Magnitude and Phase Non-Linear Responses in C/I Calculation for DS-CDMA Satellite Systems

MARIO REYES-AYALA[1], EDGAR ALEJANDRO ANDRADE-GONZALEZ[1],
JOSÉ ALFREDO TIRADO-MÉNDEZ[1], HILDEBERTO JARDÓN AGUILAR[2]
[1]Electronics Department
Metropolitan Autonomous University
San Pablo 180, Col. Reynosa Tamaulipas, Azcapotzalco, ZIP Code 02200, Mexico City
MEXICO
[2]Section of Communications
CINVESTAV-IPN
Av. IPN 2508, Col. San Pedro Zacatenco, Zip Code 07360 Mexico City
Apartado postal 14-740, 07000 Mexico City
MEXICO

Abstract: - This paper shows an algorithm to calculate synchronous DS-CDMA satellite links with non-linear response amplifiers, where the probability error, active device parameters, and back-off compensation, are used to evaluate the performance. The analysis of carrier to interference ratio is carried out for N-carrier up-link, where a single carrier uses DS-CDMA.

Key-words: - Spread spectrum, DS-CDMA, link budget, non-linear response, carrier to interference ratio.

1 Introduction

Many digital satellite systems use spread spectrum techniques, because reduces significantly several impairments. Bit rate, security, number of simultaneous users and Bit Error Rate (BER), are some of the most important advantages of spread spectrum.

In this paper, we analyze a digital satellite communication system where Direct Sequence Code Division Multiple Access (DS-CDMA) is used to maximize the number of simultaneous users in the transmission media. In this technique, the satellite transponders identify the earth station (up-link), with a pseudorandom sequence (PN). The length and rate of the sequence determine the spread bandwidth and number of simultaneous user of the system. The architecture employed to obtain pseudo-random sequences is named PN sequence generator, and the features of the most important configurations are shown in [10].

In multi-carrier systems the non-linear effects are increased, intermodulation products generation reduces the power of the desired carriers [11].

There are two main techniques to achieve CDMA, Direct Sequence and Frequency Hopping (FH), but FH-CDMA is more sensible to Doppler effect, as a consequence of satellite velocities. Then, DS-CDMA is the only practical choice to use spread spectrum in satellite communication. In Figure 1 a DS-CDMA satellite system for N users is illustrated.

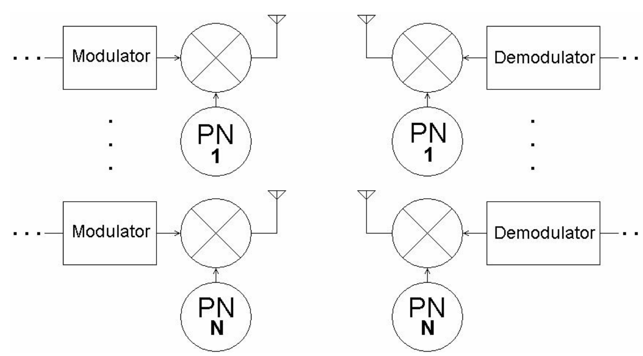

Fig. 1 DS-CDMA Satellite System.

In section two, the carrier to interference ratio is presented. The amplitude non-linear response for a single carrier is analyzed in section three. The case for a large number of carriers in the up-link is analyzed in detail in section four. The main results and conclusions are presented in section five and six.

2 C/I in Digital Satellite Systems

The total carrier to noise ratio is determined by (1).

$$\left(\frac{C}{N}\right)_T^{-1} = \left(\frac{C}{N}\right)_u^{-1} + \left(\frac{C}{N}\right)_d^{-1} + \left(\frac{C}{N}\right)_i^{-1} + \left(\frac{C}{I}\right)^{-1} \quad (1)$$

Where $(C/N)_T$ is total carrier to noise ratio, $(C/N)_u$ is the uplink carrier to noise ratio, $(C/N)_d$ is the downlink carrier to noise ratio, $(C/N)_i$ is the carrier to intermodulation noise ratio, and (C/I) is the carrier to interference ratio.

The total carrier to noise ratio is very important to determine the ratio of energy per bit to noise density and error probability as well. The error probability for non-linear magnitude response for DS-CDMA is illustrated in [11], where the analysis assume a single carrier in the up-link.

