Performance Analysis of Ku-Band VSAT Networks

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Advancements in satellite transmission technology have led to the development of low-cost, compact, integrated earth stations called Very Small Aperture Terminals (VSATs). VSATs are typically used in a star network configuration to provide information directly to the user's premise. The combination of a large hub antenna and multiple very small aperture antennas provides efficient transmission links leading to high-performance economical networks. A VSAT network can be used for one-way communication to broadcast video, audio or data or for two-way communication to carry interactive data or voice between the hub and VSATs. A full duplex link consists of two one-way links, one for transmission from the hub to a VSAT (outbound) and the other for transmission from the VSAT to the hub (inbound).

A critical parameter specified for a VSAT network is the availability of its links. The availability and the link design of a VSAT network are discussed in this paper. Since the availability of a link is the percentage of time that information can be transmitted and received with acceptable quality, we first quantify the information quality and describe factors that affect the information quality. Next, we discuss the link availability. Finally, we provide a performance analysis example and draw conclusions based on the analysis.

Information Quality

The quality of transmitted information is objectively specified in terms of bit-error ratio (BER) for digital signals or signal-to-noise ratio (S/N) for analog signals. BER and S/N are each related to carrier-to-equivalent-noise-spectral-density ratio (C/N_o) at the demodulator/decoder input.

BER-C/N_o Relationship

For digital information, the BER-C/N_o relationship is a function of modulation and coding schemes used. It is often supplied by the manufacturer in terms of BER and E_b/N_o as the result of IF back-to-back measurements. E_b/N_o is energy-per-(uncoded) bit-per-noise-density ratio which is directly related to C/N_o in dBHz and the (uncoded) bit rate R in bps by the following equation:

$$E_b/N_o = C/N_o - 10\log(R)\ dB \qquad (1)$$

Phase shift keying (PSK) modulation is currently used in most VSAT networks. Two-phase PSK (BPSK) and four-phase PSK (QPSK) have about the same BER performance (same BER-E_b/N_o relationship), but BPSK requires twice the bandwidth. BPSK is generally preferred to QPSK due to the power density limits imposed by official regulatory bodies to protect satellite and terrestrial systems from severe interference [1,2] and due to the phase noise sensitivity at very low data rate to radio frequency ratios. Forward-error-correction (FEC) coding (usually, rate 1/2 coding) with convolutional code and soft decision Viterbi or sequential decoding are often used to improve the BER performance and to reduce the carrier power density. Spread spectrum modulation is sometimes used to increase the link availability within the power density limits at the cost of information throughput.

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The bandwidth of a digital carrier can be computed from the following equation:

$$B = k_b \cdot R \cdot F / [R_c \cdot log_2(\phi)] \qquad (2)$$

where F is the spectrum spreading factor (F = 1 if spread spectrum is not used), R_c is the FEC coding rate ($R_c = 1$ if FEC is not used), ϕ is the number of phases (ϕ is 2 for BPSK and 4 for QPSK) and k_b is a modem constant ranging from 1.0 to 2.0. The so-called Nyquist bandwidth corresponds to $k_b = 1$.

S/N-C/N$_o$ Relationship

For analog FM-audio, the S/N-C/N$_o$ relationship can be given by the standard FM equation, adjusted for companding, pre-emphasis and weighting improvement I_{pwc} in dB,

$$S/N = C/N_o + 10\ log[(3/2)\Delta f^2/(f_M{}^3 - f_m{}^3)] + I_{pwc}\ dB \qquad (3)$$

where Δf is the peak frequency deviation of the carrier due to the audio signal in Hz, f_M is the highest frequency of the audio signal in Hz, and f_m is the lowest frequency of the signal in Hz. The term $f_m{}^3$ is very small as compared to $f_M{}^3$ and is often ignored. The FM equation (3) is valid only when the carrier-to-noise ratio C/N at the input of the demodulator is higher than the FM threshold. As C/N decreases below the threshold, S/N decreases very rapidly and becomes unacceptable. C/N is related to C/N$_o$ by the following equation:

$$C/N = C/N_o - 10\ log(B)\ dB \qquad (4)$$

B is the IF filter noise bandwidth which can be chosen according to Carson's Rule with allowance made for headroom,

$$B = 2(f_M + h\Delta f)\ Hz \qquad (5)$$

where h is the ratio between peak audio voltage level and average audio voltage level.

For analog FM-TV, the S/N for a video signal is defined as the ratio of the square of blank-to-white video voltage to the square of RMS noise voltage. Accordingly, the S/N-C/N$_o$ relationship is:

$$(S/N) = C/N_o + 10\ log\ (k_v\ \Delta f_v{}^2/f_v{}^3) + I_{pw} \qquad (6)$$

where k_v has a value of $(3/2)(2\sqrt{2} \times 100/140)^2 = 6.12$ for the NTSC format, $(3/2)(2\sqrt{2} \times 100/116)^2 = 8.92$ for the B-NTSC format, and $(3/2)(2\sqrt{2} \times 100/100)^2 = 12$ for the B-MAC format; Δf_v is the peak frequency deviation (half of peak-to-peak frequency deviation) of the main carrier due to the video signal; f_v is the highest frequency of the video signal, which is typically 4.2 MHz for the 525 line system; and I_{pw} is the pre-emphasis and weighting improvement, which is typically 12.8 dB for the NTSC or B-NTSC format and 7.2 dB for the B-MAC format. The main carrier C/N must be above the threshold and can be computed from Eq. (4), where B can be chosen to be Carson's bandwidth or slightly smaller depending on the amount of overdeviation permitted,

$$B = 2(f_c + \Delta f_c/p) \quad p \geq 1 \qquad (7)$$

where 100(p−1) is called percent overdeviation, f_c is the highest frequency of the composite baseband signal, and Δf_c is the peak deviation of the main carrier due to the composite baseband signal.

