IEEE TRANSACTIONS ON BROADCASTING, VOL. 43, NO. 2, JUNE 1997

Satellite Link Margin and Availability Issues*

Xuyen T. Vuong, *Senior Member, IEEE*
Science Applications International Corp. (SAIC)
1710 Goodridge Drive, McLean, Virginia 22102, USA
Tel: (703) 448-6470, Email: vuong@tieo.saic.com

Son T. Vuong, *Senior Member, IEEE*
Dept. of Computer Science, Univ. of British Columbia
Vancouver, B.C. V6T-1Z4, Canada
Tel.: (604) 822-6366, Email: vuong@cs.ubc.ca

Abstract *- Satellite link margin and availability issues are addressed in this paper. Typical sources of disputes in satellite link design results generated by different satellite link engineers are described and solutions to resolve the disputes are proposed. The solutions include provision of accurate and simplified methods with mathematical derivation support to estimate the availabilities of satellite links due to rainfall for a specified transponder power utilization. Derivation and description of the link availability methods are provided for one-way (simplex) link and two-way (duplex) link, with or without the use of uplink power control at the transmit earth station, and for the general case where uplink and downlink rains are uncorrelated (e.g., transmit and receive earth stations are very far from each other) as well as the specific case where the rains are completely correlated (e.g., transmit and receive earth stations are the same or very close each other). The accurate methods are based on the use of discrete probability density functions of uplink and downlink rain attenuations which are readily available from any existing rain attenuation models. The simplified methods are provided to further simplify the computation involved. Comparison between the methods is also performed.*

1.0 INTRODUCTION

The quality of information transmitted over a satellite link is objectively specified in terms of bit error rate (BER) or energy-per-bit-per-equivalent-noise-density ratio (E_b/N_O) for digital signals (or signal-to-noise ratio S/N for analog FM signals). There is a one-to-one relationship between E_b/N_O (or S/N) to carrier-to-equivalent-noise-density ratio (C/N_O) at the receive earth station demodulator input, and this C/N_O can be estimated from link power budget equations.

Availability is another important specification that is also often used for the design of a satellite link. Equipment failure, sun transit [1] and rainfall affect the availability of a satellite link. At Ku-band or higher frequencies, rainfall is the dominant factor that determines the link availability. According to CCIR/CCITT, for a microwave radio link, an outage is said to occur when the operating E_b/N_O (or C/N_O) is below a specified (minimum) threshold continuously for up to ten seconds; if this condition persists for more than ten seconds, the link is considered unavailable [2]. In satellite communication environment, however, the words unavailability and outage are used interchangeably.

From the authors' experience, designing a Ku-band satellite link with a specified link availability almost always causes disputes among satellite link design engineers on the amount of transponder power required to support the link, even the engineers use the same assumptions on the characteristics of the space and ground segment. In many cases, the disputes in the required transponder power can be as high as several dBs and may take days or even weeks to resolve among the engineers. To avoid disputes and also to be able to verify through measurements, experienced customers often specify a link design in terms of clear sky E_b/N_O or link margin (i.e., difference between clear sky E_b/N_O and minimum acceptable E_b/N_O) instead of link availability.

This paper addresses sources of satellite link result disputes among satellite link design engineers and proposes solutions to resolve the disputes. Section 2 describes typical sources of the disputes. Section 3 describes different intermodulation, interference, and thermal noise components that make up the overall C/N_O at the receive earth station demodulator and shows how these components are affected by the uplink and downlink rains. Sections 4 and 5 provide (accurate and simplified) methods with mathematical derivation support to estimate the availabilities of a one-way (simplex) link and a two-way (duplex) link, respectively. The methods are provided for cases with or without the use of uplink power control (UPC) and for cases where the uplink and downlink rains are either uncorrelated or completely correlated.

2.0 TYPICAL SOURCES OF LINK RESULT DISPUTES

From experience, typical sources of disputes among satellite link design engineers on the amount of transponder power required to support a Ku-band satellite link with a specified link availability are:

(a) Different rain attenuation statistics used (e.g., different rain attenuation models and different rain rate databases used),

(b) Different accounting of the effects of uplink and down link rains on the intermodulation, interference, and thermal noise components of the overall C/N_O at the receive earth station demodulator, and

(c) Different methods used to relate the required transponder power to the link availability.

Dispute Source (a) often occurs because, in the literature, there exists tens of rain attenuation models (e.g., CCIR - MOD I, CCIR - MOD F, Crane - Global Model, Crane - Two Component Model, Lin, Rice-Holmberg, etc. [3], [7]) that can be used. Furthermore, associated with each rain attenuation model, there may be databases whose empirical data may be updated occasionally. Examples for these databases, for Crane - Global Model, are point rain rate statistics for different rain zone areas and values of coefficients "a" and "b" for different frequencies and polarization sense/orientation. Different interpolation/ extrapolation techniques (e.g., curve fitting, linear, log-linear, quadratic) used to obtain values not directly supplied from the databases may also yield significantly different results. The differences in rain attenuation at a given cumulative occurrence probability generated from different models, databases and interpolation techniques can be several dBs. While not any of models provides better attenuation predictions for all cases (year, rain zone area, frequency, elevation angle, etc.), the Crane and CCIR models are more popular and were claimed to provide better predictions in average [3]. While it is best to use the most up-to-date empirical databases, from experience, once the databases are implemented into a computer program, they are rarely updated later on. The log-linear interpolation/extrapolation technique was recommended for use [8].

Dispute Source (b) may occur because some engineers may not properly account the uplink and downlink rain effects on the intermod, interference, and thermal noise components of the overall C/N_O and hence on the overall C/N_O. For example, uplink rain reduces the carrier satellite EIRP (if uplink power control is not

---

* The original version of this paper was presented at the 1996 IEEE Military Communications Conference, McLean, Virginia, October 1996.

Publisher Item Identifier: S 0018-9316(97)05628-X

0018-9316/97$10.00 © 1997 IEEE

used) and hence reduces all the downlink interference and thermal noise components of the overall C/N_O, but inexperienced engineers may treat the downlink and uplink to be independent and separate links and accordingly uplink rain would not have any effects on the downlink components. The effects of uplink and downlink rain on the components of the overall C/N_O are addressed in Section 3.

