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A SYSTEM DESIGN AND ANALYSIS FOR SATELLITE COMMUNICATION LINK

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ABSTRACT

A satellite RF communication link is analyzed based on a simple fundamental equations by systematic approach in this paper. The number of variables related to a design and analysis of satellite RF link is often a dozen or more, thus it is a tedious and time-consuming task. With the given input data, the important parameters are calculated step by step and three communication characteristics such as communication channel capacity, carrier-to-noise ratio (CNR) at the satellite and ground station are analyzed. It gives very useful information to the system engineers for designing and analyzing the overall satellite communication system in the conceptual design phase.

Key words: satellite, RF, link margin

1. INTRODUCTION

During the last 30 years, spacecraft placed in Geostationary Earth Orbit (GEO) have been used to support all forms of communication via satellite-voice, data, and broadcasting. The major advantages of these systems is their unchanging position with respect to the earth surface, thus no control overhead is required to track the satellites. However, more recently a number of projects involving the employment of constellations of Low Earth Orbit (LEO) and Medium Earth Orbit (MEO) satellites which are in the process of being implemented, are challenging the supremacy of GEO systems.

Satellites in roughly circular orbit probably will be in operation at different altitudes; satellites in elliptic orbit may have widely differing altitudes at perigee and apogee. Power output of the transponders in differing communication satellite may vary by an order of magnitude or more. With the advent or greater booster launch capability, communication satellites may greatly increase in weight, permitting an increased number of transponders per satellite or improved antenna gains or both.

The ground stations that will transmit to and receive messages from communication satellites in these days are equally diverse in character. Movable parabolic dish antennas range from a few meters

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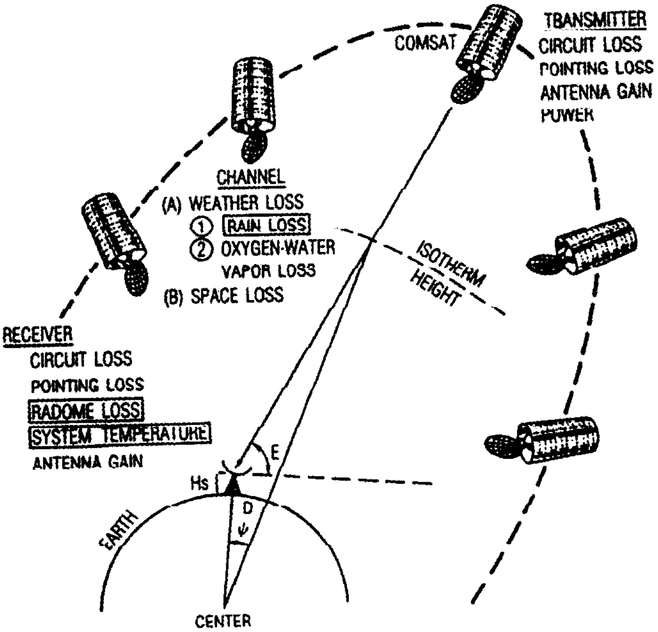

Figure 1. Satellite communication link geometry.

in diameter to an about 26m. The effective overall receiver noise temperatures available today range from as little as about 30°K to thousands of degrees Kelvin. And the required signal-to-noise-ratios at one ground receiver may differ considerably, depending on the type of modulation employed.

Even for rather simple problems resulting in overall system design or analysis, the number of variables involved is often a dozen or more, thus precluding the possibility of construction of a few simple "trade-off" curves to indicate the most desirable choice of system parameters. However, it is a tedious and time-consuming task to assimilate applicable design and computational equations to check validity of study conclusions drawn by others on the basis of assumptions of about a dozen parameters. It is the intent of this paper to bring together a majority of the computational equations which are applicable to the overall design of satellite communication systems. Figure 1 illustrates a simplified diagram for a typical satellite communication link geometry. Pertinent design equations are introduced and discussed, briefly and the utility of these simple equations computational aids is demonstrated in the solutions of simple satellite communication system design and analysis problems.

