EuMW 2015
FREEDOM THROUGH MICROWAVES

EUROPEAN MICROWAVE WEEK 2015
SIX DAYS • THREE CONFERENCES • ONE EXHIBITION
PALAIS DES CONGRÈS, PARIS, FRANCE
SEPTEMBER 6 - 11, 2015

Exhibition Opening Hours:
- Tuesday 8th September: 9.30 – 18.00
- Wednesday 9th September: 9:30 – 17.30
- Thursday 10th September: 9:30 – 16.30

Passive InterModulation (PIM) Theory and Simulation

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SCM01 High RF Power Critical Effects

Outlook of presentation

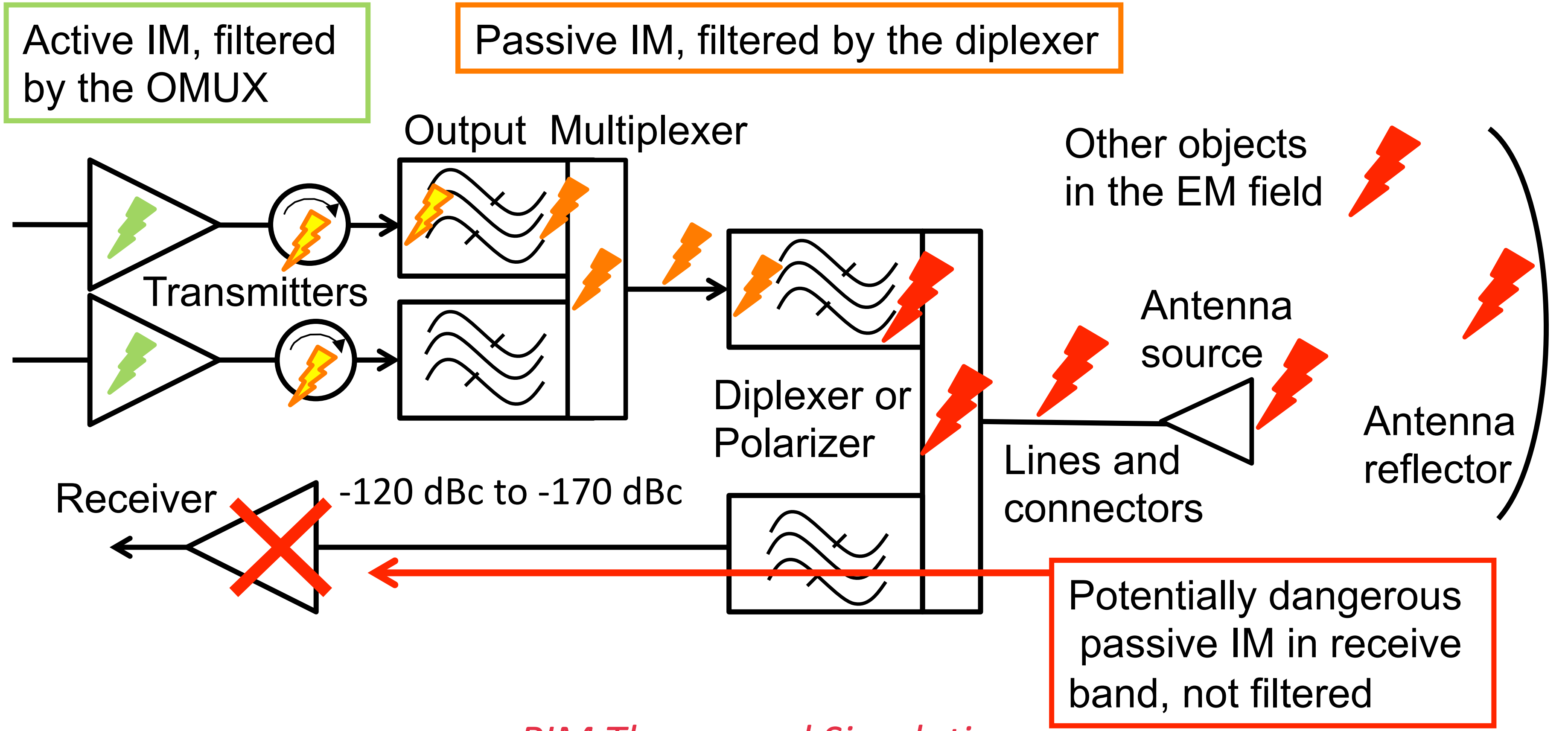
- Introduction
- Passive intermodulation phenomenon and consequences
- Classical theory of intermodulation products
- Published passive intermodulation measurement
- Non analytical behavioral models
- Consequences on predicted PIM power
- Conclusion and further work

Introduction

- Passive intermodulation (PIM)has been a problem in satellites using the same antenna or common equipment (filters, diplexers, cables, connectors, polarizers) for high power transmission and reception since 1972
- A reference article [1] in 1976 gives a bibliography of previous internal reports and presents measurements
- Since that time the problem occurred also on aircraft and more recently on telephony base stations
- PIM occurrence will continue to increase as transmitted power, bandwidth, number of channels and antennas will increase in satellites, aircrafts and base stations

Generation of IM products

PIM products are generated in the receive band after transmission filters so that they are not filtered out before entering the receiver



Active IM, filtered by the OMUX

Passive IM, filtered by the diplexer

Output Multiplexer

Other objects in the EM field

Transmitters

Antenna source

Diplexer or Polarizer

Antenna reflector

Lines and connectors

Receiver

-120 dBc to -170 dBc

Potentially dangerous passive IM in receive band, not filtered

Physical phenomenon

Many possible causes:

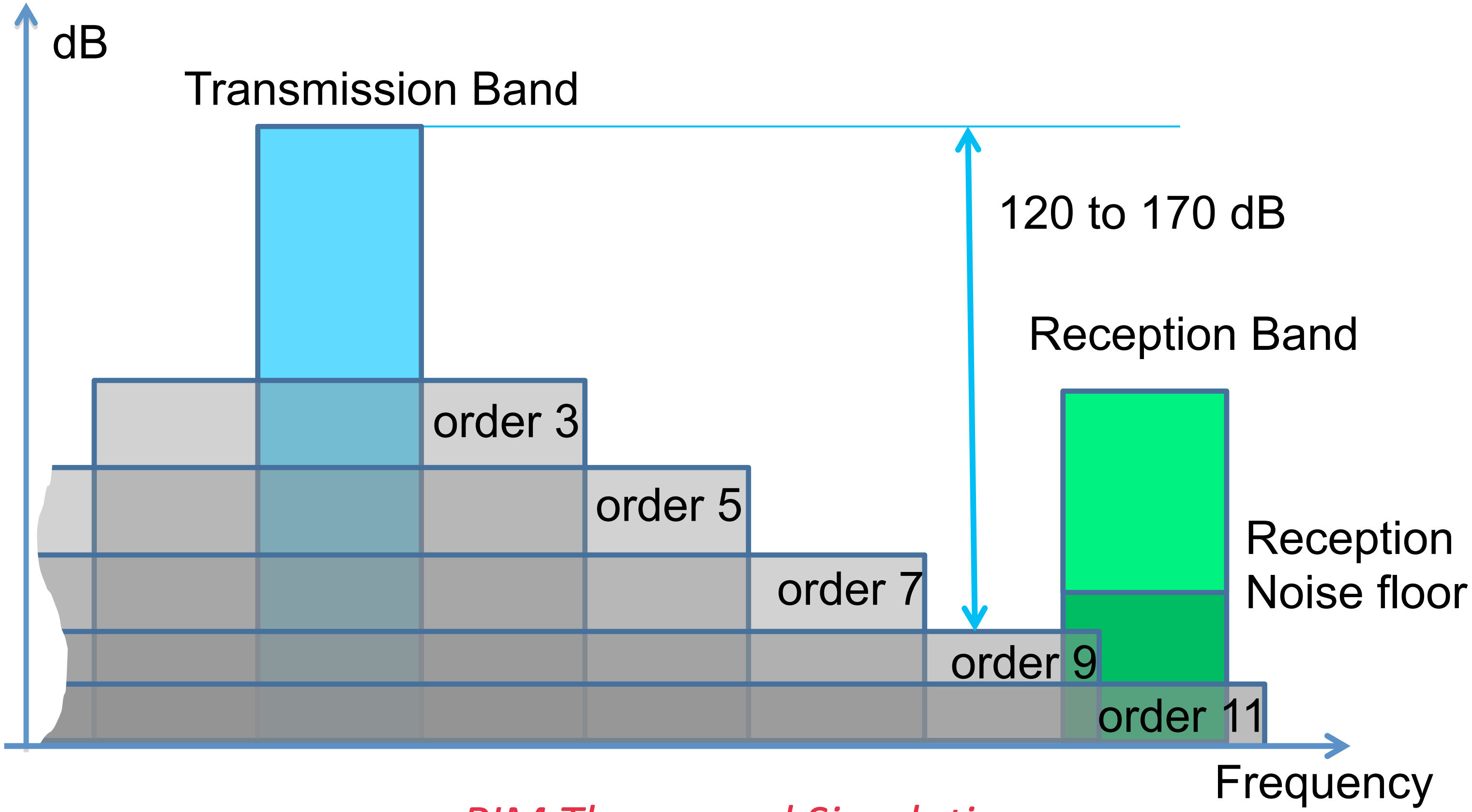
- Temperature variation of conductors:
  Resistance and losses vary with RF power
  - Metal in transmission lines and waveguides
  - Carbon fibers in antenna reflectors
  - Mesh in deployable antenna reflectors
- Non linear contacts:
  - Contacts between different metals
  - Contacts between oxidized metals, “rusty bolt” effect, rusty metallic fence around telephony base station, electrons tunneling across an oxide barrier
- Hysteresis of magnetic elements

Memory effect in addition to the non linearity effect

Odd order IM products

Bandwidth much smaller than Tx/Rx frequency separation:

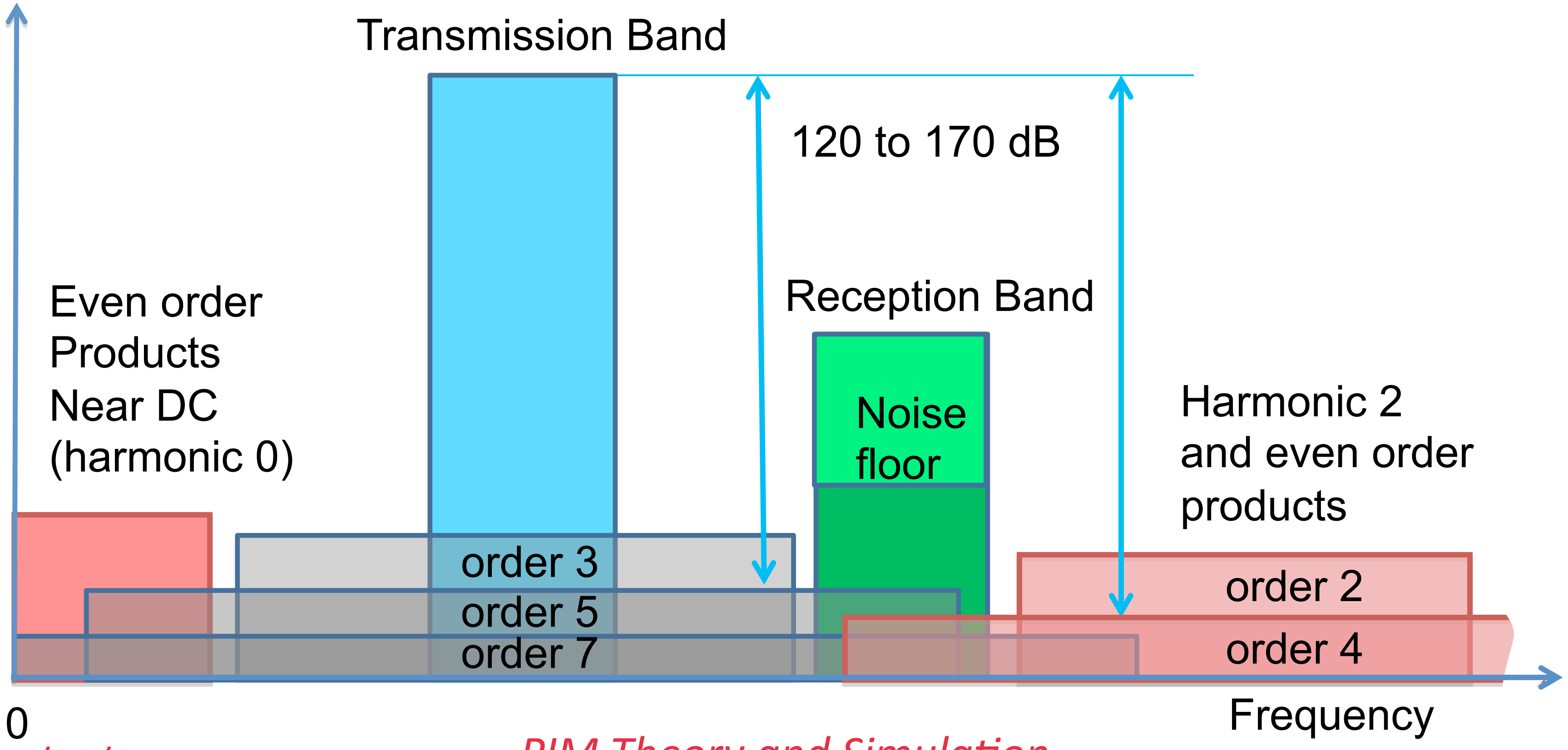
Problem with high order odd IM products only



