number of factors which can affect the strength of the received carrier and render the link unusable for a short time. On satellite links rain attenuation is the most significant factor which gives rise to fades. Refractive effects in the atmosphere are usually small as the elevated satellite path traverses the atmosphere quickly.

The reliability of satellite link depends on the margin in dB's as well as rainfall statistics. The margin is the fade depth which can be tolerated before the link becomes unsatisfactory.

1.2 Objectives of the Project

To provide sitcom engineers who will be involved in making link budget decisions prior to choosing the appropriate satellite service provider. This analysis is required in optimizing cost-performance design.

1.3 Scope of the Project

This project will mainly focus on the link budget analysis in satellite communications. It will introduce key elements which are accountable in such design and analysis. This project will cover the engineering and managing of a link that will deliver the required quality of service without being overly conservative, and be able to recognize and avoid common link budgeting errors.

The project, however, will not be in-depth due to partly its technical complexity and suitability of the three-credit course.

II. LITERATURE REVIEW

The use of satellites in communications systems is very much a fact of everyday life, as is evidenced by the many homes which are equipped with antennas, or dishes, used for reception of satellite television. What may not be so well known is that satellites form an essential part of telecommunications systems worldwide, carrying large amounts of data and telephone traffic in addition to television signals.

Satellites offer a number of features not readily available with other means of communications. Because very large areas of the earth are visible from a satellite, the satellite can form the star point of a communications net linking together many users simultaneously; linking users who may be widely separated geographically. The same feature enables satellites to provide communications links to remote communities in sparsely populated areas which are difficult to access by other means. Of course, satellite signals ignore political boundaries as well as geographic ones, which may or may not be a desirable feature.

To give some idea of cost, the construction and launch costs of the Canadian Anik-E1 satellite were $281.2 million, and the Anik-E2, $290.5 million. The combined launch insurance for both satellites was $95.5 million. A feature of any satellite system is that the cost is distance insensitive, meaning that it costs about the same to provide a satellite communications link over a short distance as it does over a large distance. Thus a satellite communications system is economical only where the system is in continuous use and the costs can be reasonably spread over a large number of users.

Satellites are also used for remote sensing, examples being the detection of water pollution and the monitoring and reporting of weather conditions. Some of these remote sensing satellites also form a vital link in search and rescue operations for downed aircraft and the like.

2.1 Frequency Allocations for Satellite Services

Allocating frequencies to satellite services is a complicated process which requires international coordination and planning. This is carried out under the auspices of the International Telecommunication Union. To facilitate frequency planning the world is divided into three regions.

Region 1: Europe, Africa, what was formerly the Soviet Union, and Mongolia

Region 2: North and South America and Greenland

Region 3: Asia, Australia, and the south-west Pacific

Within these regions frequency bands are allocated to various satellite services; although a given service may be allocated different frequency bands in different regions. Some of the services provided by satellites are:

Fixed Satellite Services (FSS)

Broadcasting Satellite Services (BSS)

Mobile Satellite Services

Navigational Satellite Services

Meteorological Satellite Services

There are many subdivisions within those broad classifications; for example, the fixed satellite service provides links for existing telephone networks as well as for transmitting television signals to cable companies for distribution over cable systems.

Broadcasting satellite services are intended mainly for direct broadcast to the home, sometimes referred to as direct broadcast satellite (DBS) service.

Mobile satellite services would include land mobile, maritime mobile, and aeronautical mobile. Navigational satellite services include global positioning systems, and satellites intended for the meteorological services often provide a search and rescue service (Roddy 2001).

Table 2.1 Frequency Band Designations (Roddy 2001)

Frequency Range, GHz	***Band Designation***
0.1 – 0.3	VHF
0.3 – 1.0	UHF
1.0 – 2.0	L
2.0 – 4.0	S
4.0 – 8.0	C
8.0 – 12.0	X
12.0 – 18.0	Ku
18.0 – 27.0	K
27.0 – 40.0	Ka
40.0 – 75	V
75 – 110	W
110 – 300	Mm
300 – 3000	μm

2.2 INTELSAT

The commercial global satellite system owned and operated by a consortium of more than 100 nations known as the International Telecommunications Satellite Organization, INTELSAT, provides modern high quality services to its member countries. Earth stations in the INTELSAT system are owned and operated by the designated telecommunications entities in the countries where they are located.

The international and also the domestic long-distance communication traffic requirements are increasing at a fascinating speed. The projected INTELSAT voice-circuit traffic and the postulated growth in North American domestic satellite system demand are even more fascinating. More and more frequently, digital techniques are used for voice and also television transmission (Feher 1983).

INTELSAT stands for International Telecommunications Satellite. The organization was created in 1964 and currently has over 140 member countries and more than 40 investing entities. Starting with the Early Bird satellite in 1965, a succession of satellites has been launched at intervals of a few years. Table 1.2 illustrates the evolution of some of the INTELSAT satellites. As the figure shows, the capacity in terms of number of voice channels increased dramatically with each succeeding launch as well as the design lifetime. These satellites are in geostationary orbit meaning that they appear to be stationary in relation to the earth. At this point it may be noted that geostationary satellites orbit in the earth's equatorial plane and that their position is specified by their longitude.

For international traffic, INTELSAT covers three main regions; the Atlantic Ocean Region, the Indian Ocean Region, and the Pacific Ocean Region. For each region the satellites are positioned in geostationary orbit above the particular ocean where they provide a transoceanic telecommunications route.

The system design is mainly around Atlantic Ocean Region requirements since traffic in the AOR is about three times that in the Indian and about twice that in the Indian and Pacific Ocean Region combined (Roddy 2001).

Table 2.2 Evolution of INTELSAT satellites (Roddy 2001)

Intelsat	**I**	**II**	**III**	**IV**	**IV A**	**V**	**V A/V B**	**VI**
Year of first launch	1965	1966	1968	1971	1975	1980	1984/85	1986/87
Prime contractor	Hughes	Hughes	TRW	Hughes	Hughes	Ford Aerospace	Ford Aerospace	Hughes
Width (m)	0.7	1.4	1.4	2.4	2.4	2.0	2.0	3.6
Height (m)	0.6	0.7	1.0	5.3	6.8	6.4	6.4	6.4
Launch vehicles	Thor Delta	Thor Delta	Thor Delta	Atlas - Centaur	Atlas - Centaur	Atlas – Centaur and Ariane	Atlas – Centaur and Ariane	STS and Ariane
Spacecraft mass in transfer orbit (kg)	68	182	293	1385	1489	1946	2140	12,100 / 3720
Communications payload mass (kg)	13	36	56	185	190	235	280	800
End-of-life power of equinox (W)	40	75	134	480	800	1270	1270	2200
Design lifetime (yrs)	1.5	3	5	7	7	7	7	10
Capacity	480	480	2400	8000	12,000	25,000	30,000	80,000
Bandwidth (MHz)	50	130	300	500	800	2137	2480	3520

2.3 U.S. Domsats

Domsat is an abbreviation for domestic satellite. Domestic satellites are used to provide various telecommunications services such as voice, data, and video transmissions within a country. In the United States, all domsats are situated in geostationary orbit. As is well known they make available a wide selection of TV channels for the home entertainment market in addition to carrying a large amount of commercial telecommunications traffic.

U.S. Domsats provide a direct-to-home television service which can be classified broadly as high power, medium power, and low power. The main distinguishing feature of these categories is the equivalent isotropic radiated power (EIRP). It should be noted that the upper limit of EIRP is 60 dBW for the high-power category and 37 dBW for the low-power category; a difference of 23 dB. This represents an increase in received power of $10^{2.3}$ or about 200:1 in the high-power category which allows much smaller antennas to be used with the receiver (Roddy 2001).

Table 2.3 Defining Characteristics of Three Categories of United States DBS Systems (Roddy 2001)

	High Power	Medium Power	Low Power
Band	Ku	Ku	C
Downlink Frequency, GHz	12.2 – 12.7	11.7 – 12.2	3.7 – 4.2
Uplink Frequency, GHz	17.3 – 17.8	14 – 14.5	5.925 – 6.425
Space Service	BSS	FSS	FSS
Primary use	DBS	Point-to-Point	Point-to-Point
Allowed additional use	Point-to-Point	DBS	DBS
Terrestrial interference possible	No	No	Yes
Satellite spacing, degrees	9	2	2 – 3
Satellite spacing determined by	ITU	FCC	FCC
Adjacent satellite interference possible?	No	Yes	Yes
Satellite EIRP range, dBW	51 – 60	40 – 48	33 – 37

As noted in the table, the primary purpose of satellites in the high-power category is to provide a DBS service. In the medium-power category the primary purpose is point-to-point services but space may be leased on these satellites for the provision of DBS services.

In the low-power category no official DBS services are provided. However, it was quickly discovered by home experimenters that a wide range of radio and TV programming could be received on this band and it is now considered to provide a de facto DBS service.

Federal Communications Commission (FCC) adopted a policy objective setting 2° as the minimum orbital spacing for satellites operating in the 6/4-GHz band and 1.5° for those operating in the 14/12-GHz band. It is clear that interference between satellite circuits is likely to increase as satellites are positioned closer together. This spacing represents the minimum presently achievable in each band at acceptable interference levels. In fact, it seems likely that in some cases home satellite receivers in the 6/4-GHz band may be subject to excessive interference where 2° spacing is employed (Roddy 2001).

2.4 Baseband Transmission Systems

A thorough knowledge of fundamental digital transmission concepts and binary baseband transmission techniques is essential for the study of digitally modulated systems. The derivation and physical interpretation of the power spectral density function of binary signals is followed by the study of bandlimiting effects and the description of the frequently used "eye diagram" concept. The most important Nyquist transmission theorems for intersymbol interference-free transmission with associated filter synthesis and equalization techniques are presented. Finally, the probability of error performance in an additive white Gaussian noise environment is studied.

Particular attention is given to binary baseband systems, that is, systems in which only two signaling levels are used. In later chapters we will see that binary systems are more power efficient, but less spectrally efficient than multistate M-any systems. Spectral efficiency (the alternative term "bandwidth efficiency" is also frequently used) may be expressed in terms of transmitted bits/second/hertz (b/s/Hz). This normalized quantity is a valuable system parameter. For instance, if a data rate of 10 Mb/s is transmitted in a 6-MHz-wide channel, the spectral efficiency is 10 Mb/s per 6 MHz, or 1.67 b/s/Hz (Feher 1983).

2.5 The Geostationary Orbit

A satellite in a geostationary orbit appears to be stationary with respect to the earth; hence the name geostationary. Three conditions are required for an orbit to be geostationary:

1. The satellite must travel eastward at the same rotational speed as the earth.
2. The orbit must be circular.
3. The inclination of the orbit must be zero.

