A Practical Simulation Tool for Predicting Spectral Regrowth in Communication Satellite Receivers

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***Abstract*— The intermodulation distortion phenomena caused by nonlinear characteristic of active RF equipments is a significant source of system impairment in satellite communications. Telecommunications signals are usually composed of more than one carrier modulated by information signal. When number of carriers passing through a nonlinear medium increases, which is the case in communications satellite receivers, the prediction of the intermodulation distortion becomes more and more complex. Considering the scarcity of frequency spectrum and other resources in orbit, satellite channel performances should delicately be examined in order to ensure efficient and uninterrupted communications through all channels and avoid any channel failure due to intermodulation phenomena. This paper presents a practical tool for calculating and simulating the effect of intermodulation signal distortion and C/I performances of the broadband satellite receivers placed at the communication satellite payload input section. With this tool, the effect of a collocated satellite system operating in an adjacent frequency band can also be easily calculated.**

Keywords- Intermodulation distortion; spectral regrowth; satellite communications.

I. INTRODUCTION

A significant amount of communications traffic is handled by communications satellites and therefore these systems fulfill a huge amount of the communication needs in today's world. Broadband receivers are used on-board satellites in order to operate over a frequency range of a few hundred MHz usually, serving a maximum number of carriers to achieve high spectral efficiency.

Multiple signals simultaneously arriving at the receiver generate intermodulation noise due to the nonlinear characteristics of the receiver itself. This noise is generated by a large number of intermodulation products which interfere with the useful carriers. Due to the existence of these products, the amplitudes of the useful carriers are limited and the system efficiency is decreased. In the frame of these arguments, simulation and prediction of intermodulation distortion is a crucial issue for arranging frequency plan of satellite communication systems.

There are several manifestations on the algorithms and techniques developed for modeling and simulating intermodulation products [1]-[6]. Fast Counting Algorithm (FCA) assumes a number of identical carriers distributed over a frequency range with equally spaced frequency positions, and the distortion is dominated by the third-order intermodulation products of $f_i+f_j-f_k$ type, neglecting the ones of $2f_i-f_j$ type [1]. FCA employs FFT algorithm together with indicator polynomials modeling the carrier configuration. Higher order intermodulation products and harmonics are also computed by extending the FCA algorithm [2]. In [3], the third-order intermodulation spectrum is calculated by convolution of the input power spectrum using the FFT method. Another alternative method suggests noise band representation replacing identical contiguous narrow band carriers with an equivalent band of thermal noise [4]. In this method, intermodulation products are restricted to $f_i+f_j-f_k$ type. Another popular technique is modeling with Volterra series. Discrete third-order Volterra model is used in [5] and [6] to compute third-order products. In [7], Volterra-Wiener technique is adopted for this purpose.

In this work, our first goal is to model and simulate intermodulation distortion taking place in communication satellite receivers with a fair accuracy and complexity. To achieve this goal, polynomial model is employed together with a counting algorithm, and only two types of intermodulation products, namely $f_i+f_j-f_k$ and $2f_i-f_j$ types, are taken into account. This is because these two types of products are dominating the in-band intermodulation distortion [8]. Secondly, we are aiming to design this simulation tool in a way that it will be useful for satellite communications systems' designers in the industry. In this respect, the inputs of the simulation tool are the uplink frequency plan of the satellite and some characteristics of the equipments. The outputs are the total third-order intermodulation noise power and carrier to intermodulation distortion power ratio (C/I), given for each predefined satellite channel, which are going to assist the designers to figure out the system linearity performances. Considering the importance of the risk management in the communication satellite industry, such tools can have a critical role in the AIT (Assembly, Integration and Test) phase.

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II. Modeling Third-Order IMPs

A. Polynomial Model

Polynomials have been used extensively to model nonlinearities for many applications. The polynomial model, also called as power series representation in literature, is a simple and highly effective technique for modeling nonlinear behavior. It provides freedom of design in choosing a higher-degree polynomial for higher accuracy, or a lower-degree polynomial for less computational complexity.