Dispute Source (c) occurs likely because the process of relating the required transponder power to the specified link availability is quite mathematically involved (stochastic in nature). In the literature, there exists a few formulas to calculate satellite link availability [9 - 12]. However, these formulas are either too complex to be implemented properly into a computer program or too simplified to be accurate and to apply to general cases ([7], Section 7.3.7). The "widely-used simplified formula", widely used among practical link engineers, is to treat the uplink and the downlink as if they were independent and separate links and accordingly, to design the satellite link: (i) the specified availability is decomposed into a product of two availabilities, called, "uplink availability" and "downlink availability"; (ii) then from a rain attenuation model, two rain attenuation values, called "uplink margin" and "downlink margin", are calculated; and (iii) satellite link budget calculations are finally performed to determine the required transponder power that equates the operating C/N_o to the minimum acceptable under the degrading condition with the uplink and downlink rain attenuations being the "uplink margin" and "downlink margin" respectively. For example, to design a Ku-band satellite link from Miami to Phoenix, an engineer may provide the following justification: since Miami is in a very wet (rainy) area and Phoenix in a very dry area, one should allocate the "downlink margin" to be 0 dB or a very small value and the "uplink margin" to be whatever it requires to meet the specified link availability. At a very first instinct, the "widely-used simplified formula" seems to be very logical: one assigns most link margin to where it needs most. Nevertheless, a more serious examination to the formula reveals that the "widely-used simplified formula" provides multiple different solutions (of the required transponder power), depending on how the specified link availability is decomposed. Also, most existing transponders are non-processing, and accordingly, uplink and downlink are not two independent and separate links and are part of a link; and therefore it is mathematically incorrect to independently assign two availabilities to the uplink and the downlink and then to expect their product to be the link availability. New, general, easy-to-implement accurate and simplified methods to estimate satellite link availability are described and derived in Sections 4 and 5. The methods are based on the use of discrete probability density functions of uplink and downlink rain attenuations which are readily available from any existing rain attenuation models. These methods are proposed for use to resolve Dispute Source (c).

3.0 C/N_O COMPONENTS AND THEIR EFFECTS BY RAINS

The overall carrier-to-equivalent-noise-density ratio (C/N_O) at the input of the receive earth station demodulator, as shown in Table 1, comprises of its thermal noise components $(C/N_O)_{ti}$, interference components $(C/I_O)_j$ and intermodulation components $(C/IM_O)_k$. The components are also classified as either uplink components or downlink components to specify the origins of the link impairment sources. The power spectrum of thermal noise (N) is flat, but the spectra of interference (I) and intermodulation products (IM) are not. The I_O's and IM_O's, as in $(C/I_O)_j$ and $(C/IM_O)_k$, are the equivalent power densities that can be computed from the measured spectral sensitivity curve of the demodulator [13]. Because, in general, the spectral shape of the overall noise is not known with certainty and the spectral sensitivity curve is not typically available from the modem manufacturer, the equivalent noise density is often approximated as the average noise density, which is the ratio of the noise power to the demodulator noise bandwidth. The overall C/N_O (in dBHz) can be estimated by adding each of its components together on a power basis,

$$C/N_O = -10\log\{\Sigma[10^{-(C/N_O)ti/10)}] + \Sigma[10^{-(C/I_O)j/10)}] + \Sigma[10^{-(C/IM_O)k/10)}]\} \quad (1)$$

Table 1. C/N_o Components and Their Effects By Uplink and Downlink Rains

C/N_o Components	Uplink Rain Effects	Downlink Rain Effects
• **Thermal Noise**		
* Uplink	x	0
* Downlink	x	x
• **Interference**		
- **Terrestrial**		
* Uplink	x	0
* Downlink	x	~
- **Adjacent Satellite**		
* Uplink	x	0
* Downlink	x	~
- **Co-Satellite**		
-- Co-Channel		
--- *Co-Pol. Xponder*		
* Uplink	x	0
* Downlink	x	0
--- *Cross-Pol. Xponder*		
* Uplink	x	0
* Downlink	x	~
-- Adjacent (Co-Pol.) Channel		
* Uplink	x	0
* Downlink	x	0
• **Intermodulation**		
* Transponder	x	0
* Carrier Tx Earth Station	0	0
* Other Tx Earth Station	x	0

x : Significant Effects, ~ : Little Effects, 0 : Insignificant or No Effects

To simplify estimation of the overall C/N_O, the uplink components are often calculated at the satellite transponder (or HPA) input (rather than at the earth station demodulator input). Estimation of C/N_O using this technique ignores i) the small signal suppression effects of the transponder nonlinearity on the uplink thermal noise, interference and intermodulation components (resulting in under-estimation of the uplink components of C/N_O) and ii) the interaction of the uplink thermal noise, interference and intermodulation components with the carriers and among themselves to cause additional intermodulation effects (resulting in over-estimation of the uplink components of C/N_O). However, as investigated in [14], these two opposing effects are approximately equal and thus cancel each other for a multiple carrier/transponder operation. Nevertheless, for a single carrier/ transponder operation, the small signal suppression effects are more dominant and for a dual carrier carrier/transponder operation, the additional intermodulation effects are more dominant [14].

It is desirable to accurately account for all of the C/N_O components in satellite link power budgets. The thermal noise components can be estimated accurately from the supplied satellite and earth stations G/Ts; the carrier earth station intermodulation component can be estimated accurately from a proper intermod analysis software tool (e.g., [4], [5]); and the terrestrial interference components can be estimated accurately by performing an RFI analysis using large terrestrial station data bases available commercially. The satellite operator (e.g., INTELSAT) has the responsibility to supply information on the other C/N_O components when they are requested by the satellite link engineer. It is because the satellite operator who sets limits to control co-satellite interference and other intermod interference and who coordinates with adjacent satellite operators to control adjacent satellite interference. Estimation of these interference and intermodulation components is, in general, straight forward mathematically. However, it often involves many system parameters (e.g., transponder traffic loading) whose characteristics change dynamically with time. Thus, it is difficult to estimate these interference and intermodulation components accurately. In practical link budget calculations, these interference and intermodulation components are sometimes ignored, set to given percentages of the thermal noise components (e.g., 25 %), or calculated from reference values supplied by the satellite operator (e.g., INTELSAT supplies typical co-satellite co-channel interference values and transponder intermod values in INTELSAT Earth Station Standard (IESS) 410).