The first condition is obvious if the satellite is to appear stationary it must rotate at the same speed as the earth; which is constant. The second condition follows from this and from Kepler's second law. Constant speed means that equal areas must be swept out in equal time and this can only occur with a circular orbit. The third condition that the inclination must be zero; follows from the fact that any inclination would have the satellite moving north and south, and hence it would not be geostationary. Movement north and south can be avoided only with zero inclination which means that the orbit lies in the earth's equatorial plane.

2.5.1 Antenna Look Angles

The look angles for the ground station antenna are the azimuth and elevation angles required at the antenna so that it points directly at the satellite. With the types of antennas used for home reception, the antenna beamwidth is quite broad and no tracking is necessary. This allows the antenna to be fixed in position as evidenced by the small antennas used for reception of satellite TV that can be seen fixed to the sides of homes.

The three pieces of information that are needed to determine the look angles for the geostationary orbit are:

1. The earth station latitude
2. The earth station longitude
3. The longitude of the sub-satellite point

For a typical home installation, practical adjustments will be made to align the antenna to a known satellite for maximum signal. Thus the look angles need not be determined with great precision but are calculated to give the expected values for a satellite whose longitude is close to the earth station longitude. In some cases, especially with direct broadcast satellites (DBS) the home antenna is aligned to one particular cluster of satellites and no further adjustments are necessary.

2.5.2 The Polar Mount Antenna

Where the home antenna has to be steer-able, expense usually precludes the use of separate azimuth and elevation actuators. Instead a single actuator is used which moves the antenna in a circular arc. This is known as a polar mount antenna. The antenna pointing can only be accurate for one satellite and some pointing error must be accepted for satellites on either side of this. With the polar mount antenna, the dish is mounted on an axis termed the polar axis such that the antenna boresight is normal to this axis. The angle between the polar mount and the local horizontal plane is set equal to the earth station latitude (Roddy 2001).

2.6 Launching of Geostationary Satellites

Satellites may be launched directly into a geostationary orbit or via lower orbits, depending on the type of launcher. Most of the satellites launched today are initially launched into a low earth 'parking orbit'. In the next phase, the satellite is injected into an elliptical transfer orbit which has an apogee at the height of the geostationary orbit and its line of apsides (perigee-apogee line) in the equatorial plane. Finally, the satellite is injected into the geostationary orbit. This is achieved by imparting a velocity increment at the apogee equal to the difference between the satellite velocity at the apogee of the transfer orbit and the velocity in the geostationary orbit. A transfer between two coplanar circular orbits via an elliptical transfer orbit requires the least velocity increment.

At present, geostationary satellites may be launched either by expendable launchers or by the reusable Space Transportation System (STS or space shuttle). The flight plan of a geostationary mission depends on the type of launcher involved.

2.6.1 Launch from an Expendable Launcher

A satellite is launched in an easterly direction and positioned as close to the equator as feasible to take maximal advantage of the Earth's rotational velocity and minimize the fuel required for reducing the inclination to zero. To minimize drag from the atmosphere a satellite is launched vertically. The vehicle is gradually tilted by its guidance system during the flight until, at the point of injection, it is tilted by 90° in an easterly direction.

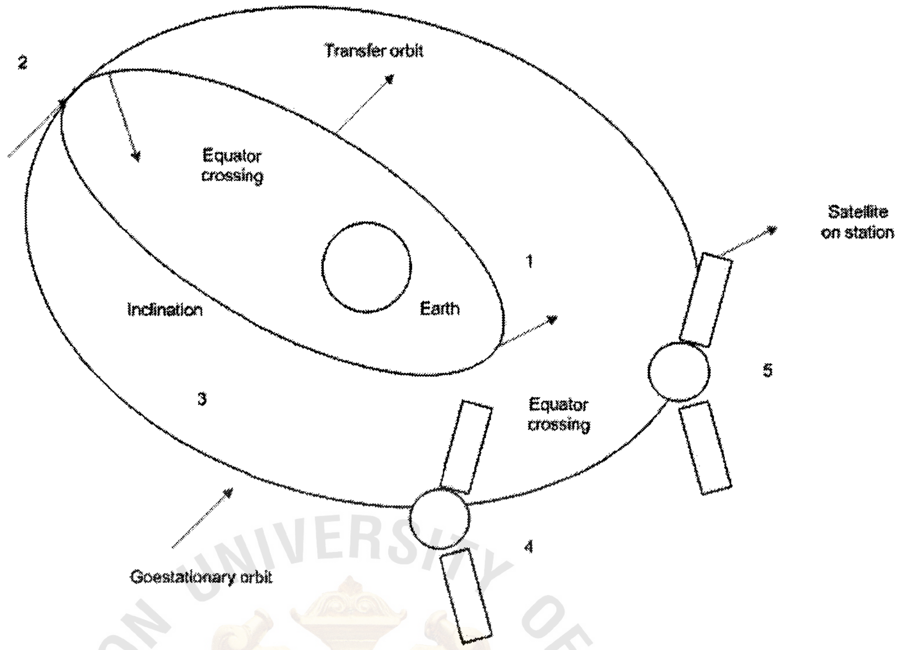
The satellite trajectory is closely monitored by a network of tracking stations until an accurate set of orbital parameters is obtained. Other operations during this phase include transition of stabilization of the satellite from the spin mode into a body-stabilized mode, solar array deployment, and Sun and Earth acquisition.

2.6.2 Launch from Space Shuttle

The expendable launchers lose most of the expensive hardware during launch. Therefore, one of the main design objectives of the space shuttle was to develop a reusable launch vehicle. In addition, the shuttle was designed with the capability to retrieve and repair satellites in low orbits.

2.6.3 Launch Window

Before the launch of a satellite it is necessary to ensure that the launch time falls within a 'launch window'. This guarantees that the position of a satellite in respect of the Sun is favorable, thus ensuring adequate power supply and thermal control throughout the mission. Further, the launch must be so timed that the satellite is visible to the control station during all the critical maneuvers. This set of conditions limits the launch time to certain specified intervals, designated the launch window (Richharia 1999).



Event number	Event
1	Velocity increment to acquire transfer orbit; satellite spun for stabilization; attitude manuevers done before apogee kick-motor firing
2	Apogee kick-motor fired to give necessary velocity increment; orbit circularized and inclination reduced to near zero
3	Satellite despun
4	Three-axis stabilization acquired
5	Minor orbit corrections performed to correct residual orbital errors in orbit tests and position satellite on station

Figure 2.1 Injection into a Transfer Orbit and Positioning of Satellite

(Richharia 1999)

2.7 Radio Wave Propagation

A signal traveling between an earth station and a satellite must pass through the earth's atmosphere including the ionosphere which can introduce certain impairments.

Table 2.4 Propagation Concerns for Satellite Communications Systems (Roddy 2001)

Propagation impairment	Physical cause	Prime importance
Attenuation and sky noise increases	Atmospheric gases, cloud, rain	Frequencies above about 10 GHz
Signal depolarization	Rain, ice crystals	Dual-polarization systems at C and Ku bands (depends on system configuration)
Refraction, atmospheric multipath	Atmospheric gases	Communication and tracking at low elevation angles
Signal scintillations	Tropospheric and ionospheric refractivity fluctuations	Tropospheric at frequencies above 10 GHz and low elevation angles; ionospheric at frequencies below 10 GHz
Reflection multipath, blockage	Earth's surface, objects on surface	Mobile satellite services
Propagation delays, variations	Troposphere, ionosphere	Precise timing and location systems; time-division multiple access systems
Intersystem interference	Ducting, scatter, diffraction	Mainly C band at present; rain scatter may be significant at higher freq.

2.7.1 Atmospheric Losses

Losses occur in the earth's atmosphere as a result of energy absorption by the atmospheric gases. These losses are treated quite separately from those which result from adverse weather conditions which of course are also atmospheric losses. To distinguish between these, the weather-related losses are referred to as atmospheric attenuation and the absorption losses as atmospheric absorption.

An effect known as atmospheric scintillation also can occur. This is a fading phenomenon; the fading period being several tens of seconds. It is caused by differences in the atmospheric refractive index which in turn results in focusing and defocusing of the radio waves; which follow different ray paths through the atmosphere. It may be necessary to make an allowance for atmospheric scintillation through the introduction of a fade margin in the link power-budget calculations.

2.7.2 Ionospheric Effects

Radio waves traveling between satellites and earth stations must pass through the ionosphere. The ionosphere is the upper region of the earth's atmosphere which has been ionized mainly by solar radiations.

The free electrons in the ionosphere are not uniformly distributed but form in layers. Furthermore, clouds of electrons may travel through the ionosphere and give rise to fluctuations in the signal that can only be determined on a statistical basis. The effects include scintillation, absorption, variation in the direction of arrival, propagation delay, dispersion, frequency change, and polarization rotation.

Ionosphere scintillations are variations in the amplitude, phase, polarization, or angle of arrival of radio waves. They are caused by irregularities in the ionosphere which change with time. The main effect of scintillations is fading of the signal. The fades can be quite severe and they may last up to several minutes.

2.7.3 Rain Attenuation

Rain attenuation is a function of rain rate. By rain rate is meant the rate at which rainwater would accumulate in a rain gauge situated at the ground in the region of interest (e.g. at an earth station). In calculations relating to the radio wave attenuation the rain rate is measured in millimeters per hour. Of interest is the percentage of time that specified values are exceeded. The time percentage is usually that of a year (Roddy 2001).

2.8 Polarization

The direction of the line traced out by the tip of the electric field vector determines the polarization of the wave. Keep in mind that the electric and magnetic fields are varying as functions of time. The magnetic field varies exactly in phase with the electric field and its amplitude is proportional to the electric field amplitude.

In the early days of radio, there was little chance of ambiguity in specifying the direction of polarization in relation to the surface of the earth. Most transmissions utilized linear polarization and were along terrestrial paths. Thus vertical polarization meant that the electric field was perpendicular to the earth's surface; and horizontal polarization meant that it was parallel to the earth's surface. Although the terms vertical and horizontal are used with satellite transmissions the situation is not quite so clear.

A linear polarized wave transmitted by a geostationary satellite may be designated vertical if its electric field is parallel to the earth's polar axis, but even so the electric field will be parallel to the earth at the equator.

2.8.1 Polarization of Satellite Signals

The directions "horizontal" and "vertical" are easily visualized with reference to the earth. Consider the situation where a geostationary satellite is transmitting a linear polarized wave. In this particular situation the usual definition of horizontal polarization is where the electric field vector is parallel to the equatorial plane; and vertical polarization is where the electric field vector is parallel to the earth's polar axis. It will be seen that at the subsatellite point on the equator; both polarizations will result in electric fields that are parallel to the local horizontal plane and care must be taken therefore not to use "horizontal" as defined for terrestrial systems. For other points on the earth's surface within the footprint of the satellite beam the polarization vector will be at some angle relative to a reference plane.