A TV program includes one or two audio signals which are transmitted as subcarriers (for the NTSC format) or in the horizontal blanking intervals (for the B-NTSC or B-MAC format). In addition, other limited information (audio or data) can be piggy-backed on the TV main carrier by the use of additional subcarriers. The carrier-to-noise-density ratio of the ith subcarrier can be computed from the C/N$_o$ of the main carrier through the equation below,

$$(C/N_o)_{sci} \cong C/N_o + 10\ log[(\Delta f_{sci}/f_{sci})^2/2] \qquad (8)$$

where f_{sci} and Δf_{sci} denote the ith subcarrier frequency and the peak deviation of the main carrier due to the ith subcarrier respectively.

Link Budget Equations

Noise at the input of the demodulator is made up of thermal noise, interference and intermodulation noise. The power spectrum of thermal noise is flat, but the spectra of the other components are not. Thus noise density N$_o$ is not uniform across the demodulator bandwidth. For digital modulation, the equivalent noise density N$_o$ can be computed from the measured spectral sensitivity curve [3]. In general, the spectral shape of the noise is not known with certainty nor is the spectral sensitivity curve available from the modem manufacturer. Therefore, the equivalent noise density N$_o$ is often approximated as the average noise density, which is the ratio between the noise power and the demodulator noise bandwidth. The overall C/N$_o$ can be estimated by adding thermal noise, intermodulation, and interference components together on a power basis,

$$C/N_o = -10\ log\{\ \Sigma\ antilog[-(C/N_o)_i/10] + antilog[-(C/IM_o)/10] + \Sigma\ antilog\ [-(C/I_o)_i/10]\ \} \qquad (9)$$

thermal noise components

Thermal noise is often specified by its equivalent noise temperature T in kelvin, K. The equivalent noise temperature is linearly related to the noise power density. N$_o$, in W/Hz by Boltzmann's constant, k, which is 1.3805×10^{-23} W/K-Hz. Thermal noise in a satellite link can be decomposed into two components: uplink thermal noise and downlink thermal noise. The uplink thermal noise consists of noise generated by the satellite transponder and noise entering the receive satellite antenna (mainly microwave energy emanating from the earth). The uplink thermal noise temperature is more or less fixed. Information on this noise component is often supplied together with the receive satellite antenna gain pattern in the form of a satellite transponder G/T footprint map (such as Figure 1). Downlink thermal noise consists of that generated by the receive earth station, and antenna noise such as solar, rain, cloud or galactic noise picked up by the receive earth station antenna. Under clear sky conditions, the receive antenna temperature varies slightly with respect to the elevation angle. The downlink thermal noise temperature combined with the receive antenna boresight gain constitute the figure of merit (G/T)$_e$ of the receive earth station. The carrier-to-

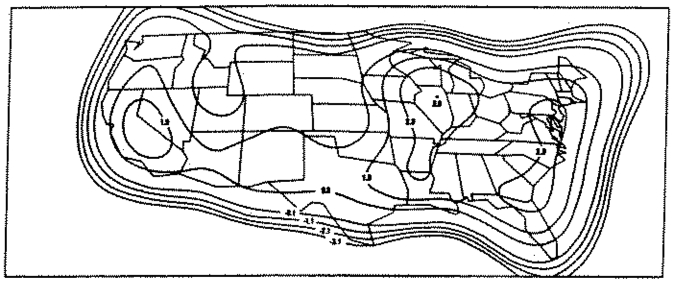

Fig. 1. Typical G/T (dB/K) Performance of a GSTAR Transponder

uplink and donwlink-thermal-noise-density ratios can be computed from the following equations:

$$(C/N_o)_{tu} = \Phi_s + (G/T)_s - G_{1u} + A_s - C_{ib} - 10\ log(k)\ \text{dBHz} \quad (10)$$

$$(C/N_o)_{td} = E_s - C_{ob} - L_d - L_d' + (G/T)_e - 10\ log(k)\ \text{dBHz} \quad (11)$$

where Φ_s is the saturation flux density SFD in dBW/m^2 (the power flux density required from the transmit earth station to saturate the satellite transponder). $(G/T)_s$ is the figure of merit of the transponder receive system in dB/K in the transmit earth station direction. For a given transponder, the sum of Φ_s and $(G/T)_s$ is constant, independent of the transmit earth station location. G_{1u} is the ideal gain of 1m^2 aperture area in dBi at the uplink carrier frequency. A_s is the operating attenuation in dB of the discretely variable attenuator used in the satellite to control the transponder sensitivity. The value of A_s can be adjusted by a ground command. This switchable attenuation is used to raise the value of $(C/N_o)_{tu}$ without raising the transponder operating point (that is without using more transponder RF power). C_{ib} is the carrier input backoff in dB, and is the difference between the input saturation level (the power level required to saturate the transponder with a single carrier) and the operating carrier input power level. E_s is the nominal satellite transponder effective isotropic radiated power EIRP (dBW) at saturation in the receive earth station direction in dBW, which can be obtained from a satellite transponder EIRP footprint map (such as Figure 2). C_{ob} is the carrier output backoff in dB, and is the power difference between the single carrier output saturation level and the operating carrier output power level. C_{ob} can be calculated from various nonlinear analysis methods, such as the time-domain method [4] as a function of the transponder AM/AM and AM/PM nonlinear characteristics, and the input backoff levels of the carriers sharing the transponder. When the carriers are equal in power, C_{ob} can be determined from C_{ib} through Figure 3 for a typical Ku-band TWTA transponder. L_d is the downlink free space path loss in dB, which can be computed from the wavelength λ_d and the slant range (the satellite-earth station distance) R_d by the relationship $[L_d = 20 \log(4\pi R_d/\lambda_d)]$. L_d' is the downlink loss excluding the free space path loss in dB, and consists of pointing loss, atmospheric loss and hydrometeor loss. The pointing loss is due to satellite drift and wind loading which affect E_s and $(G/T)_e$. The atmospheric loss is due to energy absorption by oxygen and water vapor in the atmosphere. This loss accounts for a small fraction of a dB at elevation angles greater than 30° and about a dB at an elevation angle of 10° [5]. The hydrometeor loss is due to absorption by rain, clouds, fog, snow and ice. Rain attenuation can be severe at Ku-band depending on rain rate, the vertical depth of rain cells and the elevation angle. Rain attenuation can be estimated from the well-known rain models described in [5]. Cloud attenuation ranges from a small fraction of a dB for light, thin clouds to almost a dB for very heavy clouds. Fog, dry snow and ice particle attenuation are usually so low that they are not observable at C-band and Ku-band. The figure of merit of the receive earth station $(G/T)_e$ takes a value of $(G/T)_{ec}$ under clear sky conditions which is supplied by the manufacturer, and during sun transit or rainfall it can be computed from the following equation:

