Digital Predistortion or How to Enhance Linearity by Distorting

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Jornadas "Conoce a los Investigadores de la ETSI"

Outline

- Introduction
  - Basics of Nonlinearity
- Effects of Nonlinearity
- Digital Predistortion and Volterra Series
- International Microwave Symposium Student Design Competition
- Conclusion

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Intro – Basics of Nonlinearity

Signals and Systems 101

General input-output relationship:

$$x(n) \xrightarrow{\mathcal{T}} y(n)$$

General classification

Static vs Dynamic: "A system is called static if its output at any instant n depends at most on the input sample at the same time, but not on past and future samples of the input."

System with memory of duration N: The output of the system at a time n is completely determined by the input samples in the interval from $n - N$.

Memoryless system: $x(n) \xrightarrow{\mathcal{T}} y(n) = f(x(n), n)$

Intro – Basics of Nonlinearity

General classification

Time-Invariant vs Time-Variant:

Time-invariant system: "its input-output characteristics do not change with time"

$$x(n) \xrightarrow{\mathcal{T}} y(n)$$
$$x(n-k) \xrightarrow{\mathcal{T}} y(n-k)$$

Linear versus Nonlinear Systems:

Linear system: "satisfies the superposition principle".

$$\mathcal{T}[a_1 x_1(n) + a_2 x_2(n)] = a_1 \mathcal{T}[y_1(n)] + a_2 \mathcal{T}[y_2(n)]$$

Causal vs Noncausal

Causal system:

$$y(n) = \mathcal{T}[x(n), x(n-1), x(n-2), \dots]$$

Intro – Basics of Nonlinearity

Linear time-invariant (LTI) systems: LTI system theory has many advatanges: analysis with tones, convolution sum, Fourier analysis...

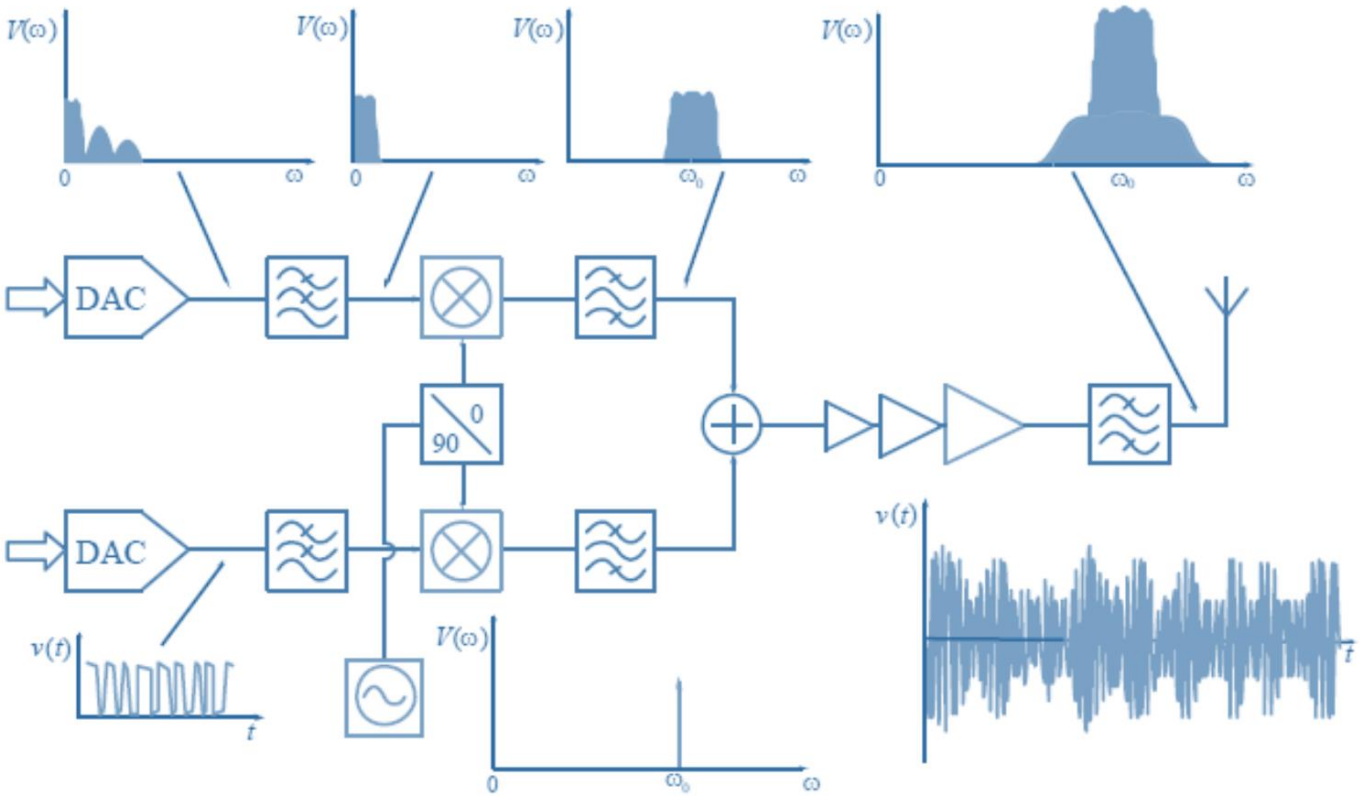
We are dealing with everything else:

