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A New Model to Determine Passive Intermodulation Terms When Non-Contributing Carriers Are Added to Classical Scenarios

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ABSTRACT This paper provides a new theoretical model for the characterization of passive intermodulation behaviour when non-contributing carriers (i.e., carriers which do not directly affect the particular non-linear contribution under analysis) are added to classical two or three carriers scenarios. According to traditional models, the power of a particular passive intermodulation frequency term is only related to the contributing carriers which combines in non-linear way to generate this term, thus the presence of additional (i.e., non-contributing) carriers should not affect to the predicted power of such an intermodulation product. However, recent laboratory tests reveal that non-contributing carriers do reduce the power of unrelated passive intermodulation terms. A heuristic model is proposed in this work to explain this effect, which shows a good matching with measured results already published in the technical literature. The study is focused in third order non-linear contributions, as being the most critical in practical applications.

INDEX TERMS Intermodulation distortion, passive circuits, non-linear systems, satellite communication, passive intermodulation, third order, non-contributing carriers.

I. INTRODUCTION

Passive intermodulation (PIM) is nowadays considered a critical factor in modern communication systems due to the continuous trend for higher capacity links, particularly for mobile [1] and satellite applications [2]. In satellite scenarios, the simultaneous operation of the payloads in both transmission (downlink) and reception (uplink) at different frequency bands, together with the increase of transmitted power levels and number of carriers at the downlink, are stimulating PIM generation at the uplink chain [3], [4]. The use of higher frequency bands of operation to satisfy the capacity demands (such as in HTS, High Throughput Satellites), implying a shrinkage in the hardware physical dimensions (wavelength reduction) and therefore an increase on the surface current density, does not help to relieve the situation. Undesired PIM terms in the reception band can interfere the low amplitude signals in the receiver, thus affecting the uplink performance.

Traditional PIM models relies on typical non-linear polynomial expansions of the output voltage/current in terms of the input one [3], [5]. According to these models, the amplitude of a particular PIM product is only related to the contributing carriers directly involved in the non-linear generation of this term. As a result, the amplitude of a given PIM product will not be modified by the presence of other non-contributing carriers at the input of the non-linear system. Namely, a third order PIM term located at the angular frequency $2\omega_2 - \omega_1$ should depend on the amplitude of the input carriers at ω_1 and ω_2, and be independent of an input carrier with angular frequency ω_3.

Practical measurements, however, belies the classical model, since the presence of additional non-contributing carriers tends to decrease the power of PIM tones. A thorough and detailed empirical study recently published confirms this point [6]. This work provides plenty of useful measured data, but lacks of providing a justification for the PIM reduction due to the presence of non-contributing carriers. To the best

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of the authors' knowledge, no models able to explain this behaviour are present in technical literature either.

This paper proposes an innovative model able to explain the role of non-contributing carriers in PIM terms, which provides a good agreement with reported measured data. The proposed model is based on a behavioural assumption, never considered so far in the technical literature, stating that the amount of spectral output PIM power for a given order is nearly the same if the overall input power of the non-linear system is kept constant (regardless the number of input carriers). This is somewhat similar to the non-linear behaviour of RF amplifiers, where the 1 dB compression point is essentially related to the overall input/output power and roughly independent on the number of carriers. As a result of this conservation of PIM energy law, an increase in the number of carriers (for the same overall input power) will cause a spread of the PIM power over the spectrum, thus reducing the power corresponding to each PIM term. As it will be proved, this theory also predicts a reduction on the power of a given PIM term when non-contributing carriers of the same amplitude are added to the contributing carries generating a particular non-linear term.

For the sake of simplicity, this model assumes all carriers having the same amplitude. The assumption of equal amplitude carriers is coherent with typical payload operation (this is in fact the case considered in all of the measurements reported in [6]). Note also that the standard PIM measurement procedure considers carriers of the same amplitude [7], being limited to only two carriers to avoid a substantial increase in terms of both cost and complexity.

Thanks to the model proposed in this paper, it will also be possible to obtain a fair estimation of the power of a given third order PIM term in a multi-carrier scenario from measurements carried out in the conventional two-carriers PIM test. The heuristic model has been developed for third order PIM, typically the most critical one in practical applications [8], [9]. Higher order PIM terms are neglected for this study, as their measured amplitude is much lower [5], [10].

II. PIM MODEL

The expressions derived in this paper will use as a reference the results of the standard two-tones PIM test. From such results, first the overall PIM power at the system output for a multi-carrier excitation is estimated. Next, the effect of the presence of non-contributing carriers in each PIM term will be obtained.

For the sake of simplicity, this model assumes all carriers having the same amplitude (the typical case for a multi-carrier payload system) and zero phase. Only third order PIM is considered.