$$(G/T)_e = (G/T)_{ec} - 10\ log[(T_a + T_{ec})/T_{ec}]\ dB/K \quad (12)$$

where T_{ec} is the equivalent noise temperature (at the antenna flange) of the receive earth station under clear sky conditions and T_a is the equivalent noise temperature of additional noise entering the receive antenna due to sun transit (T_s) and due to rainfall (T_{rd}). Values of T_s are shown in Figure 1 of reference [6] as a function of antenna aperture diameter. T_{rd} can be related to the downlink rain attenuation A_{rd} in dB by the following equation:

$$T_{rd} = T_m[1 - antilog(-A_{rd}/10)] \quad (13)$$

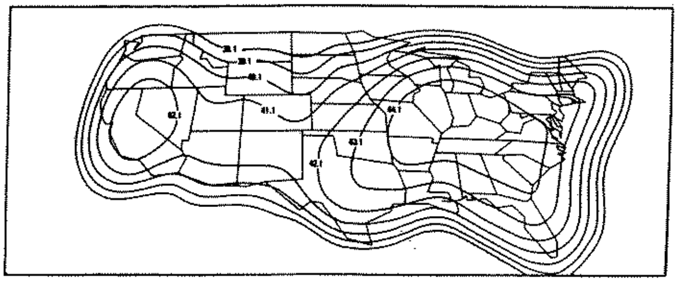

Fig. 2. Typical EIRP (dBW) Performance of a GSTAR Transponder.

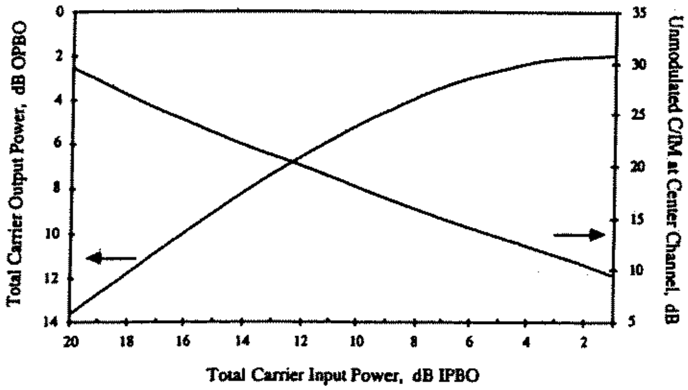

Fig. 3. Typical Ku-Band TWTA Characteristics—Multiple Carrier Operation.

where T_m is the mean path temperature ranging from 256 to 303K for the ground surface temperature of 32 to 100 °F [7].

Due to variations in the uplink pointing loss, atmospheric loss and rain loss, the carrier input backoff C_{ib} is a random variable. It can be decomposed into a fixed portion C_{ibf} and a random portion which is dominated by uplink rain attenuation, A_{ru}. The transmit earth station EIRP, E_e and the earth station HPA power, P_e required can then be computed from the following equations:

$$E_e = \Phi_s + A_s - C_{ibf} + L_u - G_{1u} \quad dBW \qquad (14)$$

$$P_e = E_e - G_t + L_o \quad dBW \qquad (15)$$

where L_u is the uplink free space path loss in dB, G_t is the transmit antenna gain in dBi, and L_o is the output circuit loss (the loss between HPA output and antenna flange) in dB.

Note that during precipitation, reflectors of VSATs and the hub may become covered with ice or snow. Attenuation due to this accretion can be as high as 25 dB at a thickness of around 1.0 mm [8]. To avoid this accretion, the reflectors can be heated (de-iced) or coated with a layer of hydrophobic paint. Note also that due to the imbalance between the antenna size of the hub and that of a VSAT, the downlink thermal noise component $(C/N_o)_{td}$ is dominant over the uplink thermal noise component $(C/N_o)_{tu}$ in an outbound link; and conversely, the uplink thermal noise component is more dominant in an inbound link.