Dynamic, Time-Variant, Nonlinear, Noncausal Systems.

What is nonlinearity?

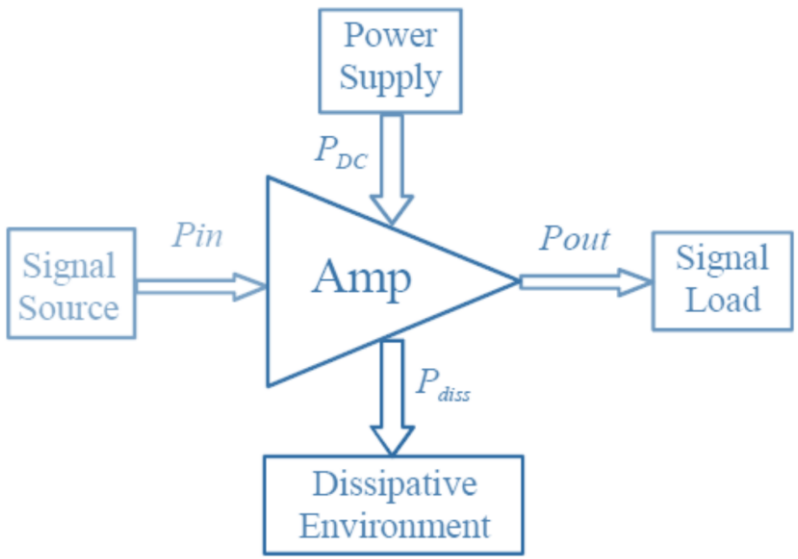
Intro – Nonlinearity in Electronic Circuits

Nonlinearity can be a form of unwanted distortion but it can also be a source of many desired functions.



Wireless communications would not be possible without nonlinearity!

Intro – Nonlinearity in Microwave Circuits



$$P_{out} = G \cdot P_{in}$$

but

$$P_{DC} + P_{in} = P_{diss} + P_{out}$$

and

$$G = \frac{P_{out}}{P_{in}} = 1 + \frac{P_{diss} + P_{DC}}{P_{in}}$$

so

If $P_{in} \uparrow \Rightarrow G \downarrow$

Gain change with input level: Active devices are inherently nonlinear!

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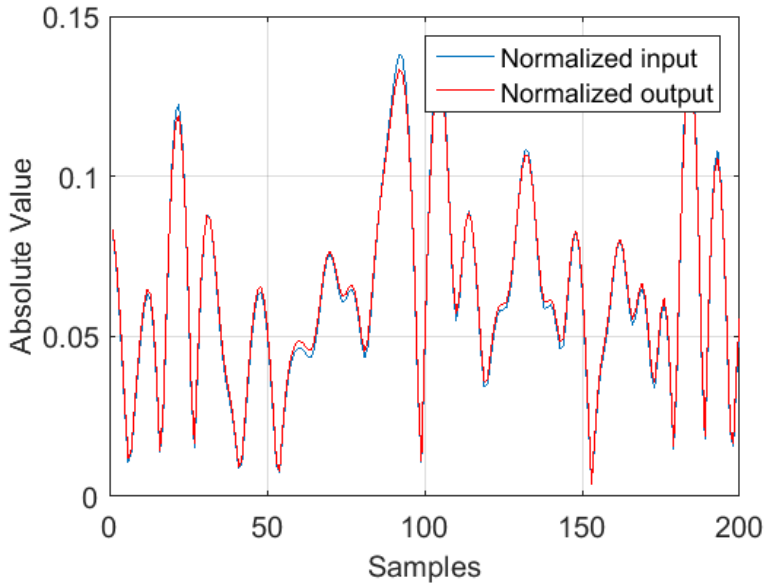
Effects of Nonlinearity – In time

