# Communication Link Performance for Commercial and Military Satellites

Wilbur L. Pritchard* and Neil MacGregor†
*Aerospace Corporation, Los Angeles, Calif.*

### Nomenclature

| | | |
|---|---|---|
| $A$ | = | antenna area |
| $B$ | = | rf link bandwidth |
| $D$ | = | frequency-modulation deviation ratio = $f_d/f_b$ |
| $f_b$ | = | maximum baseband frequency |
| $f_d$ | = | peak frequency deviation |
| $G_p$ | = | detector processing gain |
| $J$ | = | jamming signal power |
| $k$ | = | Boltzmann's constant = $1.38 \times 10^{-23}$ $w$/°K-cps |
| $I_j$ | = | $j$th interfering signal |
| $L_d$ | = | rf losses in satellite-to-ground link |
| $n$ | = | number of voice channels |
| $N$ | = | noise power |
| $N_0$ | = | baseband noise power density (noise power per cps) |
| $P$ | = | signal power plus noise power |
| $R_P$ | = | ratio of peak power to average power |
| $S$ | = | signal power |
| $T$ | = | noise temperature, °K |
| $X_t$ | = | required receiver threshold |
| $(C/N)_L$ | = | theoretical maximum carrier/noise ratio for link |
| $(S/N)_D$ | = | desired post-detection signal-to-noise ratio |
| $\alpha$ | = | constant; $\alpha = 1, B_s \leq B_r$; $\alpha = B_r/B_s, B_r < B_s$ |
| $\beta_j$ | = | fraction of signal bandwidth overlapped by an interfering signal |
| $\gamma$ | = | limiter suppression factor |

***Subscripts***

| | | |
|---|---|---|
| $t$ | = | transmitter |
| $r$ | = | receiver |
| $s$ | = | satellite input |

### Introduction

DIFFERENCES in design considerations for commercial and military communication satellites were discussed by the authors in Ref. 1. The calculation of channel capacity was discussed at length, and emphasis was laid on the differences between clear channel performance, with hundreds of telephone conversations typical of commercial systems, and the performance of a small number of channels in a jammed environment characteristic of military systems. This note presents pertinent derivations, which may be of interest to those working in this field.