Even order IM products

Bandwidth comparable to Tx/Rx separation:
Problem with low order IM products

Tx/Rx separation comparable to center frequency:
Problem with even IM products around second harmonic



Consequences of PIM

- First unavoidable consequence: PIM will increase noise power in the receiver and decrease the Signal-to-Noise ratio and the channel capacity
- Specifications to keep this increase very low or non-measurable are stringent:
  - Less than 0.1 dB = PIM 17 dB under the receiver noise floor
- Otherwise, channels in the receiver could be desensitized (noise higher than specified) or even non functional or some transmitter channels should be switched off
- In the worst case, a large part of the payload may be non functional

Mitigation of PIM generation

- Evident but bulky and costly: use separate antennas and low loss transmission lines for transmit and for receive, low coupling between antennas (direct or through objects in near coverage)
- Improvement of all high RF power contacts by using high pressure (small contact surface)
- Use of identical metals, soldering or conductive glue
- No ferromagnetic materials
- No loose lossy small particles (variable temperature and loss)
- Removing unnecessary elements from the transmitted EM field
- Elimination of rust and generally oxidization
- Periodical maintenance measurements of PIM on telephony base station (measuring equipment gives distance to fault)

Differences between active and passive IM

- Active IM products are measured with around 70 dB dynamic, this is sufficient because they will be filtered at the output of the amplifier
- Passive IM products in the receive bandwidth cannot be filtered and must be measured with 120 to 170 dB dynamic
- Much more complex test bench with filters, duplexers and low PIM connectors
- Measured behavior as a function of RF power at this high dynamic is different from what can be explained with models used for active IM products simulation
- So, a broader theory is needed

Classical theory of IM products

- Output currents, voltages or EM fields are given by a non-linear function of input currents, voltages or EM fields

$$Vout = f(Vin)$$

- The non-linear function is analytical in the mathematical sense, meaning that it is continuous and continuously derivable to all orders and it can be approximated by its Taylor development at any point
- Generally it is replaced by a polynomial or an integer series

$$Vout = a_0 + a_1 Vin + a_2 Vin^2 + a_3 Vin^3 + \cdots$$

See in bibliography: Brockbank, Wass, Blachman, Westcott, Cox, Saleh

Chebyshev transform (Blachman)

- When the input variable is a cosine, the output is:

$$V_{out} = f(V_{in}) = f\left[a\cos(\theta)\right] = \frac{1}{2} f_0(a) + \sum_{m=1}^{\infty} f_m(a).\cos(m\theta)$$

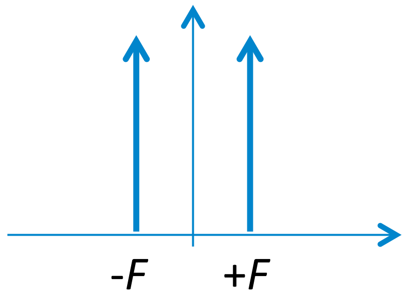
- The *m*th harmonic is given by the Chebyshev transform of order *m* of function *f*:

$$f_m(a) = \frac{1}{\pi}\int_{-\pi}^{+\pi} f\left[a\cos(\theta)\right]\cos(m\theta)d\theta$$

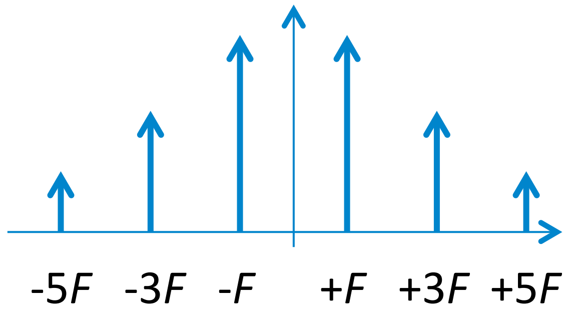
- For a polynomial term: $f(u) = u^n$
- The Chebyshev transform is also a polynomial term:

$$f_m(a) = \frac{1}{\pi}\int_{-\pi}^{+\pi}\left[a\cos(\theta)\right]^n \cos(m\theta)d\theta = 2\left(\frac{a}{2}\right)^n \frac{n!}{\left(\frac{n+m}{2}\right)!\left(\frac{n-m}{2}\right)!}$$

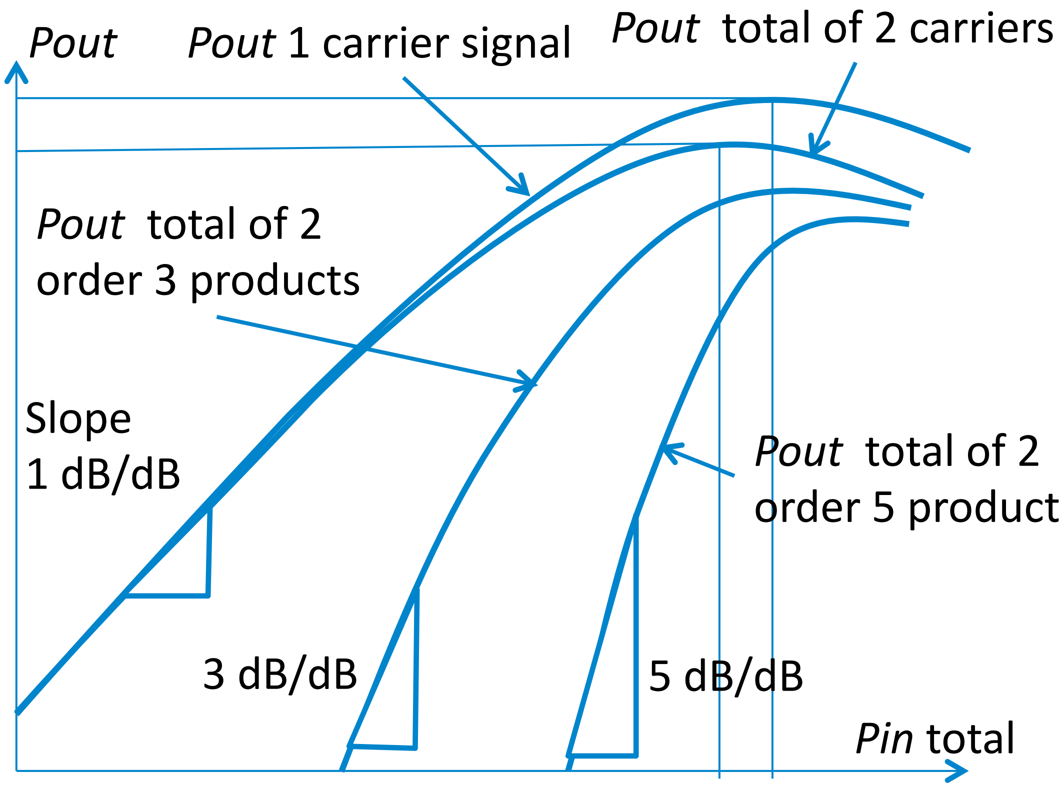
Small signal behavior of active IM



Input Spectrum, 2 carriers



Output Spectrum



“Well known result: IM power versus input power small signal slope in dB/dB = order”

True only for an analytical function (i.e. equal to its Taylor development) having a non zero coefficient for term of degree equal to the order

Published measurement

- Classical models have not been able to represent correctly the behavior of passive intermodulation products when the RF carrier power changes even in a range limited to some dBs
- Measured slopes of IM power as a function of RF carrier power may vary from 1.1 to 2.9 dB/dB instead of 3 dB/dB for 3rd order IM, 5 dB/dB for 5th order and so on.
- All IM orders vary with approximately the same slope giving a nearly constant ratio between different orders
- This is generally the case in all the measurement range of carrier power, extending up to 30 dB in some cases
- We examined published material and particularly measurement papers in order to find evidence (pros and cons) and possibly reasons for this different behavior
- The most typical measurements are presented and compared

Reference [1]   1976

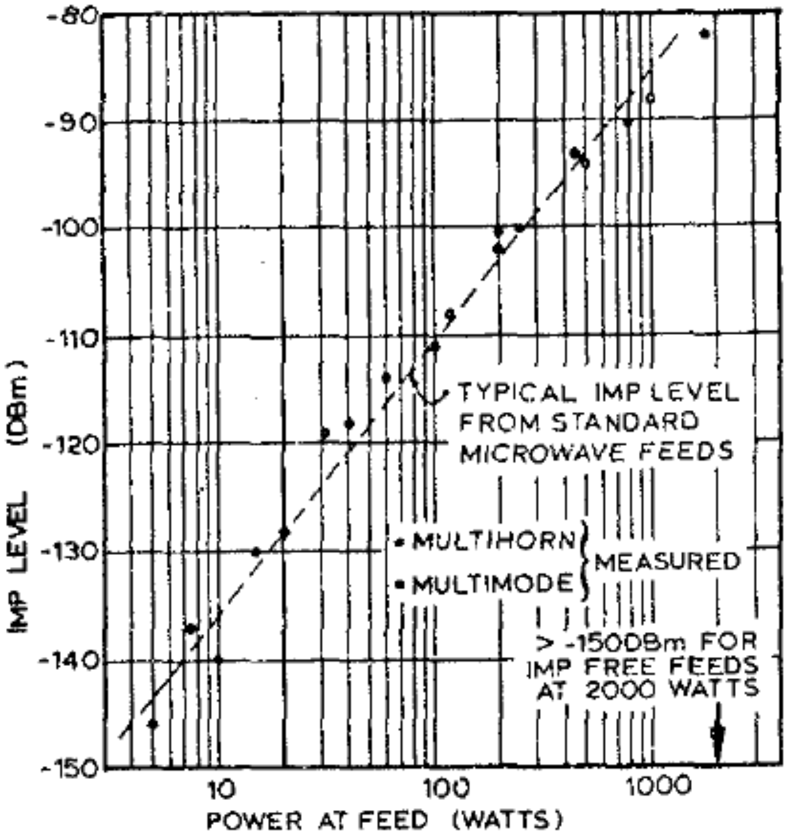


FIGURE 2 IMP LEVELS FROM TYPICAL STANDARD MICROWAVE FEEDS

First publication on 3rd order PIM slopes different from 3 dB/dB: 2.3 and 2.5 dB/dB

Chapman, Rootsey, Polidi and Davison

“Hidden threat multicarrier passive component IM generation”,

AIAA 6th Communications Satellite Systems Conference, April 1976, Montreal, Canada, pp. 296/ 1-9

