Relaxation of the multicarrier passive intermodulation specifications of antennas

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***Abstract*—Non-analytic behavioral models of passive non linearity presented in 2013 are used to define and propose new specifications for multicarrier passive intermodulation in antennas. A margin of up to 10 dB is obtained in some cases and can be used to relax 2-carrier PIM specifications.**

***Index Terms*—antenna, specification, PIM, intermodulation product, slope, non linearity, behavioural model, measurement.**

I. Introduction

We presented a non-analytic behavioral model of passive non-linearity in EuCAP 2013 [1]. This model fits the non-integer slope of 2-carrier intermodulation (IM) products power versus input signal power. This cannot be obtained when using analytic (polynomials) models. The model has been further studied and used to simulate passive intermodulation (PIM) products created by a high power multicarrier signal.

We show that many results accepted in IM computation are valid only for a polynomial of degree 3 and are wrongly applied to passive IM where the best behavioral model is not a polynomial. This results in unnecessary constraints on the equipment, leading to rejection of some technologies, increase in manufacturing cost or delays in projects due to PIM qualification failure.

Using the non-analytic model and provided that accurate measurements of the dB/dB slope of PIM power versus input signal power have been carried out, 2-carrier specifications can be relaxed by up to 10 dB depending on the measured slope.

II. Non-analytic model

The non-analytic behavioral model has been presented in [1]. It is based on a non linear gain g that depends on the absolute value of the input signal.

$$v_{out} = v_{in} \cdot g(|v_{in}|) \quad (1)$$

In an analytical model the non linear gain would be a polynomial P of the square of the absolute value of the input signal. Equation (2) is in fact a particular case of (1).

$$v_{out} = v_{in} \cdot P\left(|v_{in}|^2\right) \quad (2)$$

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When using (1) with a non linear gain that cannot be expressed by a polynomial as in (2), a non-odd-integer dB/dB slope of IM power versus input signal power can be obtained and models have been fitted to passive equipment measurements with slopes of 1.6 dB/dB to 2.5 dB/dB published in [2, 3].

Fitting the third order IM has also given a good fit on the fifth order and adequate values for the seventh and ninth order IM. Simple models are quite effective. The following model gives a 1.6 dB/dB slope for all odd order IM products:

$$v_{out} = \alpha \cdot v_{in} \cdot |v_{in}|^{0.6} \quad (3)$$

Figure 1 gives the result of fitting measurements in [2] with this simple model.

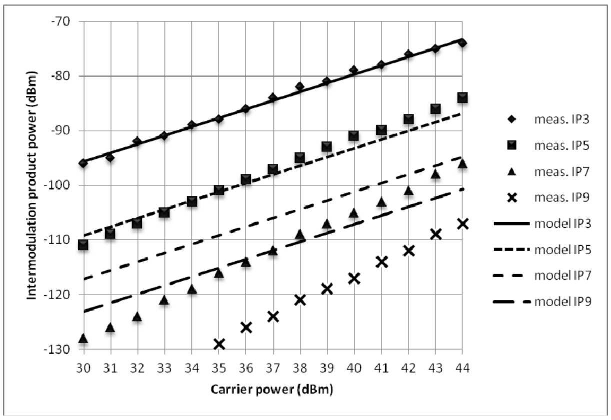

Figure 1: Measurements in [2] fitted with model (3)

A good fit is obtained for order 3 and 5 PIM, a more pessimistic fit is obtained for order 7 and 9 PIM.

More complex models have been presented in [1].

A possible model is obtained by adding more terms like the one in (3). We obtain a sum of non-analytical terms:

$$v_{out} = v_{in} \cdot \sum_k \alpha_k \cdot |v_{in}|^{\beta_k} \quad (4)$$

This model will generally give a better fit in the input range used for the optimization of the coefficients but the main disadvantage is that coefficients may have alternate signs and the modeled PIM may become too low or even 0 when extrapolating at higher input power.

Another interesting model is based on Padé approximation by replacing the polynomials in the Padé rational fraction with non-analytic functions:

$$v_{out} = v_{in} \cdot \frac{\sum_k \alpha_k \cdot |v_{in}|^{\beta_k}}{\sum_k \gamma_k \cdot |v_{in}|^{\delta_k}} \quad (5)$$

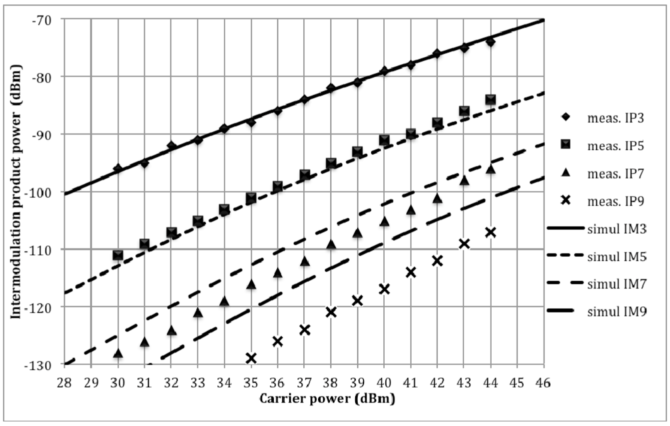

Figure 2: Measurements in [2] fitted with model (5)

Such a model can be designed so that higher power extrapolation will be less risky and higher order PIM fit will be better but the computation of the coefficients is more difficult.