Rainfall at the transmit earth station causes the uplink carrier power to be attenuated by a_u, which in turns reduces the downlink carrier power. The amount of change in the downlink carrier power depends on the transponder nonlinearity, the uplink powers of carriers that share the transponder and a_u. It can be computed by various nonlinearity analysis techniques such as Fuenzalida-Shimbo-Cook [4] and IM-Microscope [5]. For a single or dual carrier/transponder operation, the reduction in the downlink carrier power is much less than a_u; whereas for a multiple carrier/transponder operation, the reduction is typically about the same as a_u.

Since, for a multiple carrier/transponder operation, the uplink rain does not really have any effects on the thermal noise, interference and intermoduation sources (other than the intermodulation products generated from the same transmit earth station), it can be stated that due to the uplink rain, all C/N_O components (except for the carrier earth station intermod component) are typically reduced by a_u (as shown in Table 1), that is, the overall C/N_O is reduced a_u.

Rainfall at the receive earth station attenuates the downlink carrier and all intermodulation, interference and uplink thermal noise (and not downlink thermal noise) by a_d. It also raises the receive earth station antenna temperature (i.e., raises downlink thermal noise) and increases crosspolarized transponder interference (causes by rain depolarization). Thus, it can be stated (as shown in Table 1) that downlink rain practically affects only the C/N_O downlink thermal noise component (by more than a_d) and that depending on whether the link is limited (dominated) by the downlink thermal noise or not, the overall C/N_O is reduced by more than or less than a_d respectively.

4 .0 ONE-WAY (SIMPLEX) LINK AVAILABILITY

Let A_u and A_d be the uplink and downlink rain attenuation parameters respectively, then Eq. (1) for the operating overall carrier-to-equivalent-noise density ratio (C/N_o) at the input of the receive earth station demodulator can be put into the following form:

$$C/N_O = g\,(A_u, A_d, \underline{\alpha}) \tag{2}$$

where $\underline{\alpha}$ is the link parameters other than A_u and A_d that also affect C/N_O, and g is the link power budget function. When complete statistics and the correlations of these link parameters A_u, A_d and $\underline{\alpha}$ are known, complete statistic of C/N_O can be computed. Consequently, the availability of a one-way link (from a transmit earth station to a receive earth station) can be evaluated directly from its definition, shown as Eq. (3), where $f_{C/N_O}(y)$ is the probability density function of C/N_O and $(C/N_O)_{min}$ is the minimum acceptable C/N_O.

$$A_{VAIL} \equiv \mathrm{Prob}\{(C/N_O) \geq (C/N_O)_{min}\} = \int_{(C/N_o)_{min}}^{\infty} f_{C/N_O}(y)dy \tag{3}$$

At Ku-band or higher frequencies, the randomness effects of A_u and A_d are much more pronounced than $\underline{\alpha}$ (e.g., pointing losses) and accordingly for all practical purposes, $\underline{\alpha}$ can be considered as deterministic (by replacing $\underline{\alpha}$ by their worst, average, or best values). Also since the required transponder power is the really relevant parameter that affects the availability of the link, $\underline{\alpha}$ is also replaced by C_{out}, the carrier output power in dB OPBO (output backoff) under clear-sky conditions,

$$C/N_O = g(A_u, A_d, C_{out}) \tag{4}$$

In general, from the rain attenuation models, the statistics of rain attenuation A (A_u or A_d) is provided in terms of the cumulative probability distribution function $P_A(a)$, i.e., the probability that A does not exceed a. To compute the statistic of C/N_O, i.e., $f_{C/N_O}(y)$, one needs the statistics of A_u and A_d in the format of the probability density function $f_A(a)$. Thus conversion between the cumulative distribution function $P_A(a)$ and the probability density function $f_A(a)$ is needed and can be achieved through the following equations:

$$f_A(a) = dP_A(a)/da \tag{5a}$$

$$P_A(a) = \int_{-\infty}^{a} f_A(a)da \tag{5b}$$

In general it is difficult (if not impossible) to obtain $f_{C/N_O}(y)$, the probability density function of C/N_O, in a close and continuous form. To facilitate numerical computation, the probability density function of a random rain attenuation A is converted to its discrete form,

$$f_A(a) = \sum_{i=1}^{M} x_i\,\delta(a - a_i) \tag{6a}$$

$$\sum_{i=1}^{M} x_i = 1 \tag{6b}$$

One can do so by dividing the domain of A into M finite intervals: $(-\infty, b_1 = 0), (b_1, b_2), (b_2, b_3), \ldots, (b_{M-1}, b_M = \infty)$ and let a_i and x_i be defined as shown below:

$$a_i = (b_i - b_{i-1}) / 2 \qquad i = 2, 3, \ldots, M-1 \tag{7a}$$

$$a_1 = b_1 = 0 \tag{7b}$$

$$a_M = b_{M-1} \tag{7c}$$

$$x_i = \int_{b_{i-1}}^{b_i} f_A(a)da = P_A(b_i) - P_A(b_{i-1}) \quad i = 2, 3, \ldots, M-1 \tag{8a}$$

$$x_1 = P_A(b_1) = P_A(0) \tag{8b}$$

$$x_M = 1 - P_A(b_{M-1}) \tag{8c}$$

Eq. (6b) must hold by the definition of a probability density function, and the conversion of $f_A(a)$ to its discrete form as described by Eq. (6a) can be made as accurate as desired by allowing M to take a sufficient large value (say, 100). Accordingly, the probability density functions of the random uplink and downlink rain attenuations, A_u and A_d, in their discrete forms are:

$$f_{A_u}(a_u) = \sum_{i=1}^{M_u} x_{ui}\,\delta(a_u - a_{ui}) \tag{9a}$$

$$f_{A_d}(a_d) = \sum_{j=1}^{M_d} x_{dj}\,\delta(a_d - a_{dj}) \tag{9b}$$

$$\sum_{i=1}^{M_u} x_{ui} = 1 \tag{9c}$$

$$\sum_{j=1}^{M_d} x_{dj} = 1 \tag{9d}$$

4.1 Uncorrelated Rains (General Case)

When the uplink rain and downlink rain are uncorrelated (which may be assumed when the transmit and receive earth stations are quite far apart), then clearly from Eq. (4), the probability density function of the overall C/N$_O$ at the receive earth station demodulator can be put into the following equation,

$$f_{C/N_O}(y) = \sum_{i=1}^{M_u} \sum_{j=1}^{M_d} x_{ui}\, x_{dj}\, \delta(y - g(a_{ui}, a_{dj}, C_{out})) \tag{10}$$

and the availability of a one-way (simplex) link for the general case (where the uplink and downlink rains are assumed to be uncorrelated) can be found from the definition of link availability (i.e., Eq. (3)) or equivalently by the following equations,

$$A_{VAII} = \sum_{i=1}^{M_u} \sum_{j=1}^{M_d} x_{ui}\, x_d \tag{11a}$$

where i and j are such that

$$g(a_{ui}, a_{dj}, C_{out}) \geq (C/N_O)_{min} \tag{11b}$$

4.1.1 Algorithm for The Accurate Method

The following is an algorithm for the Accurate Method that can be used to compute the availability for a one-way (simplex) satellite link for the general case where the uplink rain and downlink rain are assumed to be uncorrelated:

1. The carrier power output backoff C_{out} (i.e., the transponder power utilized) and the minimum acceptable carrier-to-equivalent-noise-density ratio $(C/N_O)_{min}$ are supplied.
2. Compute the discrete probability density functions of A_u and A_d, i.e., find $\{a_{ui}, x_{ui}, a_{dj},$ and x_{dj} for $i = 1, 2, ..., M_u$ and $j = 1, 2, ..., M_d\}$ using Eqs. (7) and (8) with the cumulative probability function $P_A(a)$ generated from the rain attenuation model used.
3. For each uplink and downlink rain attenuation pair (A_u, A_d), perform satellite link calculation to evaluate $g(A_u, A_d, C_{out})$.
4. Compute the link availability using Eqs. (11a) and (11b), i.e., by adding together all products $x_{ui} \cdot x_{dj}$ whose corresponding i and j are such that $g(a_{ui}, a_{dj}, C_{out}) \geq (C/N_O)_{min}$.

Note that the problem that often exists in satellite link design is reversed: the link availability is specified and the carrier output backoff C_{out} (i.e., the required transponder power) is estimated. If this is the case, then, one can treat this problem as a one dimensional search problem which must be solved iteratively by first guess a value for C_{out} and compute the availability, then make a new improved guess for C_{out} and compute the new availability, the whole process is repeated until the newest availability is sufficiently close to the specified availability, then the last guess of C_{out} is the solution to the problem.

4.2 The Simplified Method

The Accurate Method is still time consuming, as it needs to perform satellite link calculations M_u M_d times, and typical value for M_u or M_d is around 100 or so for the representation of the probability density function by its discrete equivalent to be accurate. To further simplify the computation involved, the authors introduce here the Simplified Method. With the Simplified Method, the link availability is approximated by a product of two cumulative probabilities, $P_{A_u}(a^*_u)$ and $P_{A_d}(a^*_d)$,

$$A_{VAII} \cong P_{A_u}(a^*_u)\, P_{A_d}(a^*_d) \tag{12}$$

where a^*_u is the "uplink margin", the maximum uplink rain attenuation supportable by the link conditioned to no downlink rain; and a^*_d is the "downlink margin", the maximum downlink rain attenuation supportable by the link conditioned to no uplink rain. The "uplink margin" can directly be found by solving Eq. (13a) and the "downlink margin" by solving Eq. (13b),

$$g(a^*_u, 0, C_{out}) = (C/N_O)_{min} \tag{13a}$$

$$g(0, a^*_d, C_{out}) = (C/N_O)_{min} \tag{13b}$$

The two cumulative probabilities $P_{A_u}(a^*_u)$ and $P_{A_d}(a^*_d)$ are also respectively "link availability conditioned to no downlink rain" and the "link availability conditioned to no uplink rain". To simplify the callings, $P_{A_u}(a^*_u)$ and $P_{A_d}(a^*_d)$ can be addressed as "uplink availability" and "downlink availability" respectively. Nevertheless, it should bear in mind that the words "uplink availability" and "downlink availability" may cause misinterpretation that the uplink and downlink were two complete links and not part of the link.

Note that the "uplink margin", "downlink margin", "uplink availability", and "downlink availability" used here are different from those used by the "widely-used simplified formula" addressed in Section 1. Here, these values are calculated based on Eqs. (13a) and (13b), whereas in the "widely-used simplified formula", they are independently assigned to the uplink and downlink (as if the uplink and downlink are two separate and independent complete links).

Note also that for a multiple carrier/transponder operation, the "uplink margin" a^*_u is about the same as the link margin (i.e., the difference between the clear sky overall C/N$_O$ and the minimum acceptable overall C/N$_O$); and the "downlink margin" a^*_d can be either higher or lower than the link margin, depending on whether the link is more uplink-limited or more downlink-limited.

4.2.1 Algorithm for The Simplified Method

The following is an algorithm for the Simplified Method that can be used to compute the availability for a one-way (simplex) satellite link for the general case where the uplink rain and downlink rain are assumed to be uncorrelated:

1. The carrier power output backoff C_{out} (i.e., the transponder power utilized) and the minimum acceptable carrier-to-equivalent-noise-density ratio $(C/N_O)_{min}$ are supplied.
2. Compute the "uplink margin" a^*_u from Eq. (13a) and the "downlink margin" a^*_d from Eq. (13b).
3. Calculate the two cumulative probabilities $P_{A_u}(a^*_u)$ and $P_{A_d}(a^*_d)$, i.e., the "uplink availability" and "downlink availability", from the rain attenuation model used.
4. Compute the link availability by multiplying out these two cumulative probabilities.

