Effect of Satellite Transponder Nonlinearity on Uplink Thermal Noise*

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Abstract - **The satellite transponder nonlinearity causes the uplink thermal noise to be suppressed relative to the carriers. It also causes the uplink thermal noise to interact with the carriers to generate intermodulation products. For the single carrier access where one FM-TV carrier, one FM-FDM carrier or one TDMA-PSK carrier operating at or very close to saturation, the net effect is an improvement in the carrier to uplink thermal noise ratio $(C/N)_u$ of about 2.2 to 3.5 dB. When there are two or more carriers accessing the transponder at the same time, the net effect is reversed. For a typical dual TV operation, it results in a degradation in $(C/N)_u$ of 0.5 to 0.7 dB when the total carrier input power level is 1 dB IPBO and is negligible when the total carrier input power level is 3 dB IPBO or lower; and for a typical multiple SCPC carrier access, due to the backoff operation, it is negligible.**

INTRODUCTION

The performance of a satellite communication system is specified in terms of signal to noise ratio S/N for analog baseband signals or bit error rate (or ratio) BER for digital baseband signals. It is a function of carrier to noise ratio C/N at the input of a demodulator which can be found by performing an RF link budget calculation. To obtain C/N, one often just computes separately carrier to uplink thermal noise ratio $(C/N)_u$, carrier to downlink thermal noise ratio $(C/N)_d$ and carrier to intermodulation noise ratio C/IM and add them up together powerwise, ignoring the transponder nonlinearity effect on the uplink thermal noise. The transponder nonlinearity causes the uplink thermal noise to be suppressed relative to the carriers, resulting in an improvement in $(C/N)_u$. It also causes the uplink thermal noise to interact with the carriers to generate intermodulation products. The net effect may be positive or negative, small or large, depending on the relative uplink thermal noise level, the carrier characteristics and the transponder nonlinearity. When the system is intermodulation noise limited or downlink thermal noise limited, the ignorance is acceptable. However, when the system is uplink thermal noise limited, the net effect must be included in the link budget calculation, if it is large.

In the literature, noise suppression has been studied. Davenport [1], Kuhar and Schilling [2], and Blachman [3,4] have derived the relationship between input and output carrier to noise ratios for a case where one carrier and additive white Gaussian noise commonly access a bandpass limiter or a power law device. Loo [5], through measurements on a CTS/Hermes satellite transponder and through Monte-Carlo simulation with the FFT technique studied the uplink thermal noise suppression due to the presence of a large saturating carrier. His conclusion was that there is no net gain in carrier to noise ratio but there is a net gain in carrier to intermodulation ratio.

In this paper, through computer simulation using typical Ku band and C band transponders, the net nonlinearity effect on the uplink thermal noise is assessed for various traffic types, uplink thermal noise levels and transponder operating points. Here, uplink interference is not directly taken into consideration. When uplink interference is strong enough to be considered, it can be treated as either part of the uplink thermal noise if its bandwidth is wide (comparable to the transponder bandwidth) or an additional carrier if its bandwidth is small.

SIMULATED RESULTS

To perform simulation, Fuenzalida *et al.* 's Time Domain method [6], briefly summarized in Appendix A, was implemented into a computer program and used. The characteristics of the Ku band and C band transponders in the Bessel series form {L, α and b_s for s = 1,..., L}, required by the Time Domain method, are tabulated in Table 1.

Single Carrier Operation

For the single carrier access case where there is one large analog FM carrier (FM-TV or FM-FDM) or one large digital PSK carrier (TDMA-PSK) operating at or very close to saturation, the results are shown in Tables 2 and 3 for the Ku band and C band transponders respectively.

From the tables and those after, $(C/N)_u$ is the carrier to uplink thermal noise ratio at the transponder input in dB, ΔC_{out} is the change in the carrier output power level C_{out} due to the presence of the uplink thermal noise in dB (positive value means improvement), $\Delta(C/N)_{u-s}$ is the change in $(C/N)_u$ due to noise suppression alone in dB, $\Delta(C/N)_{fm}$ is the change in $(C/N)_u$ in dB due to both noise

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Table 1 Typical Ku Band and C Band Transponder Characteristics in the Bessel Series Form.