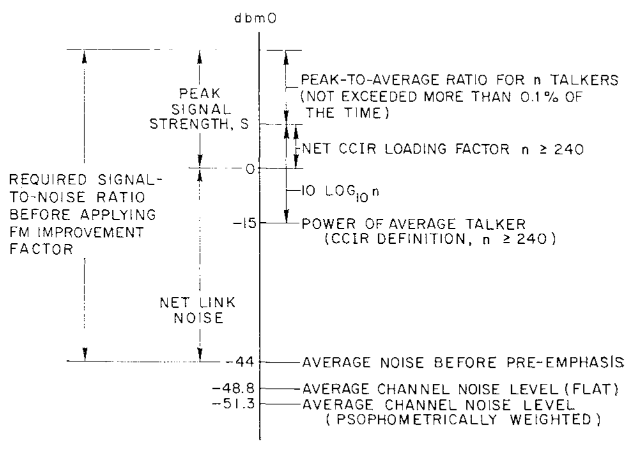


**Fig. 1 Derivation of signal-to-noise ratio.**

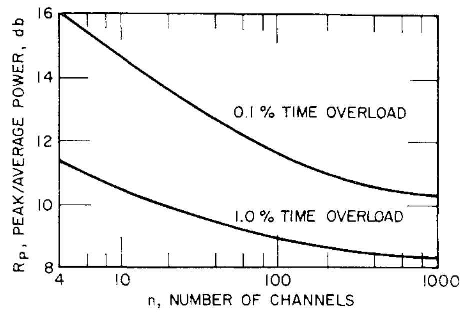


**Fig. 2 Overload curves, $R_P$ vs $n$.**

### Link Capacity Using FDM/FM

The calculation is performed for the single access case. The first part is illustrated by Fig. 1. All calculations follow standard telephone practice[2] and are relative to a circuit reference point just after the detector. This is assumed to be 0 dbm, and all voice statistics are referenced to a test tone at the reference point, also at a level of 0 dbm. Powers, referred to the reference point, are given as dbm0. International Radio Consultative Committee (CCIR) recommendations[3] assume that, for $n \geq 240$ voice channels, the average talker's power is $-15$ dbm0. Thus, $n$ talkers have an average power of $(-15 + 10 \log_{10}n)$ dbm0. If $60 \leq n < 240$, then the CCIR recommends using $(-1 + 4 \log_{10}n)$ dbm0 for the average power; the latter expression is also tentatively usable for $12 \leq n < 60$. However, the link must allow for that *peak* power, which (statistically) will not be exceeded more than, say, 0.1% of the time (Fig. 2). Combining the result for $n$ channels with the average power requirement yields a peak signal strength required of

$$S = -15 + 10 \log_{10}n + 10 \log_{10} R_P \text{ dbm0} \quad (1)$$

Let us now consider the noise in the link. Start with a fixed down-link allowance of, say, 7400 picawatt of noise (i.e., 38.7 db above 1 pw), psophometrically weighted. Add 2.5 db to transform to uniform weighting. Therefore, noise is 41.2 db above 1 pw, flat. But 1 pw = $-90$ dbm0; therefore, noise = $-48.8$ dbm0, flat.

Assume 4.8 db pre-emphasis as an easily attainable value; the flat noise before pre-emphasis is $N = -44.0$ dbm0, which, with Eq. (1), yields

$$S/N = 29 + 10 \log_{10}n + 10 \log_{10}R_P \quad (2)$$

This is the required $S/N$ (in db) in 3 kc/sec bandwidth at the receiver output. If FM is being used, however, the detection process yields an improvement of $1.5D^2$, where $D$

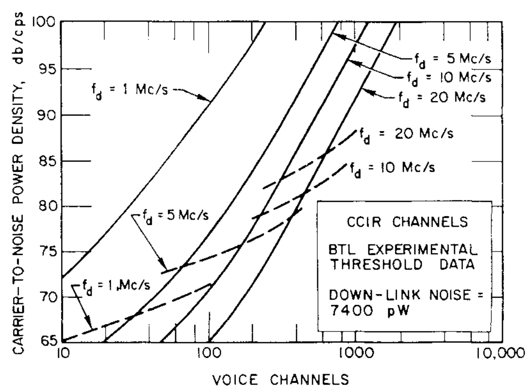


**Fig. 3 Down-link carrier-to-noise requirements.**

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* Group Director, Group II Program Directorate, Satellite Systems Division. Associate Fellow Member AIAA.
† Staff Engineer, Group II Program Directorate, Satellite Systems Division.

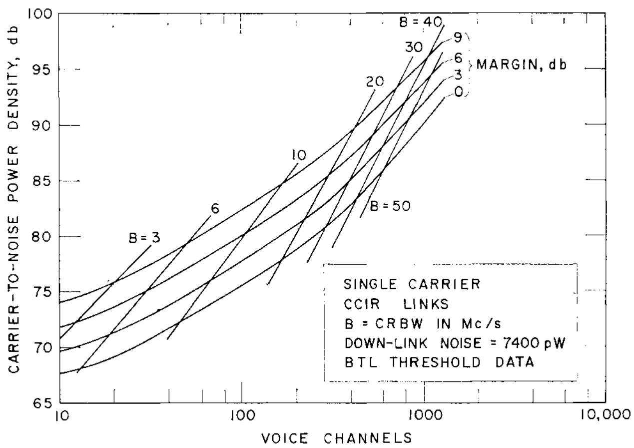


**Fig. 4 Carrier-to-noise power density vs number of CCIR channels.**

is the deviation ratio. For conventional telephonic channel stacking (4 kc/sec/channel starting 12 kc/sec from the carrier), $D$ becomes

$$D = f_d/f_b = f_d/(12{,}000 + 4000n) \qquad (3)$$

Thus, from Eq. (2) and the FM improvement factor, the required predetection $S/N$ in 3 kc/sec is found. Since total bandwidth is variable, it is convenient to convert the result to carrier-to-noise power density. Conversion to the carrier bandwidth (6 kc/sec) requires adding 3 db, whereas conversion to noise power density requires adding the db equivalent of 3 kc/sec with respect to 1 cps, that is, 34.8 db. Thus, one obtains

$$C/N_0 = 66.8 + 10\log_{10}n + 10\log_{10}R_P - 10\log_{10}(1.5D^2) \qquad (4)$$

Equations (3) and (4) were used to form the solid curves of Fig. 3.