Cites internal reports on PIM from Lincoln Experimental Satellite 5 in 1968, unexplained measured PIM slopes in FLTSATCOM in 1974 and published measurements of contact PIMs in 1970-1974

Reference [1] 1976

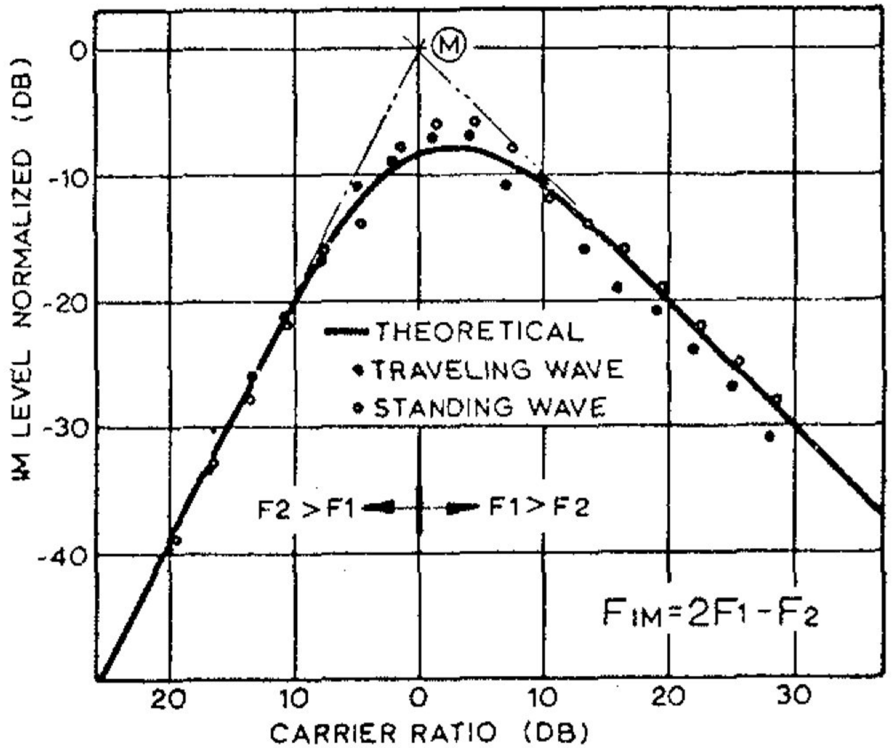
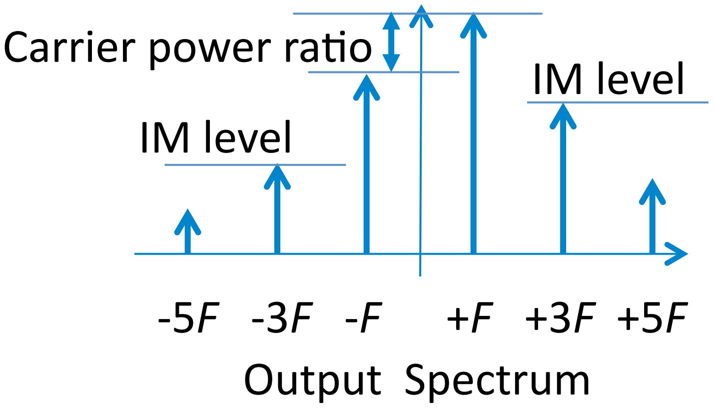


FIGURE 4 COMPARISON OF MEASURED & THEORETICAL RESPONSES



The behavior of 2-carrier third order products at fixed total carrier power as a function of power ratio between carriers (1 dB/dB and 2 dB/dB slopes) is presented as a “proof” that the degree is 3 even if the slope as a function of total power is not 3 dB/dB

It proves only that the measured product is at frequency:
either ② f1 – ① f2
or ② f2 – ① f1

References [1] 1976

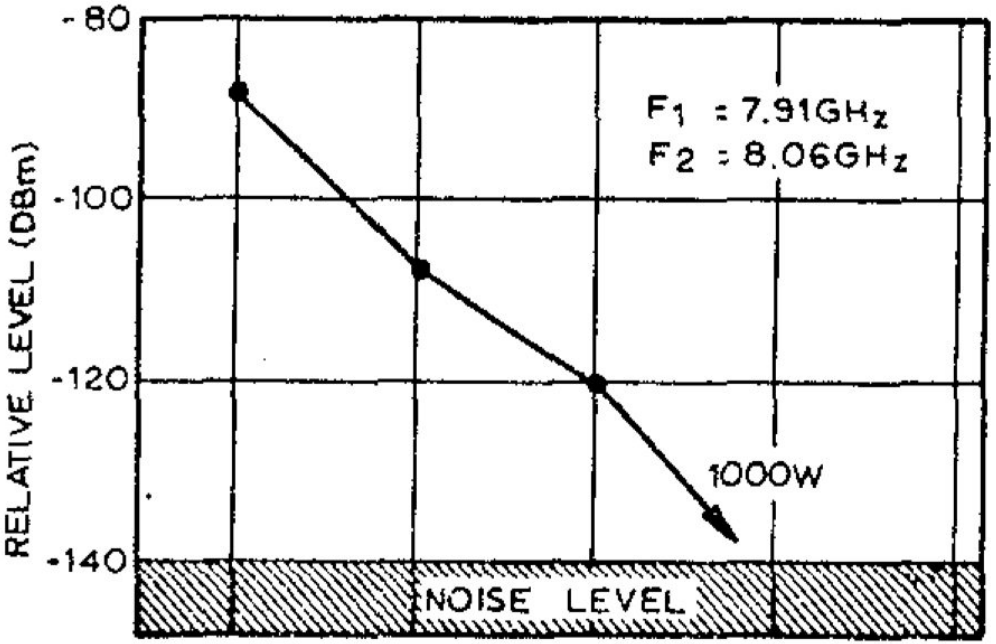


FIGURE 5 RELATIVE LEVELS OF HIGH ORDER IMP's

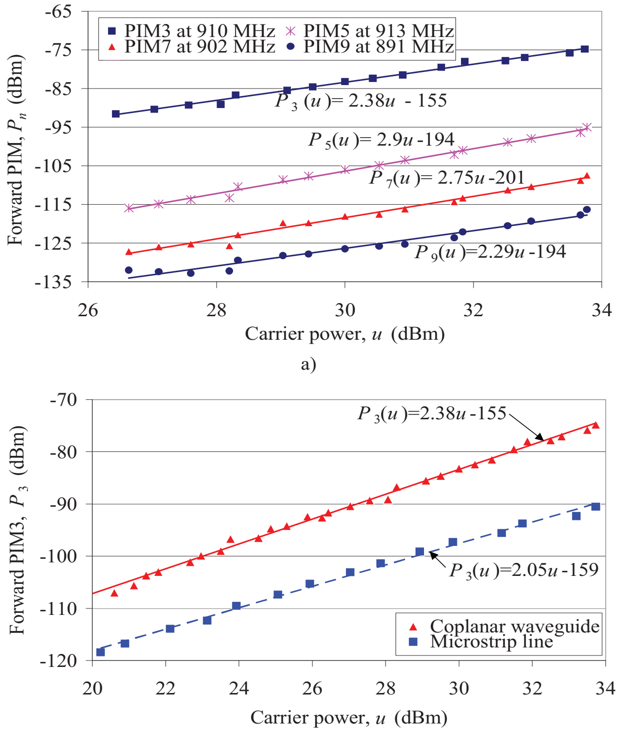
Generally monotonic decrease of PIM power as a function of order

Different for different carrier powers because 5th order has a 4 dB/dB slope instead of 2.5 dB/dB (like 3rd order)

Important result is that the power ratio between 2 successive orders is low, around 15 to 25 dB instead of around the same value as the ratio between carrier and 3rd order IM: C/IM3

Reference [2] 2009

3rd, 5th, 7th and 9th order IM Slopes 1.6 to 2.9 dB/dB



a)

b)

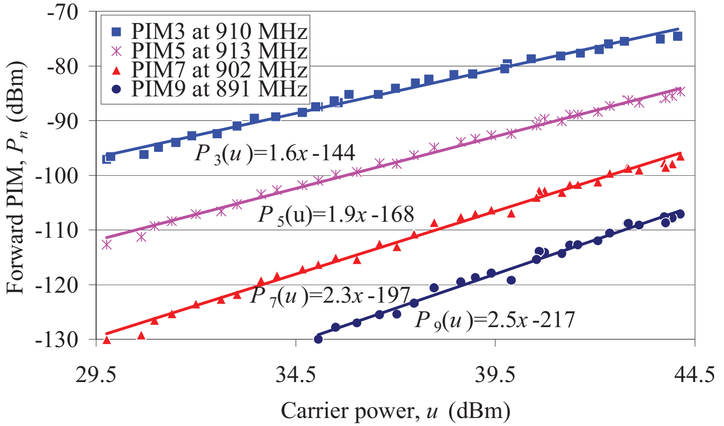
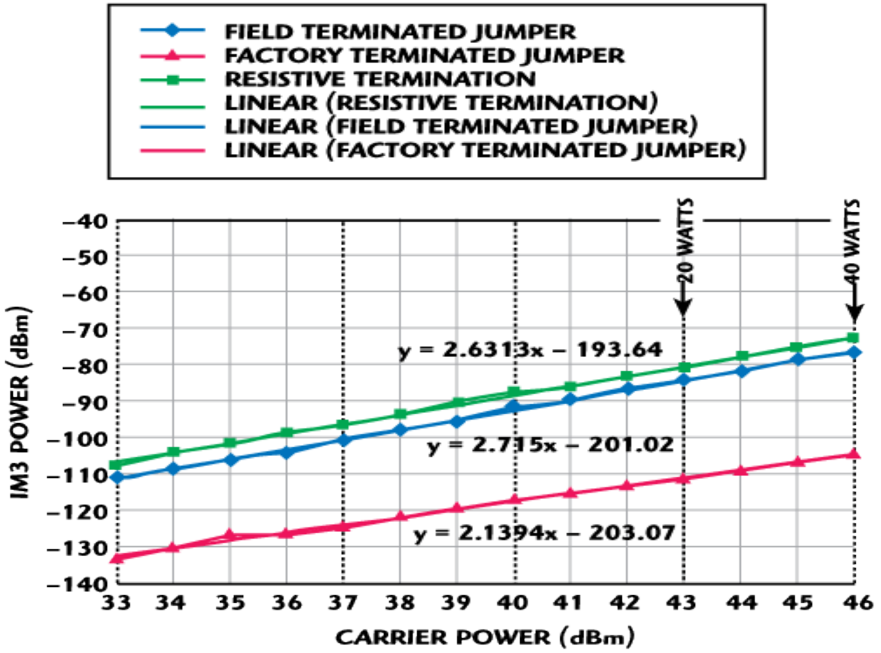


Fig. 4 Measured forward PIM3, PIM5, PIM7 and PIM9 products vs. carrier power on the microstrip line with central section of width *Wc*=7.44 mm with the tapered matching transformers.