s	Ku Band Transponder $L = 10,\ \alpha = 1.1$		C Band Transponder $L = 10,\ \alpha = 1.1$	
	$Re\{b_s\}$	$Im\{b_s\}$	$Re\{b_s\}$	$Im\{b_s\}$
1	.21163117E+1	.14906197E+1	.18506016E+1	.17300732E+1
2	.32099428E+0	-.37914322E+0	.43380980E+0	-.36462013E+0
3	.30195947E+0	.24121633E+0	.28637301E+0	.12501524E+0
4	-.25670939E -3	-.22417753E+0	.94873917E -2	-.21355044E+0
5	.89393119E -1	.54378490E -1	.79056357E -1	.33474782E -2
6	-.46568082E -1	-.10806299E+0	-.22964139E -1	-.73775641E -1
7	.37825147E -1	.34664966E -1	-.49740383E -2	-.25750468E -1
8	-.39065922E -1	-.46297471E -1	-.12382438E -1	-.10398350E -1
9	.25091904E -1	.85316806E -2	.12478467E -1	-.36352698E -1
10	-.13147228E -1	-.12726821E -1	-.85845745E -3	.32849801E -1

Table 2 Single Carrier Operation Results - Ku Band.

$(C/N)_u$	C_{in} = 0 dB IPBO				C_{in} = 3 dB IPBO			
	ΔC_{out}	$\Delta(C/N)_{u-s}$	$\Delta(C/N)_{fm}$	$\Delta(C/N)_{psk}$	ΔC_{out}	$\Delta(C/N)_{u-s}$	$\Delta(C/N)_{fm}$	$\Delta(C/N)_{psk}$
(dB)	(dB)	(dB)	(dB)	(dB)	(dB)	(dB)	(dB)	(dB)
10	-0.44	5.03	2.45	2.19	-0.39	3.43	2.25	2.11
15	-0.16	5.51	3.13	2.81	-0.13	3.76	2.69	2.53
20	-0.07	5.66	3.41	3.06	-0.04	3.88	2.86	2.67
25	-0.04	5.69	3.50	3.15	-0.02	3.91	2.90	2.71
30	-0.03	5.69	3.51	3.16	-0.01	3.93	2.91	2.72
35	-0.03	5.69	3.52	3.16	-0.01	3.93	2.92	2.72
40	-0.03	5.69	3.52	3.16	-0.01	3.93	2.92	2.72

Table 3 Single Carrier Operation Results - C Band.

$(C/N)_u$	C_{in} = 0 dB IPBO				C_{in} = 3 dB IPBO			
	ΔC_{out}	$\Delta(C/N)_{u-s}$	$\Delta(C/N)_{fm}$	$\Delta(C/N)_{psk}$	ΔC_{out}	$\Delta(C/N)_{u-s}$	$\Delta(C/N)_{fm}$	$\Delta(C/N)_{psk}$
(dB)	(dB)	(dB)	(dB)	(dB)	(dB)	(dB)	(dB)	(dB)
10	-0.51	4.83	2.05	1.78	-0.33	3.09	1.86	1.72
15	-0.17	5.30	2.75	2.43	-0.12	3.40	2.33	2.16
20	-0.06	5.60	3.32	2.82	-0.04	3.54	2.50	2.31
25	-0.02	5.78	3.35	2.97	-0.02	3.59	2.54	2.34
30	-0.01	5.84	3.40	3.02	-0.01	3.61	2.55	2.36
35	-0.01	5.86	3.42	3.03	-0.01	3.62	2.56	2.36
40	-0.01	5.86	3.42	3.03	-0.01	3.62	2.56	2.36

suppression and additional intermodulation noise generated when the carrier is assumed to have a Gaussian power spectrum (which is a close approximation to an FM carrier), and $\Delta(C/N)_{psk}$ is the same as $\Delta(C/N)_{fm}$ except that the carrier is assumed to have a uniform power spectrum (which is a close approximation to a filtered PSK carrier).

For the Ku band transponder with the carrier input power C_{in} set at saturation (0 dB IPBO), the improvement in $(C/N)_u$ due to noise suppression alone is 5.0 dB at $(C/N)_u$ = 10 dB and 5.7 dB at $(C/N)_u \geq 25$ dB. When corrected for intermodulation noise, the improvement is reduced to 2.4 dB at $(C/N)_u$ = 10 dB and 3.5 dB at $(C/N)_u \geq 25$ dB for the Gaussian spectrum carrier, and to 2.2 dB at $(C/N)_u$ = 10 dB and 3.2 dB at $(C/N)_u \geq 25$ dB for the uniform spectrum carrier. When the carrier input power C_{in} is reduced by 3 dB, the net improvement in $(C/N)_u$ is slightly reduced (by no more than .6 dB). For the C band transponder, the corresponding net improvement in $(C/N)_u$ is about 0.1 to 0.4 dB less.

A satellite communication system is generally operated with $(C/N)_u$[1] of somewhere between 15 to 35 dB, and therefore a correction of 2.5 to 3.5 dB for the Ku band transponder (2.2 to 3.4 dB at C band) in $(C/N)_u$ should be made in the link budget calculation. For systems operating in the uplink thermal noise limited condition such as Satellite News Gathering with transportable earth stations, such a correction is significant.