The output *y(t)* of a nonlinear system with respect to an input signal *x(t)* can be modeled by a polynomial function as

$$y(t) = \sum_{i=1}^{\infty} a_i x^i(t) = a_1 x(t) + a_2 x^2(t) + a_3 x^3(t) + \cdots \tag{1}$$

where a_i represents nonlinearity coefficients that characterizes the system's behavior. The second, third and higher order terms of (1) explain the spectral regrowth.

B. Two-Tone Input Model

Assume an input signal composed of two carriers with the same amplitude and at different frequencies, as shown in (2). The phase values are taken to be zero for simplicity. In the output spectrum, there are elements originated from interaction of these two tones, which are called "intermodulation products", as well as the "harmonics" of the fundamental frequencies.

$$x_{2\_tone}(t) = A\cos(\omega_1 t) + A\cos(\omega_2 t) \tag{2}$$

Substituting (2) in the polynomial model which is truncated to third order gives:

$$\begin{aligned} y(t) = {} & \left(a_1 A + \frac{9}{4} a_3 A^3\right)\cos(\omega_1 t) + \left(a_1 A + \frac{9}{4} a_3 A^3\right)\cos(\omega_2 t) \\ & + a_2 A^2 \cos\left((\omega_2 \pm \omega_1)t\right) + \frac{1}{2} a_2 A^2 \cos(2\omega_1 t) \\ & + \frac{1}{2} a_2 A^2 \cos(2\omega_2 t) + \frac{3}{4} a_3 A^3 \cos\left((2\omega_1 \pm \omega_2)t\right), \\ & + \frac{3}{4} a_3 A^3 \cos\left((2\omega_2 \pm \omega_1)t\right) + \frac{1}{4} a_3 A^3 \cos(3\omega_1 t) \\ & + \frac{1}{4} a_3 A^3 \cos(3\omega_2 t) + a_2 A^2 \end{aligned} \tag{3}$$

The 3rd order intermodulation products have an in-band distortion effect whereas the harmonics gather at distinct frequencies constituting out-of-band distortion. In fact, all odd order intermodulation products appear exactly over, or very close to the output fundamental frequencies.

Signal to third-order intermodulation distortion ratio (C/I_3) is an important figure of merit of a system's nonlinearity described by two-tone characterization method. It is defined as the ratio between one of the output fundamental's power and the power of the nearest third-order intermodulation product, given as

$$\frac{C}{I_3} = \frac{P(\omega_1)}{P(2\omega_1 - \omega_2)} = \frac{P(\omega_2)}{P(2\omega_2 - \omega_1)} = \frac{\left(a_1 A + \frac{9}{4} a_3 A^3\right)^2}{\left(\frac{3}{4} a_3 A^3\right)^2} \tag{4}$$

C. Three-Tone Input Model

Three-tone response should also be investigated to be able to compare both $f_i+f_j-f_k$ and $2f_i-f_j$ types of products. With the same assumptions made for two-tone response, the input signal is written as

$$x_{3\_tone}(t) = A\cos(\omega_1 t) + A\cos(\omega_2 t) + A\cos(\omega_3 t) \tag{5}$$

Injecting (5) in the polynomial model, the resultant third-order products' amplitudes are given below:

$$IM_{2fi-fj} = \frac{3}{4} a_3 A^3 \tag{6}$$

$$IM_{fi+fj-fk} = \frac{3}{2} a_3 A^3 \tag{7}$$

Thus, the power of each $f_i+f_j-f_k$ type product is approximately 6 dB higher than that of $2f_i-f_j$ types. Having this information, the power of both types of individual products can be calculated since the C/I_3 specification of the receiver reveals the power of $2f_i-f_j$ type products. Therefore, the parameters values in (1) are not necessarily calculated since the relationship between the powers of both types of products are known.