4.2.2 Comparison Between The Accurate and Simplified Methods

It is obvious that from the Simplified Method defined above, the availability for the Simplified Method can also be computed from the following equations, using the discrete probability density functions (and assuming that M_u. and M_d are chosen large enough so that a^*_u and a^*_d fall right into some sampled discrete rain attenuations),

$$A_{VAII} = \sum_{i=1}^{M_u} \sum_{j=1}^{M_d} x_{ui}\, x_{dj} \tag{14a}$$

where i is such that

$$g(a_{ui}, 0, C_{out}) \geq (C/N_O)_{min} \tag{14b}$$

and j is such that

$$g(0, a_{dj}, C_{out}) \geq (C/N_O)_{min} \tag{14c}$$

It can also be easily seen that,

$$P_{A_u}(a^*_u) = \sum_{i=1}^{M_u} x_{ui} \tag{15a}$$

where i is such that

$$g(a_{ui}, 0, C_{out}) \geq (C/N_O)_{min} \tag{15b}$$

and that

$$P_{A_d}(a^*_d) = \sum_{j=1}^{M_d} x_{dj} \tag{16a}$$

where j is such that

$$g(0, a_{dj}, C_{out}) \geq (C/N_O)_{min} \tag{16b}$$

Results of the two methods can be compared graphically as shown in Figure 1 where the availability of each method is represented by an area spanned by appropriate area elements $(x_{ui}\, x_{dj})$'s. The area of the Simplified Method is a rectangle of $P_{A_u}(a^*_u)$ by $P_{A_d}(a^*_d)$. The area of the Accurate Method is the rectangle taken away the shaded area elements at the upper right hand corner. From design experience with many different satellite communication links, most of the availability differences in these two methods are found to be within 0.002 %, and none of the differences are more than 0.05 %. The availability differences are indeed small when comparing to the uncertainties in other link parameters. The Simplified Method can be implemented at ease with a spread sheet computer program such as Excel, whereas the Accurate Method cannot.

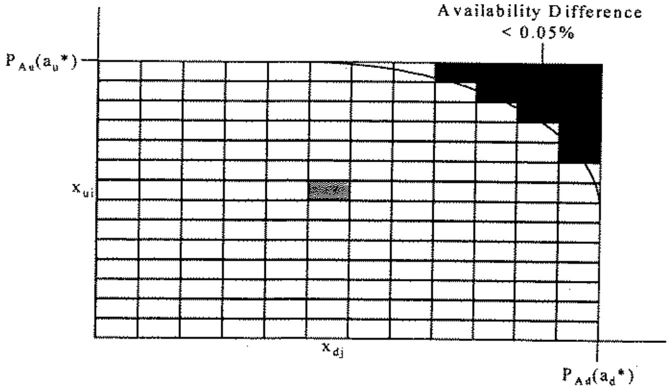

Figure 1. Availability Comparison Between The Accurate Method And The Simplified Method

4.3 Correlated Rains (Special Case)

When the uplink rain and downlink rain are completely correlated (which may be assumed when the transmit and receive earth stations are either the same or very close to each other), complete rain statistics of the downlink rain attenuation can be derived from those of the uplink rain attenuation. From CCIR [6], if the difference between the uplink and downlink are just frequencies, the uplink and downlink rain attenuations can be considered to relate to each other by the following simple empirical equations (17a) and (17b),

$$A_d / A_u = k(f_d) / k(f_u) = k_{du} \tag{17a}$$

$$k(f) = f^{1.72} / (1 + 3 \times 10^{-7} f^{3.44}) \tag{17b}$$

where f_u and f_d are the uplink and downlink frequencies. Thus, the availability of a one-way link for the completely correlated rain case, A_{VAIIc}, can be computed from Eqs. (18a) and (18b),

$$A_{VAIIc} = \sum_{i=1}^{M_u} x_{ui} \tag{18a}$$

where i is such that

$$g(a_{ui}, k_{du}\, a_{ui}, C_{out}) \geq (C/N_O)_{min} \tag{18b}$$

or equivalently from Eqs. (19a) and (19b),

$$A_{VAIIc} = P_{A_u}(a^*_u) \tag{19a}$$

where a^*_u is such that

$$g(a^*_u, k_{du}\, a^*_u, C_{out}) = (C/N_O)_{min} \tag{19b}$$

Note that the availability for the completely correlated rain case may or may not be higher than the availability for the completely uncorrelated rain case. For any two nearby locations, say Baltimore and Washington, D.C., the two rain statistics are somewhat correlated and therefore the availability results should be bounded by the two extreme cases (completely correlated and completely uncorrelated).

4.4 With Uplink Power Control

To increase the availability and/or to reduce the transponder power required to support a satellite link, uplink power control (UPC) may be used at a large transmit earth station, e.g., a hub station in a VSAT satellite network. It is assumed here that the uplink power control is ideal and limited, to facilitate computation and to provide ideal, upper bound results. Under these assumptions, the uplink rain attenuation is compensated for without any time delay by boosting up the carrier power at the transmit earth station by the same amount (as the uplink rain attenuation) or by the maximum allowable amount D_m, whichever is smaller. Typically, D_m is around 10 to 15 dB. Note that when $D_m = 0$, cases with UPC are reduced to cases without UPC.

4.4.1 With Uncorrelated Rains

For the uncorrelated rain case, from the Accurate Method, the availability can be computed from Eqs. (20a) and (20b),

$$A_{VAII} = \sum_{i=1}^{M_u} \sum_{j=1}^{M_d} x_{ui}\, x_{dj} \tag{20a}$$

where i and j are such that

$$g(\mathrm{Max}\{0, a_{ui} - D_m\}, a_{dj}, C_{out}) \geq (C/N_O)_{min} \tag{20b}$$

and Max(x, y) is the higher value of x and y. Likewise, from the Simplified Method, the availability can be computed from Eq. (21),

$$A_{VAII} = P_{A_u}(a^*_u + D_m)\, P_{A_d}(a^*_d) \tag{21}$$

where a^*_u and a^*_d are defined as before, i.e., by Eqs. (13a) and (13b). Note that for cases with UPC, the "uplink margin" is $(a^*_u + D_m)$ instead of a^*_u.