2.8.2 Cross-Polarization Discrimination

The propagation path between a satellite and earth station passes through the ionosphere and possibly through layers of ice crystals in the upper atmosphere and rain. All of which are capable of altering the polarization of the wave being transmitted. An orthogonal component may be generated from the transmitted polarization referred as depolarization. This can cause interference where orthogonal polarization is used to provide isolation between signals as in the case of frequency reuse.

2.8.3 Ionospheric Depolarization

The ionosphere is the upper region of the earth's atmosphere that has been ionized mainly by solar radiation. The free electrons in the ionosphere are not uniformly distributed but form layers. Moreover, clouds of electrons known as traveling ionospheric disturbances may travel through the ionosphere and give rise to fluctuations in the signal. One of the effects of the ionosphere is to produce a rotation of the polarization of a signal.

When a linearly polarized wave traverses the ionosphere, it sets in motion the free electrons in the ionized layers. These electrons move in the earth's magnetic field and therefore, they experience a force. The direction of electron motion is no longer parallel to the electric field of the wave and as the electrons react back on the wave; the net effect is to shift the polarization. The angular shift in polarization is dependent on the length of the path in the ionosphere; the strength of the earth's magnetic field in the ionized region and the electron density in the region.

2.8.4 Rain Depolarization

The ideal shape of a raindrop is spherical since this minimizes the energy (the surface tension) required to hold the raindrop together. The shape of small raindrops is close to spherical but larger drops are better modeled as oblate spheroids with some flattening underneath as a result of the air resistance (Roddy 2001).

2.9 Multibeam Satellite Networks

With a single beam satellite, it is therefore necessary to choose between interconnection of a large number of stations (extended coverage) and provision of a favorable link budget by means of a high satellite antenna gain (reduced coverage). The multibeam satellite, on the other hand, permits these two alternatives to be reconciled; satellite coverage is extended since it results from the juxtaposition of several beams and each beam provides an antenna gain which increases as the beamwidth decreases. The performance improves as the number of beams increase; the limit is provided by the antenna technology and the mass of the satellite whose complexity increases with the number of beams (Bousquet 1998).

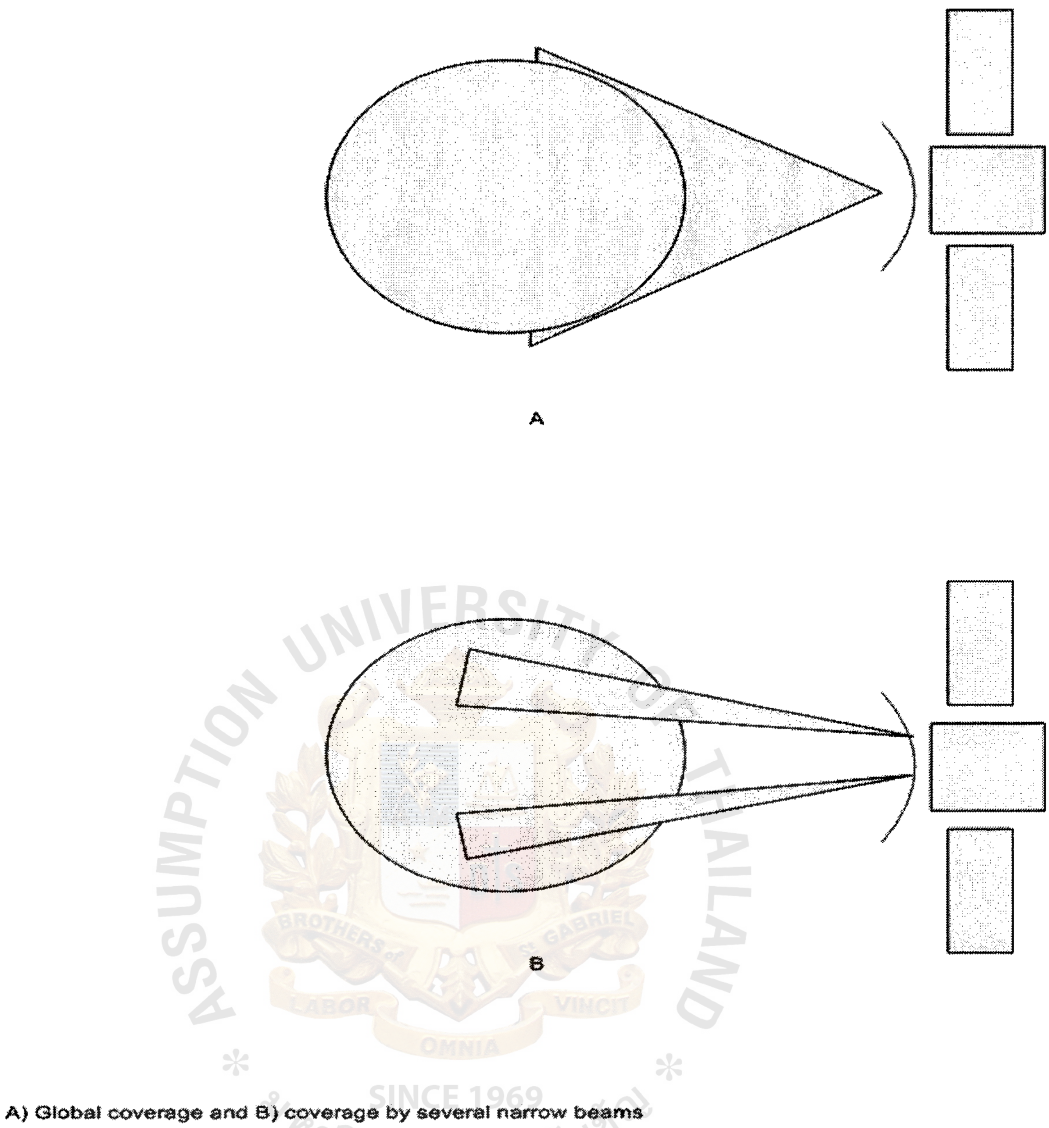


Figure 2.2 Multibeam Coverage (Bousquet 1998)

2.10 Antennas

Antennas can be broadly classified according to function as transmitting antennas and as receiving antennas. Although the requirements for each function or mode of operation are markedly different, a single antenna may be used for transmitting and receiving signals simultaneously. Many of the properties of an antenna such as its directional characteristics apply equally to both modes of operation.

Certain forms of interference can present particular problems for satellite systems which are not encountered in other radio systems and minimizing these requires special attention to those features of the antenna design which control interference (Roddy 2001).

2.11 Satellite Services and the Internet

On October 24, 1995, the Federal Networking Council (FNC) in the United States passed a resolution defining the Internet as a global information system that

(i) is logically linked together by a globally unique address space based on the Internet Protocal (IP) or its subsequent extensions/follow-ons;

(ii) is able to support communications using the Transmission Control Protocal / Internet Protocal (TCP/IP) suite or its subsequent extensions/follow-ons, and/or other IP-compatible protocols; and

(iii) provides, uses or makes accessible, either publicly or privately, high level services layered on the communications and related infrastructure described herein.

This formal description of the Internet summarizes what in fact were many years of evolutionary growth and change. The key elements in this definition are the Transmission Control Protocol (TCP) and the Internet Protocol (IP), both of which are described shortly. These protocols are usually lumped together as TCP/IP and are embedded in the software for operating systems and browsers such as Windows.

The internet does not have its own physical structure. It makes use of existing physical plants, the copper wires, optical fibers, satellite links, etc. Although there is no identifiable structure, access to the Internet follows well-defined rules. Users connect to

Internet Service Providers (ISPs) who in turn connect to network service providers (NSPs) who complete the connections to other users and to servers.

The uplink and downlink between satellite and earth stations form what is known as the physical layer in a data communication system. By data communications is meant communications between computers and peripheral equipment. The signals are digital and the satellite links must be able to accommodate the special requirements imposed by networks. The terminology used in networks is highly specialized to provide the background needed to understand the satellite aspects.

2.11.1 Satellite Links and TCP

Although satellite links have formed part of the Internet from its beginning, the rapid expansion of the Internet and the need to introduce congestion control have highlighted certain performance limitations imposed by the satellite links. It should be pointed out that the increasing demand for Internet services may well be met best with satellite direct-to-home links and many companies are actively engaged in setting up just such systems.

In the ideal case the virtual link between TCP layers should not be affected by the physical link and certainly the Transmission Control Protocol (TCP) is so well established that it would be undesirable to modify it to accommodate peculiarities of the physical link. The factors that can adversely affect TCP performance over satellite links are as follows:

Bit error rate (BER) – Satellite links have a higher bit error rate (BER) than the terrestrial links forming the Internet. Typically the satellite link BER without error control coding is around 10^{-6} whereas a level of 10^{-8} or lower is needed for successful TCP transfer. The comparatively low BER on terrestrial links means that most packet losses are the result of congestion and the TCP send layer is programmed to act on this assumption.

The round-trip time (RTT) of interest here is the time interval that elapses between sending a TCP segment and receiving its ACK (acknowledgement). With geostationary satellites the round-trip propagation path is ground station to satellite to ground station and back again. The propagation is calculated to be 0.532 of a second. This is just the space propagation delays on the terrestrial circuits and the delays resulting from signal processing. For order of magnetic calculations an RTT value of 0.55 second would be appropriate. Thus, we must take the RTT value into account to determine the TCP timeout period.

The RTT is also used in determining an important factor known as the bandwidth delay product (BDP). The delay part of this refers to the RTT since a sender has to wait this amount of time for the ACK before sending more data. The bandwidth refers to the channel bandwidth. In network terminology the bandwidth is usually specified in bytes per second where it is understood that 1 byte is equal to 8 bits. For instance, a satellite bandwidth of 36 MHz carrying a BPSK signal could handle a bit rate as 30 megabits per second (Mb/s) or about 3662 kilobytes per second (kB/s). If the sender transmits at this rate the largest packet it can send within the RTT of 0.55 second is 3662 x 0.55 = 2014 kilobytes approximately. This is the BDP for the two-way satellite channel. The channel is sometimes referred to as a pipeline and one that has a high BDP as a long fat pipe. Now the receive TCP layer uses a 16-bit word to notify the send TCP layer of the size of the receive window it is going to use. Allowing 1 byte for certain overheads the biggest segment size that can be declared for the receive window is 65,535 bytes or approximately 64 kilobytes. This falls well short of the 2014 kilobytes set by the BDP for the channel and thus the channel is underutilized.

Where lower earth orbiting satellites are used such as those in low earth orbits (LEOs) and medium earth orbits (MEOs), the propagation delays will be much less than that for the GEO. The slant range to LEOs is typically on the order of a few thousand kilometers at most and for MEOs a few tens of thousand kilometers. The problem with these orbits is not so much the absolute value of delay as the variability. Because these satellites are not geostationary the slant range varies and for continuous communications there is the need for intersatellite links which also adds to the delay and the variability.