intermodulation component

When two or more carriers are simultaneously passed through a satellite transponder, intermodulation products are generated. The intermodulation products are considered noise and affect the information quality if their power spectra fall into the carrier bandwidth. Only odd order products are of concern as they are the only products which can fall into the transponder bandwidth. The third order products dominate. There are two types of third order products. The first is the (A+B−C) products, whose (center) frequency is the difference between the sum of two carrier frequencies and a third carrier frequency, and the second is the (2A−B) products, whose frequency is the difference between twice the frequency of one carrier and the frequency of another. The power and spectral shape of an intermodulation product depend on those of the carriers and the nonlinear characteristics of the transponder. They can be estimated by the time-domain method mentioned earlier. When the carriers accessing the transponder have the same power and are equally spaced, the center carrier receives the most intermodulation products and its corresponding C/IM for a typical Ku-band transponder can be estimated from Figure 3. Through selective carrier frequency spacing, an improvement in C/IM (the so-called IM-advantage) can be also obtained [9].

interference components

Interference is an important source of information quality degradation which must be taken into the link budget calculation. This is particularly crucial since the FCC has instituted closer satellite orbital spacing (2°) and VSATs use wider beamwidth antennas. Interference consists of many components, namely, adjacent satellite uplink and downlink $(C/I_o)_{asu}$ and $(C/I_o)_{asd}$, adjacent transponder uplink and downlink $(C/I_o)_{atu}$ and $(C/I_o)_{atd}$, crosspolarized transponder uplink and downlink $(C/I_o)_{xtu}$ and $(C/I_o)_{xtd}$, adjacent channel uplink and downlink $(C/I_o)_{acu}$ and $(C/I_o)_{acd}$, and terrestrial uplink and downlink $(C/I_o)_{tu}$ and $(C/I_o)_{td}$.

Uplink adjacent satellite interference occurs due to the receipt of power transmitted from earth stations associated with the adjacent satellites. Downlink adjacent satellite interference occurs as a result of receiving power transmitted from adjacent satellites. To avoid excessive adjacent satellite interference, frequency bands corresponding to several MHz around the center frequencies of copolarized FM-TV carriers of the two adjacent satellites are often not assigned by the satellite operator to VSAT data carriers. Based on the FCC's blanket licensing constraints and the two degree orbital spacing, the interference components are typically found to be bounded by the equations below:

$$(C/I_o)_{asu} \geq \Phi_{sm} + A_s - C_{ib} + 187.0 \quad dBHz \qquad (16)$$

$$(C/I_o)_{asd} \geq E_s - C_{ob} + G_r + 4.4 \quad dBHz \qquad (17)$$

where Φ_{sm} is the lowest SFD (SFD corresponding to maximum receive satellite antenna gain) in dBW/m^2 and G_r is the receive earth station antenna gain in dBi.

Uplink adjacent transponder interference occurs because sidelobes of the adjacent transponder carriers and/or intermodulation products generated from earth stations associated with adjacent transponders interfere with the carrier. The satellite operator imposes constraints to limit this interference density to within k_1 so that

$$(C/I_o)_{atu} \geq - C_{ib} + k_1 \quad dBHz \qquad (18)$$

where k_1 typically has a value between 100 to 110 dB input backoff per Hertz. Downlink adjacent transponder interference occurs because the increase of sidelobe levels of the adjacent transponder carriers and/or intermodulation products generated by the nonlinearity of the adjacent transponders interferes with the considered carrier. The satellite is often designed with transponder output filters to suppress this interference. The satellite operator has the responsibility of assigning transponders and frequencies to the carriers to insure that this interference is bounded, that is

$$(C/I_o)_{atd} \geq - C_{ob} + k_2 \quad dBHz \qquad (19)$$

where k_2 typically ranges between 110 and 120 dB output backoff per Hertz.

Uplink crosspolarized transponder interference occurs when uplink power transmitted to the crosspolarized transponders of the same satellite is received by the considered carrier. Downlink crosspolarized transponder interference occurs when downlink power transmitted from the crosspolarized transponders is received. These types of interference are due to imperfect alignment of the earth stations' feeds and antennas to get correct polarization angles, imperfections in polarization discrimination of the earth station and satellite antennas, depolarization caused by rainfall and Faraday polarization rotation caused by the atmosphere (which is negligible at

Ku-band). To avoid excessive interference, frequency bands corresponding to several MHz around the center frequencies of the crosspolarized TV/FM carriers are not assigned to VSAT data carriers. Based on the FCC's blanket licensing limits, the interference is typically found to be bounded by the following equations,

$$(C/I_o)_{xtu} \geq \Phi_{sm} - C_{ib} + (X_{et} \oplus X_{sr}) + 156.4 \ dBHz \tag{20}$$

$$(C/I_o)_{xtd} \geq E_s - C_{ob} + (X_{er} \oplus X_{st} \oplus X_{rd}) + 30.0 \ dBHz \tag{21}$$

where X_{st}, X_{sr}, X_{et} and X_{er} are the crosspolarization discriminations XPDs (dB) of the transmit satellite antenna, receive satellite antenna, transmit earth station antenna and receive earth station antenna respectively; X_{rd} is the downlink rain depolarization in dB; and $\oplus$ denotes the inverse addition on a voltage basis (i.e., $A \oplus B = -20 \log[\text{antilog}(-A/20) \oplus \text{antilog}(-B/20)]$). Typically, the XPD of a satellite antenna is at least 33 dB, that of a hub antenna is at least 30 dB and that of a VSAT antenna is at least 26 dB. X_{rd} depends on the downlink rain attenuation A_{rd}, carrier frequency, elevation angle and polarization tilt angle. X_{rd} can be estimated from the CCIR rain depolarization model [5], from which typically it exceeds 35 dB for $A_{rd} \leq 5$ dB and 20 dB for $A_{rd} \leq 25$ dB.