Let the carrier-to-baseband noise ratio, which will just operate the receiver, be the threshold $X_t$. Then, using $f_b$ as given in Eq. (3), and taking into account the up-link noise, say, 1600 pw, which requires a correction of $(1600 + 7400)/7400 = 0.9$ db, we have

$$C/N_0 = 0.9 + 10\log_{10}X_t + 10\log_{10}(12{,}000 + 4000n) \qquad (5)$$

Equation (5) was used to plot the dashed curves of Fig. 3. The values of $X_t$ were taken from Ref. 4. The intersections form the zero margin curve plotted in Fig. 4, the other margins allowing for down-link noise increases. The Carson's Rule Bandwidth (CRB) is also superimposed as "$B$" curves.

### Limited Repeater

When the link shown in Fig. 5 is used with spread spectrum modulation, the behavior shown in Figs. 6 and 7 results. The satellite transmitter power is constant and made up of the desired signal, noise, and undesired signals (potential interference)

$$P_t = S_t + N_t + \sum_j I_{tj} \qquad j = 1, 2, 3 \ldots \qquad (6)$$

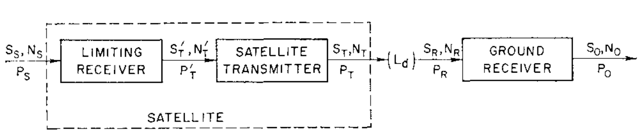


**Fig. 5 Satellite down-link.**

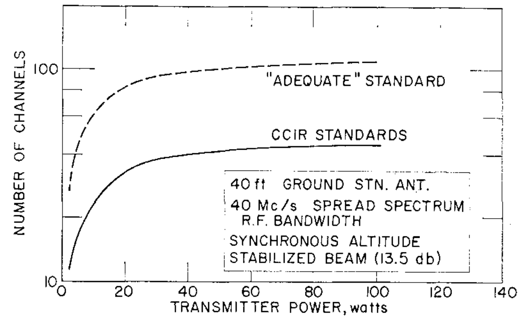


**Fig. 6 Number of channels vs transmitter power.**

The received signal is related to the satellite's signal output by $S_r = S_t L_d$, where $L_d$ is over-all loss. Multiplying and dividing by Eq. (6) gives

$$S_r = P_t L_d S_t/(S_t + N_t + \sum_j I_{tj}) \qquad (7)$$

Similarly, there is an expression for $N_r$, but $N_r$ must account for possible differences in receiver and satellite bandpasses. The bandpass of the interfering signals may only partially overlap that of the receiver. Let us define a constant $\alpha$, as 1 for $B_s \geq B_r$, and as $B_r/B_s$ for $B_r < B_s$. Let us also define the constant $\beta_j$ as that fraction of the receiver's bandpass that is overlapped by the $j$th interfering signal:

$$N_r = P_t L_d(\alpha N_t + \sum_j \beta_j I_{tj})/(S_t + N_t + \sum_j I_{tj}) \qquad (8)$$

The total noise within the receiver $N_0$ is $(N_r + kT_rB_r)$; hence, with suitable rearrangement,

$$\frac{S_0}{N_0} = \frac{(C/N)_L \cdot S_t}{[(S_t + N_t + \sum_j I_{tj}) + \left(\frac{C}{N}\right)_L (\alpha N_t + \sum_j \beta_j I_{tj})]} \qquad (9)$$

where $(C/N)_L \equiv P_t Ld/kT_rB_r$ is the "ideal" carrier-to-noise ratio that would be obtained at the receiver if all of $P_t$ were the desired signal.