In this paper, we will use the simplest model given by:

$$v_{out} = \alpha \cdot v_{in} \cdot |v_{in}|^{\beta} \quad (6)$$

The exponent β gives an IM power dB/dB slope of $\beta+1$ that is equaled to the measured slope in the input power measurement range. The α coefficient is then fitted to give the correct IM power at the nominal input power.

The simple model is better adapted to extrapolate the behavior of the measured device for a higher number of carriers or for higher total power. A more complex model such as (4) or (5) would be better for interpolation but could be much worse for extrapolation and more difficult to validate.

III. Measurements

Telephony base station and space telecommunications antennas, passive equipment and metallic environment have been measured with passive IM that do not follow the classical 3dB/dB slope. The first problem detected on a satellite was reported on FLTSATCOM in 1974 and measurements were published in 1976 [3]. Measurements of for a metallic horn antenna show a constant slope of 2.5 dB/dB for an input range of 30 dB (1W to 1 kW).

More papers have been published these last 2 years as telephony base stations are impacted by the PIM problem because of the increase of the number of antennas, number of bands and power. Specific measurement equipment has been developed and specifications have been proposed [4, 5].

These measurements confirm that PIM power versus input signal power is nearly a straight line (in a log-log scale) on more than 13 to 30 dB range and that the slope is generally lower than the classical slope of 3 dB/dB. Such a constant slope cannot be obtained on such an extended range when using an analytic model.

Most of these measurements have been published for 2-carrier measurements only.

IV. Prediction of multicarrier PIM

These 2-carrier measurements are then used to predict multicarrier intermodulation products by using theoretical coefficients obtained with small signal analytical models such as the ones used for amplifiers and given in [6].

These theoretical coefficients are in fact valid only for an exponent $\beta = 2$ in (6) giving an analytical term of degree 3 and the classical small signal slope of 3 dB/dB.

They are not even valid for analytical models with integer degrees higher than 3 nor for the influence of analytical terms with degree higher than 3 in a polynomial model.

Equivalent coefficients for non-integer slopes must be obtained either through experiment or through simulation. For the simple model given in (6), these coefficients can also be computed easily from α and β, see [7].

Due to the difficulty of multi-carrier experiments, we propose to compute these coefficients by simulation and then to validate the model and computation by experiments.

V. Simulation results

We have simulated models with slopes between 1.5 and 3.5 dB/dB. Quite evidently, the model with slope 3 dB/dB is analytical and is used as the reference for the other cases.

A. 3-carrier results

Typical IM spectra at the output of an analytical non-linearity of degree 3 (slope 3 dB/dB) are given in fig. 3 for 2 and 3 carriers at same carrier input power.

The main difference between an analytical model of degree 3 and a non-analytical model is that the power of each IM product of type $2f_1 - f_2$ obtained with 3 carriers of given input power is no longer the same as the power of each IM product obtained with 2 carriers of the same input power.

Furthermore, the power of a 3-carrier IM of type $f_1 + f_2 - f_3$ is no longer 6 dB higher than a 2-carrier IM of type $2f_1 - f_2$ as is the case for degree 3.

Because of these results, major errors can be introduced in multicarrier computations based on 2-carrier measurements and extrapolation using 3^{rd} degree or 3dB/dB slope hypothesis.

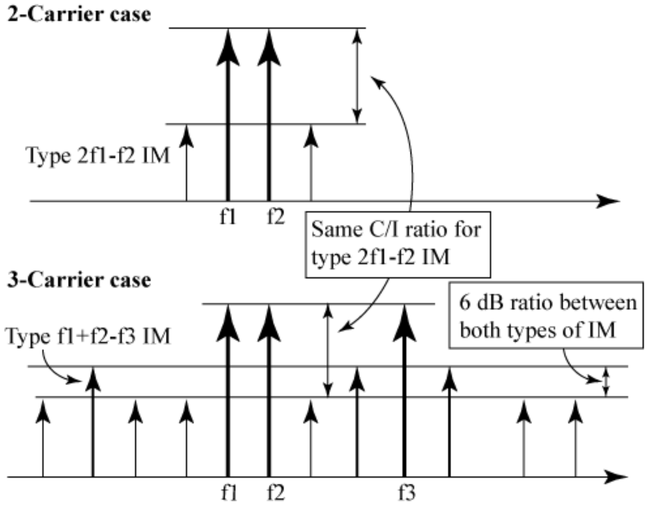

Figure 3: Typical 2-carrier and 3-carrier spectra, at same carrier power, for an analytical model with slope equal to 3 dB/dB, no longer true for a non-analytical model.