Uplink adjacent channel (cotransponder) interference occurs due to overlap in carriers sharing the same transponder and/or intermodulation products generated in the earth stations. The satellite operator limits this interference so that

$$(C/I_o)_{acu} \geq -C_{ib} + k_3 \tag{22}$$

where k_3 typically ranges between 100 and 110 dB input backoff per Hertz. Downlink adjacent channel interference occurs due to spectral spreading of the adjacent carriers caused by the transponder nonlinearity. This can be virtually eliminated by having wide guardbands between the carrier channels or by operating the transponder with sufficient backoff to limit spectral spreading.

Terrestrial interference degrades satellite transmission when power from terrestrial microwave systems is received by the satellite and earth stations. In North America, satellite services have received primary allocation of the Ku-band and therefore terrestrial interference is not an issue at Ku-band. For this reason, earth station licensing issues greatly favor the use of Ku-band for VSAT networks.

Transponder Utilization

The percentage of transponder bandwidth utilization is defined as the ratio of the carrier bandwidth plus guard bands, to the usable transponder bandwidth. Similarly, the percentage of transponder power utilization is defined as the ratio of the transponder RF power required by the carrier, to the usable transponder RF power. Typically, billing for transponder usage is based on the larger of the bandwidth or power usage. The carrier bandwidth can be computed from Eq. (2), (5) or (7). Guard bands are required to reduce adjacent channel interference and intermodulation for a multicarrier/transponder operation. These guardbands can range up to 100% of the carrier bandwidth. The usable transponder bandwidth and RF power vary with respect to the number and types of carriers accessing the transponder.

Availability

Equipment failure, sun transit and rainfall affect the availability of a link. According to CCIR/CCITT recommendations, an outage is said to occur when the operating BER is below a specified threshold continuously for up to ten seconds. If this condition persists for more than ten seconds, the link is considered unavailable [10]. In the commercial satellite environment, however, the words unavailability and outage are used interchangeably.

Equipment Availability

Equipment availability is the percentage of time that the equipment is operational. The equipment associated with a link is: the satellite transponder, the VSAT, and the hub earth station. Each of these consists of many interconnected components. Active components such as amplifiers have higher failure rates. Redundant active components are often placed in parallel to increase reliability. Components are also integrated into modules to reduce repair or replacement time. The availability of a component can be computed from the following steady state availability equation:

$$A_v = \tau_f/(\tau_f + \tau_r) \tag{23}$$

where τ_f is the mean time before (between) failures MTBF and τ_r is the mean time to restore (to repair) MTTR. When components, each with availability A_{vi}, are interconnected, the composite availability is $[\Pi A_{vi}]$ for serial connection and $[1 - \Pi(1-A_{vi})]$ for parallel connection. The equipment availabilities of a transponder, a VSAT and a hub are typically 99.990% to 99.999%, 99.800% to 99.990% and 99.995% to 99.999% respectively. The MTBF of a VSAT is 3 to 4 years and that of a hub is 6 to 7 years. The MTTR of a VSAT is around one day and that of a hub is a couple of hours.

Sun Transit Availability

Sun transit availability is the percentage of time that there are no sun transit outages. A sun transit outage occurs when the sun is so close to the boresight axis of a directional receive antenna that the additional noise power presented by the sun causes the link to operate below acceptable quality. This outage occurs around the time of both the Spring and Fall equinoxes, for a few minutes a day, for several days. The number of outages, outage duration and time of the outage depend on the radio emission activity of the sun, the movement of the earth with respect to its own axis and with respect to the sun, the pointing and location of the receive antenna, and the link characteristics. Sun transit outages have been extensively studied [6,11]. For an outbound link, there may be up to 12 outages a year, each of which lasts from a few minutes to at most 10 minutes; and for an inbound link, there may be up to 6 outages, each of which lasts less than 4 minutes. Thus the sun transit availability is 99.960 to 99.999+% for an outbound link and 99.996 to 99.999+% for an inbound link. The sun transit outage time can be reduced or even eliminated by designing the link with higher margin. Table 2 of reference [6] provides the outage time as a function of the link margin (the difference between the clear sky C/N_o and the minimum acceptable C/N_o). In general, the use of site diversity is not recommended for improving sun transit availability, as the two different sites must be at least several hundred miles apart.

Rainfall Availability

Rainfall availability is the percentage of time that there are no rainfall outages. A rainfall outage occurs when rainfall at the transmit earth station and/or at the receive earth station causes the link to operate below acceptable quality. Rainfall at the transmit earth station causes the uplink carrier power to be attenuated by A_{ru}, which in turn reduces the downlink carrier power. The amount of change in downlink carrier power depends on the transponder nonlinearity, the uplink power of the carriers sharing the transponder, and A_{ru}. For a multicarrier/transponder operation, the downlink carrier power is also typically found to be reduced by A_{ru}. Rainfall at the receive earth station reduces the carrier power at the receive earth station by A_{rd} (there is also a negligible loss due to rain depolarization), raises the antenna noise level and increases crosspolarized transponder interference. A complete statistic of rain attenuation, in the form of the cumulative probability function P_A (a) (the probability that attenuation A does not exceed a value a), can be estimated directly from well-known rain models described by Crane, the CCIR and others [5].