2.11.2 Enhancing TCP over Satellite Channels using Standard mechanisms

In keeping with the objective that where possible the TCP itself should not be modified to accommodate satellite links the Request for Comments 2488 (RFC-2488) describes in detail several ways in which the performance over satellite links can be improved. These are summarized in the Table below. The first two mechanisms listed do not require any changes to the TCP. The others do require extensions to the TCP. As always any extensions to the TCP must maintain compatibility with networks that do not employ the extensions.

MTU stands for maximum transmission unit and Path MTU-Discovery is a method that allows the sender to find the largest packet and hence largest TCP segment size that can be sent without fragmentation. The congestion window is incremented in segments; hence larger segments allow the congestion window to increment faster in terms of number of bytes carried. There is a delay involved in implementing Path MTU-

Discovery and of course, there is the added complexity. Overall it improves the performance of TCP over satellite links.

Table 2.5 Summary of Objectives in RFC-2488 (Roddy 2001)

Mechanism	Use	RFC-2488 Section	Where Applied
Path MTU-Discovery FEC	Recommended	3.1	Sender
FEC	Recommended	3.2	Link
	TCP Congestion-	-Control	
Slow Start	Required	4.1.1	Sender
Congestion avoidance	Required	4.1.1	Sender
Fast retransmit	Recommended	4.1.2	Sender
Fast recovery	Recommended	4.1.2	Sender
	TCP Large-	-Windows	
Window Scaling	Recommended	4.2	Sender & Receiver
PAWS	Recommended	4.2	Sender & Receiver
RTTM	Recommended	4.2	Sender & Receiver
TCP SACKS	Recommended	4.4	Sender & Receiver

A) Forward Error Correction (FEC)

Lost packets whether from transmission errors or congestion are assumed by the TCP to happen as a result of congestion, which means that congestion control is implemented, with its resulting reduction in throughput. Although there is ongoing research into ways of identifying the mechanisms for packet loss, the problem still remains. Application of FEC should be used where possible.

B) Slow start and congestion avoidance

Slow start and congestion avoidance control the number of segments transmitted but not the size of the segments. Using Path MTU-Discovery as described earlier can increase the size and hence the data throughput is improved.

C) Fast retransmit and fast recovery

From the nature of the ACKs received the fast retransmit algorithm enables the sender to identify and resend a lost segment before its timeout expires. Since the data flow is not interrupted by timeouts the sender can infer that congestion is not a problem and the fast recovery algorithm prevents the congestion window from reverting to slow start. The fast retransmit algorithm can only respond to one lost segment per send window. If there is more than one lost segment the others will trigger the slow start mechanism.

2.11.3 Satellite Services

The idea that three geostationary satellites could provide communications coverage for the whole of the earth was sound but the practicalities led to the development of a much more complex undertaking than perhaps was envisioned originally. Technological solutions were found to the many problems that were encountered and as a result satellite services expanded into many new areas. Geostationary satellites are still the most numerous and well in excess of three.

Rapid development also has been taking place in services using non-geostationary satellites. Radarsat is a large polar-orbiting satellite designed to provide environmental monitoring services. Possibly the most notable development in the area of non-geostationary satellites is the GPS (Global Positioning Satellite) system which has come into everyday use for surveying and position location generally.

Although the developments in satellites generally have led to a need for larger satellites, a great deal has been happening at the other end of the size spectrum.

A) Satellite Mobile Services

There still remain large areas and population groups that have very limited access to telecommunication services. Most of the systems that offer telephone services provide the users with dual-mode phones that operate to GSM standards. GSM stands for Global System for Mobile Communications which is the most widely used standard for cellular and personal communications. A number of these systems have broad coverage.

B) VSATs

VSAT stands for Very Small Aperture Terminal system. This is the distinguishing feature of a VSAT systems, the earth station antennas being typically less than 2.4-m in diameter. Typical user groups include banking and financial institutions, airline, hotel, and large retail stores with geographically dispersed outlets. The basic structure of a VSAT network consists of a hub station which provides a broadcast facility to all the VSATs in the network and the VSATs themselves which access the satellite in some form of multiple-access mode. The hub station is operated by the service provider and it may be shared among a number of users. But each user organization has exclusive access to its own VSAT network. Time-division multiplex is the normal downlink mode of transmission from hub to the VSATs in a network.

Most VSAT systems operate in the Ku band although there are some C-band systems in existence. For fixed-area coverage by the satellite beam, the system performance is essentially independent of the carrier frequency. For a given size of antenna at the earth station and a fixed EIRP from the satellite the received power at the earth station is independent of frequency. This ignores the propagation margins needed to combat atmospheric and rain attenuation.

C) Global Positioning Satellite System

In the Global Positioning Satellite (GPS) system, a constellation of 24 satellites circles the earth in near-circular inclined orbits. By receiving signals from at least four of these satellites, the receiver position (latitude, longitude, and altitude) can be determined accurately. In effect the satellites substitute for the geodetic position markers used in terrestrial surveying. In terrestrial surveying it is only necessary to have three such markers to determine the three unknowns of latitude, longitude, and altitude by means of triangulation. With the GPS system a time marker is also required which necessitates getting simultaneous measurements from four satellites.

The GPS system uses one-way transmissions from satellites to users so that the user does not require a transmitter only a GPS receiver. The only quantity the receiver has to be able to measure is time from which propagation is delayed; hence, the range to each satellite can be determined. If the positions of three points relative to the coordinate system are known and the distance from an observer to each of the points can be measured then the position of the observer relative to the coordinate system can be calculated. In the GPS system the three points are provided by three satellites. Of course, the satellites are moving so their positions must be tracked accurately. The satellite orbits can be predicted from the orbital parameters. These parameters are continually updated by a master control station which transmits them up to the satellites where they are broadcast as part of the navigational message from each satellite (Roddy 2001).

III. LINK BUDGET ANALYSIS

The link-power budget calculations basically relate two quantities, the transmitted power and the received power. Link budget calculations are usually made using decibel or decilog quantities. Where no ambiguity arises regarding the units, the abbreviation dB is used. Where it is desirable to show the reference unit, this is indicated in the abbreviation, dBHz (decibels relative to one hertz).

3.1 Equivalent Isotropic Radiated Power (EIRP)

A key parameter in link budget calculations is the equivalent isotropic radiated power conventionally denoted as EIRP. The effective isotropic radiated power of an earth station or of a transponder can be expressed as EIRP = PG or EIRP (in dB) = P (in dBW) + G (in dB); where P = transmit power of the earth station or (transponder) high-power amplifier, G = antenna gain (Feher 1983).

3.2 Transmission Losses

The EIRP may be thought of as the power input to one end of the transmission link and the problem is to find the power received at the other end. Losses will occur along the way; some of which are constant. Other losses can only be estimated from statistical data and some of these are dependent on weather conditions; especially rainfall.

The first step in the calculations is to determine the losses for clear-weather or clear-sky conditions. These calculations take into account the losses including those calculated on a statistical basis which do not vary significantly with time. Losses which are weather-related and other losses which fluctuate with time are then allowed for by introducing appropriate fade margins into the transmission equation.

3.2.1 Free-Space Transmission

As a first step in the loss calculations, the power loss resulting from the spreading of the signal in space must be determined. This calculation is similar for the uplink and the downlink of a satellite circuit.

The received power in dBW is therefore given as the sum of the transmitted EIRP in dBW plus the receiver antenna gain in dB minus a third term which represents the free-space loss in decibels.

3.2.2 Feeder Losses

Losses will occur in the connection between the receive antenna and the receiver proper. Such losses will occur in the connecting waveguides, filters, and couplers. These will be noted by RFL for receiver feeder losses. Similar losses will occur in the filters, couplers, and waveguides connecting the transmit antenna to the high-power amplifier (HPA) output.

3.2.3 Antenna Misalignment Losses

When a satellite link is established, the ideal situation is to have the earth station and satellite antennas aligned for maximum gain. There are two possible sources of off-axis loss; one at the satellite and one at the earth station.

The off-axis loss at the satellite is taken into account by designing the link for operation on the actual satellite antenna contour. The off-axis loss at the earth station in referred to as the antenna pointing loss. Antenna pointing losses are usually only a few tenths of a decibel.

3.2.4 Fixed Atmospheric and Ionospheric Losses

Atmospheric gases result in losses by absorption. These losses usually amount to a fraction of a decibel (Roddy 2001).

3.3 The Link-Power Budget Equation

As mentioned earlier that the EIRP can be considered as the input power to a transmission link. Now that the losses for the link have been identified, the power at the receiver (the power output of the link) may be calculated simply as EIRP – Losses + Receiver Antenna Gain.

The major source of loss in any ground-satellite link is the free-space spreading loss. However, the other losses also must be taken into account (Wilson 1994).

3.4 System Noise

The receiver power in a satellite link is very small in terms of picowatts. This by itself would be no problem because amplification could be used to bring the signal strength up to an acceptable level. However, electrical noise is always present at the input and unless the signal is significantly greater than the noise; amplification will be of no help because it will amplify signal and noise to the same extent. In fact, the situation will be worsened by the noise added by the amplifier.

The major source of electrical noise in equipment is that which arises from the random thermal motion of electrons in various resistive and active devices in the receiver. Thermal noise is also generated in the lossy components of antennas and thermal-like noise is picked up by the antennas as radiation.

The main characteristic of thermal noise is that it has a flat frequency spectrum; that is, the noise power per unit bandwidth is a constant. The noise power per unit bandwidth is termed the noise power spectral density. The noise temperature is directly related to the physical temperature of the noise source but is not always equal to it. The noise temperature of various sources which are connected together can be added directly to give the total noise.

The noise contribution in a receiving system is determined by the noise temperature at a given point in the system, most often the receiver input. This noise temperature is called the system noise temperature. It is obtained by summing all noise temperatures corresponding to noise generated upstream and all noise temperatures equivalent to the noise generated downstream of the point considered (Bousquet 1998).

3.4.1 Antenna Noise

Antennas operating in the receiving mode introduce noise into the satellite circuit. Although the physical origins of the noise in either case are similar, the magnitudes of the effects differ significantly.

The antenna noise can be broadly classified into two groups; noise originating from antenna losses and sky noise. Sky noise is a term used to describe the microwave radiation which is present throughout the universe and which appears to originate from matter in any form at finite temperatures. Such radiation in fact covers a wider spectrum than just the microwave spectrum.

Any absorptive loss mechanism generates thermal noise; there being a direct connection between the loss and the effective noise temperature. Rainfall introduces attenuation and therefore, it degrades transmissions in two ways. It attenuates the signal and noise. The detrimental effects of rain are much worse at Ku-band frequencies than at C-band. Also the downlink rainfade margin must allow for the increased noise which is generated.