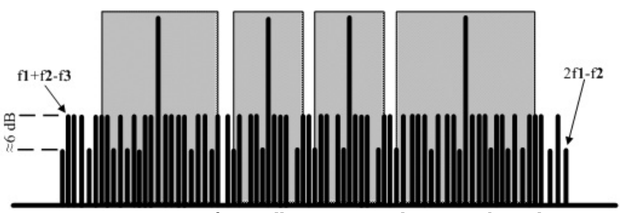

Figure 1. A portion of a satellite spectrum depicting channels, carriers and IMPs.

III. Simulation Tool

A tool has been developed for modeling and simulation of intermodulation distortion caused by the broadband receivers placed at the input section of communication satellite payloads. It can be helpful for both satellite manufacturers and operators to predict intermodulation distortion within the utilized bandwidth. This is because satellite manufacturers need to predict accurately this kind of signal distortion to ensure communication system

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performances, whereas the operators need to decide on the configuration of the satellite frequency plan for minimizing the risk of interruptions and providing the best to their customers.

A. *Assumptions and Inputs*

In order to simulate this kind of distortion, it is assumed that the $2f_i$-f_j and f_i+f_j-f_k types of third-order intermodulation products dominate the in-band intermodulation noise and the higher order terms can be neglected. Unlike many other studies, the carriers are not necessarily being equally spaced. What is assumed in this tool is that there exists one single-level carrier at the center frequency of each satellite channel. Thus, the carrier configuration reflects exactly the frequency plan of the satellite.

Under these assumptions, the tool can be initialized with the following inputs as shown in Fig. 2:

a) *Input power / Carrier (dBm):* Carrier levels at the receiver input. It can be extracted from uplink budget.
b) *C/I_3 (dB):* Signal to third-order intermodulation distortion ratio. C/I_3 is a parameter from receiver datasheets.
c) *Satellite frequency plan (MHz):* Min. and max. frequencies of each channel.
d) If there is a collocated satellite using an adjacent band:
   - *Collocated satellite frequency plan (MHz):* Min. and max. frequencies of each channel.
   - *Main satellite's input filter rejection ratio for the adjacent band (dB).*

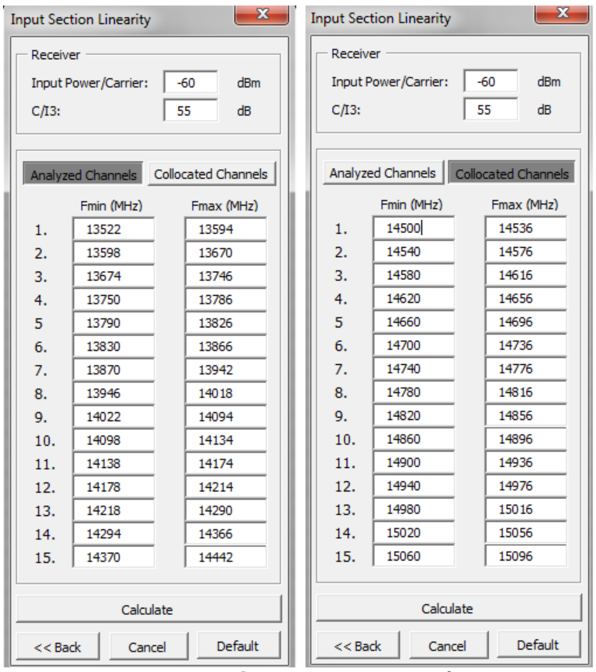

Figure 2. Simulation program user interface

B. *Outputs*

The algorithm is composed of five main steps. First step is the initialization. After providing the necessary data, program parameters are loaded. Some preliminary calculations are also performed at this stage. In the second and third steps, the frequencies and powers of all $2f_i$-f_j and f_i+f_j-f_k types of products emerging from the given carrier configuration are computed and stored, respectively. Then, all third-order products are sorted and counted with respect to the satellite channel frequencies in order to figure out C/I performances of each channel. Finally, the results are printed on screen in tabular and graphical forms.