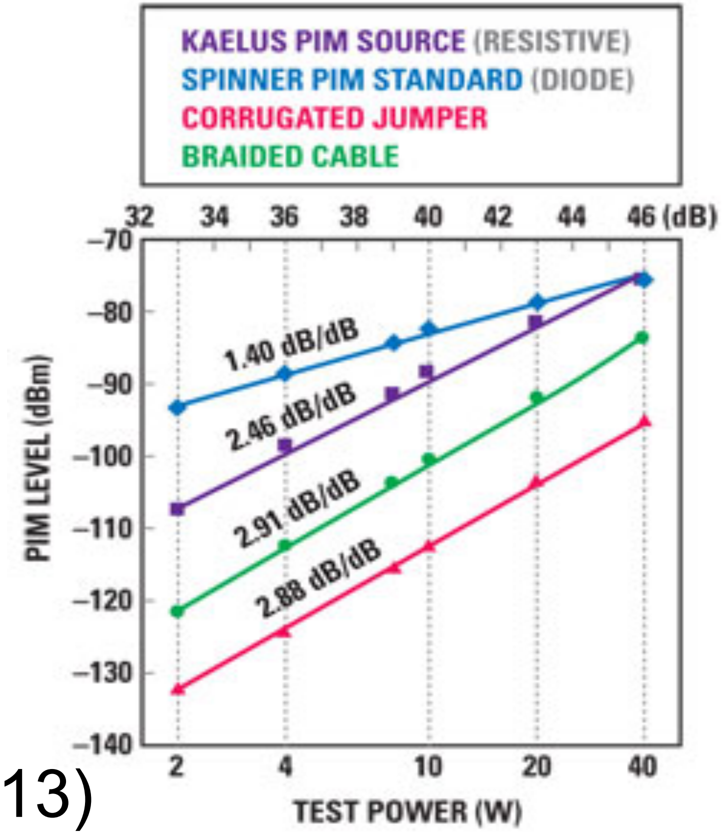
Data used for validation of model

A. Shitvov, D. Zelenchuk, A. Schuchinsky,
"Carrier-Power Dependence of Passive Intermodulation Products in Printed Lines", 2009
Loughborough Antennas & Propagation Conference, 16-17 November 2009, pp. 177-180

Reference [3] 2011 and [4] 2013



Hartman (2011)



Hartman and Bell (2013)

R. Hartman “Passive Intermodulation (PIM) Testing Moves to the Base Station” Microwave Journal , May 11, 2011
R. Hartman and T. Bell “PIM Test Power Levels For Mobile Communication Systems” Microwave Journal , March 15, 2013

Reference [5] 2014

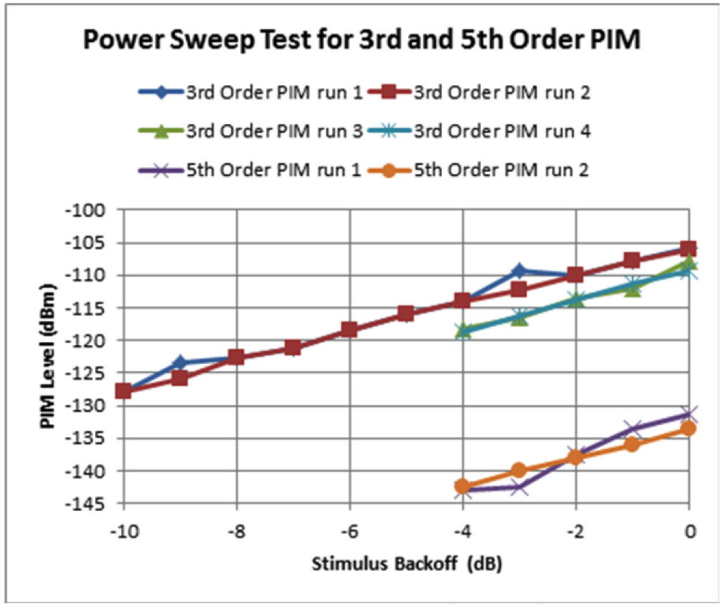


Figure 6. Power Sweep Test for 3rd and 5th Order PIM.

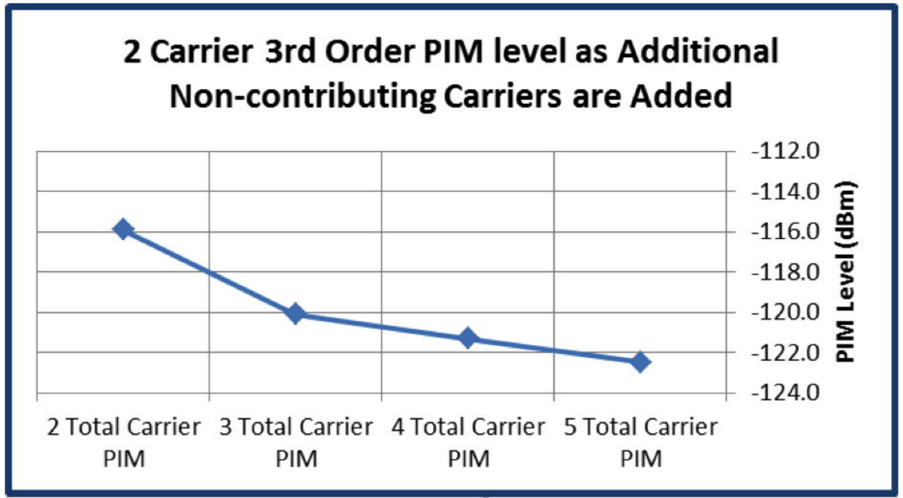


Figure 8. Two Carrier 3rd Order PIM level as Additional Non-Contributing Carriers are Added.

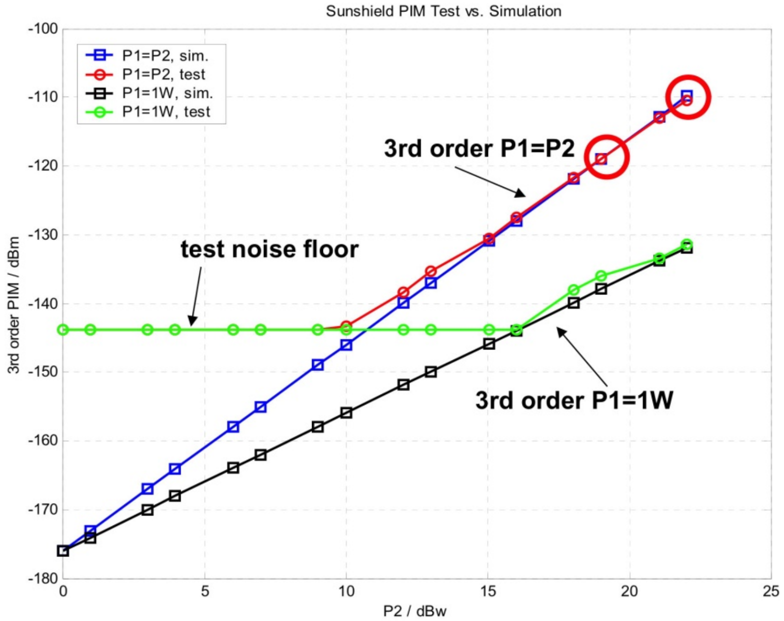
Space System Loral - Same type of results on 3rd and 5th order PIM:

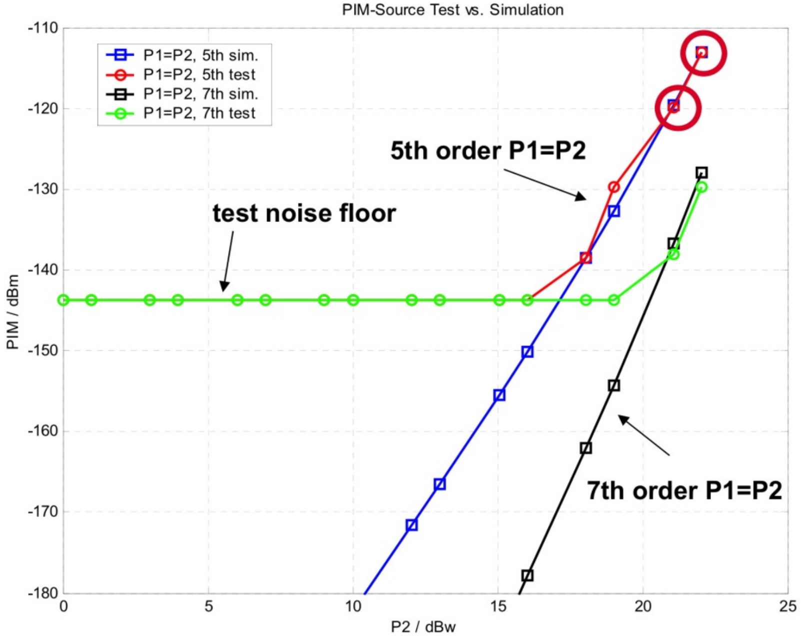
- slope around 2.5 dB/dB
- 20 to 25 dB difference between 3rd and 5th order IM level

Decrease of 3rd order IM level when non-contributing carriers are added

Shayegani, Salmon and Singh, “Multicarrier PIM behavior and testing in communications satellites”, 32nd AIAA ICSSC, 4-7 August 2014, San Diego, CA, USA

Reference [6] 2014



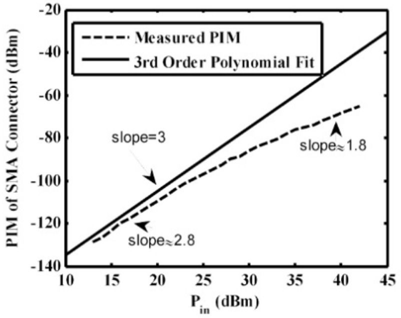


AIRBUS Defense and Space - Same type of results on 3rd, 5th and 7th order PIM:

slope around 2.5 dB/dB,
slope around 2 dB/dB for the smallest IM if 2 carriers with different power (not conclusive)
20 to 25 dB difference between 3rd and 5th order IM level

Un-Pyo Hong, "Analysis and measurement of passive intermodulation for feed components for telecommunication satellites", 8th International Workshop on MULCOPIM, 17-19 September 2014, Valencia, Spain

References [7] 2008 and [8] 2010



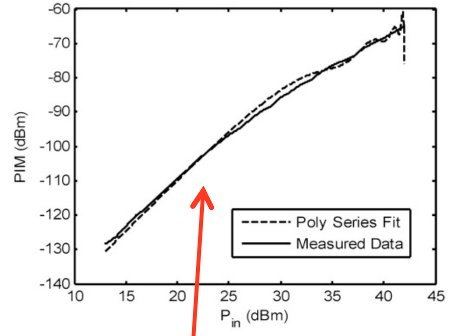
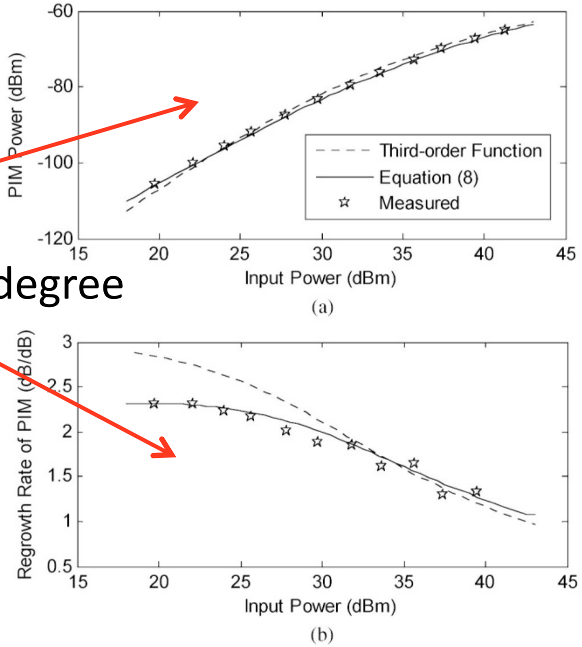
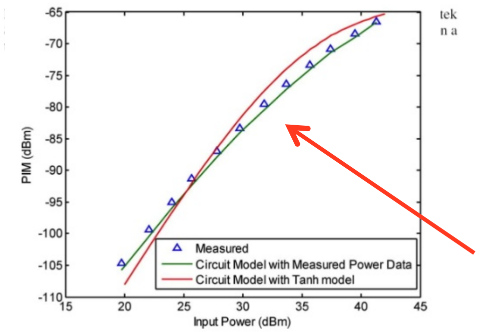


Fig. 10. Measured P_{IP} versus P_{in} curve of an SMA connector under two-tone test, along with a fit provided by a 24-term 49th-order polynomial I–V curve.