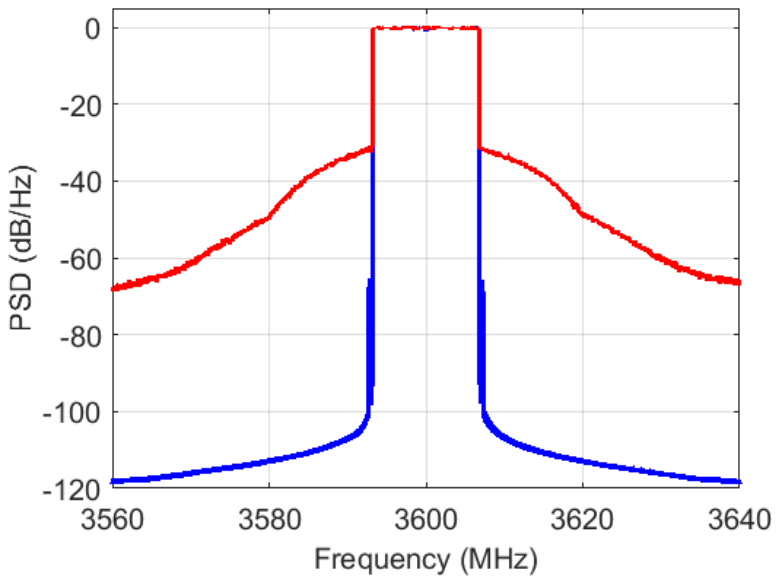


The output is not a scaled version of the input.

Merit figure: Normalized Mean Square Error (NMSE)

$$NMSE(dB) = 20\log\frac{\|y - y_{ref}\|_2}{\|y_{ref}\|_2}$$

Effects of Nonlinearity – In spectrum

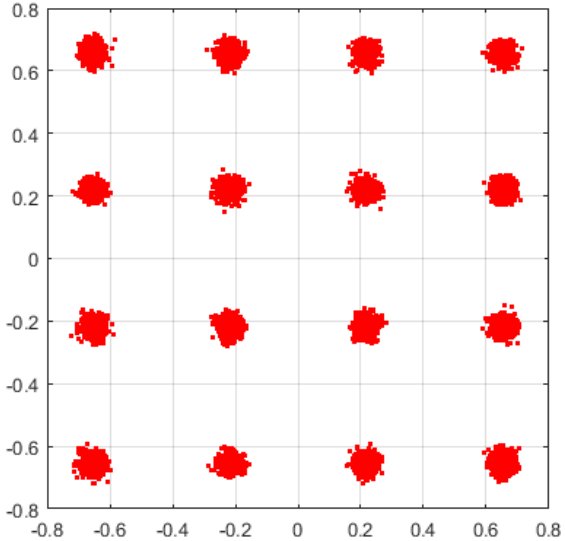


Spectral regrowth and asymmetry

Merit figure: Adjacent Channel Power Ratio

$$ACPR(dBc) = 10\log\frac{P_{band}}{P_{\substack{side\\channel}}}$$

Effects of Nonlinearity – Constellation

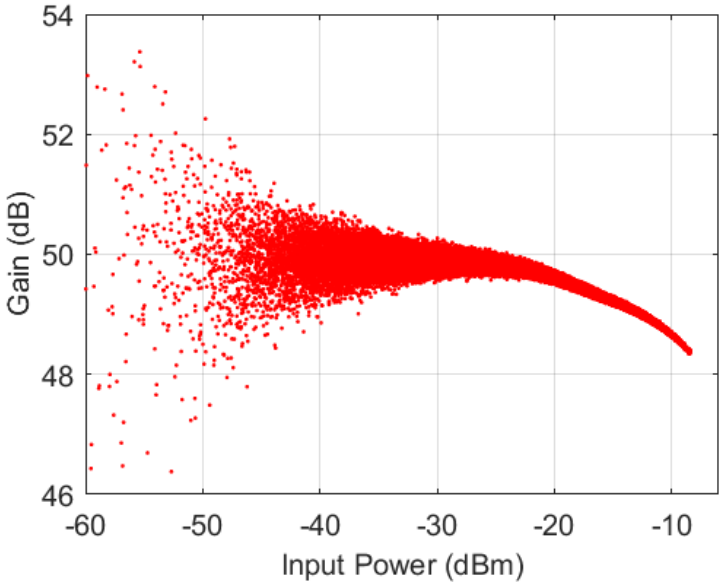


Scattering

Merit figure: Error Vector Magnitude (EVM)

$$EVM(\%) = \sqrt{\frac{P_{error}}{P_{ref}}} \cdot 100$$

Effects of Nonl. – AM/Gain Characteristic



Spreading and compression

Merit figure: Gain compression

$$\Delta G = G_{avg} - G_{comp}.$$

Effects of Nonlinearity – Mitigation

It is known that the PA is nonlinear near saturation.