Satellite antennas are generally pointed towards the earth; henceforth, they receive the full thermal radiation from it. In this case the equivalent noise temperature of the antenna (excluding antenna losses) is approximately 290K.

Antenna losses add to the noise received as radiation and the total antenna noise temperature is the sum of the equivalent noise temperatures of all these sources. For large ground-based C-band antennas the total antenna noise temperature is typically about 60K. For the Ku-band it is about 80K under clear-sky conditions.

3.4.2 Noise Factor

An alternative way of representing amplifier noise is by means of its noise factor. In defining the noise factor of an amplifier, the source is taken to be at room temperature (usually around 290 Kelvin).

As a matter of convenience in a practical satellite receiving system, noise temperature is specified for low-noise amplifiers and converters; while noise factor is specified for the main receiver unit.

3.4.3 Noise Temperature of Absorptive Networks

An absorptive network is one which contains resistive elements. These introduce losses by absorbing energy from the signal and converting it to heat. Resistive attenuators, transmission lines, and waveguides are all examples of absorptive networks. Even rainfall absorbs energy from radio signals passing through it can be considered a form of absorptive network, because an absorptive network contains resistance, it generates thermal noise (Wilson 1994).

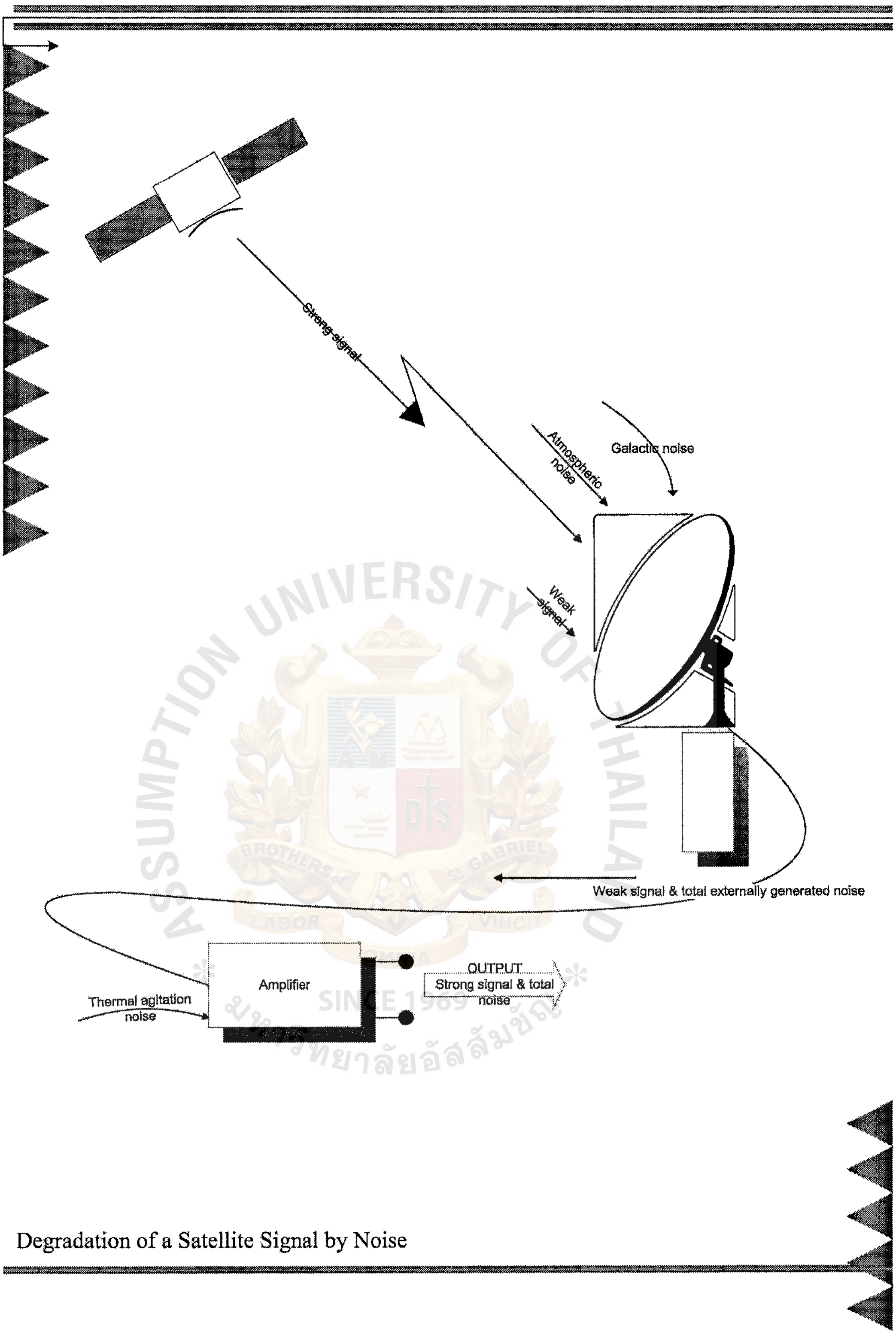


Figure 3.1 Degradation of a Satellite Signal by Noise (Wilson 1994)

3.5 Carrier-to-Noise Ratio

A measure of the performance of a satellite link is the ratio of carrier power to noise power at the receiver input, and link budget calculations are often concerned with determining this ratio. Conventionally, the ratio is denoted by C/N in terms of decibels. The link equation, [C/N] = [EIRP] + [G/T] - [LOSSES] - [k] dBHz

The G/T ratio is a key parameter in specifying the receiving system performance. The following example shows a link budget calculation in practical usage. Example 1: In a link budget calculation at 12 GHz, the free-space loss is 206 dB, the antenna pointing loss is 1 dB and the atmospheric absorption is 2 dB. The receiver G/T ratio is 19.5 dB/K. Receiver feeder losses are 1 dB and the EIRP is 48 dBW. Calculate the C/N ratio.

Table 3.1 A Link Budget Calculation Example (Richharia 1999)

Quantity	Decilogs
Free-space loss	- 206.00
Atmospheric absorption loss	- 2.00
Antenna pointing loss	- 1.00
Receiver feeder losses	- 1.00
Polarization mismatch loss	0.00
Receiver G/T ratio	19.50
EIRP	48.00
- [k]	228.60
[C/N]	86.10

As noted above, the main objective in the link design is to establish the desired carrier-to-noise ratio at the input of an earth station demodulator, within all practical constraints. The carrier-to-noise ratio at the demodulator input is a function of the uplink and downlink EIRP; the noise introduced in the earth station receiver and the satellite link; and the amount of interference (Richharia 1999).

3.6 Uplink

The uplink of a satellite circuit is one in which the earth station is transmitting the signal and the satellite is receiving it. In some situations, the flux density appearing at the satellite receive antenna is specified rather than the earth station EIRP.

3.6.1 Saturation flux density

The traveling-wave tube amplifier (TWTA) in a satellite transponder exhibits power output saturation. The flux density required at the receiving antenna to produce saturation of the TWTA is termed as saturation flux density. The saturation flux density is a specified quantity in link budget calculations and therefore is helpful for the required EIRP calculation at the earth station.

3.6.2 Input Backoff

Where a number of carriers are present simultaneously in a TWTA, the operating point must be backed off to a linear portion of the transfer characteristic to reduce the effects of inter-modulation distortion. Such multiple carrier operation occurs with frequency-division multiple access (FDMA). The point being made here is that backoff must be allowed for in the link budget calculations.

3.6.3 The Earth Station HPA

The earth station high-power amplifier has to supply the radiated power plus the transmit feeder losses. These include waveguide, filter, and coupler losses between the HPA output and the transmit antenna.

The earth station itself may have to transmit multiple carriers and its output also will require back off. The HPA will be operated at the backed-off power level so that it provides the required power output. To ensure operation well into the linear region, an HPA with a comparatively high saturation level can be used and a high degree of back-off introduced. The large physical size and high power consumption associated with larger tubes do not carry the same penalties they would if used aboard the satellite. Again it is emphasized that back-off at the earth station may be required quite independently of any back-off requirements at the satellite transponder. The power rating of the earth station HPA also should be sufficient to provide a fade margin (Wilson 1994).

3.7 Downlink

The downlink of a satellite circuit is the one in which the satellite is transmitting the signal and the earth station is receiving it. Equation below can be applied to the downlink.

$$[\ C/N\ ] = [\ EIRP\ ] + [\ G/T\ ] - [\ LOSSES\ ] - [\ k\ ]$$

The values to be used are the satellite EIRP, the earth station receiver feeder losses and the earth station receiver G/T. The free-space and other losses are calculated for the downlink frequency. The resulting carrier-to-noise density ratio appears at the detector of the earth station receiver.

3.7.1 Output Back-Off

Where input back-off is employed, a corresponding output back-off must be allowed for in the satellite EIRP. Output back-off is not linearly related to input back-off. A rule of thumb frequently used is to take the output back-off as the point on the curve which is 5 dB below the extrapolated linear portion.

For the uplink, the saturation flux density at the satellite receiver is a specified quantity. For the downlink, there is no need to know the saturation flux density at the earth station receiver since this is a terminal point and the signal is not used to saturate a power amplifier.

3.7.2 Satellite TWTA output

The satellite power amplifier which usually is a traveling-wave tube amplifier, has to supply the radiated power plus the transmit feeder losses. These losses include the waveguide, filter, and coupler losses between the TWTA output and the satellite's transmit antenna (Wilson 1994).

3.8 Effects of Rain

Up to this point all calculations have been made for clear-sky conditions meaning the absence of weather-related phenomena might affect the signal strength. In the C-band and the Ku-band, rainfall is the most significant cause of signal fading. Rainfall results in attenuation of radio waves by scattering and by absorption of energy from the wave. Rain attenuation increases with increasing frequency and is worse in the Ku-band compared with the C-band. Studies have shown that the rain attenuation for horizontal polarization is considerably greater than for vertical polarization.

Rain attenuation data are usually available in the form of curves or tables showing the fraction of time that a given attenuation is exceeded or the probability that a given attenuation will be exceeded.

Table 3.2 Rain Attenuation for cities in Ontario, Canada (Roddy 2001)

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

From the above table the percentage figures at the head of the first three columns give the percentage of time, averaged over any year, that the attenuation exceeds the dB values given in each column. For example, at Thunder Bay, the rain attenuation exceeds 0.2 dB for 0.1 percent of the time. Alternatively, one could say that for 99 percent of the time, the attenuation will be equal to or less than 0.2 dB; for 99.5 percent of the time it will be equal to or less than 0.3 dB; and for 99.9 percent of the time, it will be equal to or less than 1.3 dB.