Degree 49 polynomial



3-term model,
one of second degree



Hyperbolic tangent model

Slope of 3rd order PIM varying :
from 3 to 5 dB/dB on one sample (electro-thermal effect),
from 2.8 to 1.8 or 2.3 to 1 on other samples (connectors)

Model using a second degree term

Henrie, Christianson and Chappell, “Prediction of passive intermodulation from coaxial connectors in microwave networks”, IEEE Trans. On MTT, Vol. 56, No. 1, January 2008, pp. 209-216

Henrie, Christianson and Chappell, “Linear-nonlinear interaction and passive intermodulation distorsion”, IEEE Trans. On MTT, Vol. 58, No. 5, May 2010, pp. 1230-1237

Reference [9] 2013

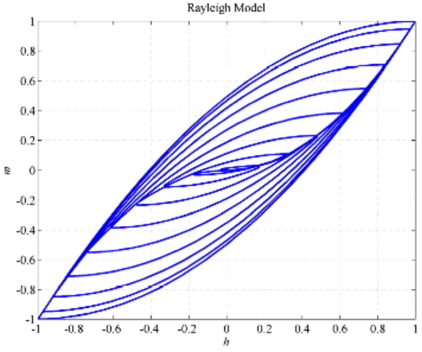


Fig. 3. Response of the nonlinear system

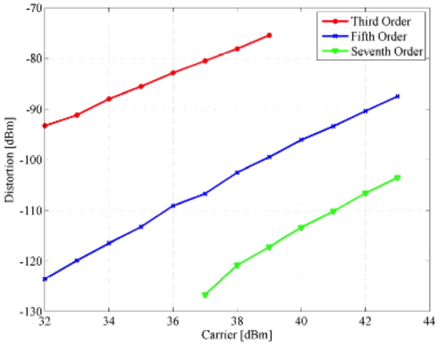


Fig. 7. Third, fifth and seventh order distortion levels versus carriers l
for a 15 cm long line in the 900 MHz frequency band.

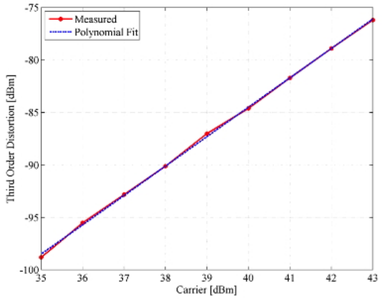


Fig. 6. Third order distortion level versus carriers level for a 23 cm long line in the 1800 MHz frequency band.

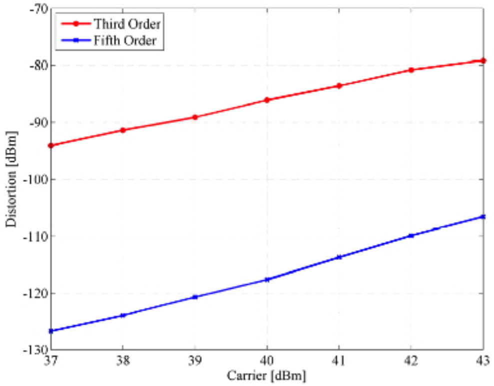


Fig. 8. Third and fifth order distortion levels versus carriers level for a 15 cm long line in the 1800 MHz frequency band.

Measurement on ferromagnetic devices show slopes different from 3 dB/dB also

De Sabata, Ignea, "Passive intermodulation distortions induced by ferromagnetic materials at GSM frequencies", Intl. Symposium on Signals, Circuits and Systems, ISSCS 2013

A. Ignea, A. De Sabata, "Hysteresis Distorsions for Two-Tone Signals", Proc. of 15th IMEKO Symposium on Novelties in Electrical Measurements and Instrumentation, Iaşi, România, pp. 61-63, sept. 2007

Non-analytical behavioral model

- None of the analytical models is able to reproduce the behavior of IM product power as a function of carrier power, only the model with 2nd order term is correct.
- Proposition in 2013 to use a non-analytical model
- Discontinuity of the non-linear “function” (more rigorously a distribution) or of one of its derivatives at origin
- Physically acceptable with some conditions

Sombrin, “Non-analytic at the origin, behavioral models for active or passive non-linearity”, International Journal of Microwave and Wireless Technologies, 2013, 5(2), pp. 133–140.

Sombrin, Soubercaze-Pun, Albert, “New models for passive non linearities generating intermodulation products with non-integer slopes”, EuCAP 2013, Gotegorg, Sweden

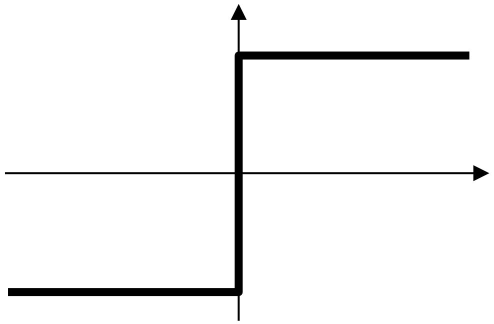
Sombrin, Soubercaze-Pun, Albert, “Modélisation et prédiction des produits d’intermodulation passifs”, JNM 2013, Paris

Sombrin, Soubercaze-Pun, Albert, “Discontinuity at origin in Volterra and band-pass limited models”, IMS 2013, Seatle, USA

Simple non-analytical models

Ideal relay or Schmidt trigger:

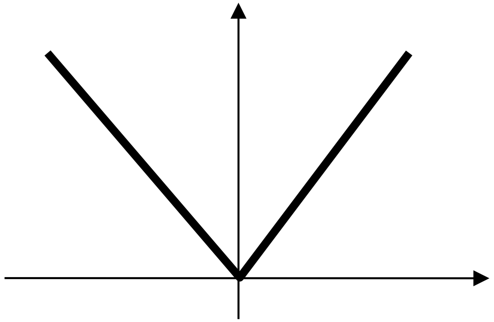
$$y = \operatorname{sign}(x)$$



Constant output:
Slope = 0 dB/dB

Full-wave rectifier:

$$y = |x| = \operatorname{sign}(x).x$$



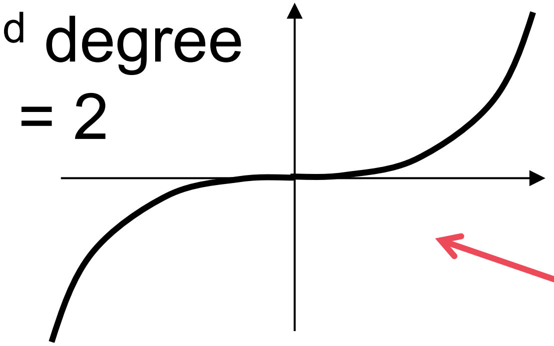
Proportional output:
Slope = 1 dB/dB

No Taylor development at origin

Symbolic computation or simulation possible anyway

First generalization of model

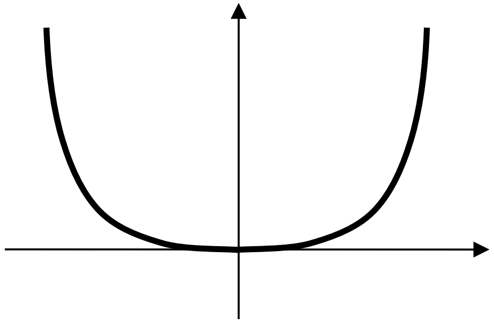
Odd function
of 2nd degree
for $p = 2$



$$y = \text{sign}(x).x^p$$

Parity is opposite to degree p parity

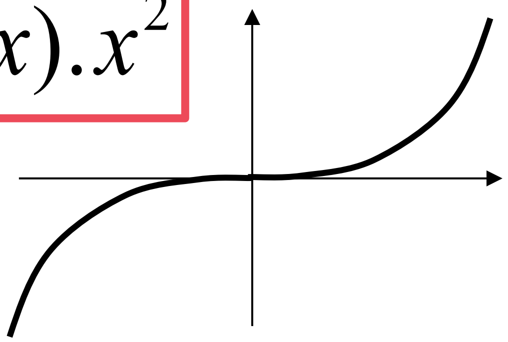
Even function
of 3rd degree
for $p = 3$

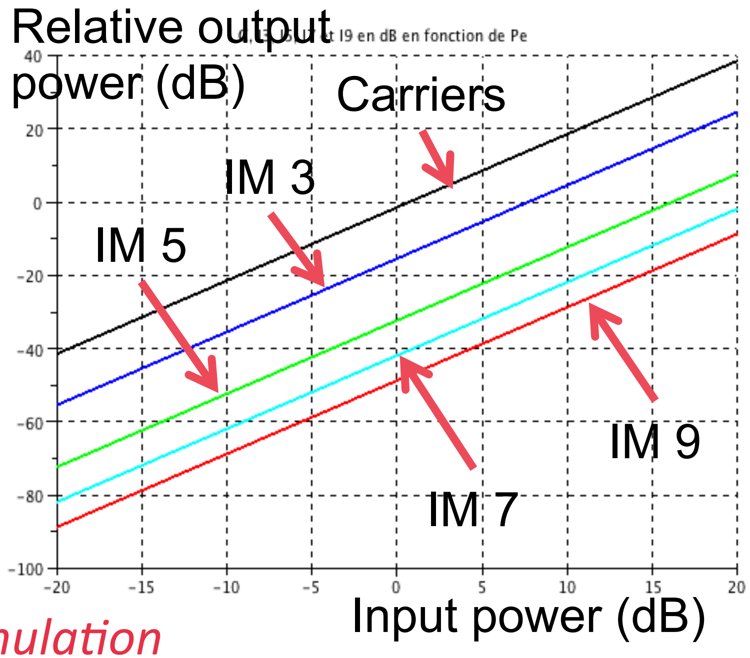


Mix of even and odd functions is possible as for polynomials

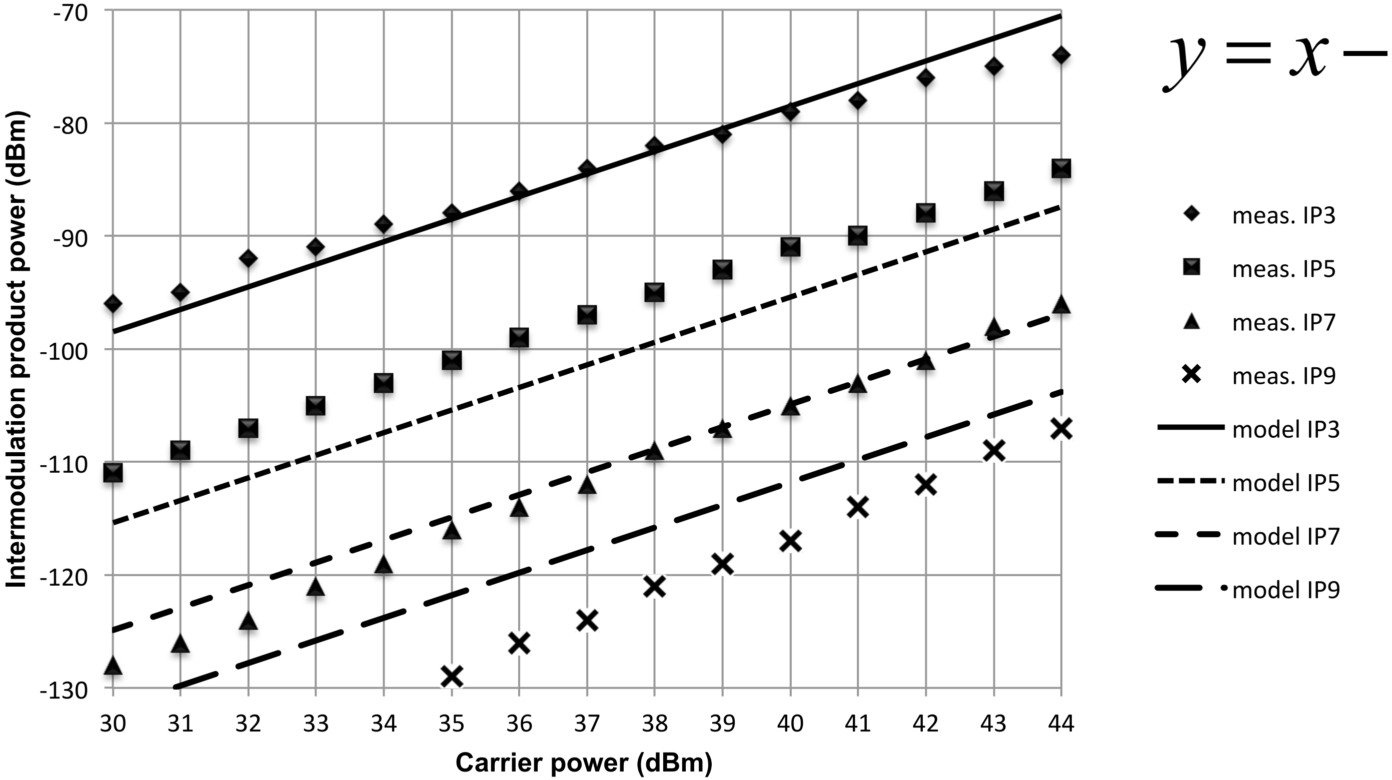
Simulation with a non-analytical model

- Example: p = 2 → $\boxed{y = \mathrm{sign}(x).x^2}$
- Generates all odd harmonics (carriers included)
- Odd IM slopes = 2 dB/dB
- All successive IM ratios are constant:
  - I3/I5 = 17 dB, …
  - With a linear term, C slope would be 1 dB/dB and C/I slopes would be -1 dB/dB