Why don't we operate with a high backoff?

New proposals for spectral efficiency demand active devices as power amplifiers (PAs) to **operate near saturation.**

Linearity may not **comply with restrictions** of out-of-band emissions and in-band distortion required by wireless standards.

Evolution of processing capabilites turn digital predistortion (**DPD**) into an **attractive linearization technique** which relies on behavioral modeling.

Spectral Efficiency → High Power Operation → Nonlinearity → Linearization Techniques

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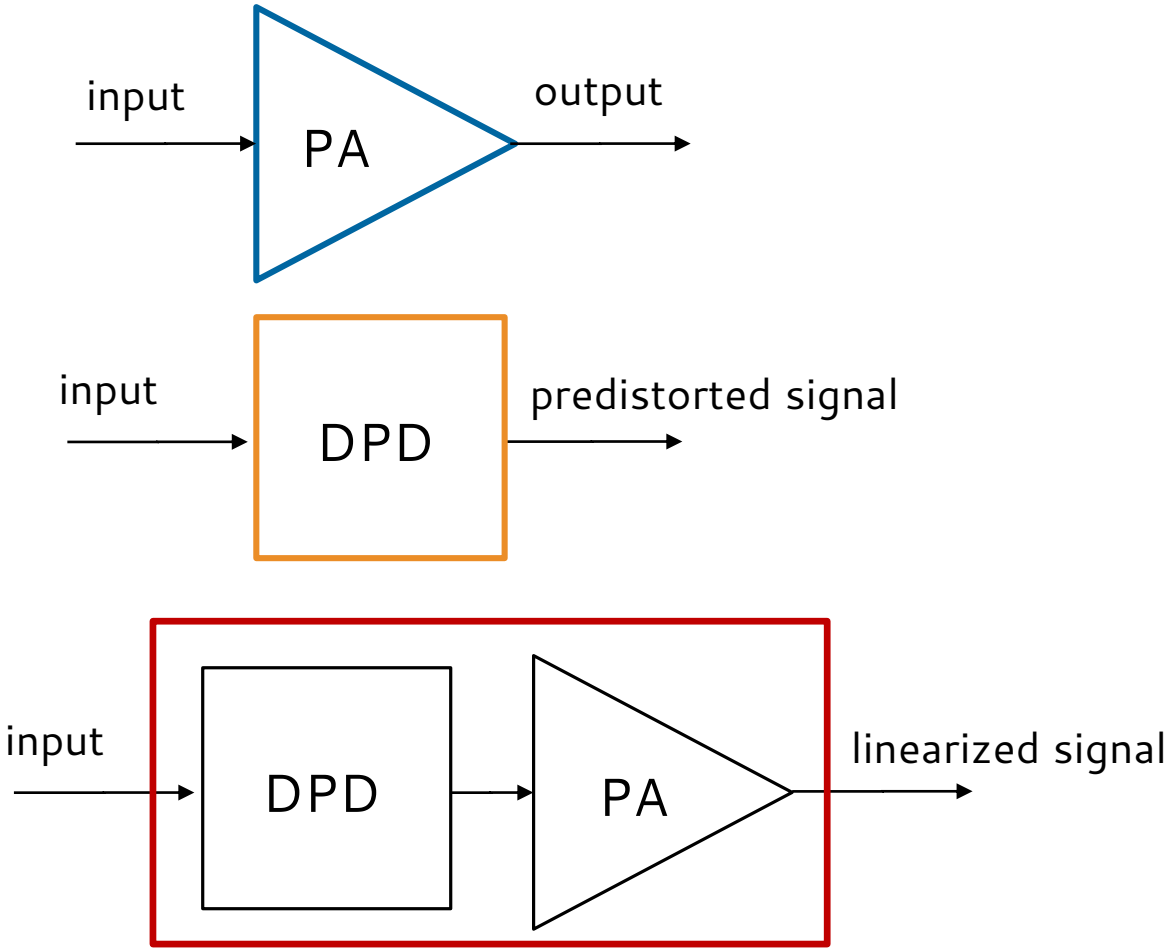
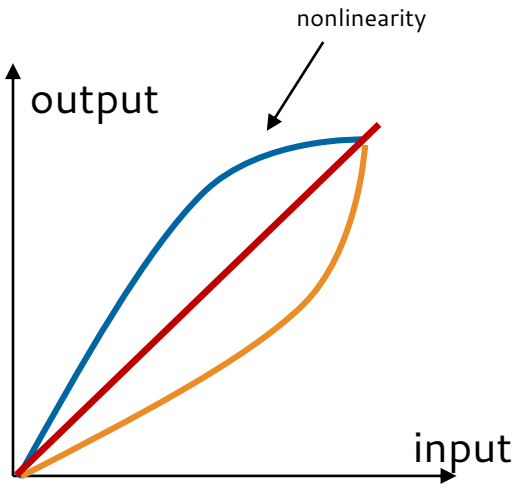
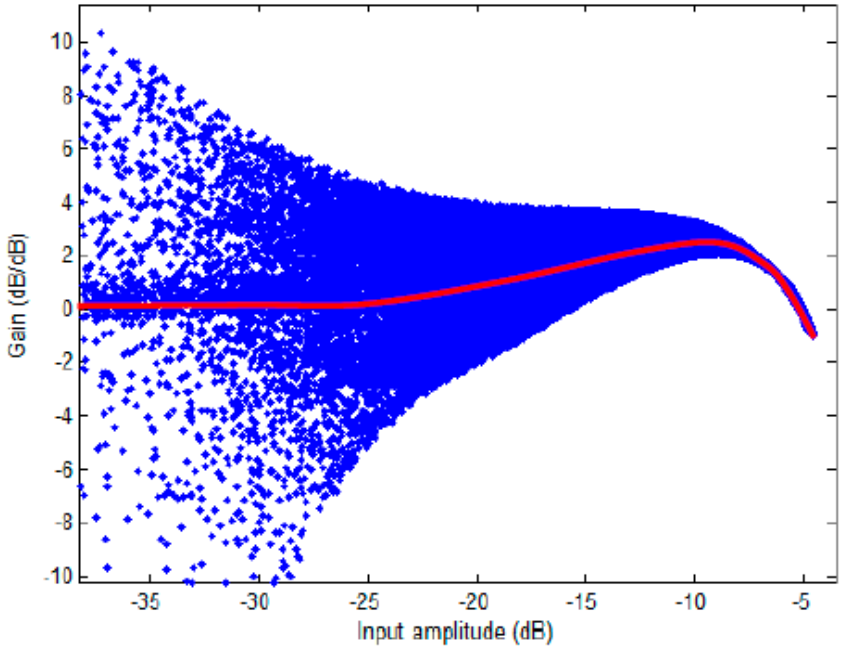
Digital Predistortion