A. EVALUATION OF THE OVERALL PIM OUTPUT POWER

Let us start with the classic two-carriers scenario, indicated by the sub-index $2-\mathrm{c}$ in the equations below. The input signal will be the sum of two carriers at angular frequencies $\omega_1 = 2\pi f_1$ and $\omega_2 = 2\pi f_2$ of the same amplitude $A_{2-\mathrm{c}}$, namely $A_{2-\mathrm{c}}\cos(\omega_1 t) + A_{2-\mathrm{c}}\cos(\omega_2 t)$. It is possible to evaluate the overall output power of the third-order PIM ($OP_{2-\mathrm{c}}$) by simply adding the power ($PIM_{2-\mathrm{c},i}$) of each contribution:

$$OP_{2-\mathrm{c}}\,(\mathrm{mW}) = \sum_i PIM_{2-\mathrm{c},i}\,(\mathrm{mW})\,. \tag{1}$$

Analogously, if we now consider a multi-carrier excitation composed of N carriers of equal amplitude, we will get an input signal of the form $A_{N-\mathrm{c}}\cos(\omega_1 t) + A_{N-\mathrm{c}}\cos(\omega_2 t) + A_{N-\mathrm{c}}\cos(\omega_3 t) + \ldots + A_{N-\mathrm{c}}\cos(\omega_N t)$. The ratio between the input power in the multi-carrier and two-tones cases is called *IPR* and expressed in logarithm terms as:

$$IPR\,(\mathrm{dB}) = 10\log_{10}\left(\frac{N}{2}\right) + 20\log_{10}\left(\frac{A_{N-\mathrm{c}}}{A_{2-\mathrm{c}}}\right). \tag{2}$$

From a theoretical point of view, an increase of x dB in the input power should cause an increase of $3 \cdot x$ dB in the third-order non-linear terms. However, laboratory measurements show that the increase is in the form $SF \cdot x$ dB, where SF is the PIM slope factor located in the range between 1.5 to 3 [5], [10], [11]. The effect of higher order non-linearities (5th order and above), or the interaction between linear and non-linear parts of the circuit, can explain a slope of the PIM curve lower than 3. As a result, the overall output power for the N-carriers case will be:

$$OP_{N-\mathrm{c}}\,(\mathrm{dBm}) = OP_{2-\mathrm{c}}\,(\mathrm{dBm}) + SF \cdot IPR\,(\mathrm{dB}) \tag{3}$$

under the key assumption of this paper, which states that the output PIM power of the non-linear system mainly depends on the overall input power (and therefore, if the input power is constant, the aggregated output power of the third order PIM terms is kept constant).

B. EVALUATION OF THE OUTPUT POWER FOR A PARTICULAR PIM TERM

The overall output power computed in the previous section must be distributed into the different third order PIM terms. Table 1 summarizes the number of third order PIM terms, overall voltages and powers for the 2, 3 and N carriers case (it is assumed that the set of angular frequencies ω_i are chosen to avoid more than one third order term at the same frequency, thus allowing a direct power sum of the different contributions).

For a generic m-carriers scenario, the power of a given i PIM term can be expressed as:

$$PIM_{m-\mathrm{c},i}\,(\mathrm{mW}) = OP_{m-\mathrm{c}}\,(\mathrm{mW}) \cdot \frac{AF_i^2}{\sum_i AF_{m-\mathrm{c},i}^2} \tag{4}$$

where AF_i is the amplitude factor (voltage) of the term in the classic polynomial approach (i.e., the factor multiplying the third-order coefficient a_3 in the polynomial expansion of the output voltage).

Applying (4) for the N-carriers case and computing its ratio with the j PIM term in the two-carriers case, we obtain:

$$\frac{PIM_{N-\mathrm{c},i}\,(\mathrm{mW})}{PIM_{2-\mathrm{c},j}\,(\mathrm{mW})} = \frac{OP_{N-\mathrm{c}}\,(\mathrm{mW})}{OP_{2-\mathrm{c}}\,(\mathrm{mW})} \cdot \frac{\sum_j AF_{2-\mathrm{c},j}^2}{\sum_i AF_{N-\mathrm{c},i}^2} \cdot \frac{AF_i^2}{AF_j^2} \tag{5}$$

TABLE 1. Number of PIM terms, amplitude factors (*AF*) and overall output power for 2, 3 and *N* carriers scenarios.