2. FUNDAMENTAL DESIGN PARAMETERS

2.1 Antennas

Antennas are often characterized by their ability to direct radiated power, especially with respect to an idealized isotropic antenna, radiating power equally in all directions. The maximum effective

Table 1. Antenna Gain and effective area for several common antennas.

Antenna	Gain above IsotropicAntenna, G	Maximum Effective Area, A
Isotropic (hypothetical)	1	$\frac{\lambda^2}{4\pi} = 0.079\lambda^2$
Infinitesimal dipole or loop	1.5	$\frac{3}{8\pi}\lambda^2 = 0.119\lambda^2$
Linear half-wavelength dipole	1.64	$\frac{30}{73\pi}\lambda^2 = 0.13\lambda^2$
Optimum horn (Mouth area = A)	$10\frac{A}{\lambda^2}$	$0.81A$
Parabolic reflector($aperture = A, \eta \cong 0.5 to 0.6$)	$\frac{4\pi\eta A}{\lambda^2}$	ηA
Broadside array (area = A)	$4\pi\frac{A_{max}}{\lambda^2}$	A_{max}
Turnstile	1.15	$1.15\frac{\lambda^2}{2\pi} = 0.0915\lambda^2$

area of any antenna is given by

$$A = G\frac{\lambda^2}{4\pi} \tag{1}$$

The maximum power gain and effective area of several common antennas are given in table 1 (Vincent et al. 1994).

PARABOLIC ANTENNA GAIN

The parabolic reflector antenna is of particular interest in communication satellite systems. Let the physical aperture of the parabolic reflector be given by $A_{phy} = \pi\frac{D^2}{4}$, it is apparent that the gain of an antenna can be expressed as $G = \frac{4\pi A}{\lambda^2}$. Thus, the gain of the parabolic reflector is generally written as $G = \frac{4\pi\eta A_{phy}}{\lambda^2}$. Theoretically, for a circular aperture, $A \le A_{phy}$; hence $0 \le \eta \le 1.0$, and η is taken to be equivalent to antenna "efficiency". Usually, η is found to lie in the range 0.5 to 0.6. In this paper an efficiency of 54% will be assumed, thus giving an apparent power gain for a parabolic antenna of

$$G = 0.54\left(\frac{\pi D}{\lambda}\right)^2 \tag{2}$$

which can be expressed in decibels,

$$G = 20\log f + 20\log D - 42.2 \tag{3}$$

where f is in MHz and D in meters. It is noted that an efficiency of 54% is conventional, an efficiencies of 60% or higher have been attained with some of the most recent large parabolic antennas.

PARABOLIC ANTENNA BEAMWIDTH

If the circular aperture of a large parabolic reflector is uniformly illuminated, the beam angle (in degrees) between the half-power points is given by $\theta = 58\frac{\lambda}{D}$. In actual antenna installations, illumination intensity across the aperture often is not uniform, but decreases from the center out to the edges with a corresponding reduction in gain, increase in beamwidth, and reduction in side lobes. Thus, more realistic expression for beam angle between half-power points is

$$\theta = 70\frac{\lambda}{D} \tag{4}$$

2.2 Space Path Loss

When a receiver and transmitter axially aligned and displaced in space by a distance much greater than the transmitted wavelength, the received power is given by

$$P_R = \frac{P_T G_T}{4\pi d^2} A_R = P_T \frac{A_R A_T}{\lambda^2 d^2} \tag{5}$$

When both receiving and transmitting antennas are isotropic, the ratio of transmitted to received power is

$$\left(\frac{P_T}{P_R}\right)_{Iso} = \frac{(4\pi)^2 d^2}{\lambda^2} \tag{6}$$

Free space path loss between receiving and transmitting antenna is defined to be

$$L_{FS} = 10 \log\left(\frac{P_T}{P_R}\right) = 10 \log \frac{(4\pi)^2 d^2}{\lambda^2} \tag{7}$$

And it is convenient to use

$$L_{FS} = 32.5 + 20 \log f + 20 \log d(decibels) \tag{8}$$

where f is in MHz, and d is in km.