The overall carrier-to-noise-density ratio at the demodulator input can be put into the following general form,

$$C/N_o = f(A_{ru}, A_{rd}, \underline{\alpha}) \qquad (24)$$

where $\underline{\alpha}$ is the link parameters excluding A_{ru} and A_{rd} that affect C/N_o. When the complete statistics of A_{ru}, A_{rd} and $\underline{\alpha}$ are known, the complete statistic of C/N_o can be computed, and hence the link availability can be calculated. Detailed descriptions on how to calculate the rainfall availability of a link (one-way and two-way) can be found in [12]. To reduce the amount of computation involved, the rainfall availability of a one-way link is often approximated by the product of two conditional rainfall availabilities: "availability when downlink does not rain" $P_A(a^*_{ru})$ and "availability when uplink does not rain" $P_A(a^*_{rd})$. These two conditional availabilities are sometimes called "uplink availability" and "downlink availability", respectively. These names are somewhat misleading, as the uplink and the downlink are each only part of a one-way link. The uplink and downlink rain attenuation margins a^*_{ru} and a^*_{rd} are found in such a way that $f(a^*_{ru}, 0, \underline{\alpha}) = (C/N_o)_m$ and $f(0, a^*_{rd}, \underline{\alpha}) = (C/N_o)_m$ where $(C/N_o)_m$ is the specified minimum acceptable C/N_o.

The rainfall availability can be increased by designing the link with a larger link margin, which can be achieved by using a larger receive antenna and/or a higher EIRP at the transmit earth station. The latter utilizes more satellite transponder power and may violate regulatory power density limits. Uplink power control can be used to compensate for uplink rain attenuation. There are other techniques to overcome rain attenuation. They include adaptive rate FEC, downlink power control, site diversity, focused satellite beams, frequency diversity, and onboard regeneration [5]. However, these techniques may not be desirable for use with VSAT networks.

Spread Spectrum

The power required to operate satellite transmission links with VSATs sometimes exceeds spectral power density allowed by regulation. In order to overcome this difficulty it is necessary to deliberately increase the carrier bandwidth. The use of BPSK over QPSK reduces the power density by a factor of two. With 1/2 rate FEC coding, the bandwidth required is doubled and the carrier power required is three to four times less (due to a coding gain of about 5.0 dB), giving a total reduction factor of six to eight times in carrier power density. In the USA, for C-band VSAT networks, the use of BPSK and 1/2 rate FEC coding is not sufficient to spread the carrier to a density level acceptable to the FCC. This is also true for Ku-band VSAT networks in certain cases, where

TABLE I
SYSTEM PARAMETERS USED IN THE LINK DESIGN

Carriers	
Data	
Data Rate:	56 kbps for TDM Outbound Carriers and 56 kbps for DA-TDMA Inbound carriers
Modulation:	BPSK
Coding:	1/2 Rate FEC Convolutional Code Soft Decision, Viterbi Decoding
Carrier Spacing:	Twice the Nyquist Bandwidth
RF Power:	At FCC's Blanket Licensing Limits
Min. Acceptable E_b/N_o:	6.7 dB (for BER of about 10^{-7})
TV	
Format	NTSC
Highest Video Frequency:	4.2 MHz
Peak Deviation by Video:	9.6 MHz
IF Noise Bandwidth:	27.0 MHz
RF Power:	At Transponder Saturation
Min. Acceptable S/N:	43.5 dB (corresponding to C/N Threshold)
Satellite and Transponder	
Satellite Location:	105° West Longitude
Transponder Type:	GSTAR II, Ku-Band, CONUS Coverage
Transponder Usable BW:	38 MHz for Data and 54 MHz for Video
Transponder Operation:	4 dB output backoff for Data, and 0 dB output backoff for Video
Switched Atten. Setting:	6 dB
Reference SFD:	- 93.1 dBW/ m^2 at 0 dB S. Atten. Setting
Reference G/T:	0 dB/K
Hub	
Location:	New York (Rain Zone = D2, Satellite G/T = 2.8 dB/K, EIRP = 43.8 dBW)
Aperture Diameter:	5.5 or 11.0 m
Receive G/T:	31.2 or 36.5 dB/K
Transmit Antenna Gain:	56.6 or 62.1 dBi
Receive Antenna Gain:	55.1 or 60.6 dBi
Output Circuit Loss:	2.0 dB
VSATs	
Locations:	All Over Continental U.S. Los Angeles (Rain Zone = F, Satellite G/T = 0.4 dB/K, EIRP = 42.0 dBW) Miami (Rain Zone = E, Satellite G/T = -0.5 dB/K, EIRP = 40.6 dBW) Washington (Rain Zone = D2, Satellite G/T = 2.9 dB/K, EIRP = 44.1 dBW)
Diameters :	1.2, 1.8 or 2.4 m
Receive G/Ts:	18.0, 21.3 or 23.2 dB/K
Transmit Antenna Gains:	42.7, 46.2 or 49.0 dBi
Receive Antenna Gains:	41.7, 45.0 or 47.2 dBi
Output Circuit Loss:	0.5 dB