		2 carriers		3 carriers		N carriers	
		Terms	AF	Terms	AF	Terms	AF
Angular frequencies	ω_i	2	9/4	3	15/4	N	$(6N-3)/4$
	$3\omega_i$	2	1/4	3	1/4	N	$1/4$
	$2\omega_i \pm \omega_j$	4	3/4	12	3/4	$4\binom{N}{2} = 2N(N-1)$	$3/4$
	$\omega_i \pm \omega_j \pm \omega_k$	-	-	4	6/4	$4\binom{N}{3} = 2N(N-1)(N-2)/3$	$6/4$
Overall Voltage	$\sum_i AF_i$	8		27		N^3	
Overall Power	$\sum_i AF_i^2$	12.5		58.125		$5\left(3N^3/4 - 9N^2/8 + N/2\right)$	

TABLE 2. Comparison between predicted and measured PIM contributions for 2 and 3 carriers excitations.

PIM Term	2-c scenario (measured)	3-c scenario			
		Classic theory	Predicted (SF=2)	Predicted (SF=2.3)	Measured
$2\omega_2 - \omega_1$	-115.9 dBm (ref.)	-115.9 dBm	-119.0 dBm	-118.5 dBm	-120.1 dBm
$\omega_2 + \omega_3 - \omega_1$	-	-109.9 dBm	-113.0 dBm	-112.5 dBm	-112.7 dBm

and after using (3) and the results in the last row of Table 1, it can be expressed in logarithm terms as:

$$PIM_{N-\mathrm{c},i}\,(\mathrm{dBm}) = PIM_{2-\mathrm{c},j}\,(\mathrm{dBm}) + SF \cdot IPR\,(\mathrm{dB}) - 10\log_{10}\left(\frac{3N^3}{4} - \frac{9N^2}{8} + \frac{N}{2}\right) + 4 + 20\log_{10}\frac{AF_i}{AF_j}. \qquad (6)$$

Equation (6) allows to obtain the power of a given third order PIM term for a generic N-carriers scenario from measurements performed in the classic two-carriers PIM test at $2\omega_i \pm \omega_j$. For a term of the form $2\omega_i \pm \omega_j$ in the N-carriers case, both amplitude factors are the same (i.e. 3/4, according to Table 1), and the last term in (6) vanishes. On the other hand, for a PIM contribution at an angular frequency $\omega_i \pm \omega_j \pm \omega_k$, the corresponding amplitude factor is twice the one of the term $2\omega_i \pm \omega_j$ in the two-carriers case, and therefore the last term in equation (6) involving the ratio of amplitude factors is equal to 6 dB.

III. EXPERIMENTAL VALIDATION

Measuring PIM in a multi-carrier scenario requires a huge effort in terms of both human and technical equipment resources. Note that each carrier must be amplified by a different High Power Amplifier (HPA) in order to avoid active intermodulation, which would probably mask the PIM signal to be detected. Moreover, all the high-power channels must be combined together by using a customly designed output multiplexer before being injected to the Device Under Test (DUT). Finally, the PIM signal should be separated from the carriers to be measured [6], [9]. As a result, a vast number of expensive equipment is required, being the assembly of the test bed also a cumbersome task. The complexity and cost clearly increase with the number of carriers involved in the setup. This is the reason why the standard PIM experimental setup considers only a two-carriers excitation [7].

In this paper, the proposed model is verified by taking profit of the large amount of measurements reported in the previous work of Shayegani *et al.* [6] for a multi-carrier scenario. The frequencies of the carriers for such experimental tests were chosen in such a way that the different PIM contributions fall at different frequencies. Moreover, a power sweep test was also performed to evaluate the 3rd order PIM power reduction due to the stimulus back-off, obtaining a slope factor SF in the range between 2 and 2.3 dB of output power/dB of input power [6].

The amplitudes of the carriers were always the same, regardless the number of input carriers considered. As a result, and after applying (2), the increase in the input power with regard to a two-carriers excitation takes the form:

$$IPR\,(\mathrm{dB}) = 10\log_{10}\left(\frac{N}{2}\right) \qquad (7)$$

where N is the number of input carriers applied to the system.

Taking as reference the power of the PIM contribution at $2\omega_i \pm \omega_j$ for the classic two-tones PIM test, the power of a term of the same form for a multi-carrier case (i.e., generic excitation of N carriers with the same amplitude) is obtained by just substituting (7) into (6):

$$PIM_{N-\mathrm{c},i}\,(\mathrm{dBm}) = PIM_{2-\mathrm{c},i}\,(\mathrm{dBm}) + SF \cdot 10\log_{10}\left(\frac{N}{2}\right) - 10\log_{10}\left(\frac{3N^3}{4} - \frac{9N^2}{8} + \frac{N}{2}\right) + 4 \qquad (8)$$

where the last term of 4 dB should be replaced by 10 dB, in order to estimate the power of a third order PIM contribution of the form $\omega_i \pm \omega_j \pm \omega_k$.