The program provides the following results for each satellite channel:

a) Total number and power of $2f_i$-f_j type products
b) Total number and power of f_i+f_j-f_k type products
c) Cumulative third-order intermodulation power
d) C/I, carrier to intermodulation noise ratio

IV. CASE STUDIES

Two cases have been considered and simulated. In the first case a single satellite in the orbit is considered, whereas in the second case, a collocated satellite is assumed to be operating at the same orbital location.

A. *First Scenario*

We consider a hypothetical communication satellite "Sat_1" that has 15 Ku-band transponders with 36 and 72 MHz bandwidth channels totaling 920 MHz bandwidth. 4 MHz guard bands exist between each channel. The intermodulation products are calculated for the vertical polarization. This calculation should be done for each polarization. In our case, frequency plan is exactly the same for both polarizations. Based on the equipment specifications, the input parameters are given as follows:

a) Input power / Carrier = -60 dBm
b) C/I_3 = 55 dBc
c) Sat_1 Frequency Plan = as seen in Fig. 2.

When the simulation is performed under the assumptions of this scenario, the results are summarized in Table 1. C/I values for each channel are shown graphically in Fig. 3. The number of IMPs of each type generated within each channel is shown graphically in Fig. 4.

B. *Second Scenario*

In this case, we assume that there exists a collocated satellite "Sat_2" sharing the same orbital position with Sat_1. Sat_2 utilizes a 600 MHz bandwidth in the adjacent band which is comprised of 15 transponders with 36 MHz bandwidths. The input parameters in reference to the equipment specifications are given as follows:

a) Sat_1 Input Filter Rejection @ Sat_2 Freq. = 20 dB
b) Sat_2 Frequency Plan = as seen in Fig. 2.

The simulation results are given in Table 2. The C/I values and the number of IMPs for each channel are also shown in graphical form in Fig. 5 and 6, respectively.

RECEIVER INTERMODULATION SIMULATOR										
Receiver:		Input Power/Carrier : -60 dBm C/I3 : 55 dBc			INTERMODULATION PRODUCTS					
Input Filter:		Adj. Band Rejection : N/A			Analysis Results					
Interfering Carriers		Analyzed Channels			(2fi-fj) Type		(fi+fj-fk) Type		∑ Power	C / I (dBc)
Channels	Carriers	Fmin	Fmax	BW	∑ Number	∑ Power	∑ Number	∑ Power		
Sat_1 Ch.1	13558	13522	13594	72	8	-105.97	51	-91.90	-91.74	31.74
Sat_1 Ch.2	13634	13598	13670	72	8	-105.97	67	-90.72	-90.59	30.59
Sat_1 Ch.3	13710	13674	13746	72	8	-105.97	70	-90.53	-90.41	30.41
Sat_1 Ch.4	13768	13750	13786	36	5	-108.01	51	-91.90	-91.80	31.80
Sat_1 Ch.5	13808	13790	13826	36	4	-108.98	27	-94.67	-94.51	34.51
Sat_1 Ch.6	13848	13830	13866	36	5	-108.01	55	-91.58	-91.48	31.48
Sat_1 Ch.7	13906	13870	13942	72	8	-105.97	82	-89.84	-89.74	29.74
Sat_1 Ch.8	13982	13946	14018	72	10	-105.00	89	-89.49	-89.37	29.37
Sat_1 Ch.9	14058	14022	14094	72	8	-105.97	82	-89.84	-89.74	29.74
Sat_1 Ch.10	14116	14098	14134	36	5	-108.01	55	-91.58	-91.48	31.48
Sat_1 Ch.11	14156	14138	14174	36	4	-108.98	27	-94.67	-94.51	34.51
Sat_1 Ch.12	14196	14178	14214	36	5	-108.01	51	-91.90	-91.80	31.80
Sat_1 Ch.13	14254	14218	14290	72	8	-105.97	70	-90.53	-90.41	30.41
Sat_1 Ch.14	14330	14294	14366	72	8	-105.97	67	-90.72	-90.59	30.59
Sat_1 Ch.15	14406	14370	14442	72	8	-105.97	51	-91.90	-91.74	31.74

Table 1. Simulation results for the first scenario. (On the left hand side of the table, inputs and other information derived from the inputs, such as channel bandwidth, are listed. On the right hand side, total number and power of both types of third-order intermodulation products, cumulative intermodulation noise power and *C/I* values are given for each channel. Frequencies are given in MHz and the power values are in dBm.)