4.4.2 With Completely Correlated Rains

For the completely correlated rain case, from the Accurate Method, the availability can be computed from Eqs. (22a) and (22b),

$$A_{VAIIc} = \sum_{i=1}^{M_u} x_{ui} \tag{22a}$$

where i is such that

$$g(\mathrm{Max}\{0, a_{ui} - D_m\}, k_{du}\, a_{ui}, C_{out}) \geq (C/N_O)_{min} \tag{22b}$$

or equivalently from Eqs. (23a) and (23b),

$$A_{VAIIc} = P_{A_u}(a^*_u) \tag{23a}$$

where a^*_u is such that

$$g(\mathrm{Max}\{0, a^*_u - D_m\}, k_{du}\, a^*_u, C_{out}) = (C/N_O)_{min} \tag{23b}$$

4.5 Example

A sample link budget calculation with availabilities calculated from the Simplified Method are shown in Table 2 for cases with and without UPC. It is assumed that a) the link is operated such that the percentage of utilized transponder power is balanced with the percentage of utilized transponder bandwidth and b) the equivalent total interference and intermod power densities are 6 dB below thermal noise floor.

Based on the usable transponder bandwidth, bit rate, modulation and coding and the assumption of 1.6 for the utilized bandwidth / symbol rate factor, the carrier utilizes 3.034 % of the available transponder bandwidth. Based on the assumption that the transponder is operated at 3.5 dB output backoff, the carrier needs to be operated at 18.68 dB output backoff in order to consume 3.034 % of the available transponder power. The corresponding clear sky E_b/N_o is 12.65 dB which provides a link margin of 6.25 dB over the minimum acceptable E_b/N_o of 6.4 dB. Accordingly, the "uplink margins" for the case without uplink power control (UPC) and the case with maximum ideal UPC compensation of 10 dB are 6.25 dB and 16.25 dB respectively. The corresponding "uplink availabilities" (i.e., link availabilities conditioned to no downlink rain) are 99.943 % and 99.989 % for the two cases respectively. The "downlink margin" is 4.46 dB and the corresponding "downlink availability" (i.e., link availability conditioned to no uplink rain) is 99.977 %. Thus, from the Simplified Method, the link availabilities are 99.920 % and 99.966 % for the case without UPC and the case with maximum ideal UPC compensation of 10 dB, respectively. The carrier EIRP required (without the backoff) at the transmit earth station for the two cases are 57.76 dBW and 67.76 dBW, respectively.

Table 2. Sample One-Way Satellite Link Power Budget With Availabilities Calculated From The Simplified Method

Xponder:	Ku-Band, 54-MHz BW, Operating Point: 6.5/3.5 dB
Tx Station:	20° EL, 55° LAT, Crane Rain Zone D2
Rx Station:	30° EL, 40° LAT, Crane Rain Zone C, Clear Sky G/T = 22.3 dB/K (1.8 m) and T = 200 K
Link:	512 kbps, BPSK, 1/2-Rate FEC, $(E_b/N_o)_{min}$ = 6.4 dB, Operated w/o UPC and w/ UPC (D_m=10 dB) and @ Utilized Xponder Power = Utilized Xponder BW

Ref. SFD, dBW/m^2	(+)	-82.00
Ref. G/T, dB/K	(+)	1.00
Carrier Input Backoff, dB	(-)	21.68
Ideal Gain of 1m^2 Aperture, dBi	(-)	44.53
Boltzmann Constant, dBW/K/Hz	(-)	-228.60
C/N_o - Thermal - Up, dBHz		81.39
$C/(I_o + IM_o)$ - Up, dBHz		87.41
C/N_o - Total - Up, dBHz		80.42
Saturated Sat. EIRP @ Rx E.S., dBW	(+)	45.00
Carrier Output Backoff, dB	(-)	18.68
Downlink Free Space Loss, dB	(-)	205.72
Downlink Atmospheric Loss, dB	(-)	0.40
Rx Earth Station G/T, dB/K	(+)	22.30
Boltzmann Constant, dBW/K/Hz	(-)	-228.60
C/N_o - Thermal - Down, dBHz		71.10
$C/(I_o + IM_o)$ - Down, dBHz		77.12
C/N_o - Total - Down, dBHz		70.13
C/N_o - Total, dBHz	(+)	69.74
Information Rate (512 kbps), dBbps	(-)	57.09
Clear Sky E_b/N_o, dB	(+)	12.65
Minimum Acceptable E_b/N_o, dB	(-)	6.40
Link Margin, dB		6.25

		w/o UPC	w/ UPC (D_m=10 dB)
"Uplink Margin", dB		6.25	16.25
"Downlink Margin", dB		4.46	4.46
"Uplink Availability"		99.943 %	99.989 %
"Downlink Availability"		99.977 %	99.977 %
Link Availability		99.920 %	99.966 %
Ref. SFD, dBW/m^2	(+)	-82.00	-82.00
Ref. G/T, dB/K	(+)	1.00	1.00
Sat. G/T @ Xmit Station, dB/K	(-)	3.00	3.00
Carrier Input Backoff, dB	(-)	21.68	21.68
Spreading Loss, dB	(+)	162.94	162.94
Uplink Atmospheric Loss, dB	(+)	0.50	0.50
Max. UPC Compensation, dB	(+)	0.00	10.00
Carrier EIRP @ Xmit Station, dBW		57.76	67.76