2.3 Effective Noise Temperature

It is becoming increasingly common to characterize the noise at the input of a receiver in terms of the effective noise temperature. The total noise power at the input of the receiver is taken to be

$$N_t = kT_{eff}B \tag{9}$$

The receiver noise density, N (watts/Hz) can be directly related to noise temperature, T. It is noted that effective noise temperature tends to be the resultant of a myriad of noise effect, and all of which are directly attributable to the internally generated noise in the receiver itself.

2.4 Carried-to-noise Ratio

The radiated carrier power, transmitter and receiver gains, system losses, and bandwidth are related by the equations below for one-way and two-way (passive reflector) communications.

One-way Transmission

The carrier-to-noise power ratio is described as

$$\frac{C}{N_t} = \frac{P_T G_T G_R}{kT_{eff} B_{IF} L_{FS}} \tag{10}$$

In decibel form,

$$\frac{C}{N_t}(dB) = P_T(dBW) + G_T(dB) + G_R(dB) - L_{Fs}(dB) - kT_{dff}B_{if}(dBW) \tag{11}$$

Two-way Transmission (Passive reflector)

$$\frac{C}{N_t} = \frac{P_T G_T G_R G_{PR}}{kT_{eff} B_{IF} L_{FS_u} L_{FS_d}} \tag{12}$$

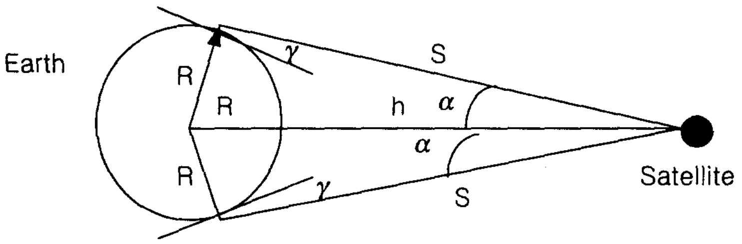

Figure 2. Geometry of the slant range.

The receiver intermediate frequency (IF) bandwidth will usually be assumed to be twice the information bandwidth (baseband). The general form suitable for use, Eq. (12) becomes

$$N_t(dB) = P_T(dBW) + G_T(dB) + G_R(dB) + G_{PR}(dB) - L_{FS_u}(dB) - L_{FS_d}(dB) - kT_{eff}B_{if}(dBW \quad (13)$$

2.5 SLANT LANGE

The communication path length from a satellite to a point on earth varies from the altitude H to the maximum slant range S_M , where S_M is defined as the distance from the satellite to a point of tangency on the earth's surface, and is a function of h. Due to noise from the ground in the vicinity of the antenna, it is generally necessary to maintain the receiving antenna elevation angle at least 5 to 10 degree above the local horizontal. Hence, for a given satellite altitude, the maximum communication path distance will also be a function of elevation angle γ. The geometry of the slant range is illustrated in figure 2, where it is seen that for a given elevation angle γ and satellite altitude h, the largest slant range, S, over which communication would take place is given by (Timothy et al, 1986)

$$S = (R+h)\frac{\sin\left[\frac{\pi}{2} - \gamma - \sin^{-1}(\frac{R}{R+h}\cos\gamma)\right]}{\cos\gamma} \quad (14)$$

3. COMMUNICATION SATELLITE SYSTEM DESIGN AND ANALYSIS

The RF communication links of current communication satellite systems have been designed and analyzed using the fundamental parameters in this section; communication channel capacity, variation in carrier-to-noise ratio, and validity of a carrier-to-noise ratio, for illustrative examples. However, the particular methods of signal processing will not be explicitly considered here.