3 Amplitude Non-Linear Response (Single Carrier)

The amplifiers have a non-linear response if the input power level is high and it is possible to employ a polynomial model, in the output level prediction. The input back-off is calculated by (2).

$$[BO_i] = [EIRP_R] - [EIRP_S] \quad (2)$$

Where: $[BOi]$ is the input back-off, dBW; $[EIRP_R]$ is the real up-link EIRP, dBW; and $[EIRP_S]$ is the EIRP for HPA saturation, dBW. The input back-off is the uplink compensation needed to saturate satellite HPA. In order to use a normalized curve of TWT non-linear response, it is necessary to define R_{TWTA}.

$$R_{TWTA} = [EIRP_R]/[EIRP_S] \quad (3)$$

Where: R_{TWTA} is the real to saturation EIRP Ratio. It is obvious that response of a particular TWTA may be modified, if its TWT is changed, because each tube has a particular response. The following equations offer a way to obtain a normalized prediction for TWTA non-linear input-output ratio [2].

$$P = \frac{R_{TWTA}\alpha_p}{\left(1+\beta_p R_{TWTA}{}^2\right)} \quad (4)$$

$$Q = \frac{R_{TWTA}{}^3\alpha_q}{\left(1+\beta_q R_{TWTA}{}^2\right)^2} \quad (5)$$

$$Z = \sqrt{P^2 + Q^2} \quad (6)$$

Where: α_P, β_P, α_q and β_q are TWT coefficients; P is the in-phase normalized non-linear response, and; Q is the in-quadrature normalized non-linear response.

$$\lfloor EIRP_{R,S} \rfloor = \lfloor EIRP_{S,S} \rfloor Z \quad (7)$$

Where: Z is the magnitude of normalized non-linear response. It is possible to back with the real non-normalized parameters. Finally, we can obtain the output back-off in the real amplifier, as a consequence of compensating the input power level.

$$[BO_O] = [EIRP_{S,S}] - [EIRP_{R,S}] \quad (8)$$

Where: $[BOo]$ is the output back-off, dBW; $[EIRP_{R,S}]$ Is the real output EIRP, dBW; and, $[EIRP_{S,S}]$ is the output EIRP in saturation, dBW. In this paper, we use three TWT devices to compare the non-linear response in satellite HPA, see Table 1.

TABLE 1.
TWT DEVICES USED IN SIMULATION

	TWT_1	**TWT_2**	**TWT_3**
α_p	1.90947	2.11075	2
β_p	1.07469	2.22764	1
α_q	4.35023	7.33959	0
β_q	2.33525	2.11475	0

The TWT_1 and TWT_2 are commercial tubes, and TWT_3 is an ideal tube, where there is not phase distortion.

4 Amplitude and Phase Non-Linear Responses (Multi-Carrier)

In the previous section, the amplitude non-linearities have been analyzed and modeled. But, in many digital satellite communications systems, the modulation techniques employed to transmit are very sensible to Doppler effect. The velocity of the LEO satellites in some PCS satellite systems causes a large Doppler shift in the carrier frequency. Then the analysis of phase non-linearities are quite important in satellite applications specially in non-GEO orbits. Consider the multi-carrier input signal in equation (9).

$$v = \sum_{i=1}^{n} \{A_i \cos(\omega_i t + \theta_i(t))\} \tag{9}$$

Where $\theta_i(t)$ is the modulated phase, and n is the number of carriers in the system. It is possible to express this set as a carrier having a mean angular frequency, equations (10) and (13).

$$v = R(t)\cos(\omega_0 t + \theta(t)) \tag{10}$$

$$R^2(t) = \left\{\sum_{i=1}^{n}[A_i \cos[(\omega_i - \omega_0)t + \theta_i(t)]]\right\}^2 + \left\{\sum_{i=1}^{n}[A_i \mathrm{sen}[(\omega_i - \omega_0)t + \theta_i(t)]]\right\}^2 \tag{11}$$

$$\theta(t) = \tan^{-1}\left\{\frac{\left\{\sum_{i=1}^{n}[A_i \mathrm{sen}[(\omega_i - \omega_0)t + \theta_i(t)]]\right\}^2}{\left\{\sum_{i=1}^{n}[A_i \cos[(\omega_i - \omega_0)t + \theta_i(t)]]\right\}^2}\right\} \tag{12}$$

$$\omega_0 = \frac{\omega_1 + \omega_n}{2} \tag{13}$$

Where ω_1 and ω_n are the first and last carriers in the system, respectively.

In the amplitude-phase non-linear behavior in the TWTA, the corresponding output signal V(t) is determined by equation (14).

$$V(t) = G[R(t)]\cos\{\omega_0 t + \theta(t) + F[R(t)]\} \tag{14}$$

Where G[R(t)] and F[R(t)] represent the amplitude and phase transfer characteristics of the TWTA, respectively.

In Figure 2, the phase non-linear response of the same three TWT amplifiers are shown (TWT_1, TWT_2 and TWT_3, see Table 1.

The amplitude of the individual output carrier is determined by (15) [12].