Xponder Power Utilized	3.034 %
Xponder BW Utilized	3.034 %

5 .0 TWO-WAY (DUPLEX) LINK AVAILABILITY

A two-way (duplex) satellite link consists two one-way (simplex) satellite links: a forward link from an earth station A to an earth station B and a return link from B to A. For a two-way link, the word availability may be ambiguous as they may vary for different protocols used. For example, for certain protocols, the two-way link may still be available for transmission, even one of the its one-way link is not available for a short while (before time-out is reached). Here, the availability for a two-way link is defined as the availability of both the forward link and the return link simultanuosly, i.e.,

$$A_{VA12} \equiv \mathrm{Prob}\{(C/N_O)_F \geq (C/N_O)_{Fmin} \text{ and } (C/N_O)_R \geq (C/N_O)_{Rmin}\} \quad (24)$$

where the subscripts F and R stand for forward link and return link respectively. Using the same notation convention, the overall carrier-to-equivalent-noise-density ratios at the receive earth station demodulators for the forward and return links are respectively,

$$(C/N_o)_F = g_F(A_{Fu}, A_{Fd}, C_{Fout}) \quad (25a)$$

$$(C/N_o)_R = g_R(A_{Ru}, A_{Rd}, C_{Rout}) \quad (25b)$$

Except for the frequency differences, the uplink of the forward link is the same as the downlink of the return link and the downlink of the forward link is the same as the uplink of the return link. That is, according to the CCIR report discussed earlier,

$$A_{Fd} / A_{Ru} \approx k(f_{Fd}) / k(f_{Ru}) = k_{FdRu} \quad (26a)$$

$$A_{Rd} / A_{Fu} \approx k(f_{Rd}) / k(f_{Fu}) = k_{RdFu} \quad (26b)$$

Combining Eqs. (25a), (25b) with Eqs. (26a) and (26b) provides

$$(C/N_o)_F = g_F\,(A_{Fu}, k_{FdRu}\,A_{Ru}, C_{Fout}) \quad (27a)$$

$$(C/N_o)_R = g_R\,(A_{Ru}, k_{RdFu}\,A_{Fu}, C_{Rout}) \quad (27b)$$

Let the discrete probability density functions of the uplink rain attenuations for the forward and return links, A_{Fu} and A_{Ru}, be defined with the same notation convention,

$$f_{A_{Fu}}(a_{Fu}) = \sum_{i=1}^{M_{Fu}} x_{Fui}\,\delta(a_{Fu} - a_{Fui}) \qquad (28a)$$

$$f_{A_{Ru}}(a_{Ru}) = \sum_{j=1}^{M_{Ru}} x_{Ruj}\,\delta(a_{Ru} - a_{Ruj}) \qquad (28b)$$

5.1 Uncorrelated Rains

For the case where rains at the earth station A and at the station B are uncorrelated, then clearly from the definition of the availability of a two-way link (i.e., Eq. (24), the two-way link availability can be computed from Eqs. (29a), (29b) and (29c),

$$A_{VAI2} = \sum_{i=1}^{M_{Fu}} \sum_{j=1}^{M_{Ru}} x_{Fui}\, x_{Ruj} \qquad (29a)$$

where i and j are such that

$$g_F(a_{Fui}, k_{FdRu}\, a_{Ruj}, C_{Fout}) \geq (C/N_O)_{Fmin} \qquad (29b)$$

$$g_R(a_{Ruj}, k_{RdFu}\, a_{Fui}, C_{Rout}) \geq (C/N_O)_{Rmin} \qquad (29c)$$

It should be noted that from the above equations, there may be more than one combinations of C_{Fout} and C_{Rout} that yield the same two-way link availability. If the availability is specified in the link design, one should perform optimization to pick up the combination that provides the lowest transponder power utilization.

5.2 Completely Correlated Rains

For the case where the earth station A and the station B are either the same or very close to each other, then the rains can be treated to be completely correlated to each other and therefore

$$A_{Fd} / A_{Fu} = k(f_{Fd}) / k(f_{Fu}) = k_{FdFu} \qquad (30a)$$

$$A_{Ru} / A_{Fu} = k(f_{Ru}) / k(f_{Fu}) = k_{RuFu} \qquad (30b)$$

and Eqs. (25a) and (25b) become

$$(C/N_o)_F = g_F(A_{Fu}, k_{FdFu}\, A_{Fu}, C_{Fout}) \qquad (31a)$$

$$(C/N_o)_R = g_R(k_{RuFu}\, A_{Fu}, k_{RdFu}\, A_{Fu}, C_{Rout}) \qquad (31b)$$

and the two-way availability can be computed from Eqs. (32a) and (32c),

$$A_{VAI2} = \sum_{i=1}^{M_{Fu}} x_{Fui} \qquad (32a)$$

where i is such that

$$g_F(a_{Fui}, k_{FdFu}\, a_{Fuj}, C_{Fout}) \geq (C/N_O)_{Fmin} \qquad (32b)$$

$$g_R(k_{RuFu}\, a_{Fui}, k_{RdFu}\, a_{Fui}, C_{Rout}) \geq (C/N_O)_{Rmin} \qquad (32c)$$

5.3 With Uplink Power Control

5.3.1 Uncorrelated Rains

With ideal and power-limited uplink power control and for the uncorrelated rain case, the two-way link availability can be computed from the equations below.

$$A_{VAI2} = \sum_{i=1}^{M_{Fu}} \sum_{j=1}^{M_{Ru}} x_{Fui}\, x_{Ruj} \qquad (33a)$$

where i and j are such that

$$g_F(\mathrm{Max}\{0, a_{Fui} - D_{Fm}\}, k_{FdRu}\, a_{Ruj}, C_{Fout}) \geq (C/N_O)_{Fmin} \qquad (33b)$$

$$g_R(\mathrm{Max}\{0, a_{Ruj} - D_{Rm}\}, k_{RdFu}\, a_{Fui}, C_{Rout}) \geq (C/N_O)_{Rmin} \qquad (33c)$$

where D_{Fm} and D_{Rm} are the maximum additional carrier power (in dB relative to carrier power) that can be used at the transmit earth stations during uplink rainfalls for the forward and return links respectively.