Two things remain: 1) to express everything relative to $S_t$, and 2) to allow for passing $S_t$, $N_t$, and $I_{tj}$ through a limiter. We account for the limiter suppression by applying a multiplying factor $(\gamma_n)$ to the noise, and a factor $\gamma_j$ to the $j$th interfering signal. If there are several signals, the result is gaussian, $\gamma_1 = \gamma_2 = \ldots\ldots \gamma_n = \gamma$, and we can apply

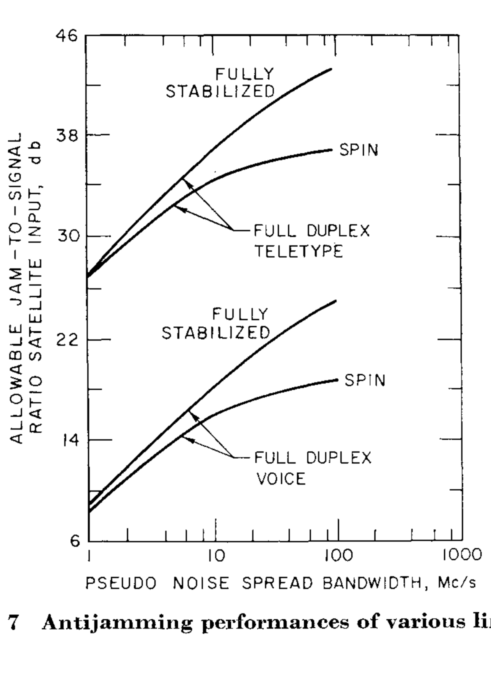


**Fig. 7 Antijamming performances of various links.**

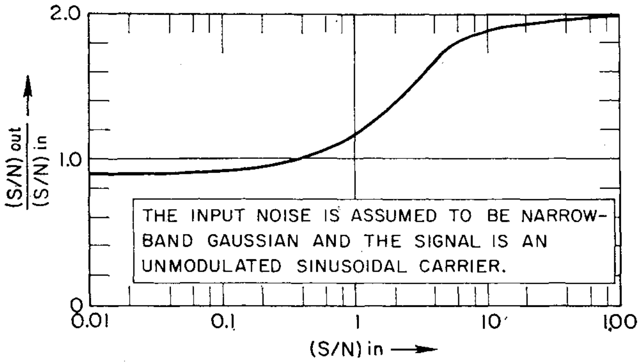


**Fig. 8 Baghdady's result for a bandpass limiter whose output and input noise bandwidths are equal.**

the results obtained by Baghdady[5] (Fig. 8). Thus, $N_t = \gamma_n N_s$, and

$$\sum_j I_{tj} = \sum_j \gamma_j I_{sj}$$

Substituting these into Eq. (9) and normalizing to $S_s$ yields

$$\frac{S_0}{N_0} = \left(\frac{C}{N}\right)_L \left[1 + \gamma_n \frac{N_s}{S_s} + \frac{1}{S_s}\Sigma\gamma_j I_{sj} + \left(\frac{C}{N}\right)_L \left(\alpha\gamma_n \frac{N_s}{S_s} + \frac{1}{S_s}\sum_j \beta_j\gamma_j I_{sj}\right)\right]^{-1} \quad (10)$$

which is the basic expression for link behavior. The first three terms within the brackets represent power division, and the last two represent the degradation due to interference and noise. Note that $S_0/N_0$ is a predetection ratio. If the detector has a processing gain $G_p$, then the postdetection ratio is $(S/N)_D = (S/N)_0 G_p$. In the case of a correlation detector, $G_p$ is simply the ratio of pre- and postdetection bandwidths; $(S/N)_D$ may also, of course, represent a required detection threshold.

The following three cases can be deduced from Eq. (10):

1) *n equal noiselike, pseudo-random signals, with their spectra completely overlapping, and with all bandwidths (signal, receiver, and satellite) equal:* Thus, all $\beta_j = 1$, and the $I_{sj}$'s are $(n - 1)$ of the equal signals, so that

$$\frac{S_0}{N_0} = \left(\frac{C}{N}\right)_L \left[1 + \gamma\left(\frac{N_s}{S_s} + n - 1\right) + \left(\frac{C}{N}\right)_L \times \left(\frac{N_s}{S_s} + n - 1\right)\gamma\right]^{-1} \quad (11)$$

Figure 6 was plotted from this equation using both CCIR standards and reduced "adequate" voice standards. Notice that $n$ appears twice, since the signals not only divide power but look like additional noise to each other.