B. Multi-carrier results

Multi-carrier simulation has been done with 8 carriers. The signal is composed of two blocks of 4 nearly equally spaced in frequency carriers with a notch between the two blocks. Small frequency differences ensure that all third order IM products have different frequencies.

TABLE I. FIXED C/I IN 2- CARRIER CASE

Slope of PIM (dB/dB)	C/I (dB) versus number of carriers and slope of NL at constant carrier power		
	2-carrier, type $2f_1 - f_2$	*8-carrier, type* $2f_1 - f_2$	*8-carrier, type* $f_1 + f_2 - f_3$
1.5	121	134	127.7
2	121	129.75	123.5
2.5	121	125.4	119.3
3	121	121	115
3.5	121	116.5	110.6

Table I gives us the C/I as a function of the PIM slope β+1 of the model for 2 and 8 carriers at constant carrier power. For each model, coefficient α has been fixed for a 2-carrier C/I equal to 121 dB.

Table II gives the same C/I as a function of slope β+1 for 2 and 8 carriers at constant carrier power. In this case, for each model, coefficient α has been fixed for an 8-carrier C/I of type $f_1 + f_2 - f_3$ equal to 115 dB.

The same type of simulation or measurement can be done for higher order of intermodulation, typically for the order interfering most with reception.

TABLE II. FIXED C/I IN 8-CARRIER CASE

Slope of PIM (dB/dB)	C/I (dB) versus number of carriers and slope of NL at constant carrier power		
	2-carrier, type $2f_1 - f_2$	*8-carrier, type* $2f_1 - f_2$	*8-carrier, type* $f_1 + f_2 - f_3$
1.5	108.3	121.3	115
2	112.5	121.3	115
2.5	116.7	121.1	115
3	121	121	115
3.5	125.4	120.9	115

As can be seen in tables I and II the difference between types $2f_1 - f_2$ and $f_1 + f_2 - f_3$ of 8-carrier intermodulation is not far from the theoretical 6 dB value that is exactly obtained for the classical case of 3 dB/dB slope.

However, the difference between 2-carrier and multicarrier can be high when the slope differs from 3 dB/dB.

VI. Preliminary validation

Table II has been partially validated by some preliminary measurements results given by satellite operator and industry. Slopes between 2.2 and 2.3 dB/dB have been measured on carbon fiber space type antennas and differences between type $2f_1 - f_2$ 2-carrier and 8-carrier C/I of 6 to 7 dB have been measured on the same type of antennas.
This is in complete agreement with the value obtained from table II and table III.

TABLE III. C/I DIFFERENCE BETWEEN 8 AND 2-CARRIER CASES

Slope of PIM (dB/dB)	C/I (dB) for 2 and 8 carriers at constant carrier power		C/I difference (dB)
	2-carrier, type $2f_1 - f_2$	*8-carrier, type* $2f_1 - f_2$	*Types* $2f_1 - f_2$
1.5	108.3	121.3	13
2	112.5	121.3	8.8
2.5	116.7	121.1	4.4
3	121	121	0
3.5	125.4	120.9	-5.5

As can be seen, the predicted C/I difference for a slope of 2.25 dB/dB is around 6.6 dB.
More extensive validation on different types of antennas and passive connectors and devices will be done in 2014.

VII. Specifications relaxation

From the values in table III, we see that we can relax the 2-carrier C/I specification by around 4 dB each time the slope decreases by 1/2 and nevertheless obtain the same 8-carrier C/I.

On the contrary, for a slope higher than 3 dB/dB, a more stringent 2-carrier specification would be needed.

From these tables we can see that it is interesting for the antenna manufacturer to perform measurements in a wide input power range and to compute the slope of C/I versus input power as a way to relax the C/I specification.

A wider input power range will permit to compute more accurately the C/I slope.

Because the C/I curve is convex in most measurements a higher value for the highest power in the range will give a lower slope and a better relaxation of specification. However, this power must not heat the device too much or be much higher than the nominal power for the model to be representative.

It is proposed to measure C/I and slope at the nominal carrier power. As shown in [7], a good fit for these values should also gives a correct value for the next higher order intermodulation ratio. Measurement of next higher order IM (and next lower order if applicable) can be used to improve the precision of extrapolation to multicarrier performance.

The relaxation and the new margins to be applied will have to be validated by experiments on some non-linearity before general use in satellites.

VIII. Conclusion

We have shown that analytical models cannot be used for antenna PIM computation. We have presented non-analytical models that much better fit published measurements, particularly the non-integer PIM slopes.

These models have different behavior in multi-carrier conditions and they permit to relax the 2-carrier specifications for the same multi-carrier specification.

A preliminary validation has been obtained and more extensive measurements on a test antenna or reflector and other devices will be done in 2014.

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