Table 2 compares, for a three-carriers scenario, the measured results at the antenna level test (those performed under a more controlled environment) in the work of Shayegani *et al.* [6] with predictions obtained from the measured power of the PIM term at $2\omega_2 - \omega_1$ in the two-carriers scenario. According to the classic theory, the addition of a non-contributing carrier at the input should not modify the power of the PIM contribution. However, measured results show a reduction of about 4.2 dB. On the other hand, the theory proposed in this paper predicts a power reduction of

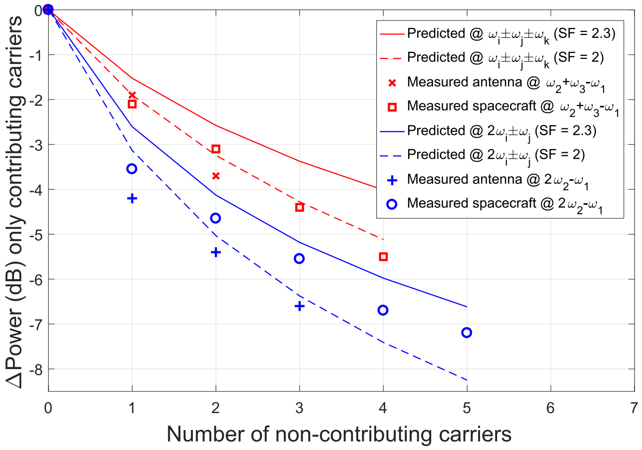

FIGURE 1. **Third order PIM output power reduction in terms of the number of additional non-contributing carriers of the same amplitude.**

3.1 dB and 2.6 dB for a *SF* of 2 and 2.3, respectively. Note that an accuracy of ±1 dB in PIM measurements are quite common, so predictions are within measurement uncertainty range. The addition of a new carrier increases the overall power at the input of the non-linear system, but also creates new PIM contributions in the spectrum. According to the proposed theory, a redistribution of a higher overall output PIM power into a larger number of PIM contributions is performed, leading eventually to a reduction of the PIM power of a particular term due to the presence of the additional non-contributing carrier.

The PIM term at $\omega_2 + \omega_3 - \omega_1$ cannot appear in a two-carriers test as it requires at least 3 input carriers in the system (at angular frequencies ω_1, ω_2 and ω_3), but its power for a three-carriers excitation can be estimated from the measured PIM power at $2\omega_2 - \omega_1$ as well. Using the classic theory, an increase of 6 dB is expected since the amplitude factor AF of this term is twice the one of the reference term at $2\omega_2 - \omega_1$ (see Table 1). Measured results, however, provides an increase of only 3.2 dB. The theory proposed in this paper justifies this lower increase from the spreading of the output PIM power in a wider range of spectral PIM contributions, leading to an increase between 2.9 dB and 3.4 dB depending on the slope factor *SF* as shown in Table 2. The agreement with measured results is excellent in this case.

On the other hand, Figure 1 plots the power reduction in terms of the number of non-contributing carriers for two PIM terms, the ones placed at $2\omega_2 - \omega_1$ (two contributing carriers) and at $\omega_2 + \omega_3 - \omega_1$ (three contributing carriers). The measured results are obtained from the experimental results reported in the work of Shayegani *et al.* for both antenna and spacecraft ground levels [6]. For the case of spacecraft ground level, only the results corresponding to co-polar polarization (the most sensitive to PIM) are used (the ones related to the cross polarization are lower and therefore less limiting in practice). For the PIM term at $2\omega_2 - \omega_1$, the average value of the two measurements carried out in such a experimental work has been considered. There is a good agreement between the measured power reduction and the predicted values by the proposed model, particularly for a slope factor *SF* of 2. As a result, the new theory presented in this paper is able to predict the power of the PIM terms for a multi-carrier excitation with non-contributing carriers starting from the measurements for the classic two-tones PIM test.

IV. CONCLUSION

In this paper, a simple heuristic model capable to explain the third order PIM behaviour when non-contributing carriers are added to the system is presented. This model is based on the law of conservation of energy, and assumes that the overall output PIM power mainly depends on the overall input power at the non-linear system. From this key assumption, a useful expression to estimate the power of a given PIM term in a multi-carrier scenario from measurements carried out in the two-carriers case is provided. This expression could be of interest, since it provides a link between a real case and typical laboratory PIM tests conducted with only two carriers.

The theoretical approach proposed has been verified with the full set of PIM measurements already reported in the technical literature by one of the main payload manufacturers worldwide. A good agreement has been obtained when a few number of non-contributing carriers (up to 5) are added to the system, thus validating the behavioural model. It has also been proved how an increase in the number of carriers (with the same amplitude) cause a reduction of a given PIM term due to the redistribution of the PIM power in a larger number of PIM contributions, as shown in actual laboratory tests.

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