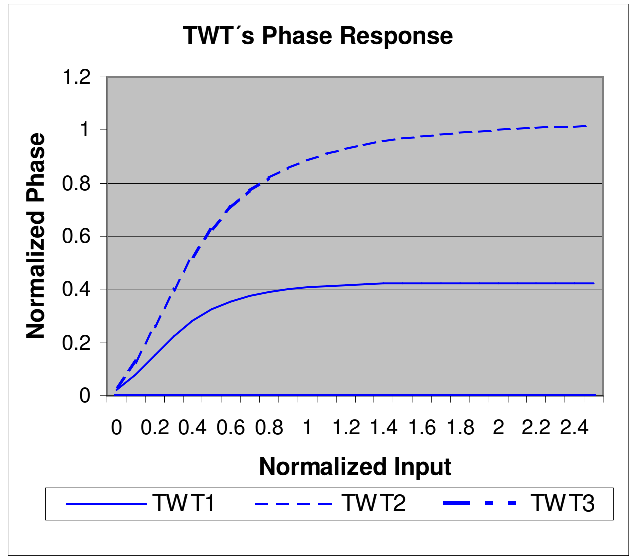

Fig. 2 TWT_2 Non-Linear Phase Response.

$$B_n = a_1\sqrt{\frac{2P_{ti}}{n}}\left\{1 + 3\frac{a_3}{a_1}\left(\frac{P_{ti}}{n}\right)\left(n - \frac{1}{2}\right) + \ldots\right\} \tag{15}$$

Where P_{ti} is the total input power, W. The third-order intermodulation products are the most important, because their amplitudes are frequently the highest. The amplitudes of these intermodulation products can be obtained using (16) and (17) [5].

$$V_{2,1} = \frac{3}{4}a_3\left(\frac{2P_{ti}}{n}\right)^{3/2}\left\{1 + \frac{2a_5}{3a_3}\left(\frac{P_{ti}}{n}\right)[12.5 + 15(n-2)] + \ldots\right\} \tag{16}$$

$$V_{1,1,1} = \frac{3}{2}a_3\left(\frac{2P_{ti}}{n}\right)^{3/2}\left\{1 + 10\frac{a_5}{a_3}\left(\frac{P_{ti}}{n}\right)\left[\frac{3}{2} + (n-3)\right] + \ldots\right\} \tag{17}$$

Finally, the carrier to interference ratio can be computed by (18).

$$\left(\frac{C}{I}\right)_r = \frac{B_n^2}{D_{2,1}(r,n)V_{2,1}^2 + D_{1,1,1}(r,n)V_{1,1,1}^2} \tag{18}$$

Where $D_{2,1}(r,n)$ and $D_{1,1,1}(r,n)$ are the number of third-order intermodulation products that fall right on the r-th carrier.

The active device selected to obtain the results presented in the following section was the $TWTA_2$.

This device has a moderate non-linear response. AM-PM conversion is one of the most important problem to solve in digital satellite communications, because phase and frequency modulations are almost always chosen as a consequence of noise level and very high media attenuations.

5 Results

The main results obtained in this work, were the output back-off and carrier to interference ratio in the DS-CDMA multi-carrier satellite system. The output back-off calculated for a practical system is illustrated in Table 2.

TABLE 2.
OUTPUT BACK-OFF

Pti	BOi	A0	B1	Bn	BOo
0.02	13.9794	0.2000	0.3856	0.0309	7.0947
0.04	10.9691	0.2828	0.5305	0.0414	3.9420
0.06	9.2082	0.3464	0.6320	0.0482	2.9111
0.08	7.9588	0.4000	0.7099	0.0529	2.4105
0.10	6.9897	0.4472	0.7721	0.0564	2.1214
0.12	6.1979	0.4899	0.8228	0.0591	1.9376
0.14	5.5284	0.5292	0.8646	0.0610	1.8134
0.16	4.9485	0.5657	0.8993	0.0626	1.7260
0.18	4.4370	0.6000	0.9280	0.0637	1.6628
0.20	3.9794	0.6325	0.9518	0.0647	1.6160
0.22	3.5655	0.6633	0.9714	0.0654	1.5812
0.24	3.1876	0.6928	0.9874	0.0659	1.5554
0.26	2.8400	0.7211	1.0002	0.0663	1.5366
0.28	2.5181	0.7483	1.0103	0.0666	1.5240
0.30	2.2185	0.7746	1.0181	0.0667	1.5170
0.32	1.9382	0.8000	1.0238	0.0668	1.5156
0.34	1.6749	0.8246	1.0277	0.0667	1.5203
0.36	1.4267	0.8485	1.0300	0.0664	1.5318
0.38	1.1919	0.8718	1.0309	0.0660	1.5514
0.40	0.9691	0.8944	1.0306	0.0654	1.5807
0.42	0.7572	0.9165	1.0293	0.0645	1.6222
0.44	0.5552	0.9381	1.0271	0.0634	1.6789
0.46	0.3621	0.9592	1.0241	0.0620	1.7553
0.48	0.1773	0.9798	1.0204	0.0603	1.8578
0.50	0.0000	1.0000	1.0162	0.0582	1.9956

In Figure 3, the output back-off corresponding to Table 2 is shown.