3.1 Communication Channel Capacity

An active repeater, geostationary earth orbit (GEO) communication satellite system is considered in which, for more reliable operation, each satellite contains more than one transponder. For a set of transponder and ground-station characteristics, it is desired to know how many duplex data channels can be accomplished by a single satellite. A matching "up-link" channel capacity can be assured by requiring adequate ground transmitter antenna gain and power output. The required input data information is given below (Shin et al. 2000) and the analysis results are shown in Table 2.

Table 2. Analysis results of communication channel capacity.

Analysis and Design procedures	Values	Equations and parameters
(1) The equipment gain	108.8 dB	← + ↑ + →
←Antenna gain of the ground station	54.7 dB	given D, f and Eq(3)
↑Satellite transponder power output	16.7 dBW	given
→Satellite transmitter antenna gain	37.4 dB	given
(2) Received power at the ground station	-98 dBW	Equipment gain - path loss
←Maximum slant range	41,230 km	given h, γ and Eq(14)
↑Free space path loss	206.7 dB	Eq(8)
(3)Allowable effective receiver noise power	-118 dBW	Received power minus CNR
←Required carrier-to-noise ratio over twice the baseband(CNR)	20dB	given
(4)Equivalent information bandwidth	780 MHz	
←Effective noise density	-207dBW/Hz	given T_{eff} and Eq(9)
↑Difference between noise power and density	89 dB	
(5)channels/transponder	10	← / ↑(round down)
←Half of the information bandwidth	390 MHz	0.5×780 MHz
↑Channel allocation	36MHz/ch	given
(6)Duplex channels/satellite	60	0.54*12*10 ch/transponder
Transponders/satellite	12	

Input Data

(1) Satellite-to-ground transmitting frequency (Ku-band)	12500 MHz
(2) Parabolic antenna diameter of the ground receiver	$5.6m$
(3) Satellite transponder power output	47 watts
(4) Satellite transmitter effective antenna gain	$37.4dB$
(5) Satellite orbital altitude	35,880 km
(6) Ground antenna minimum elevation angle	5 deg
(7) Required carrier-to-noise ratio over twice the baseband	20 dB
(8) Ground receiver effective noise temperature	$150^{\circ}K$
(9) Required bandwidth/channel	36 MHz
(10) Number of transponders/satellite	12

It is shown that the required a 20 dB carrier-to-twice baseband noise ratio provides for a conservative design.

The analysis results indicated that 10 channels per transponder and 60 duplex channels per payload, in which EIRP of RF system is 54dBw and 12 transponders are installed, can be supported for internet service with data rate of 10Mbps with the above input data using geostaionary earth orbit satellite.

3.2 Variation in carrier-to-noise ratio

Narrow-band, active repeater, ellipse orbit satellite system is considered in this analysis with one-way communication. For a set of satellite, orbital, and ground-station characteristics, it is desired to determine the variation in carrier-to-noise ratio as a function of satellite altitude at perigee and apogee. The analysis results are shown in Table3 for uplink and Table4 for downlink.

Table 3. Analysis results of Variation in carrier-to-noise ratio(Uplink).

Analysis and Design procedures	Values	Equations and parameters
(1) The equipment gain	114 dB	$\leftarrow + \uparrow + \rightarrow$
$\leftarrow$Transmitter antenna gain of the ground station	55.84 dB	given D, f and Eq(3)
$\uparrow$Ground transmitter power output	20.8 dBW	given
$\rightarrow$Satellite receiver antenna gain	37.4 dB	given
(2) Received power at the satellite	-66.4$\sim$-83 dBW	(1)minus path loss
$\leftarrow$Maximum usable slant range	1,740$\sim$11,678 km	given h, γ and Eq(14)
$\uparrow$Free space path loss	180.4$\sim$197 dB	Eq(8)
(3) Input carrier-to-noise ratio at the satellite	58.4$\sim$41.8 dB	CNR(carrier-to-noise ratio)
$\leftarrow$Effective noise density	-197.8 dBW/Hz	given T_{eff} and Eq(9)
$\uparrow$Twice the information bandwidth	73 dB	given $10\log(2 * 10MHz)$
$\rightarrow$Resultant noise power	-124.8 dB	$\leftarrow + \uparrow$