Rain attenuation is accompanied by noise generation and both the attenuation and the noise adversely affect satellite circuit performance. As a result of falling through the atmosphere, raindrops are somewhat flattened in shape becoming elliptical rather than spherical. When a radio wave with some arbitrary polarization passes through raindrops, the component of electric field in the direction of the major axes of the raindrops will be affected differently from the component along the minor axes. This produces a depolarization of the wave; in effect, the wave becomes elliptically polarized. This is true for both linear and circular polarizations and the effect seems to be much worse for circular polarization. Where only a single polarization is involved the effect is not serious. But where frequency reuse is achieved through the use of orthogonal polarization depolarizing devices which compensate for the rain depolarization may have to be installed.

Where the earth station antenna is operated under cover of a radome, the effect of the rain on the radome must be taken into account. Rain falling on a hemispherical radome forms a water layer of constant thickness. Such a layer introduces losses both by absorption and by reflection. It is desirable therefore that earth station antennas be operated without radomes where possible. Without a radome water will gather on the antenna reflector but the attenuation produced by this is much less serious than that produced by the wet radome.

3.8.1 Uplink Rain-Fade Margin

Rainfall results in attenuation of the signal and an increase in noise temperature, degrading the [C/N] at the satellite in two ways. The increase in noise; however, is not usually a major factor for the uplink. This is so because the satellite antenna is pointed toward a "hot" earth and this is added to the satellite receiver noise temperature tends to mask any additional noise induced by rain attenuation. What is important is that the uplink carrier power at the satellite must be held within close limits for certain modes of operation and some form of uplink power control is necessary to compensate for rain fades. The power output from the satellite may be monitored by a central control station or in some cases by each earth station and the power output from any given earth station may be increased if required to compensate for fading. Thus the earth-station HPA must have sufficient reserve power to meet the fade margin requirement.

Some typical rain-fade margins are shown in Table 1.4. As an example, for Ottawa, the rain attenuation exceeds 1.9 dB for 0.1 percent of the time. This means that to meet the specified power requirements at the input to the satellite for 99.9 percent of the time the earth station must be capable of providing a 1.9-dB margin over the clear-sky conditions.

3.8.2 Downlink Rain-Fade Margin

Rainfall introduces attenuation by absorption and scattering of signal energy; henceforth, the absorptive attenuation introduces noise. Rainfall degrades the received [C/N] in two ways: By attenuating the carrier wave and by increasing the sky-noise temperature.

For low frequencies (6/4 GHz) and low rainfall rates (below 1 mm/h), the rain attenuation is almost entirely absorptive. At higher rainfall rates, scattering becomes significant especially at the higher frequencies. When scattering and absorption are both significant the total attenuation must be used to calculate the reduction in carrier power and the absorptive attenuation to calculate the increase in noise temperature.

As mentioned earlier that a minimum value of [C/N] is required for satisfactory reception. In the case of frequency modulation the minimum value is set by the threshold level of the FM detector and a threshold margin is normally allowed. Sufficient margin must be allowed so that rain-induced fades do not take the [C/N] below threshold more than a specified percentage of the time (Roddy 2001).

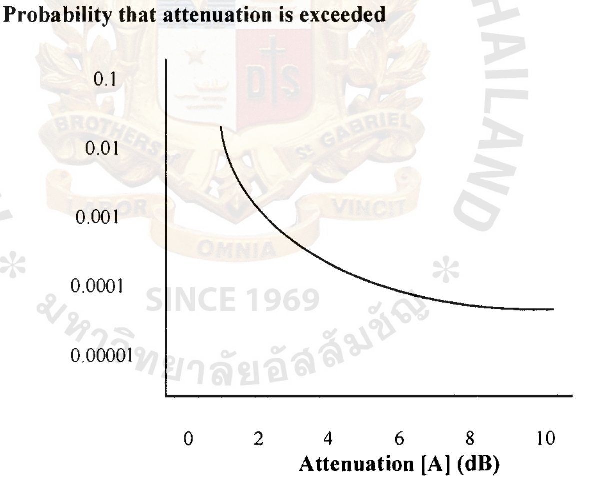


Figure 3.2 Typical Rain Attenuation Curve (Roddy 2001)

3.9 Intermodulation Noise

Intermodulation occurs where multiple carriers pass through any device with nonlinear characteristics. In satellite communications systems this most commonly occurs in the traveling-wave tube high-power amplifier aboard the satellite. Both amplitude and phase nonlinearities give rise to intermodulation products.

Third-order intermodulation products fall on neighboring carrier frequencies where they result in interference. Where a large number of modulated carriers are present the intermodulation products are not distinguishable separately but instead appear as a type of noise which is termed intermodulation noise.

The carrier to intermodulation noise ratio is usually found experimentally or in some cases it may be found by computer methods. Once this ratio is known it can be combined with the carrier to thermal noise ratio by the addition of the reciprocals.

In order to reduce intermodulation noise the TWT must be operated in a back-off condition as mentioned previously. Figure 3.3 shows how the [C / N] ratio improves as the input back-off is increased for a typical TWT. At the same time increasing the back-off decreases both uplink and downlink [C / N]. The result is that there is an optimal point where the overall carrier-to-noise ratio is a maximum (Roddy 2001).

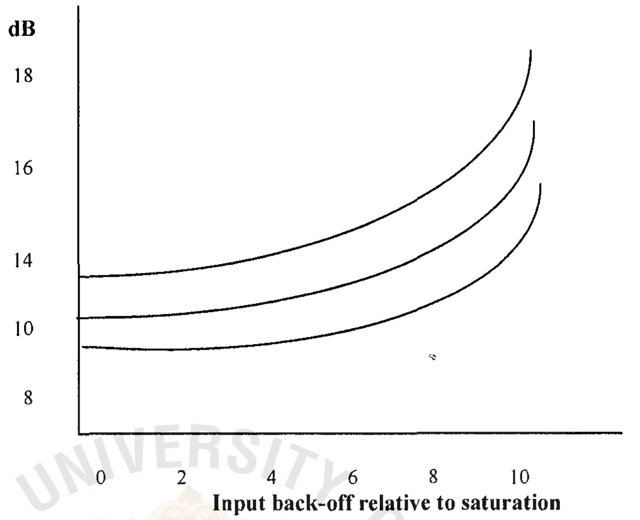


Figure 3.3 Intermodulation in a typical TWT (Roddy 2001)

3.10 Link Budget Details

The next Table gives the link budget details follow with references notes.

Table 3.3 Downlink Signal Powers (Wilson 1994)

(Satellite – ASTRA 1A Receiving Location – London (51.3 °N, 0.1 °W)

SATELLITE:	
Position	**19.2°E**
(1) $Ø_d$	**-19.3 °**
(2) Frequency	**11.406 GHz**
(3) Transponder Output Power	**45 Watts (+ 16.5 dBW)**
(4) Antenna Gain (G_t)	**34.5 dB**
(5) Waveguide and Wiring Losses (L_{wt})	**1.0 dB**
(6) E.I.R.P.	**51 dBW**
TRANSMISSION PATH:	
(7) Length (d)	**38744 km**
(8) Basic Path Loss (L_{fs})	**205.3 dB**
(9) Atmospheric Loss (L_{at})	**1.7 dB**
(10) Total Path Loss	**207 dB**
(11) P.f.d. on ground	**-114.5 dBW/m^2**
RECEIVING ANTENNA:	
(12) Diameter (D)	**80 cm**
(13) Efficiency	**65%**
(14) Gain (G_r)	**37.7 dB**
(15) Losses (L_r)	**4.5 dB**
(16) A_{eff}	**- 4.9 dB**
(17) Output Signal Power	**- 123.9 dBW**

(1) $Ø_d$ is the difference in longitude between the satellite and the earth station.

(2) This is the frequency of a single television channel. The range for this particular satellite at present is 11.214 – 11.436 GHz.

(6) EIRP = G_tP_t = 34.5 dB + 16.5 dBW = 51 dBW

(7) $d = h\sqrt{\{1+0.42(1 - \cos \Theta_r \cos Ø_d)\}}$

Where h is the height of a satellite above the equator which is 35,786 km; Θ_r is the receiving location, 51.3° and $Ø_d$ is -19.3°. Hence, d = 38,744 km

(8) $L_{fs} = 92.44 + 20(\log f + \log d)$ dB   Note: from a known equation

Given f (frequency) of 11.406 GHz and d (distance) of 38,744 km from (7), L_{fs} is calculated as 205.3 dB.

(9) A rough guide is given by:

Elevations of 5 - 14°, L_{at} = 5.0 dB

Elevations of 15 - 24°, L_{at} = 2.5 dB

Elevations of 25 - 45°, L_{at} = 1.7 dB

(10) Total Path Loss is simply the addition of the basic path loss and the atmospheric loss.

(11) From the known equation, Power Flux Density on Earth or p.f.d. is equal to:

EIRP – 71 – 20 log d – L_{at} dBW/m^2

(14) See Appendix A [Knowing (12) and (13)]

(15) For an ordinary home or commercial parabolic dish a total antenna and wiring loss of 4.5 dB is approximated.

(16) See Table 3.3 below:

Table 3.4 Effective Areas of Parabolic Antennas (Wilson 1994)

A_{eff} expressed in dB

Efficiency (%)

Dish diameter (cm)	50	55	60	65	70	75	80
30	- 14.5	- 14.1	- 13.7	- 13.4	- 13.1	- 12.8	- 12.5
40	- 12.0	- 11.6	- 11.2	- 10.9	- 10.6	- 10.3	- 10.0
50	- 10.1	- 9.7	- 9.3	- 8.9	- 8.6	- 8.3	- 8.0
60	- 8.5	- 8.1	- 7.7	- 7.4	- 7.0	- 6.7	- 6.5
70	- 7.2	- 6.7	- 6.4	- 6.0	- 5.7	- 5.4	- 5.1
80	- 6.0	- 5.6	- 5.2	- 4.9	- 4.5	- 4.2	- 4.0
90	- 5.0	- 4.6	- 4.2	- 3.8	- 3.5	- 3.2	- 2.9
100	- 4.1	- 3.6	- 3.3	- 2.9	- 2.6	- 2.3	- 2.0
120	- 2.5	- 2.1	- 1.7	- 1.3	- 1.0	- 0.7	- 0.4
140	- 1.1	- 0.7	- 0.3	0	0.3	0.6	0.9
160	0	0.4	0.8	1.2	1.5	1.8	2.1
180	1.0	1.5	1.8	2.2	2.5	2.8	3.1

(17) A measure of the output of a receiving antenna may be given by:

i) Raising the input signal level by the gain, G_r , here calculated from e.i.r.p. (6) – total path loss (10) + receiving antenna gain (14) – antenna losses (15); or

ii) Multiplying the surrounding power flux density by the effective area of the antenna, ie.: p.f.d. on ground (11) + A_{eff} (16) – antenna losses (15).