RECEIVER INTERMODULATION SIMULATOR										
Receiver:		Input Power/Carrier : -60 dBm C/I3 : 55 dBc			INTERMODULATION PRODUCTS					
Input Filter:		Adj. Band Rejection : 20 dB			Analysis Results					
Interfering Carriers		Analyzed Channels			(2fi-fj) Type		(fi+fj-fk) Type		∑ Power	C / I (dBc)
Channels	Carriers	Fmin	Fmax	BW	∑	∑	∑	∑		
Sat_1 Ch.1	13558	13522	13594	72	18	-105.92	258	-91.84	-91.67	31.67
Sat_1 Ch.2	13634	13598	13670	72	16	-105.93	290	-90.68	-90.55	30.55
Sat_1 Ch.3	13710	13674	13746	72	18	-105.92	323	-90.49	-90.37	30.37
Sat_1 Ch.4	13768	13750	13786	36	10	-107.97	187	-91.88	-91.78	31.78
Sat_1 Ch.5	13808	13790	13826	36	9	-108.93	171	-94.62	-94.46	34.46
Sat_1 Ch.6	13848	13830	13866	36	9	-107.98	200	-91.56	-91.46	31.46
Sat_1 Ch.7	13906	13870	13942	72	15	-105.93	379	-89.82	-89.71	29.71
Sat_1 Ch.8	13982	13946	14018	72	17	-104.98	398	-89.46	-89.34	29.34
Sat_1 Ch.9	14058	14022	14094	72	16	-105.95	403	-89.81	-89.70	29.70
Sat_1 Ch.10	14116	14098	14134	36	10	-107.99	222	-91.54	-91.45	31.45
Sat_1 Ch.11	14156	14138	14174	36	9	-108.96	201	-94.59	-94.43	34.43
Sat_1 Ch.12	14196	14178	14214	36	10	-108.00	223	-91.86	-91.76	31.76
Sat_1 Ch.13	14254	14218	14290	72	18	-105.96	417	-90.46	-90.34	30.34
Sat_1 Ch.14	14330	14294	14366	72	20	-105.96	412	-90.64	-90.51	30.51
Sat_1 Ch.15	14406	14370	14442	72	21	-105.97	424	-91.76	-91.60	31.60

Table 2**.** Simulation results for the second scenario.

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C. Discussion

For the first scenario, the maximum intermodulation distortion occurs in the 8th channel (ch.8) with -89.37 dBm, and the minimum in 5th and 11th channels with a value of -94.51 dBm. Due to the symmetric configuration of the frequency plan, the results are also symmetric around ch8. In the second scenario, the maximum distortion takes place in the 8th channel again with -89.34 dBm, whereas the minimum is in the 5th channel with -94.46 dBm. Since there is no symmetry in this case, the existence of the collocated satellite channels affects the distortion scheme. According to these results, we can conclude the followings:

a) Resultant C/I values of all channels are at least 20 dB less than the C/I_3 specification of the receiver itself i.e., the effect of third-order intermodulation distortion is quite significant.

b) The C/I values of the channels vary up to 5 dB. Thus, intermodulation distortion affects the channels differently depending on the carrier configuration.

c) $f_i+f_j-f_k$ type of intermodulation products are much greater than $2f_i-f_j$ type both in number and power. i.e., $f_i+f_j-f_k$ type products are much more dominant in determining the cumulative distortion power.

d) The existence of a collocated satellite system operating in an adjacent band affects the C/I performances. However, this effect is not significant in this case because the adjacent satellite carriers are suppressed by 20 dB by the input filter before arriving at the receiver of the first satellite. Depending upon the input filter rejection, C/I values will be different. The more rejection means much better C/I values.