Input Data

Ground-to-Satellite

(1) Ground-to-Satellite transmitting frequency	14,250 MHz
(2) Ground transmitter power output	120 watts
(3) Ground parabolic antenna diameter	5.6 m
(4) Satellite orbital altitude (Perigee/Apogee)	520 to 7,846 km
(5) Ground antenna minimum elevation angle	10 deg
(6) Satellite receiver antenna effective gain	37.4 dB
(7) Satellite receiver antenna effective noise temperature	1,200°K
(8) Satellite receiver RF bandwidth	500 MHz
(9) Satellite information bandwidth	10 MHz

Satellite-to-Ground

(10) Transmitted frequency(Ku Band)	12,500 MHz
(11) Satellite transponder power output	47 watts
(12) Satellite transmitter antenna effective gain	37.4 dB
(13) Ground parabolic antenna diameter	5.6 m
(14) Ground antenna minimum elevation angle	10 deg
(15) Ground receiver effective noise temperature	290°K
(16) Ground receiver RF bandwidth	500 MHz
(17) Ground receiver information bandwidth	10 MHz

The carrier-to-noise ratio (CNR) variation at perigee and apogee of the elliptic orbit satellite was analyzed to estimate the communication quality for 10Mbps internet service. The results showed that the variation range of CNR is about 16.6dB between perigee and apogee both in up-link and down-link and the value of CNRs are 42 $\sim$ 58dB and 47 $\sim$ 64dB at the two point, respectively. These level of CNR guarantees good quality of communication with below 10^{-8} BER (Bit Error Rate). The analysis results are shown in Table 5.

Table 4. Analysis results of Variation in carrier-to-noise ratio(Downlink).

Analysis and Design procedures	Values	Equations and parameters
(1) The equipment gain	108.8 dB	← + ↑ + →
←Transmitter antenna gain of the ground station	54.7 dB	given D, f and Eq(3)
↑Satellite transponder power output	16.7 dBW	given
→Satellite transmitter antenna gain	37.4 dB	given
(2) Received power at the ground station	-70.2~-87 dB	(1)minus path loss
←Maximum usable slant range	1,740~11,678 km	given h, γ and Eq(14)
↑Free space path loss	179~195.8 dB	Eq(8)
(3) Input carrier-to-noise ratio at the satellite	63.6~46.8 dB	CNR(carrier-to-noise ratio)
←Effective noise density	-206.8 dBW/Hz	given T_{eff} and Eq(9)
↑Twice the information bandwidth	73 dB	given $10\log(2 * 10MHz)$
→Resultant noise power	-133.8 dB	← + ↑

Table 5. Analysis results of Validity of a carrier-to-noise ratio.

Analysis and Design procedures	Values	Equations and parameters
(1) The equipment gain	108.8 dB	← + ↑ + →
←Antenna gain of the ground station	54.7 dB	given D, f and Eq(3)
↑Satellite transponder power output	16.7 dBW	given
→Satellite transmitter antenna gain	37.4 dB	given
(2) Received power at the ground station	-97.6 dBW	(1) minus (2)- ↑
←Maximum slant range	39,660 km	given h, γ and Eq(14)
↑Free space path loss	206.4 dB	Eq(8)
(3)Allowable effective receiver noise power in twice the baseband	-117.8 dBW	← + →
←Effective noise density	-207 dBW/Hz	given $T_{eff}$and Eq(9)
↑Total Information bandwidth(baseband)	400 MHz	10channel*40MHz/channel
→twice the baseband	89.0 dB	$\log(2 \times 400MHz)10$
(4)Carrier-to-noise ratio over twice the baseband	20.2 dB	(2) minus (3)

3.3 Validity of a carrier-to-noise ratio

This analysis is to validate the parameter, CNR (Carrier-to-Noise Ratio) assumed in 3.1 paragraph, inversely. Three input data are assumed in this analysis, down-link frequency, antenna elevation angle, and required bandwidth/channel.