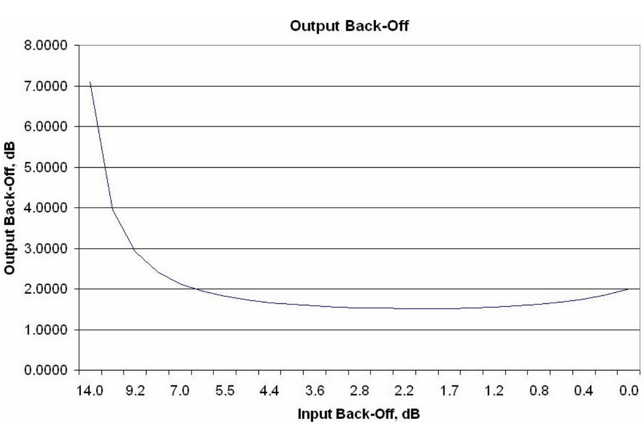

Fig. 3 Output Back-Off.

The carrier to interference ratio calculated is illustrated in Table 3 and Figure 4.

TABLE 3.
CARRIER TO INTERFERENCE RATIO

BOo	V2,1	V1,1,1	C/I r	[C/I r] dB
8.509	-3.78E-06	-7.57E-06	1633.4	32.1
5.957	-1.00E-05	-2.00E-05	420.6	26.2
4.641	-1.72E-05	-3.43E-05	193.6	22.9
3.821	-2.47E-05	-4.93E-05	113.3	20.5
3.267	-3.22E-05	-6.42E-05	75.9	18.8
2.873	-3.94E-05	-7.86E-05	55.4	17.4
2.585	-4.63E-05	-9.23E-05	43.0	16.3
2.371	-5.27E-05	-1.05E-04	34.8	15.4
2.209	-5.87E-05	-1.17E-04	29.3	14.7
2.085	-6.42E-05	-1.28E-04	25.2	14.0
1.990	-6.93E-05	-1.38E-04	22.2	13.5
1.919	-7.41E-05	-1.47E-04	19.8	13.0
1.866	-7.86E-05	-1.55E-04	17.9	12.5
1.830	-8.31E-05	-1.64E-04	16.2	12.1
1.811	-8.75E-05	-1.72E-04	14.7	11.7
1.807	-9.21E-05	-1.81E-04	13.3	11.3
1.820	-9.71E-05	-1.91E-04	12.0	10.8
1.853	-1.03E-04	-2.01E-04	10.7	10.3
1.909	-1.09E-04	-2.13E-04	9.4	9.7
1.991	-1.16E-04	-2.27E-04	8.1	9.1
2.104	-1.25E-04	-2.43E-04	6.9	8.4
2.253	-1.35E-04	-2.62E-04	5.7	7.6
2.448	-1.47E-04	-2.85E-04	4.6	6.7
2.695	-1.61E-04	-3.12E-04	3.7	5.6
3.007	-1.77E-04	-3.43E-04	2.8	4.5

In Figure 4 is possible to identify the minimum of output back-off. This parameter should be short in order to maximize the total carrier to noise ratio.

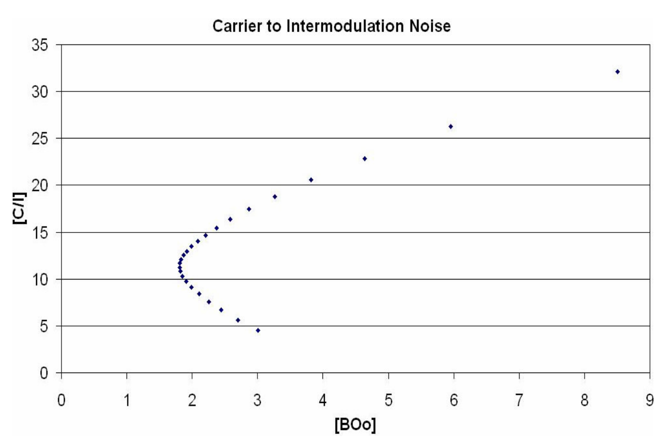

Fig. 4 Carrier to interference ratio..

6 Conclusions

The non-linear behavior of the devices used to amplify the signal in the transponders, causes several effects that can reduce the performance of the system: harmonics, intermodulation products, AM-AM and AM-PM, are some of the most important aspect to take in account. In this paper the carrier to interference ratio has been computed for DS-CDMA satellite systems, where non-linear responses (phase and magnitude) are considered.

Link budget was calculated by ViaSat software. ViaSat is a preliminary software to teach digital satellite systems in the Metropolitan Autonomous University, where we enhance its features constantly.

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