TABLE II
DIGITAL LINK CALCULATION SUMMARY FOR THE NEW YORK HUB (5.5m) TO WASHINTON VSAT (1.8m) LINK

Ref. Transponder SFD, dBW/m^2	-93.10	(+)
Ref. Transponder G/T, dB/K	0.00	(+)
Switched Attenuator Setting, dB	6.00	(+)
Ideal Gain of 1 m^2, dBi	44.53	(-)
Carrier Input Backoff, dB	28.85	(-)
Boltzmann's Constant, dBW/Hz-K	-228.60	(-)
(C/N_0) Thermal-U, dBHz	68.12	
Saturated Transponder EIRP at E/S, dBW	44.10	(+)
Carrier Output Backoff, dB	24.53	(-)
Receive E/S G/T, dB/K	21.30	(+)
Boltzmann's Constant, dBW/Hz-K	-228.60	(-)
Free Space Path Loss, dB	205.60	(-)
Other Losses	1.00	(-)
(C/N_0) Thermal-D, dBHz	62.88	
(C/N_0) Thermal-Total, dBHz	61.74	
(C/IM_0) Intermod, dBHz	72.87	
(C/I_0) Adjacent Satellite-U, dBHz	78.25	
(C/I_0) Adjacent Satellite-D, dBHz	76.57	
(C/I_0) Adjacent Xponder-U, dBHz	79.05	
(C/I_0) Adjacent Xponder-D, dBHz	114.47	
(C/I_0) Xpol Xponder-U, dBHz	76.25	
(C/I_0) Xpol Xponder-D, dBHz	78.87	
(C/I_0) Adjacent Channel-U, dBHz	76.15	
(C/I_0) Adjacent Channel-D, dBHz	111.47	
(C/I_0) Interference-Total, dBHz	67.90	
(C/N_0) Total, dBHz	60.80	
Information Rate, dBbps	47.48	(56 kbps)
Clear Sky Eb/No, dB	13.32	
Minimum Acceptable Eb/No, dB	6.70	
Link Margin, dB	6.62	
Rainfall Availability, %	99.868 (99.933)*	
Rainfall Availability / Clear Downlink, %	99.918 (99.982)	
Rainfall Availability / Clear Uplink, %	99.951 (99.951)	
Transponder Bandwidth Utilized, %	0.59	
Transponder Power Utilized, %	0.89	

* with Ideal Maximum Uplink Power Control of 10 dB

VSATs are located in heavy rain zones or poor satellite coverage regions when the required link availabilities are high. In these cases, spread spectrum can be used to provide additional spreading.

There are several spread spectrum techniques: direct sequence, frequency hopping, time hopping, and chirp. The direct sequence technique, due to its simplicity and low implementation cost, is suitable for use with commercial VSAT networks. In this technique, a pseudo noise (PN) sequence is used to spread the information signal at the transmit site. The same PN sequence is used synchronously at the receive site to despread the received signal to recover the information signal. The bits of the PN sequence are called chips. The ratio between the chip rate and the information rate is called the spreading factor. With spread spectrum, the implementation loss will be higher than without spread spectrum. Additional information security is provided against unauthorized reception, as the PN sequence must be known to despread the spread carrier. Also, interference from narrowband carriers of neighboring systems can be reduced by being spread out by the despreader.

Performance Analysis Example

Consider a private VSAT network for a corporation with headquarters located in New York and branches throughout the continental U.S. The network service consists of interactive data communication between the headquarters and branch offices and TV broadcast communication from the headquarters. The key parameters of the system used are summarized in Table I and a sample link calculation is summarized in Table II. As performance tradeoff examples, Table III summarizes the characteristics of digital links between New York headquarters and branch offices in Washington, D.C., Miami and Los Angeles, operated at the FCC's power density limits for blanket licensing (power density of −14 dBW/4 kHz at the VSAT antenna input and satellite EIRP density of 6 dBW/4 kHz at satellite beam peak); and Table IV summarizes the characteristics of TV links, operated at transponder saturation. Results with ideal uplink power control are also shown for the outbound links (ideal here means uplink rain attenuation is compensated for by increasing the transmit earth station power by the same amount or the maximum allowable amount without any time delay). They serve as an upper bound on the link availability when actual uplink power control is used. The Crane global rain model, together

TABLE III
DATA LINK CHARACTERISTICS BETWEEN THE NEW YORK HUB AND THREE TYPICAL VSAT LOCATIONS—OPERATED AT THE FCC LIMITS

VSAT Aperture		1.2 m	1.8 m	2.4 m
Equipment Availability, %				
Transponder		99.998	99.998	99.998
Hub (5.5 m or 11.0 m)		99.997	99.997	99.997
VSAT		99.954	99.954	99.954
Sun Transit Availability (at Eb/No ≥ 6.7 dB), %				
Outbound to	L.A.	99.989	99.996	99.998
	Miami	99.985	99.995	99.997
	Wash.	99.994	99.998	99.999
Inbound from (5.5 m Hub)	L.A.	99.999+	99.999+	99.999+
	Miami	99.999+	99.999+	99.999+
	Wash.	99.999+	99.999+	99.999+
Inbound from (11.0 m Hub)	L.A.	99.999+	99.999+	99.999+
	Miami	99.999+	99.999+	99.999+
	Wash.	99.999+	99.999+	99.999+
Rainfall Availability (at Eb/No ≥ 6.7 dB), %				
Outbound to	L.A.	99.615 (99.918)*	99.884 (99.963)	99.908 (99.972)
	Miami	97.240 (98.214)	99.410 (99.545)	99.653 (99.731)
	Wash.	99.743 (99.870)	99.868 (99.933)	99.897 (99.949)
Inbound from (5.5 m Hub)	L.A.	99.962	99.981	99.986
	Miami	99.565	99.807	99.867
	Wash.	99.932	99.956	99.972
Inbound from (11.0 m Hub)	L.A.	99.976	99.986	99.990
	Miami	99.639	99.827	99.885
	Wash.	99.944	99.963	99.976
Two-way	L.A.	99.615 (99.918)	99.884 (99.963)	99.908 (99.972)
	Miami	97.240 (98.214)	99.410 (99.545)	99.653 (99.731)
	Wash.	99.743 (99.870)	99.868 (99.933)	99.897 (99.949)
Clear Sky Eb/No, dB				
Outbound to	L.A.	9.40	12.04	13.36
	Miami	8.22	11.01	12.44
	Wash.	10.92	13.32	14.45
Inbound from (5.5 m Hub)	L.A.	12.65	16.15	18.95
	Miami	11.77	15.27	18.07
	Wash.	14.95	18.45	21.25
Inbound from (11.0 m Hub)	L.A.	13.20	16.70	19.50
	Miami	12.32	15.82	18.62
	Wash.	15.50	19.00	21.80
Xponder Power Utilization, %				
Outbound		0.89	0.89	0.89
Inbound from	L.A.	0.16	0.36	0.69
	Miami	0.13	0.30	0.56
	Wash.	0.28	0.62	1.17
Xponder BW Utilization, %				
Inbound or Outbound		0.59	0.59	0.59
VSAT SSPA Power, W				
(0.5 dB Output Circuit Loss)		1.25	1.25	1.25