Note that without the uplink thermal noise, corresponding to C_{in} = 0 and 3 dB IPBO, the carrier output power levels are respectively 0 and 0.4 dB OPBO. Due to the loading of the noise, the transponder operating point is slightly changed. This results in a degradation in the carrier output power C_{out} which should also be included in the link budget calculation to correct the carrier to downlink thermal noise ratio $(C/N)_d$. This degradation ($-\Delta C_{out}$) is, however, not large, less than 0.2 dB.

Dual Carrier Operation

Table 4 displays results for the two identical carrier access case where the Ku band transponder is operated at total carrier input power levels C_{in} of 1 and 3 dB IPBO. These correspond to total carrier output power levels C_{out} of 1.4 and 1.6 dB OPBO respectively, when the uplink thermal noise is ignored.

[1] The uplink thermal noise level is fixed for a given transponder, however $(C/N)_u$ can be increased while maintaining the same transponder operating point, by increasing the earth station transmit power and by the use of ground-commandable satellite switched attenuators with which some transponders are equipped. For example, with a GSTAR transponder $(C/N)_u$ can be increased by up to 21 dB in a 3 dB step [7].

Table 4 Dual Carrier Operation Results - Ku Band.

$(C/N)_u$ (dB)	C_{in} = 1 dB IPBO ΔC_{out} (dB)	$\Delta(C/N)_{u\text{-}s}$ (dB)	$\Delta(C/N)_{fm}$ (dB)	$\Delta(C/N)_{psk}$ (dB)	C_{in} = 3 dB IPBO ΔC_{out} (dB)	$\Delta(C/N)_{u\text{-}s}$ (dB)	$\Delta(C/N)_{fm}$ (dB)	$\Delta(C/N)_{psk}$ (dB)
10	-0.36	0.83	-0.65	-0.69	-0.32	0.89	-0.17	-0.19
15	-0.11	0.88	-0.60	-0.65	-0.10	0.91	-0.10	-0.13
20	-0.04	0.89	-0.58	-0.63	-0.03	0.92	-0.07	-0.11
25	-0.01	0.89	-0.57	-0.61	-0.01	0.92	-0.07	-0.10
30	-0.00	0.89	-0.56	-0.60	-0.00	0.92	-0.07	-0.09
35	-0.00	0.89	-0.56	-0.60	-0.00	0.92	-0.07	-0.09
40	-0.00	0.89	-0.56	-0.60	-0.00	0.92	-0.07	-0.09

From the table, it was observed that the net change in $(C/N)_u$ takes a negative value. For C_{in} = 1 dB IPBO, the net degradation is between 0.5 to 0.7 dB; however for C_{in} = 3 dB IPBO, it is negligible, less than 0.1 dB. The change in the carrier ouput power level C_{out} is also negligible. It was also observed that the effect of the spectrum shape of the carriers on the results is negligible.

Results for the C band transponder was also obtained. They are almost the same as those shown in Table 4 - the differences are less than 0.1 dB.

Multiple Carrier Operation

Table 5 displays results for the twenty identical carrier access case where the Ku band transponder is operated at total carrier input power levels C_{in} of 9 and 12 dB IPBO. These correspond to total carrier output power levels C_{out} of 4.4 and 6.4 dB OPBO respectively, when the uplink thermal noise is ignored.

Table 5 Multiple Carrier Operation Results - Ku Band.

$(C/N)_u$ (dB)	C_{in} = 9 dB IPBO ΔC_{out} (dB)	$\Delta(C/N)_{u\text{-}s}$ (dB)	$\Delta(C/N)_{psk}$ (dB)	C_{in} = 12 dB IPBO ΔC_{out} (dB)	$\Delta(C/N)_{u\text{-}s}$ (dB)	$\Delta(C/N)_{psk}$ (dB)
10	-0.18	0.04	-0.18	-0.10	0.02	-0.09
15	-0.06	0.04	-0.14	-0.03	0.02	-0.07
20	-0.02	0.04	-0.12	-0.01	0.02	-0.07
25	-0.01	0.04	-0.10	-0.00	0.02	-0.06
30	-0.01	0.04	-0.09	-0.00	0.02	-0.06
35	-0.00	0.04	-0.09	-0.00	0.02	-0.06
40	-0.00	0.04	-0.09	-0.00	0.02	-0.06

From the table, the net degradation in $(C/N)_u$ is about 0.1 dB and the degradation in C_{out} is negligible, much smaller than 0.1 dB. The former corresponds to the center carriers, for other carriers the degradation is slightly less.

Results for the C band transponder, the Gaussian spectrum carriers, and different number of carriers were also obtained. They are found to be almost the same as those shown in Table 5 - the differences are less than 0.1 dB.