It is all well develop a link budget as concluded above but we end up with a figure which does not seem to mean much. Evidently we have yet to decide whether this signal level is satisfactory. Naturally it all depends on the purpose of the system.

IV. PROCESS GUIDELINE

4.1 Link Budget Process Guideline

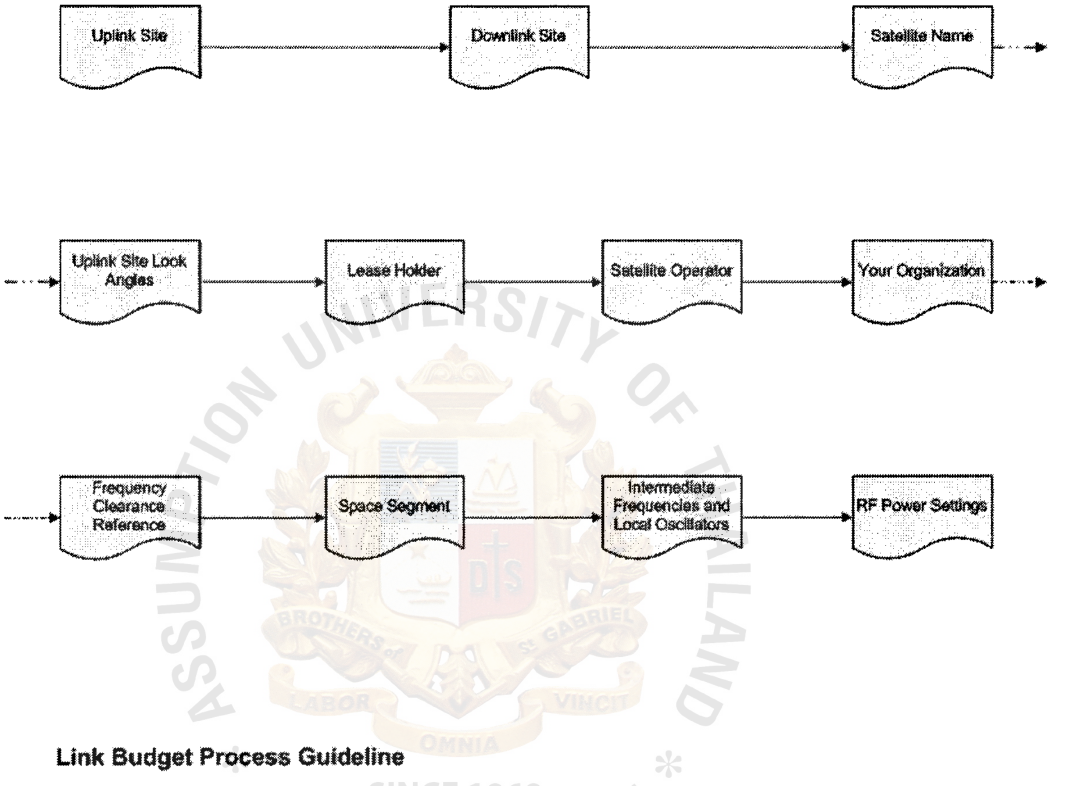


Figure 4.1 Link Budget Process Guideline (BBC 2005)

Now that we have developed a basic understanding of individual components of a satellite communication link, all the concepts must be tied together. When considering the implementation of a satellite network the following broad phases may be used: A network for the use of a satellite communication is identified; a comparative analysis with other types of transmission media is performed. In some applications the choice of satellite communications may be obvious. In others, a satellite system may be favored in a complementary role. Then the basic satellite system model is refined further and a business plan developed. The arrangement of capital to finance the project in conjunction with completion of applicable clearance and licenses is a necessity.

The running costs of a satellite communication project are high and must be considered in cost. It is also useful to discuss realistic cost estimates with manufacturers. Furthermore, implementation aspects such as equipment procurement, site selection and hiring of personnel are initiated. The system is then implemented and a mechanism set in place to operate and maintain the network to ensure reliable service and guarantee continuity. Another pre-consideration is the overall performance monitoring of the system to ascertain its future viability and upgrades.

The above Figure 4.1 shows a link budget process guideline which is detailed below with examples:

1. Uplink Site -- This is where we specify the uplink area or site given the correct latitude and longitude coordinates. Uplinks can be possible from isolated areas which may not be so critical as long as the satellite can be seen and you are within the uplink footprint. Eg. Uplink site is Wood Norton with latitude of 52.123 North and longitude of 1.977 West.

2. Downlink Site -- The downlink site can be thousands of kilometers apart from the uplink site. This is one of the known advantages in satellite communications. Eg. Downlink site is Berkshire with latitude of 45.332 North and longitude of 3.410 East.

3. Satellite Name -- Once we know both the uplink and downlink sites, a preliminary verification of satellite details such as satellite name, footprint, and its

coverage should be identified at this stage. Eg. Satellite name is Telecom2D at 8.0 West of longitude.

4. Uplink Site Look Angles -- Direction in which to point to the earth station antenna which require azimuth (angle in the horizontal plane relative to true North in degrees ETN) and elevation (angle above local horizon). Look angles depend on satellite position (degrees East or West of Greenwich) and earth station position (latitude and longitude). Eg. Azimuth (true) is 187.6 ETN, Azimuth (magnitude) is 190.8 EMN, with an elevation of 30.11.

5. Leaseholder -- Details of the satellite provider leasing in terms of contractual period and terms. Eg. Leaseholder is Globecast with contact telephone +44 207 753 3646.

6. Satellite Operator -- Once all required information are gathered, a satellite control center can then be intact. Eg. Satellite operator is France Telecom with the deputy person contact information.

7. Your Organization -- Details of your organization must be provided at this stage including name, contact telephone number, and most importantly your uplink registration code. Eg. Organization is BBC with a telephone +44 785 074 2712 and the uplink registration code of UKI214 (flyaway).

8. Frequency Clearance Reference -- In accordance to the ITU or FCC policy to get permission of frequency clearance. This is a free of charge process which can also be applied online. Eg. Frequency clearance reference number of 2433.

9. Space Segment -- This is the part of satellite booking which refers to communications channel parameters that must be pre-worked out using different formulas mentioned earlier. Eg. Booking date/time is 24/11/05 at 15:30 – 16:30 GMT,

channel name is P7 on transponder K9, type of channel is communications channel, allocated RF bandwidth of 400 KHz, frequencies / polarizations of 11.5948 / Y-polarization, EIRP is 39.3 dBW, IBO is 28.6 dB, OBO is 23.7 dB, FEC of ½, Rtx of 136.53 Kb/s using QPSK modulation with a symbol rate of 68.27 Ksymb/s, occupied RF bandwidth of 92.16 KHz.

10. Intermediate Frequencies and Local Oscillators -- For both up-converted and down-converted frequencies. Eg. DVB modulator upconvertor LO of 12.8 GHz, LNB on dish is 10.0 GHz, L-band transmit frequency of 1.5948 GHz, and L-band receive frequency of 1.5944 GHz.

11. RF Power Settings -- To ensure that all settings of your equipment are correctly tuned. Note that all values must be carefully calculated. Eg. Block diagram of output stage, HPA probe coupline factor at GHz, thermocouple power meter readings of -37.0 dBm, DVB modulator L-band of -10.0 dBm, HPA gain of 63%, power gains of 6 W.

4.2 Roadmap and Technology Trends (Richharia 1999)

In the initial years of satellite communications, costs and risks were high because of limitations in technology. Most resources were therefore expended in improving the technology. Application areas were limited to the fixed satellite services where satellite communication systems provided distinct advantages despite high costs. Significant research and development efforts were made in subsequent years to improve all the aspects of technology. The power generation capabilities of satellites have increased significantly; satellite and ground antenna sub-system performance have improved, making it possible to use shaped and spot beams and dual polarization operation.

Similarly with earth station technology that has improved considerably, benefiting from advances in solid-state technology and mass production. Earth station size and costs have decreased dramatically, giving satellite systems the capability to provide service directly at users' premises and to portable and hand-held telephones. Some of the possible future applications and emerging growth areas might be direct communication to customers' premises bypassing public switched network providing broadband services such as multimedia. Communications and distress alert facility for ships, aircraft, land vehicles and individuals. Another interesting concept is an open satellite communication systems standard for provision of a global satellite-based information infrastructure similar to the Internet model. Various satellites can be interconnected via an agreed set of interface standards. Interfaces may be defined variously such as at system architecture level, inter-satellite physical and protocol level, multiple-access and modulation level depending on the degree of desired inter-operability. Thus operators could provide local nodes and interconnect with other operators via a standard interface according to individual requirements, bearing the cost of only their part of the node.

There is no doubt that the next decade will witness satellites being used for the delivery of a variety of services – be it 3-D television pictures and holographic images, satellite radio programs in remote jungles, or such entertainment on a moon surface.

4.3 Cost Associated with Choosing Satellite Providers (BBC Handout)

There are a number of advantages of satellite links over terrestrial links for contribution circuits. First off in terms of cost, a single satellite link is often cheaper than a multiple terrestrial links as long as the program is short. Cost quotation can be requested through the satellite provider. It is advisable to do a comparison between different providers where applicable. The cost should state the distance covered in which satellite uplink and downlink stations could be a thousand of kilometers apart; maximum distance for a single terrestrial microwave hop is approximately sixty kilometers.

Another advantage is fast setup time of a satellite van or satvan in short. It could be accessing a satellite within twenty minutes of arriving on site with tool aids such as global positioning system or GPS and flux gate compasses. Some systems have self seeking dishes to allow "non technical" staff to operate. Uplinks are possible from isolated areas where sites are not so critical as long as the satellite can be seen and you are within the uplink footprint. Signals can be downloaded directly at the broadcasting center as long as suitable receiving dishes and equipments are available eliminating the cost of a third party providing the downlink and cross-country terrestrial links.

Link budget analysis enables you to work out all the required values prior to choosing a satellite provider. Thereby, cost can be greatly reduced if the values are correctly calculated as planned.

V. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

It is now appropriate to combine the various transmission considerations into a link budget so that we can estimate the signal output of a receiving antenna, knowing of course the transmitted power of the satellite. A link budget simply adds up the gains and losses a signal experiences on its way down from the satellite amplifier to the output of a ground receiving antenna. This is the downlink, we need not consider the uplink in the same way because for any particular satellite it is generally a single link carefully designed so that the satellite output is at the required power level and at an adequate carrier-to-noise ratio. The basis of all calculations is the isotropic antenna, a purely theoretical component yet. We will find that most noise on such a downlink is generated not so much in the link itself as in the receiving equipment on the ground.