Input Data

(1) Satellite-to-ground transmitting frequency (assumed)	12,500 MHz
(2) Ground parabolic antenna diameter	5.6 m
(3) Satellite transponder power output	47 watts
(4) Satellite transmitter effective antenna gain	37.4 dB
(5) Satellite orbital altitude	35,880 km
(6) Ground antenna minimum elevation angle (assumed)	20 deg
(7) Ground receiver effective noise temperature	150 °Kelvin
(8) RF-bandwidth	100MHz
(9) Required bandwidth/channel (assumed)	40 MHz
(10) Total number of channels/transponder	10

It is noted from the above analysis that a carrier-to-noise ratio (CNR) of 20 dB is quite adequate for good quality for data communication depending on a modulation-demodulation scheme.

4. CONCLUSIONS

A satellite RF communication link was analyzed with simple calculation equations, step by step and the illustrative system analysis and verification were performed with these procedures. In general, the above procedures are applicable to LEO (Low Earth Orbit), MEO (Medium Earth Orbit), and GEO satellite systems, and also are valid in satellite and ground station since the two points which communicate with each other are symmetrical in the sense of up link and down link. The key parameters are operating frequency (up-link and down-link), transmitter power output, antenna gain, elevation angle of ground station antenna, satellite altitude, receiver effective noise temperature, and system and information bandwidth. Other important parameters may be calculated by combining the key parameters.

It is very informative to estimate the overall satellite communication systems. However, the more detailed analysis will be required by taking another factors such as losses and attenuations due to space environments and RF circuits into account.

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List of variable.

A	Maximum effective area of antenna
A_R	Effective area of receiving antenna
A_T	Effective area of transmitting antenna
B	Receiver noise bandwidth (Hz)
B_{IF}	Receiver IF bandwidth
c	Velocity of light, 3510^8 m/s
$\frac{C}{N_t}$	Carrier-to-noise power ratio
d	Distance between transmitting and receiving antennas
D	Antenna aperture diameter in meters
f	Frequency in Hertz
G	Antenna gain relative to an ideal isotropic antenna
G_R	Receiver antenna gain
G_T	Gain of transmitting antenna
G_{PR}	Passive reflector gain, $\frac{4\pi}{\lambda^2} A_{PR}$
h	Satellite altitude in km
k	Boltsmann's constant, $1.38 \times 10^{-23} (joules/^\circ Kelvin)$
L_{FS}	Free space path loss
L_{FS_u}	Free space path loss for up-link
L_{FS_d}	Free space path loss for down-link
N	Noise power in watts
N_t	Total effective receiver input noise power (watts)
P_R	Power available at output terminals of receiving antenna
P_T	Power radiated from transmitting antenna
S	Slant range in km
T_{eff}	Receiver effective noise temperature $(^\circ Kelvin)$
λ	Wavelength, $c \backslash f$
η	Antenna efficiency, $A \backslash A_{phy}$
θ	Antenna beam angle between half-power points in degree
γ	Antenna elevation angle (degrees)

REFERENCES

Freeman, R. L. 1981, Telecommunication Transmission Handbook, 2nd Edition (NewYork: John Wiley &Sons)

Pisacane, V. L., & Moore, R. C. 1994, Fundamentals of Space Systems (London: Oxford Univerisy Press)

Pratt, T. & Bostian, C. W. 1996, Satellite Communications (NewYork: John Wiley &Sons)

Shin, C. S., Chung, S. W., & Shin, D. W. 2000, Technical Document, A Conceptual Design of Communications and Broadcasting Satellite Payload, Satellite Communication Technology Division, Radio & Broadcasting Technology Lab. (Taejon: ETRI)