Volterra Series

But… how do we get such a system?



$$x(n), x(n)x^*(n), x(n)|x(n)|^2, x(n)|x(n)|^4$$
$$x(n)|x(n)|^{10}, x(n)|x(n)|^{12}, \ldots$$

$$x(n-1),\ x(n-2), x(n-3),\ x(n-4), \ldots$$

$$x(n-1)|x(n-1)|^2, x(n-2)|x(n-2)|^2 \ldots$$

$$x(n-1)|x(n-2)|^2, x(n-2)|x(n-3)|^2 \ldots$$

$$x(n+1)|x(n-2)|^2, x(n+2)|x(n-3)|^2 \ldots$$

Volterra Series

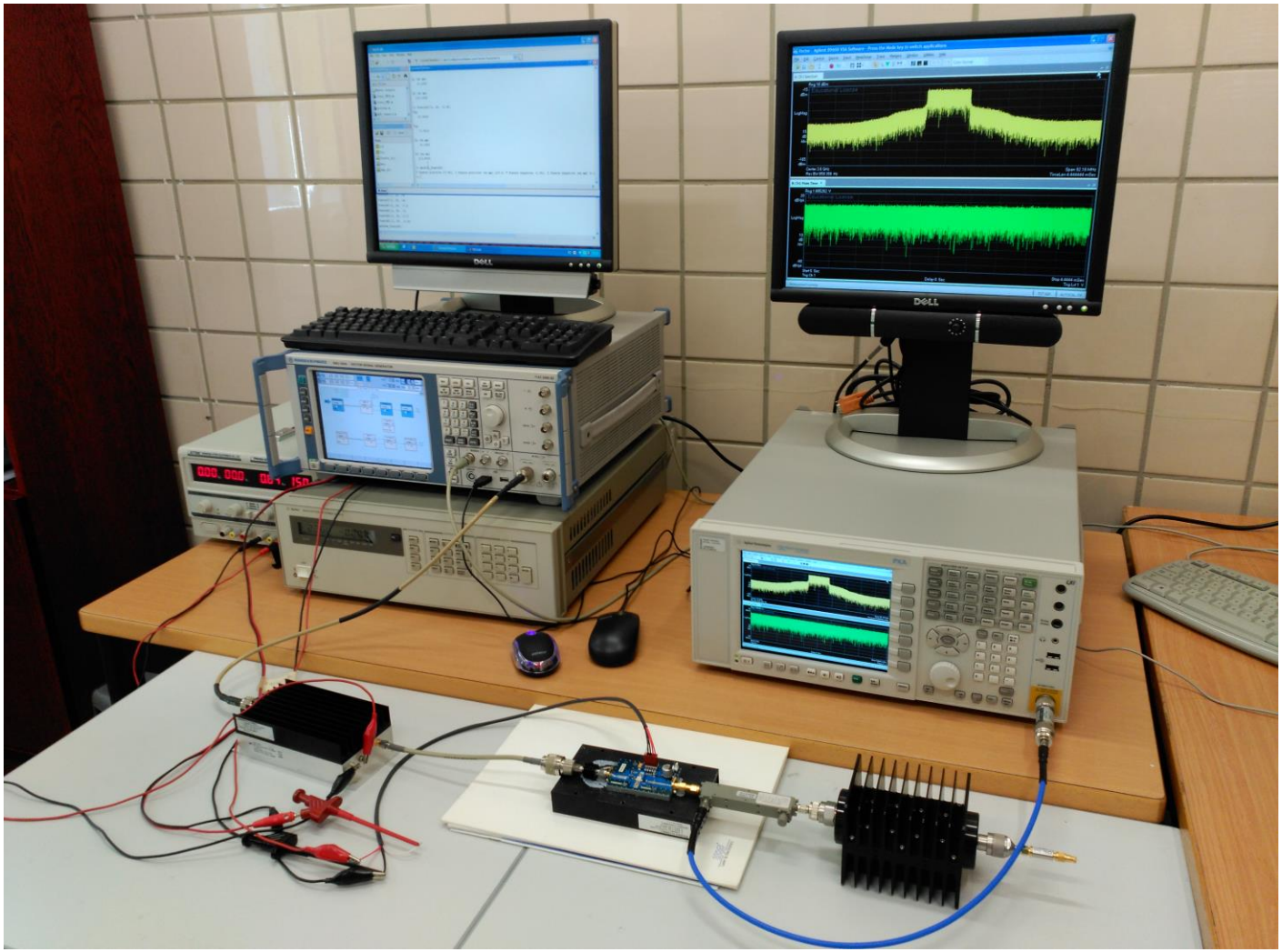
- Full Volterra model (FV)

$$y(n) = \sum_{k=0}^{K} y_{2k+1}(n)$$

$$y_{2k+1}(n) = \sum_{q_1=0}^{Q_1-1} \sum_{q_2=0}^{Q_2-1} \cdots \sum_{q_{2k+1}=0}^{Q_{2k+1}-1} h_{2k+1}(q_1, q_2, \ldots, q_{2k+1}) \prod_{r=1}^{k+1} x(n-q_r) \prod_{s=k+2}^{2k+1} x^*(n-q_s)$$