Comparison with measurements



$$y = x - \alpha \cdot \mathrm{sign}(x) \cdot x^2$$

Measurement taken from reference [2]

Simulation

- Coefficient α has been chosen for best fit with 3rd order IM
- Approximate values for higher orders IM obtained

General non-analytical models

Odd functions: $y = \mathrm{sign}(x).|x|^p = x \cdot |x|^{p-1}$

Even functions: $y = |x|^p \quad \text{or} \quad y = x^2 \cdot |x|^{p-2}$

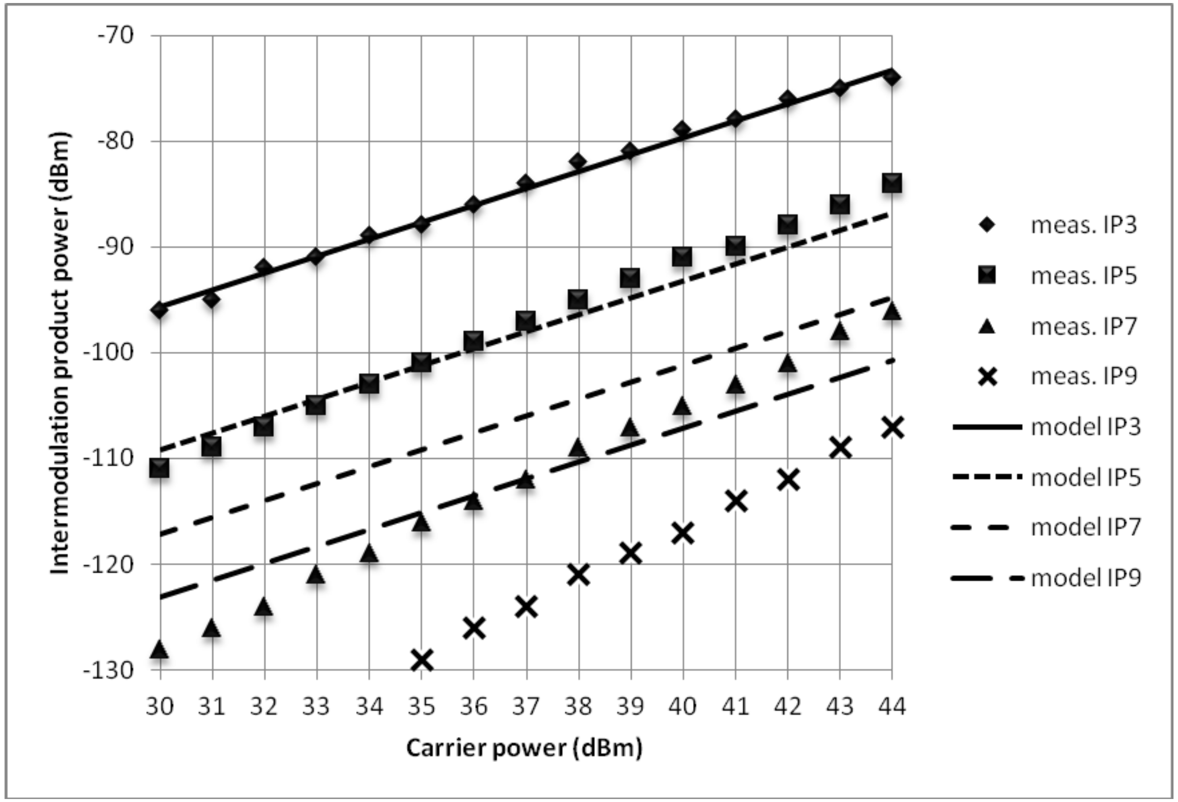
Parity (symmetry or anti-symmetry) of these functions does not depend on the parity of the degree *p*

We may use non-integer degrees *p* provided that:

- Degree *p* ≥ -1 for mathematical convergence
- Degree *p* ≥ 0 for active equipment, finite output for finite input
- Degree p ≥ 1 for passive equipment, output power ≤ input power
- And saturation of the non-linear term at high power

Polynomials and integer series terms are particular cases of these proposed functions

Non-analytical model of degree 1.6



$$y = x \cdot \left(1 - \alpha |x|^{0,6}\right)$$

Measurement taken from reference [2]

Simulation with non analytical model

- Coefficient α has been chosen for best fit with 3rd order IM
- 5th IM around 13 dB under the 3rd IM

Chebyshev transform

The non-analytic models are invariant by the Chebyshev transforms, just as polynomials terms

Same formulas, replacing factorials with Gamma functions

- For symmetric (even) models and *m* even:

$$f(u) = |u|^n \qquad f_m(a) = 2.\left(\frac{|a|}{2}\right)^n \frac{n!}{\Gamma\left(\frac{n+m}{2}+1\right)\Gamma\left(\frac{n-m}{2}+1\right)}$$

- For anti-symmetric (odd) models and *m* odd:

$$f(u) = sign(u).|u|^n \qquad f_m(a) = 2.sign(a).\left(\frac{|a|}{2}\right)^n \frac{n!}{\Gamma\left(\frac{n+m}{2}+1\right)\Gamma\left(\frac{n-m}{2}+1\right)}$$

Relative level of Harmonics or IM products

- The level of all harmonics or IM products coming from a single term vary with a slope equal to the degree *p* of the term
- The relative level of two harmonics or two IM products depends only on the degree *p* of the term

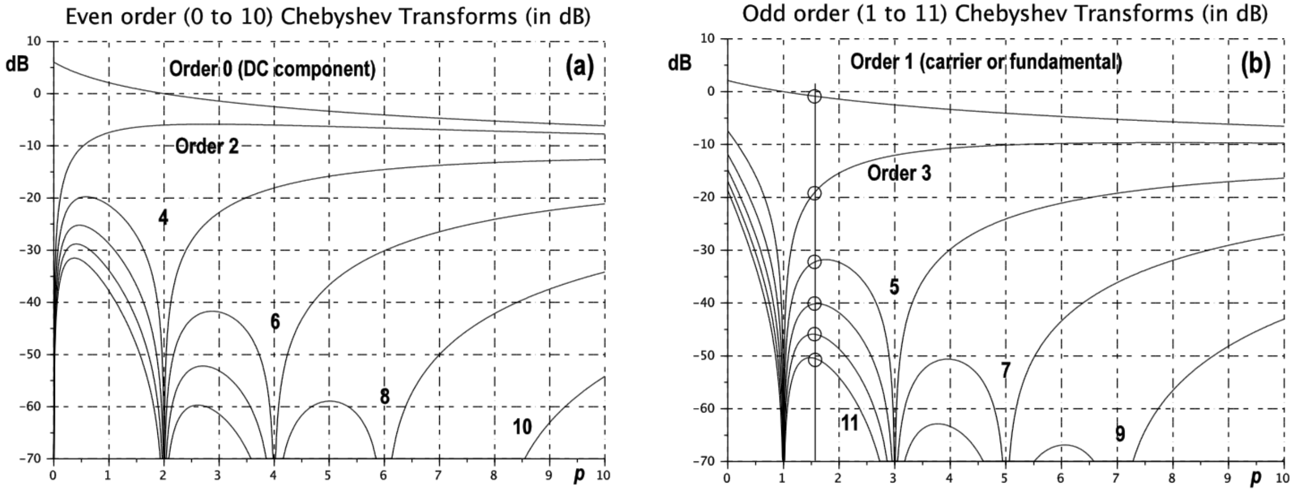


Fig. 2. Harmonics (or products) levels as a function of real exponent p *in power function:*

(a) even order (0 to 10) transforms of even functions of type $f(u) = |u|^p$

(b) odd order (1 to 11) transforms of odd functions of type $f(u) = sign(u).|u|^p$

Tips on complex enveloppe simulation

Carriers and in-band IM (fundamental or zone 1): $y = x \cdot g_1(|x|)$

DC components (zone 0): $y = g_0(|x|)$

Second harmonic components (zone 2): $y = x^2 \cdot g_2(|x|)$

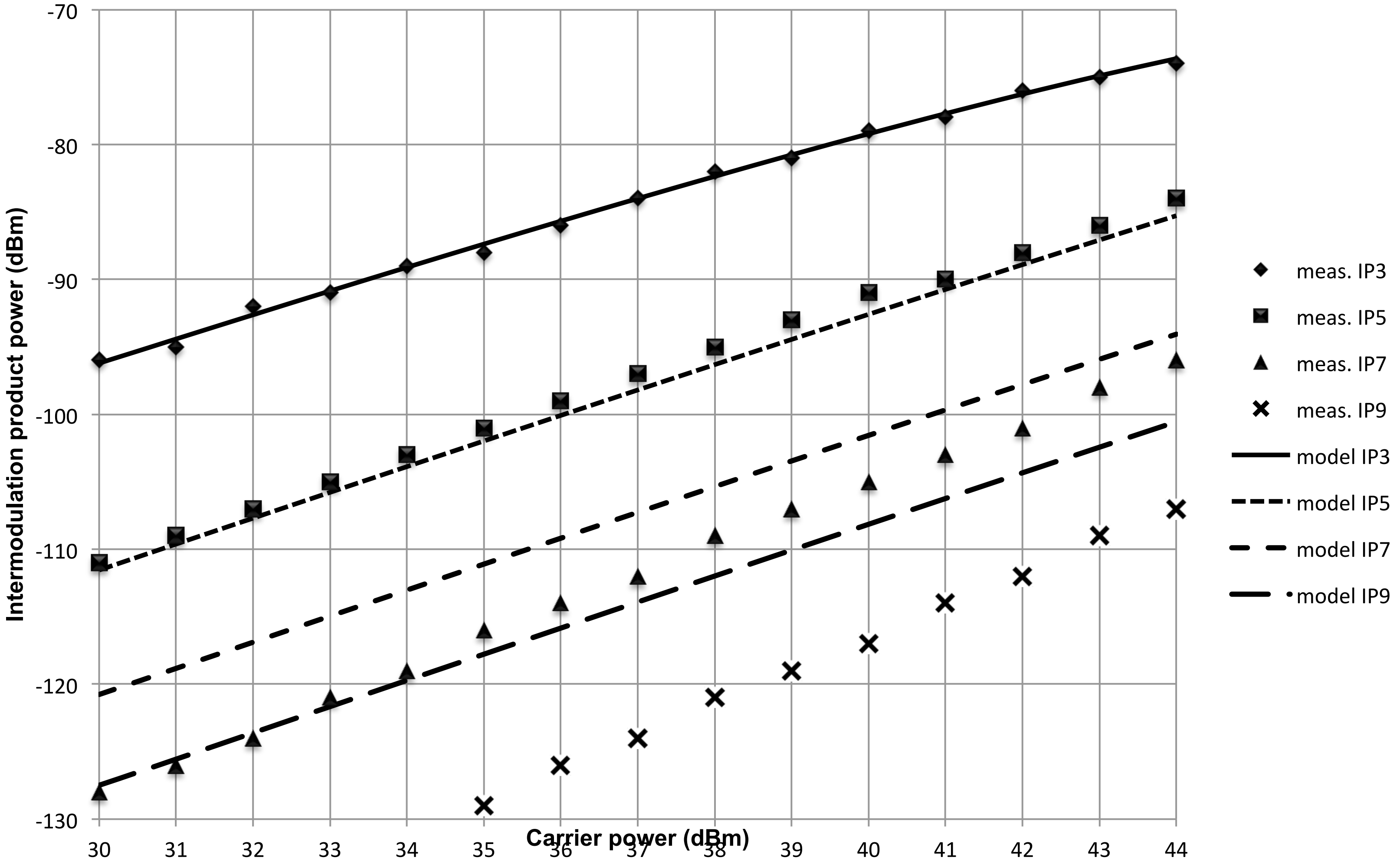
Non-linear non-analytic gain functions *g* can be computed from the square of the complex envelope of bandwidth limited input signal