2) *One signal, with jamming greatly in excess of the satellite noise:* Then $N_s$ is assumed negligible, and $\beta_1 = \beta$, $\beta_2 = \beta_3 = \ldots = \beta_j = 0$, and $\sum_j \gamma_j I_{sj} = \gamma J$. Substituting these relations into Eq. (10) and assuming that the satellite, signal, and receiver have identical bandpasses, we have

$$\frac{S_0}{N_0} = \left(\frac{C}{N}\right)_L \left[1 + \gamma\frac{J}{S_s} + \left(\frac{C}{N}\right)_L \beta\gamma\frac{J}{S_s}\right]^{-1} \quad (12)$$

This equation was used to plot Fig. 7, assuming $\beta = 1$.

3) *The commercial FDM case, with n equal but nonoverlapping signals:* $\sum_j \gamma_j I_{sj} = (n - 1)S_s\Sigma\gamma_j$. If the $n$ input signals are equal, they will stay so, and the $\gamma_j$ may be put equal to unity; in addition, all $\beta_j = 0$, so that

$$\frac{S_0}{N_0} = \left(\frac{C}{N}\right)_L \left[n + \gamma\frac{N_s}{S_s} + \left(\frac{C}{N}\right)_L \alpha\gamma\frac{N_s}{S_s}\right]^{-1} \quad (13)$$

In this case, calculation of $S_0/N_0$ must include the effects of companding, FM improvement factor, the use of voice statistics, and intermodulation noise, so that Eq. (13) is virtually impossible to use as it stands. It is worth noting that $n$ appears only once for power division, since the signals are not selfinterfering. Thus, it does illustrate the difference between "vertically" and "horizontally" stacked modulated channels.

### References

[1] Pritchard, W. L. and MacGregor, N., "Military vs commercial Comsat design," Astronaut. Aeronaut. **2**, 70 (October 1964).

[2] Fagot, J. and Mague, P., *Frequency Modulation Theory* (Pergamon Press, London, 1961).

[3] "Recommendations," *CCIR Documents of the 9th Plenary Assembly, Los Angeles,* **1959** (International Telecommunications Union, Geneva, Switzerland, 1959), Vol. 1, Sec. F.

[4] "A system of multiple access for satellite communications," Bell Telephone Labs., Communication Satellite Corp. Contract CSC-CD-101.

[5] Baghdady, E. J. (ed.), *Lectures on Communication System Theory* (McGraw-Hill Book Co., Inc., New York, 1961), p. 540.

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# Refrigeration in Space by the Fluidized Technique

FRANK J. HENDEL* AND J. C. MULLIGAN†
*North American Aviation, Inc., Downey, Calif.*

### Nomenclature

| | | |
|---|---|---|
| $A$ | = | inside tube area, ft² |
| $C$ | = | suspension concentration, lb carbon/lb suspension |
| $c_p$ | = | specific-heat capacity, Btu/lb-°R |
| $D$ | = | inside tube diameter, in. |
| $G$ | = | suspension flow rate, lb/hr |
| $h$ | = | heat-transfer coefficient of suspension, Btu/hr-°R-ft² |
| $k$ | = | thermal conductivity, Btu/hr-°R-ft²/in. |
| $K, m, n,$ | = | const |
| $P$ | = | suspension pressure, lb/ft² |
| $R$ | = | gas constant, 386 ft/°R for He |
| $T$ | = | absolute temperature, °R |
| $V$ | = | suspension velocity, fps |
| $Nu, Re, Pr$ | = | Nusselt, Reynolds, and Prandtl numbers, respectively |
| $\epsilon$ | = | suspension voidage, ft³ He/ft³ suspension |
| $\mu$ | = | absolute viscosity, lb/ft-sec |
| $\rho$ | = | density, lb/ft³ |

***Subscripts***

| | | |
|---|---|---|
| C | = | carbon |
| He | = | gaseous helium |
| $s$ | = | suspension (carbon in He) |

CRYOGENIC fluids will be needed in future space operations as propellants, for life support, for electrical power generation, pressurization of propellant tanks, pneumatic controls, and cooling.

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* Staff Scientist; now Engineering Specialist, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, Calif.; also Instructor of courses on Space Vehicles and Missiles at the University of California at Los Angeles, Los Angeles, Calif. Associate Fellow Member AIAA.

† Research Engineer; now at University of Mississippi, Chemical Engineering Department.