- Characteristics:
  - No restrictions imposed on the circuit structure or characteristics
  - Extremely high computational complexity, even for truncated structures
  - Exponential increase of the number of coefficients with the order of the nonlinearity and memory length.

Lab @ ETSI



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IMS Student Design Competition

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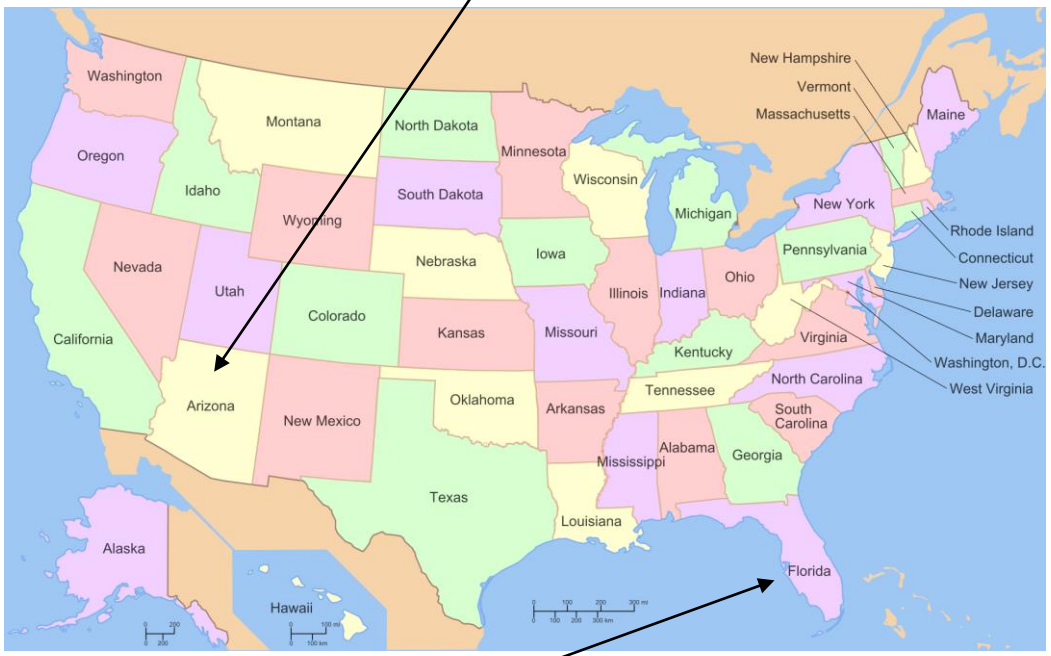
International Microwave Symposium
17-22 May 2015, Phoenix