$$\tilde{y} = \tilde{x} \cdot g_1\left(\sqrt{|\tilde{x}|^2}\right)$$

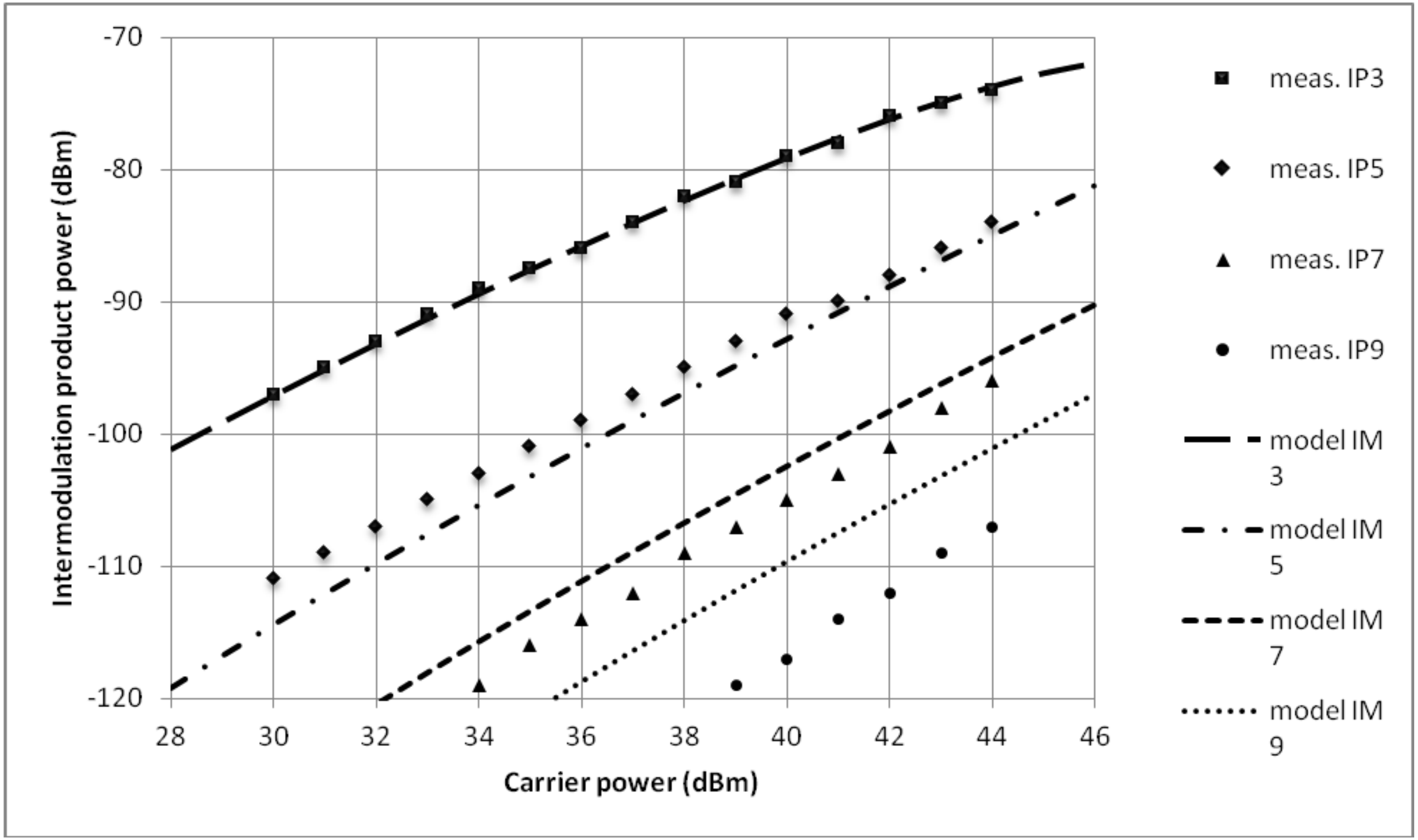
$$\tilde{y} = g_0\left(\sqrt{|\tilde{x}|^2}\right)$$

$$\tilde{y} = \tilde{x}^2 \cdot g_2\left(\sqrt{|\tilde{x}|^2}\right)$$

Non-analytical model with 2 terms of degrees 2 and 2.5



Non-analytical model with 3 terms of degrees 1.5, 2 and 2.5



Simulation with multi-carrier signal

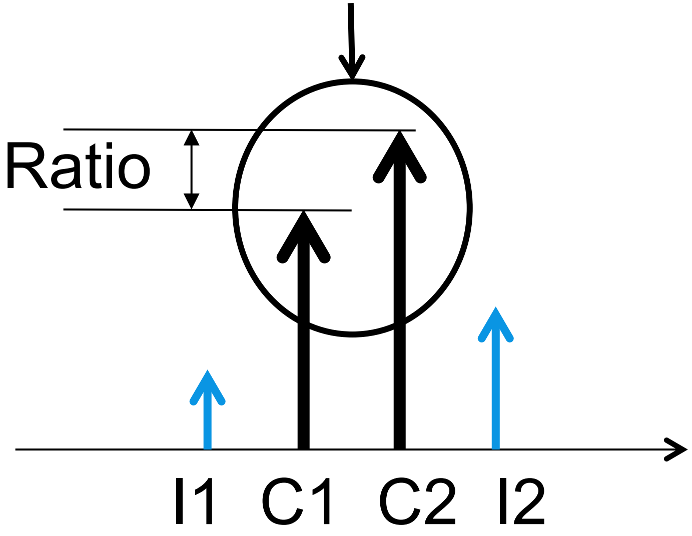
Many accepted results are valid only for degree 3

- If carrier power increases by *X* dB, 3rd order IM increase by 3*X* dB (true only if slope is 3 dB/dB)
- In a given multi-carrier signal, 3-carrier 3rd order IM at frequency (f1+f2-f3) are 6 dB higher than 2-carrier 3rd order IM at frequency (2f1-f2)
- When adding carriers, (e.g. going from 2-carrier to 3-carrier, 4-carrier…) and keeping each carrier power constant, existing products do not vary, new products of the same type have the same power

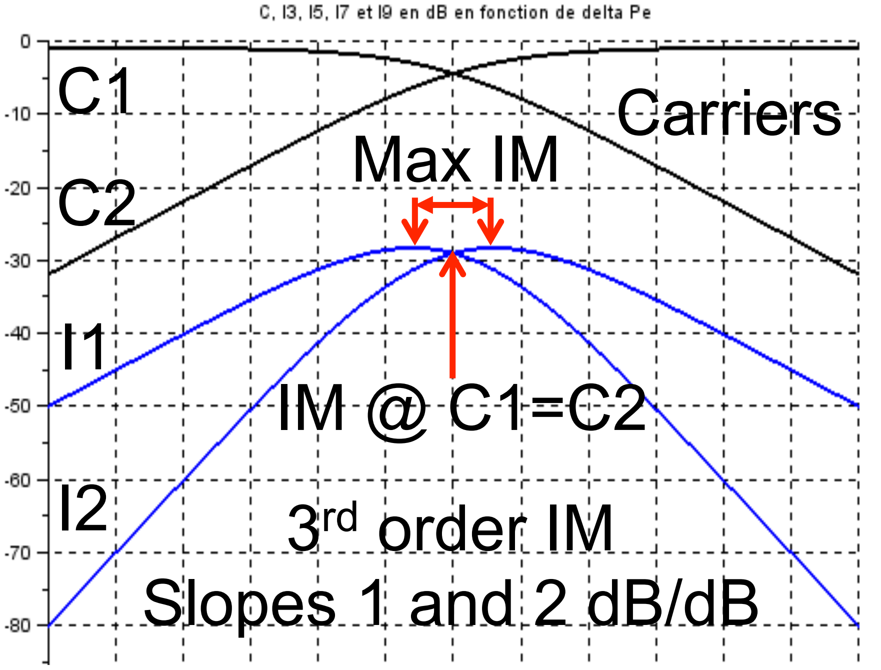
Simulation of 3rd order IM power with two non-equal carriers

Measurement method proposed in [1]
Classical simulation with a 3rd degree polynomial

Total input carrier power = constant



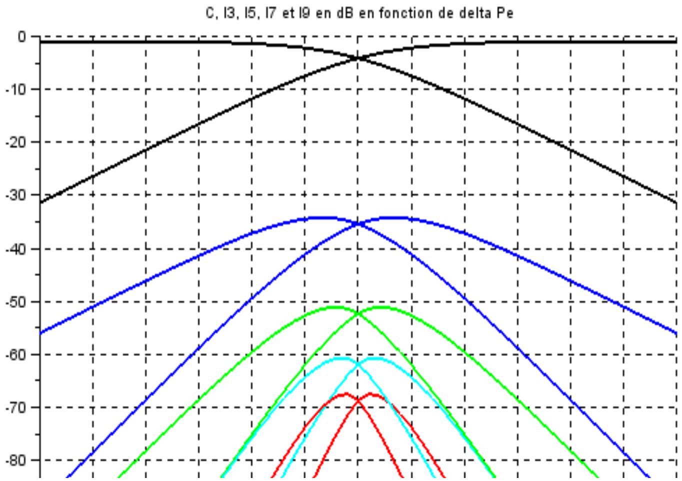
Output spectrum



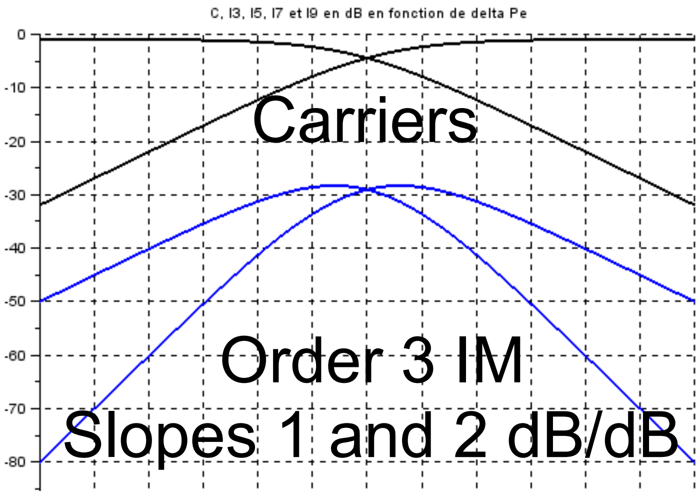
Input ratio in dB (-30 to +30)

Simulation with degrees 2, 3, 4 and 5:

Measurement proposed in [1] is not sensitive enough



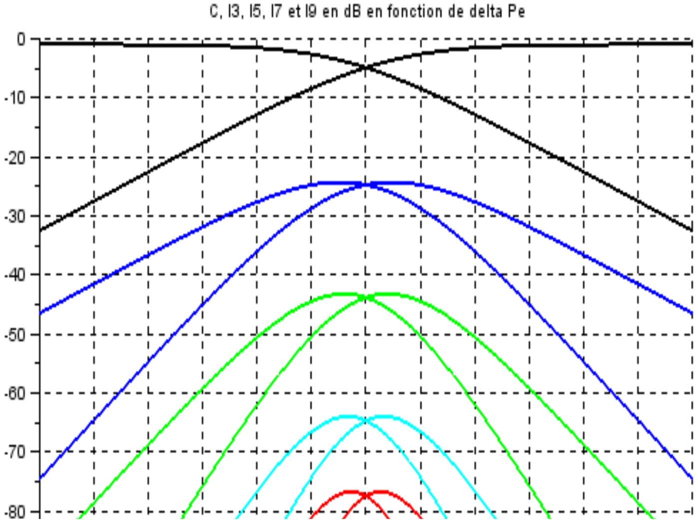
2 3



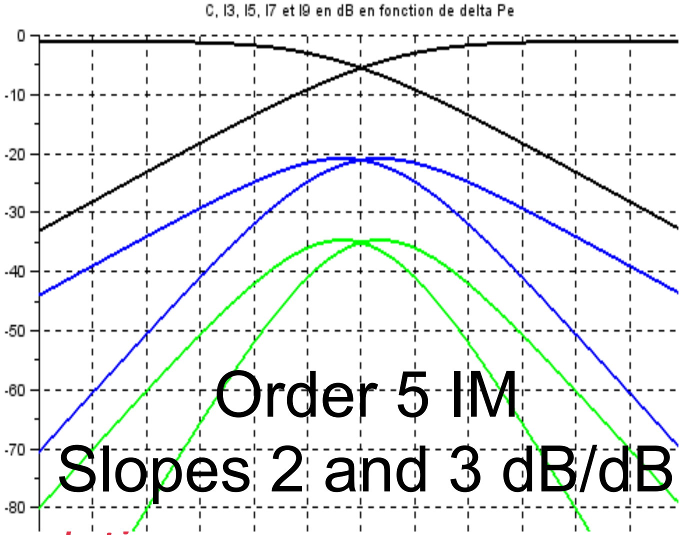
Carriers

Order 3 IM
Slopes 1 and 2 dB/dB

Degree

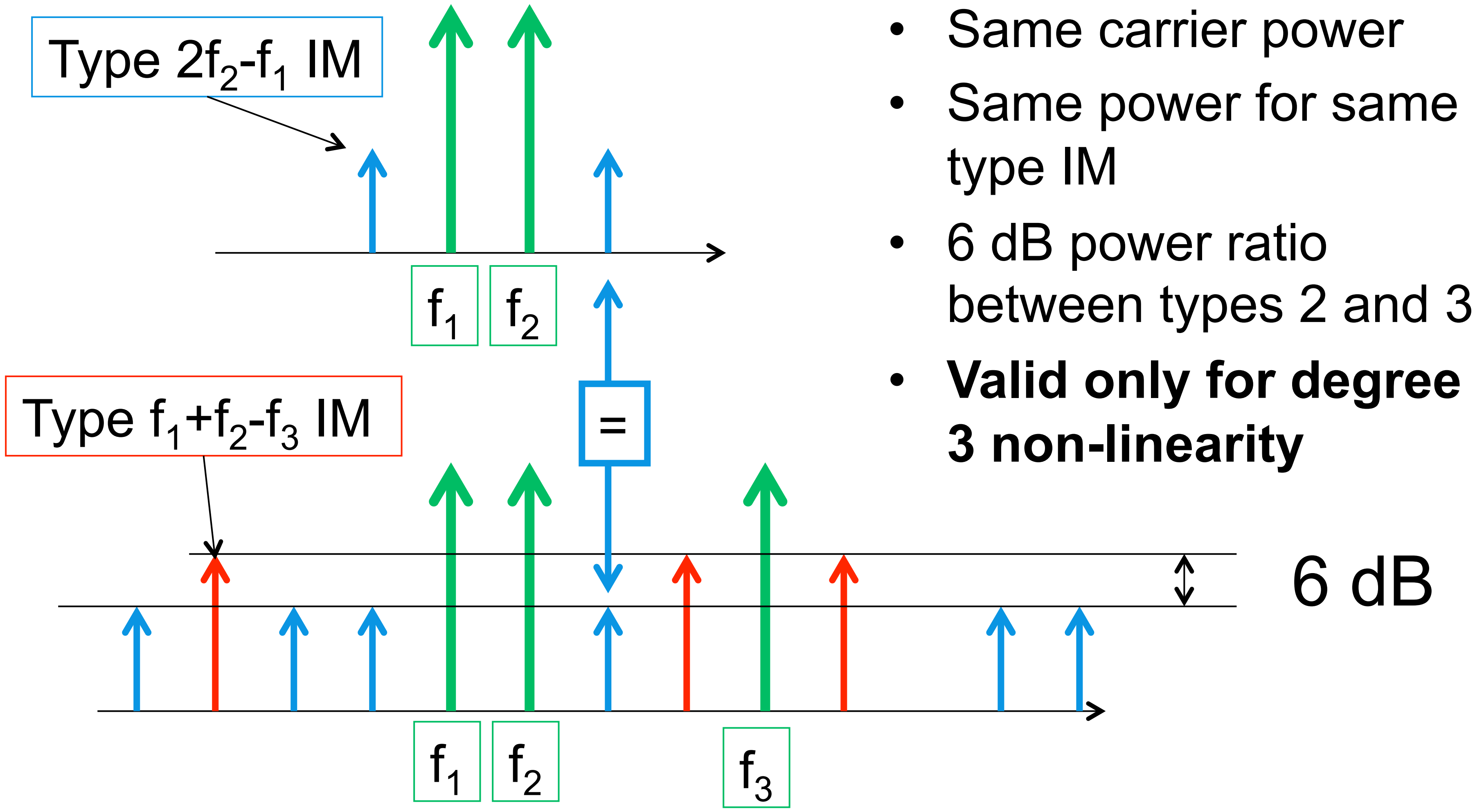


4 5



Order 5 IM
Slopes 2 and 3 dB/dB

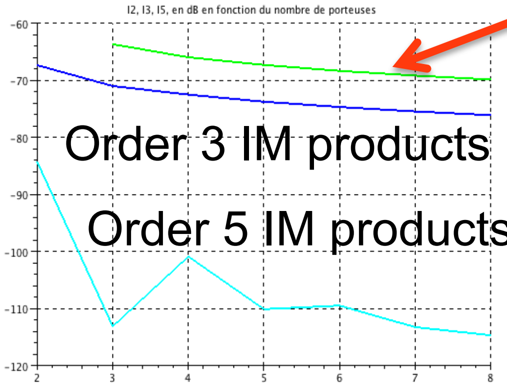
Comparison of 2-carrier and 3-carrier IM



- Same carrier power
- Same power for same type IM
- 6 dB power ratio between types 2 and 3
- **Valid only for degree 3 non-linearity**

Power of 3rd and 5th order IM products versus number of carriers at constant power per carrier

Explains measurement reported by SSL in [5]



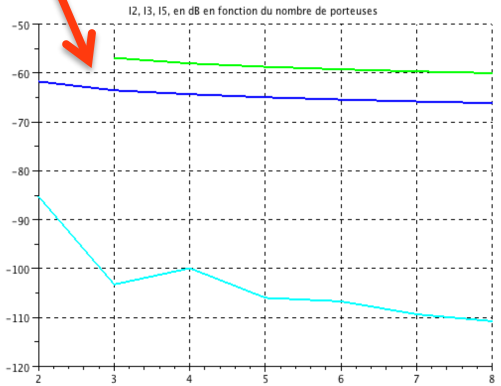
Order 3 IM products

Order 5 IM products

2 3 4 5 6 7 8

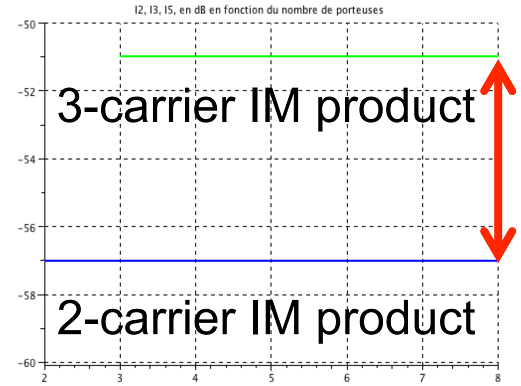
2

2,5



2 3 4 5 6 7 8 carriers

Degree



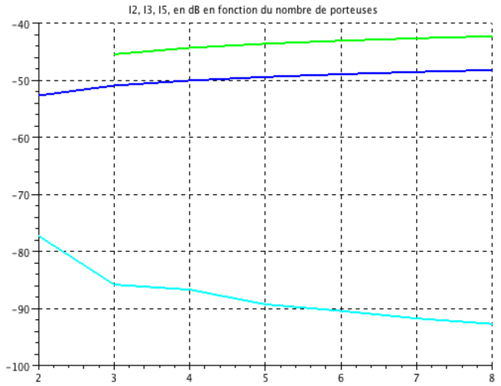
3-carrier IM product

2-carrier IM product

6 dB

3

3,5



Effect on multicarrier IM noise (NPR)

For the same total carrier power, Noise Power Ratio in an 8-carrier signal is lower than the C/I measured on a 2-carrier signal by the following values:

Degree	**1,5**	**2**	**2,5**	**3**	**3,5**	**4**	**5**	**6**	**7**	**8**	**9**
Degradation of NPR versus 2-carrier C/I (dB)	**2,8**	**4,2**	**5,2**	**6,5**	**7**	**9,1**	**12,3**	**15,8**	**19,6**	**23,6**	**27,8**

Note that in a 8-carrier signal the NPR is around 18.5 dB worse than the individual C/I between 2 of the 8 carriers, there is only a small deviation from this value for degrees between 1.5 and 4

Comparison of 2-carrier and multicarrier C/I

For the same power per carrier,
the same 8-carrier C/I is obtained for
a different 2-carrier C/I specification

Degree of NL	2-carrier C/I_3 (dB)	8-carrier C/I_3 (dB) type $2f_1 - f_2$	8-carrier C/I_3 (dB) type $f_1 + f_2 - f_3$	Δ (dB)
1.5	108.3	121.3	115	12.4
2	112.5	121.3	115	8.5
2.5	116.7	121.1	115	4.3
3	121	121	115	Ref.
3.5	125.4	120.9	115	-4.4

Higher order IM must be taken into account in the simulation

Consequences

If you specify a given 2-carrier PIM measurement to obtain the wanted multi-carrier performance using a classical (polynomial) model for the computation of the difference and if the measured slope (in dB/dB) of IM power versus carrier power is lower than 3 dB/dB:

- You have a hidden margin of 4 to 12 dB depending on the value of this slope
  (8 dB margin for 2 dB / dB slope)
- In addition to the known margin that you use (generally around 10 dB because analytical model does not work and the computation is empirical)

You may relax 2-carrier PIM specifications for a given multicarrier performance by decreasing both margins (if you have not already done it empirically)

Conclusion

- Passive intermodulation phenomenon has been presented with measurement and classical theory
- The proposed non-analytical behavioral model allows us to simulate correctly and obtain results comparable to all previously published measurement that cannot be explained with the classical theory
- The use of this type of models to interpret measurement will permit to perform system simulation
- Consequences on predicted PIM power and systems specifications are significant and may permit to use equipment that would be rejected today

Further work

- The theory has been developed for a single memoryless non-linear behavioral model
- Measurement and physics show that the non-linearity
  - has a memory (thermal effects, capacitors across contacts and hysteresis)
  - is distributed along transmission lines, reflectors or other microwave equipment
- More work on measurement and physical models is needed to apply the non-analytical model to a large set of distributed microscopic non-linearity with memory
- Forcing each microscopic non-linearity model to follow the classical theory by restricting it to an analytical function or a polynomial will result in large discrepancies with measurement

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