5.3.2 Completely Correlated Rains

With ideal and power-limited uplink power control and for the completely correlated rain case, the two-way link availability can be computed from the equations below.

$$A_{VAI2} = \sum_{i=1}^{M_{Fu}} x_{Fui} \qquad (34a)$$

where i is such that

$$g_F(\mathrm{Max}\{0, a_{Fui} - D_{Fm}\}, k_{FdFu}\, a_{Fui}, C_{Fout}) \geq (C/N_O)_{Fmin} \qquad (34b)$$

$$g_R(\mathrm{Max}\{0, k_{RuFu}\, a_{Fui} - D_{Rm}\}, k_{RdFu}\, a_{Fui}, C_{Rout}) \geq (C/N_O)_{Rmin} \qquad (34c)$$

5.4 Approximation Methods

If let A_{VAIIF} and A_{VAIIR} be the availabilities of the forward link and the return link respectively, then directly from the probability theory, the two-way link availability is bounded as shown below.

$$(A_{VAIIF}) \times (A_{VAIIR}) \leq A_{VAI2} \leq \mathrm{Min}(A_{VAIIF}, A_{VAIIR}) \qquad (35)$$

Since the forward link and the return link are correlated (but not completely correlated in general): uplink of one link is downlink of the other, the two-way link availability should be closer to its upper bound and this approximation is sometimes employed,

$$A_{VAI2} \cong \mathrm{Min}(A_{VAIIF}, A_{VAIIR}) \qquad (36)$$

There is another approximation that the authors have seen but could not find or derive any rational or proof to support it. This approximation is defined below,

$$A_{VAI2} \cong \mathrm{Min}\{P_{A_{Fu}}(a^*_{Fu}), P_{A_{Rd}}(a^*_{Rd})\} \times \mathrm{Min}\{P_{A_{Fd}}(a^*_{Fd}), P_{A_{Ru}}(a^*_{Ru})\} \qquad (37)$$

where $P_{A_{Fu}}(a^*_{Fu})$, $(P_{A_{Fd}}(a^*_{Fd})$, $P_{A_{Ru}}(a^*_{Ru})$, and $P_{A_{Rd}}(a^*_{Rd})$ are the uplink and downlink availabilities of the forward and return links respectively.

REFERENCE

[1] X.T. Vuong and R.J. Forsey, "Prediction of Sun Transit Outages in an Operational Communication Satellite System," *IEEE Transactions on Broadcasting*, Dec. 1983.

[2] L.J. Greenstein and M. Shafi, "Outage Calculation Methods for Microwave Digital Radio," *IEEE Comm. Magazine*, Feb. 1987.

[3] M. Yamada, Y. Karasawa, M. Yasunaga, and B. Arbesser-Ratstburg, "An Improved Prediction Method for Rain Attenuation in Satellite Communications Operating at 10-20 GHz," *Radio Science*, Nov. 1987.

[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] D.S. Arnstein, X.T. Vuong, C.B. Cotner, and H.M. Daryanani, "The IM Microscope: A New Approach to Nonlinear Analysis of Signals in Satellite Communications Systems," *COMSAT Technical Review*, Spring 1992.

[6] *Propagation Data and Prediction Methods Required for Earth-Space Telecommunication Systems*, CCIR Report 564-3, 1986.

[7] L.J. Ippolito, R.D. Kaul, and R.G. Wallace, *Propagation Effects Handbook for Satellite Systems Design*, NASA Publication 1082.

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

[9] C. Bantin and R. Lyons, "The Evaluation of Satellite Link Availability,"*IEEE Transactions on Communications*, June 1978.

[10] C. Kittiver and D. Westwood, "The Composite Margin Plane - A Tool to Compute Overall Satellite Communications Link Availability," *National Telecommunication Conference Record*, Dallas, 1976.

[11] S. Calo, L. Shiff and H. Staras, "Effects of Rain on Multiple Access Transmission of Data Via Satellite, *IEEE Proceedings of International Conference on Communications*, Toronto, 1978.

[12] D.N. McGregor, *Communication Satellite System Availability Models*, ORI Technical Report 1890, Contract NASW-3436 for NASA Headquarters, 1981.

[13] M.E. Ferguson, "On Interference into Digital Systems," *Satellite Operator and User Technical Committee Meeting*, FCC Headquarters, Washington, D.C., March 1985.

[14] X.T. Vuong, "Effects of Satellite Transponder Nonlinearity on Uplink Thermal Noise," *IEEE Transactions on Broadcasting*, June 1987.

Xuyen T. Vuong has twenty years of experience in systems engineering, analysis, design, and testing of commercial and military satellite communication payloads, earth stations, and communication networks, through employment with leading satellite communication companies such as Comsat Labs., Spar Aerospace, and Telesat Canada. Currently, he is a Staff Scientist at SAIC, McLean, Virginia, performing satellite communication consulting work to support various government organizations including DISA (Defense Information Systems Agency), DARO (Defense Airborne Reconnaissance Office) and the U.S. Air Force.

He has performed pioneering work and advanced the state-of-the-art in several satellite engineering fields including matrix amplifier, active transmit phased array antenna analysis, sun transit outage prediction, carrier frequency assignment, and nonlinear/intermod analysis. He has developed communication analysis techniques and software programs that are used in several countries.

Dr. Vuong obtained the B.S.E.E. with Honors from California State University, M.Eng. (electrical) from Carleton University and Ph.D. (systems engineering) from the University of Western Ontario, and taught computer science and electrical engineering courses at the University of Ottawa and Concordia University.

Son T. Vuong received his B.S. in electrical engineering from California State University, Sacramento, U.S.A. in 1972, M.Eng. in electrical engineering from Carleton University, Ottawa, Canada in 1977, and Ph.D. in computer science from the University of Waterloo, Waterloo, Canada in 1982. In 1974 and 1975 he was with the Canada Center for Remote Sensing working on image processing, and in 1978 with Bell Northern Research working on routing and flow control for packet-switched networks. In 1981 and 1982 he was on the faculty of the Department of Computer Science of the University of Waterloo. Since 1983 he has been with the Department of Computer Science of the University of British Columbia, Vancouver, Canada, where he was a founder of the Distributed Systems Research Group and is presently an Associate Professor.

Dr. Vuong served on several conference program committees and was the (co)chair and (co)organizer of the following major conferences: ICDCS'95, PSTV'94, FORTE'89, and IWPTS'88. He will be a cochair of DMS'97.

His areas of research interests include protocol engineering, computer communications, highspeed networks, multimedia systems, and mobile computing.