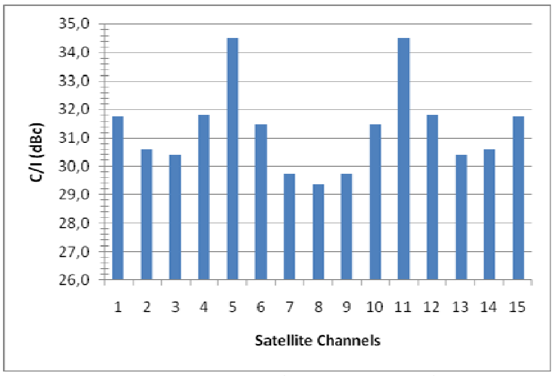

Figure 2. C/I at receiver output for each channel (first scenario)

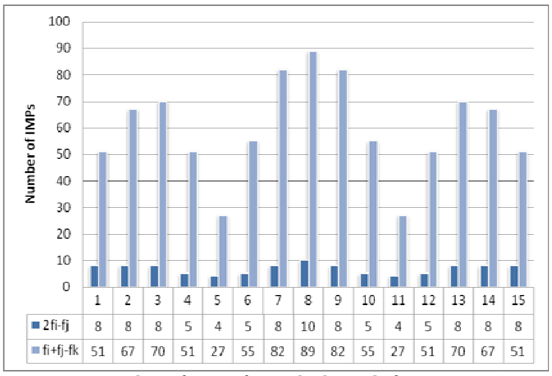

Figure 3. Number of IMPs for each channel (first scenario)

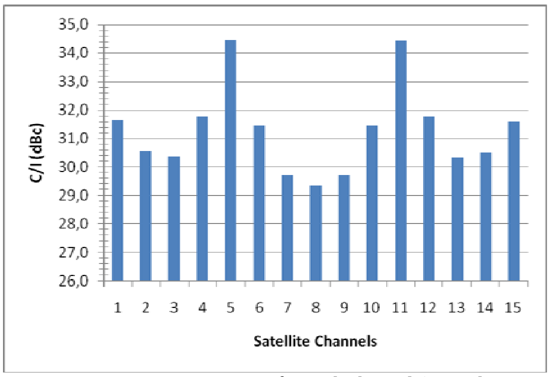

Figure 4. C/I at receiver output for each channel (second scenario)

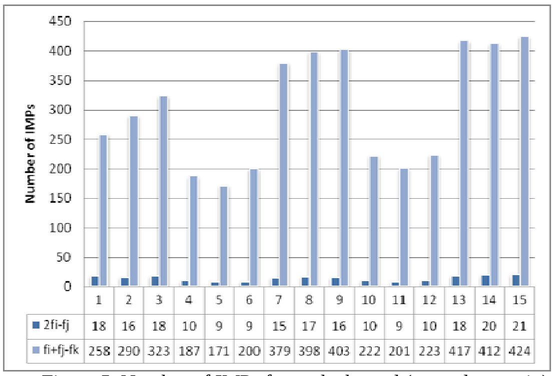

Figure 5. Number of IMPs for each channel (second scenario)

V. CONCLUSION

The two case studies demonstrate that significant degradation in the C/I performance may occur due to intermodulation phenomena. Besides, the level of degradation varies among the satellite transponders. Therefore, the C/I performances of each channel should carefully be analyzed. In this work, we have presented a practical simulation tool to compute the effect of third order intermodulation distortion caused by the nonlinear characteristics of communication satellite receivers. It presents channel by channel results and helps optimizing

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satellite frequency plan. Besides, the effect of collocated satellite system on the linearity performance of the payload input section can also be simulated. In order to achieve a good balance between computational complexity and accuracy, third order intermodulation products are taken into account, namely $2f_i$-f_j and f_i+f_j-f_k types. The tool is configured for the use of satellite communications experts.

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