* with Ideal Maximum Uplink Power Control of 10 dB

TABLE IV
VIDEO LINK CHARACTERISTICS FROM THE NEW YORK HUB TO THREE TYPICAL VSAT LOCATIONS—OPERATED AT TRANSPONDER SATURATION

VSAT Aperture		1.2 m	1.8 m	2.4 m
Equipment Availability, %				
Transponder		99.998	99.998	99.998
Hub (5.5 m or 11.0 m)		99.997	99.997	99.997
VSAT		99.954	99.954	99.954
Sun Transit Availability (at S/N ≥ 43.5 dB), %				
Broadcast to	L.A.	99.968	99.993	99.995
	Miami	00.000	99.991	99.995
	Wash.	99.986	99.995	99.998
Rainfall Availability (at S/N ≥ 43.5 dB), %				
Broadcast to	L.A.	94.804 (94.901)*	99.915 (99.933)	99.948 (99.965)
	Miami	00.000 (00.000)	98.822 (98.848)	99.330 (99.346)
	Wash.	99.243 (99.265)	99.868 (99.885)	99.912 (99.925)
Clear Sky S/N, dB				
Broadcast to	L.A.	43.65	46.85	48.65
	Miami	42.31	45.53	47.36
	Wash.	45.49	48.64	50.38

* with Ideal Maximum Uplink Power Control of 5 dB

with the Laws-Parsons rain drop size distribution was used to obtain the rain attenuation statistics and the CCIR model was implemented to take into account the effect of rain depolarization.

For the data links, to obtain availabilities higher than those shown in Table III, more transponder power is required and spread spectrum must then be used to limit the carrier power density to regulatory constraints. The two-way link availability is dominated by the outbound link rainfall availability. The inbound carrier can be operated at a couple of dB below the FCC limit without really changing the two-way link availability. The use of an 11 m hub (instead of a 5.5 m hub) slightly increases the inbound link rainfall availability, and has no effect on the outbound link availability and insignificant effect on the two-way link availability. Although the results are for a bit rate of 56 kbps, they can be used for any bit rate (up to several Mbps), as long as the transponder power, the transponder bandwidth and the transmit power are adjusted linearly with the bit rate and the modem performance remains the same.

Conclusions

The analysis presented in this paper shows that VSAT networks can be designed to provide the network performance desired. This includes taking into account all of the relevant factors that contribute to the performance degradation. An availability of greater than 99.9% (at BER $\leq 10^{-7}$ or S/N ≥ 43.5 dB) can be achieved with 2.4 meter or smaller antennas in all but the most heavy rain and worst satellite coverage areas. Even in these areas, high availability for data links can be achieved by using increased satellite transponder power per carrier. This can be accomplished without causing excessive interference to other systems by the use of spread spectrum, which enables the system designer to increase the total power per carrier without exceeding regulatory density limits. The overall performance for satellite communication compares favorably with terrestrial transmission and yet is considerably more flexible in terms of relocating, expanding or increasing capacity.

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References

[1] *Code of Federal Regulations—Telecommunication 47, Part 25 Sections 25.204 and 25.208,* Office of the Federal Register National Archives and Records Administration, U.S. Government Printing Office, Washington, D.C., 1986.

[2] *FCC Declaratory Order,* In the Matter of Routine Licensing of Large Networks of Small Antenna Earth Stations Operating in the 12/14 GHz Frequency Bands, 1986.

[3] M. E. Ferguson, "On interference into digital systems," *Satellite Operator and User Technical Committee Meeting,* March 1985.

[4] J. C. Fuenzalida, O. Shimbo and W. L. Cook, "Time domain analysis of intermodulation effects caused by nonlinear amplifiers," *COMSAT Technical Review,* Spring 1973.

[5] L. J. Ippolito, *Radiowave Propagation in Satellite Communications,* Van Nostrand Reinhold, New York, 1986.

[6] X. T. Vuong and M. Lee, "Sun transit outage prediction," *Satellite Communications,* Oct. 1986.

[7] K. N. Wolfsburg, "Noise measurements at millimeter wavelengths," *Proc. of the IEEE,* March 1964.

[8] A. Kumar, "Attenuation due to accretion of snow on reflector antennas at microwave frequencies," *Proc. of IEEE Conference on Antennas and Communications,* Montreal, Sept. 1986.

[9] X. T. Vuong, F. N. Ozmizrak, L. G. Birta and K. D. Nguyen, "Some practical strategies for reducing intermodulation in satellite communications," *IEEE Trans. on Aerospace and Electronic Systems,* Sept. 1988, to be published.

[10] L. J. Greenstein and M. Shafi, "Outage calculation methods for microwave digital radio," *IEEE Communications Magazine,* Feb. 1987.

[11] X. T. Vuong and R. J. Forsey, "Prediction of sun transit outages in an operational communication satellite system," *IEEE Trans. on Broadcasting,* Dec. 1983.

[12] X. T. Vuong, "A Simple and accurate method to compute rain fall availability of a satellite link," being submitted for publication.

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