CONCLUSION

The transponder nonlinearity effect on the uplink thermal noise is very small and can be ignored when a transponder is accessed by two or more carriers. For the single carrier operation, however, it results in an improvement in $(C/N)_u$ by about 2.2 to 3.5 dB which should be corrected in the link budget calculation.

APPENDIX A : THE TIME DOMAIN METHOD

From the Time Domain method [6], input to a bandpass effectively memoryless nonlinear element such as a satellite transponder exhibiting both AM/AM transfer characteristic G(A) and AM/PM transfer characteristic F(A) is assumed to consist of M modulated narrow band carriers and Gaussian noise,

$$u(t) = \mathrm{Re}\{ \sum_{i=1}^{M} A_i \exp\{j[2\pi f_i t + \theta_i(t)] + [N_c(t) + jN_s(t)]\exp\{j2\pi f_N t]\}$$

where A_i, $\theta_i(t)$ and f_i are, respectively, the real envelope assumed to be constant, phase and frequency of the carrier i; and $N_c(t)$ and $N_s(t)$ are the real and imaginary parts of the noise complex envelope centered at frequency f_N and normally distributed with zero-mean and σ^2-variance.

Through the use of the double Fourier transformation, the output power spectrum can be put into the following form:

$$S(f) = (1/2) \sum_{\substack{k_1,k_2,\ldots,k_{M+1}=-\infty \\ k_1+k_2+\ldots+k_{M+1}=1}}^{\infty} \mathop{\mathbf{\Sigma}}_{q=0}^{\infty} |N(k_1,k_2,\ldots,k_{M+1};q)|^2 \cdot \Omega(k_1,k_2,\ldots,k_{M+1};q;f-\sum_{i=1}^{M} k_i f_i - k_{M+1} f_N)$$

where

$$\mathop{\mathbf{\Sigma}}_{q=0}^{\infty}(.) = \begin{cases} \sum_{q=0}^{\infty}(.) & \text{if } k_{M+1} \neq 0 \\ (.)\big|_{q=0} & \text{if } k_{M+1} = 0 \end{cases}$$

$$N(k_1,k_2,\ldots,k_{M+1};q) = \sum_{s=1}^{L} \{b_s \exp(-\alpha^2 s^2 \sigma^2/2) \cdot \prod_{i=1}^{M} J_{k_i}(\alpha s A_i) [\frac{(\alpha^2 s^2 \sigma^2/2)^{2q+|k_{M+1}|}}{q!(|k_{M+1}|+q)!}]^{1/2}\}$$

with L being an integer, α being a real constant and b_s's being complex constants which are related to the nonlinear element characteristics F(A) and G(A) by the following equation for all operating values of A (the method that can be used to compute these constants from G(A) and F(A) can be found in [8]),

$$G(A)\exp[jF(A)] \cong \sum_{s=1}^{L} b_s J_1(\alpha s A)$$

and finally,

$$\Omega(k_1,\ldots,k_{M+1};q;f) = S_{1,k_1} * \ldots * S_{M,k_M} * S_{M+1,2q+|k_{M+1}|}$$

with

$$S_{i,j} = \begin{cases} \delta(f) & \text{if } j=0 \\ S_i(f) & \text{if } j=1 \\ \underbrace{S_i(f)*S_i(f)*\ldots*S_i(f)}_{(j-1)\text{ times}} & \text{if } j>1 \end{cases}$$

$\delta(.)$ being the impulse function, * being the convolution operator, $S_i(f)$ $i \le M$ being the low pass equivalent of the power spectrum of the ith modulated carrier normalized to unit power, and $S_{M+1}(f)$ being the power spectrum of $N_c(t)$ or $N_s(t)$ normalized to unit power.

Each value of an (M+2)-tuple $(k_1,k_2,\ldots,k_{M+1};q)$ corresponds to the power spectrum of a carrier, noise or an intermodulation product. For the ith carrier, $k_i = 1$, $k_j = 0$ for $j \neq i$ and $j = 1,\ldots,M+1$ and $q = 0$. For the noise, $k_{M+1} = 1$, $k_j = 0$ for $j = 1,\ldots,M$ and $q = 0$. And for an intermodulation product, its order and center frequency are determined by the following equations:

$$\text{Order} = \sum_{i=1}^{M+1} |k_i| + 2q$$

$$\text{Frequency} = \sum_{i=1}^{M} k_i f_i + k_{M+1} f_N$$

The Time Domain method has been implemented into a FORTRAN program called IMSHIMOD to compute carrier output powers, noise output power, unmodulated carrier to intermod ratios, and modulated carrier to intermod ratios. IMSHIMOD was used to generate results presented in this paper.

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