International Microwave Symposium
1-6 June 2014
Tampa Bay, Florida

IMS Student Design Competition

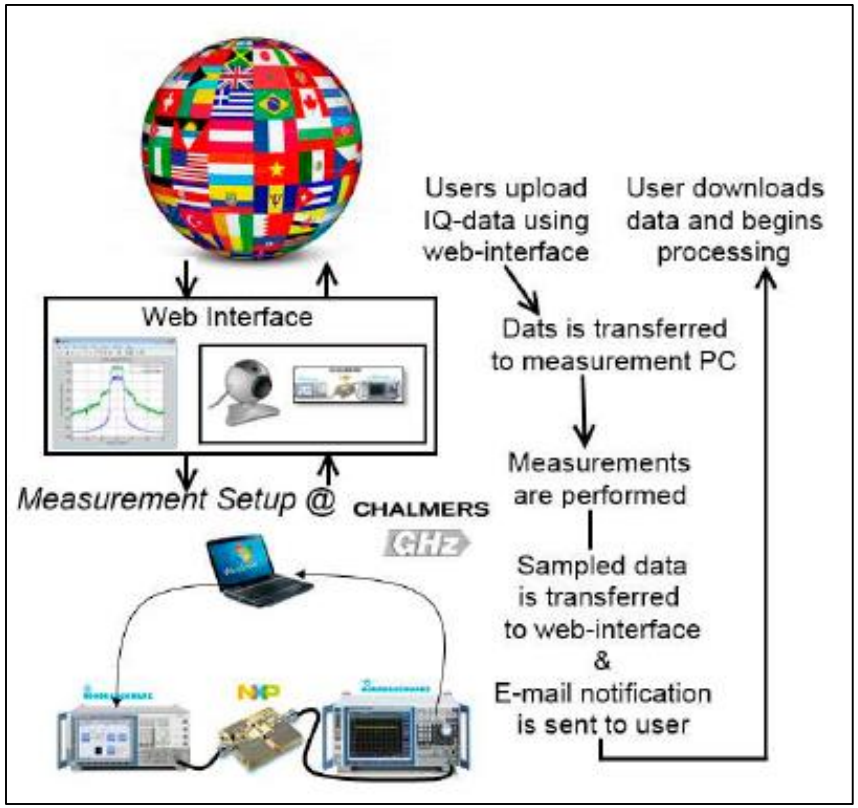
The students participating in the competition should develop their own digital predistortion algorithms for linearization of a commercial 2.14 GHz power amplifier (PA).

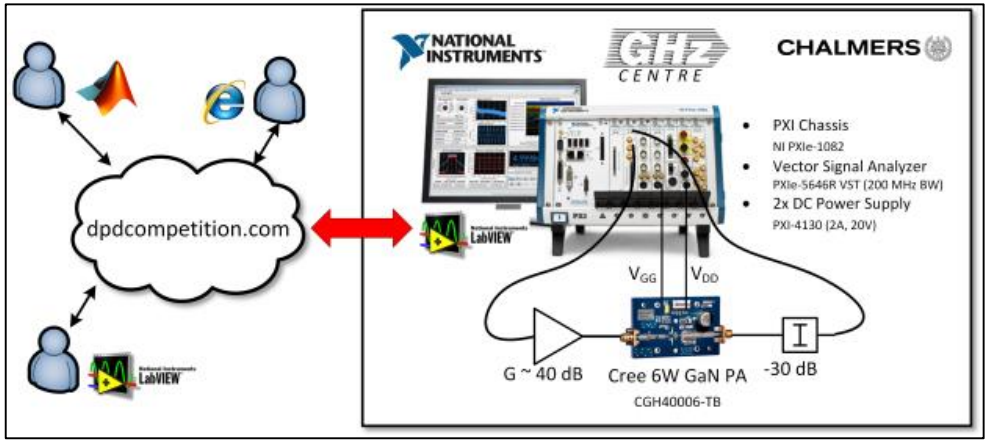
The performance of their linearization algorithms will be judged by measurements on a realistic dual-carrier LTE-like signal.