A link budget is most conveniently expressed in decibels for then, analysis is reduced simply to addition and subtraction. Such budgets are applicable to any satellite system. Opportunities for satellite communication are opened since the advancement in transmission technology have let to the availability of low-cost satellite earth terminal and air-time fees. The superior remote access capabilities of satellite networks are foreseen to provide broadband services to geographically diverse user groups. The desire to support a wide range of broadband services in satellite networks implies many features present in terrestrial multimedia networks will also emerge in satellite networks.

A satellite system can act as an access network or as a core network. In an access network the signal sent from the subscriber's terminal is received by a satellite, which retransmits it to a gateway. The transmission of the signal to the recipient's terminal or to its nearby vicinity and further to the recipient's terminal proceeds via a gateway to a terrestrial network which acts as a core network.

5.2 Recommendation

Recommendations can be made considerably upon the result of studies on the use of a vast range of wireless services including popular new mobile communication technologies; the management of the radio-frequency spectrum and satellite orbits; the efficient use of the radio-frequency spectrum by all radio-communication services; terrestrial and satellite radio-communication broadcasting; radiowave propagation; systems and networks for the fixed-satellite and mobile services; space operation, earth exploration-satellite, meteorological-satellite and radio astronomy services.

In the foreseeable future, more organizations will rely on satellite communication technologies due to cost-performance benefits which provide real-time broadcastings. Therefore, an in-depth analysis must be undertaken prior to choosing the carrier per your requirements.

When calculating the link budget, be mindful that all values are accurately computed because having just one wrong value could lead to disastrous which might overrun the budget. It is advisable to re-work the values more than once before making a final decision as mentioned earlier that cost associated with choosing a satellite provider is costly.

Owing to the unique properties of satellite communications, the provision of certain services will be much easier and will serve a considerably wider group of interested users. However, like any other study, this project only focuses on the analysis of the satellite communications link budget which is partially accountable for the whole satellite communications. The author recommends further studies on various topics of satcoms to fulfill the overall system knowledge. Most existing data eg. Textbooks are outdated and publications can be biased. Thereby, the author suggests to gather information from accredited sources and to use your judgment wisely.

APPENDIX A

HYPOTHETICAL GAIN OF PARABOLIC ANTENNAS (dB)

Table A.1 Hypothetical Gain of Parabolic Antennas (dB) (Wilson 1994)

Efficiency = 50%

		Diameter (cm)										
Frequency (GHz)	Wavelength (cm)	35	60	70	80	90	100	110	120	130	140	150
11.0	2.73	29.1	33.8	35.1	36.3	37.3	38.2	39.1	39.8	40.5	41.2	41.8
11.2	2.68	29.3	34.0	35.3	36.4	37.5	38.4	39.2	40.0	40.7	41.3	41.9
11.4	2.63	29.4	34.1	35.4	36.6	37.6	38.5	39.4	40.1	40.8	41.5	42.1
11.6	2.59	29.6	34.3	35.6	36.8	37.8	38.7	39.5	40.3	41.0	41.6	42.2
11.8	2.54	29.7	34.4	35.7	36.9	37.9	38.8	39.7	40.4	41.1	41.8	42.3
12.0	2.50	29.9	34.5	35.9	37.0	38.1	39.0	39.8	40.6	41.3	41.9	42.5
12.2	2.46	30.0	34.7	36.0	37.2	38.2	39.1	39.9	40.7	41.4	42.0	42.6
12.4	2.42	30.2	34.8	36.2	37.3	38.3	39.3	40.1	40.8	41.5	42.2	42.8
12.6	2.38	30.3	35.0	36.3	37.5	38.5	39.4	40.2	41.0	41.7	42.3	42.9
12.8	2.34	30.4	35.1	36.4	37.6	38.6	39.5	40.4	41.1	41.8	42.5	43.1

Efficiency = 60%

		Diameter (cm)										
Frequency (GHz)	Wavelength (cm)	35	60	70	80	90	100	110	120	130	140	150
11.0	2.73	29.9	34.6	35.9	37.1	38.1	39.0	39.9	40.6	41.3	41.9	42.5
11.2	2.68	30.1	34.7	36.1	37.2	38.3	39.2	40.0	40.8	41.5	42.1	42.7
11.4	2.63	30.2	34.9	36.2	37.4	38.4	39.3	40.2	40.9	41.6	42.3	42.9
11.6	2.59	30.4	35.0	36.4	37.5	38.6	39.5	40.3	41.1	41.8	42.4	43.0
11.8	2.54	30.5	35.2	36.5	37.7	38.7	39.6	40.4	41.2	41.9	42.5	43.1
12.0	2.50	30.7	35.3	36.7	37.8	38.9	39.8	40.6	41.3	42.0	42.7	43.3
12.2	2.46	30.8	35.5	36.8	38.0	39.0	39.9	40.7	41.5	42.2	42.8	43.4
12.4	2.42	30.9	35.6	37.0	38.1	39.1	40.1	40.9	41.6	42.3	43.0	43.6
12.6	2.38	31.1	35.8	37.1	38.3	39.3	40.2	41.0	41.8	42.5	43.1	43.7
12.8	2.34	31.2	35.9	37.2	38.4	39.4	40.3	41.2	41.9	42.6	43.3	43.9

Efficiency = 65%

		Diameter (cm)										
Frequency (GHz)	Wavelength (cm)	35	60	70	80	90	100	110	120	130	140	150
11.0	2.73	30.3	34.9	36.3	37.4	38.5	39.4	40.2	41.0	41.6	42.3	42.9
11.2	2.68	30.4	35.1	36.4	37.6	38.6	39.5	40.4	41.1	41.8	42.4	43.0
11.4	2.63	30.6	35.2	36.6	37.7	38.8	39.7	40.5	41.3	42.0	42.6	43.2
11.6	2.59	30.7	35.4	36.7	37.9	38.9	39.8	40.7	41.4	42.1	42.8	43.4
11.8	2.54	30.9	35.5	36.9	38.0	39.1	40.0	40.8	41.6	42.2	42.9	43.5
12.0	2.50	31.0	35.7	37.0	38.2	39.2	40.1	40.9	41.7	42.4	43.0	43.6
12.2	2.46	31.2	35.8	37.2	38.3	39.3	40.3	41.1	41.8	42.5	43.2	43.8
12.4	2.42	31.3	36.0	37.3	38.5	39.5	40.4	41.2	42.0	42.7	43.3	43.9
12.6	2.38	31.4	36.1	37.5	38.6	39.6	40.6	41.4	42.1	42.8	43.5	44.1
12.8	2.34	31.6	36.3	37.6	38.7	39.8	40.7	41.5	42.3	43.0	43.6	44.2

Efficiency = 70%

		Diameter (cm)										
Frequency (GHz)	Wavelength (cm)	35	60	70	80	90	100	110	120	130	140	150
11.0	2.73	30.6	35.3	36.6	37.8	38.8	39.7	40.5	41.3	42.0	42.6	43.2
11.2	2.68	30.7	35.4	36.8	37.9	38.9	39.8	40.7	41.4	42.1	42.8	43.4
11.4	2.63	30.9	35.6	36.9	38.1	39.1	40.0	40.8	41.6	42.3	42.9	43.5
11.6	2.59	31.0	35.7	37.1	38.2	39.2	40.2	41.0	41.7	42.4	43.1	43.7
11.8	2.54	31.2	35.9	37.2	38.4	39.4	40.3	41.1	41.9	42.6	43.2	43.8
12.0	2.50	31.3	36.0	37.4	38.5	39.5	40.4	41.3	42.0	42.7	43.4	44.0
12.2	2.46	31.5	36.2	37.5	38.7	39.7	40.6	41.4	42.2	42.9	43.5	44.1
12.4	2.42	31.6	36.3	37.6	38.8	39.8	40.7	41.6	42.3	43.0	43.7	44.3
12.6	2.38	31.8	36.4	37.8	38.9	40.0	40.9	41.7	42.5	43.2	43.8	44.4
12.8	2.34	31.9	36.6	37.9	39.1	40.1	41.0	41.8	42.6	43.3	43.9	44.5

Efficiency = 75%

		Diameter (cm)										
Frequency (GHz)	Wavelength (cm)	35	60	70	80	90	100	110	120	130	140	150
11.0	2.73	30.9	35.6	36.9	38.1	39.1	40.0	40.8	41.6	42.3	42.9	43.5
11.2	2.68	31.0	35.7	37.1	38.2	39.2	40.1	41.0	41.7	42.4	43.1	43.7
11.4	2.63	31.2	35.9	37.2	38.4	39.4	40.3	41.1	41.9	42.6	43.2	43.8
11.6	2.59	31.3	36.0	37.4	38.5	39.5	40.5	41.3	42.0	42.7	43.4	44.0
11.8	2.54	31.5	36.2	37.5	38.7	39.7	40.6	41.4	42.2	42.9	43.5	44.1
12.0	2.50	31.6	36.3	37.7	38.8	39.8	40.7	41.6	42.3	43.0	43.7	44.3
12.2	2.46	31.8	36.5	37.8	39.0	40.0	40.9	41.7	42.5	43.2	43.8	44.4
12.4	2.42	31.9	36.6	37.9	39.1	40.1	41.0	41.9	42.6	43.3	44.0	44.6
12.6	2.38	32.1	36.7	38.1	39.2	40.3	41.2	42.0	42.8	43.5	44.1	44.7
12.8	2.34	32.2	36.9	38.2	39.4	40.4	41.3	42.1	42.9	43.6	44.2	44.8

Efficiency = 80%

		Diameter (cm)										
Frequency (GHz)	Wavelength (cm)	35	60	70	80	90	100	110	120	130	140	150
11.0	2.73	31.2	35.8	37.2	38.3	39.4	40.3	41.1	41.9	42.6	43.2	43.8
11.2	2.68	31.3	36.0	37.3	38.5	39.5	40.4	41.3	42.0	42.7	43.4	44.0
11.4	2.63	31.5	36.1	37.5	38.6	39.7	40.6	41.4	42.2	42.9	43.5	44.1
11.6	2.59	31.6	36.3	37.6	38.8	39.8	40.7	41.6	42.3	43.0	43.7	44.3
11.8	2.54	31.8	36.4	37.8	38.9	40.0	40.9	41.7	42.5	43.2	43.8	44.4
12.0	2.50	31.9	36.6	37.9	39.1	40.1	41.0	41.9	42.6	43.3	44.0	44.6
12.2	2.46	32.1	36.7	38.1	39.2	40.3	41.2	42.0	42.8	43.5	44.1	44.7
12.4	2.42	32.2	36.9	38.2	39.4	40.4	41.3	42.1	42.9	43.6	44.2	44.8
12.6	2.38	32.3	37.0	38.4	39.5	40.5	41.5	42.3	43.0	43.7	44.4	45.0
12.8	2.34	32.5	37.2	38.5	39.7	40.7	41.6	42.4	43.2	43.9	44.5	45.1

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