The goal is to achieve maximum output power under given linearity requirements.

IMS Student Design Competition

Power Amplifier Linearization through Digital Predistortion (DPD)



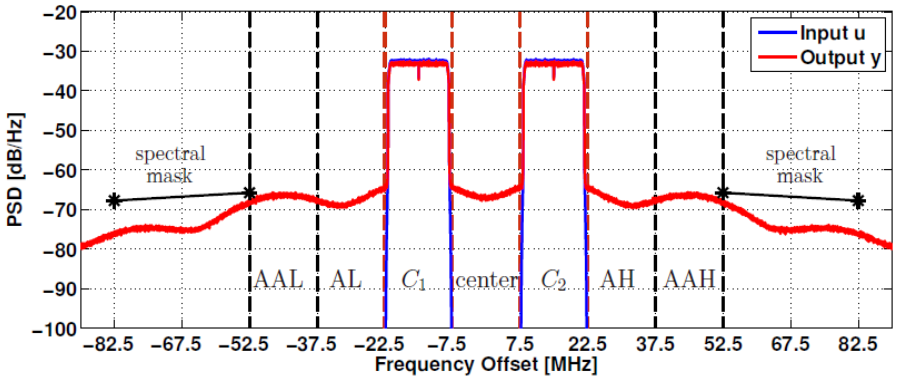


IMS Student Design Competition

Potential Universities and Companies to participate

- **Universitat Politecnica de Catalunya, Spain**
- Centre Tecnologic de Telecomunicacions de Catalunya, Spain
- University of Calgary, Canada
- University of Science and Technology of China, China
- Ohio State University, USA
- University of California San Diego, USA
- Tsinghua University, China
- University of Westminster, UK
- University of Belgrade, Serbia
- The College of New Jersey, USA
- **University of Waterloo, Canada**
- RWTH Aachen University, Germany
- National Taiwan University, Taiwan
- University of Zaragoza, Spain
- Massachusetts Inst. of Technol., USA
- Southeast Univ., China
- University of Gävle, Sweden
- Kwangwoon University, Rep. of Korea
- University of Kiel, Germany
- Pohang Univ. of Sci. & Technol.(POSTECH), South Korea
- **Univ. of Seville, Spain**
- XLIM, Univ. of Limoges, France
- University of Birmingham, UK
- Konkuk University, Rep. of Korea
- KTH Royal Institute of Technology, Sweden
- Vrije Universiteit Brussel, Belgium
- **Universidad de Aveiro, Portugal**
- **Chalmers University of Technology, Sweden**
- University of Victoria, Canada
- K.U. Leuven, Belgium
- Linköping University of Technology, Sweden.
- Texas Instruments
- Altera
- Powerwave Technologies
- Linear Space Technology
- NEC Corporation
- Freescale Semiconductor
- TriQuint Semiconductor
- Qualcomm
- RF Micro Devices
- WJ Communications
- Applied Wave Research
- TriQuint Semiconductor
- TOSHIBA Corporation
- Thales Alenia Space France
- Eudyna Devices Inc.
- Green Radio Technol. Inc.

IMS Student Design Competition



- SCORE
  - Max. Pout
  - Fail NMSE
  - Fail Mask
  - Fail Pout
  - Fail ACLR

IMS Student Design Competition

IMS Student Design Competition

IEEE

IEEE Microwave Theory and Techniques Society
Power Amplifier Linearization Through Digital Pre-distortion
Student Design Competition
Third Place

is hereby awarded to

Juan Antonio Becerra González

MTT-S International Microwave Symposium
Phoenix, Arizona, 17 – 22 May 2015

Tim Lee
President, MTT-S

Charles M. Jackson
Awards Chairman, MTT-S

MTT-S

What's next?

IMS
Connecting Minds. Exchanging Ideas.
2017 INTERNATIONAL MICROWAVE SYMPOSIUM
4 – 9 JUNE 2017 HONOLULU, HAWAI'I

Thank you for your attention! ;)

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