



Departament de Teoria
del Senyal i Comunicacions



UNIVERSITAT POLITÈCNICA DE CATALUNYA

Ph.D. Thesis

MULTI LOOK-UP TABLE DIGITAL
PREDISTORTION FOR RF POWER
AMPLIFIER LINEARIZATION

Author: Pere Lluís Gilabert Pinal

Advisors: Dr. Eduard Bertran Albertí
Dr. Gabriel Montoro López

Control Monitoring and Communications Group
Department of Signal Theory and Communications
Universitat Politècnica de Catalunya

Barcelona, December 2007

Chapter 1

Introduction

1.1 Motivation

Signal integrity, together with low cost and low consumption, is a bottleneck in wireless systems. In future, from an European perspective, the goal is to be '*always best connected and served*' (ABC & S) in a world populated by multiple overlapping heterogeneous wireless access networks [O'D03]. Wireless equipment will be supported by network and terminal dynamic reconfigurability capabilities (e.g. auto-installation of a new air interface based on software defined radio, SDR, platform) and application adaptability. Much of this functionality will be supported by a greatly increased intelligence at the network edge, especially in the mobile terminals.

On the other hand, current works regarding the needs of *wireless communications equipment* agree in highlighting the importance of reducing power consumption to cut running costs as an added value [Ali05], [Cri05]. Besides, linearity requirements are specified in communication standards and thus reducing unacceptable distortions is mandatory. Nevertheless, new standards enhancing high data rates by means of spectrally efficient complex modulation schemes require amplifiers handling signals presenting high Peak-to-Average Power Ratios (PAPRs).

The *power amplifier* (PA) is not only one of the most power consuming components in the transmitter, but also the responsible for the main nonlinear effects in the transmitter chain. In addition, spectrally efficient modulation formats are unfortunately very sensitive to the intermodulation distortion (IMD) that results from nonlinearities in the RF transmitter chain, mainly due to PA nonlinear behavior. This implies that for having linear amplification, significant *back-off* levels are required, thus penalizing PAs power efficiency. For example, in the cellular telephony context, PAs have to support some of the code division multiple access family (CDMA2000, W-CDMA) of wireless standards exhibiting in single carrier applications typical PAPR figures around 10 dB. In a broadband access context, communications standards such as IEEE 802.11a, DVB-T or the IEEE 802.16 consider the use of OFDM signals presenting even higher PAPRs

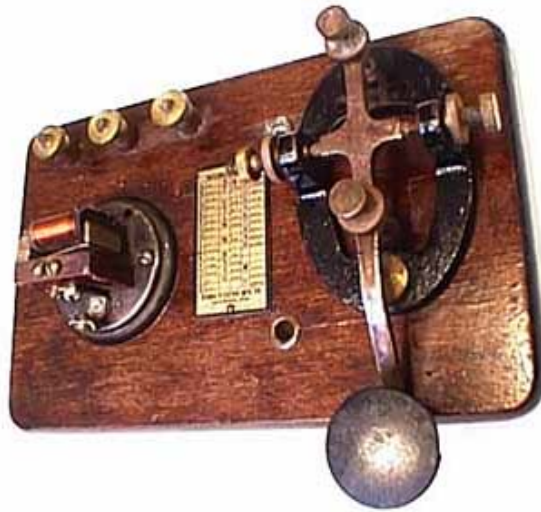


Figure 1.1: Nineteenth century wireless telegraph.

(up to 14 dB) and bandwidths up to 20 MHz or wider.

Furthermore, multicarrier PA technology in base stations, in which the PA handles a composite RF signal resulting from the sum of several independent modulated carriers, the linearity against efficiency trade-off, is aggravated. The PA has to cope with wider bandwidths and significantly higher PAPR figures, thus back-off has to be further increased to provide linear amplification, unless we consider the use of PA *linearizers*.

Among linearizers, *digital predistortion* (DPD) has arisen as a versatile linearization technique with a high potential in linearization performance due to the availability of current fast Digital Signal Processing (DSP) hardware, replacing feedforward as mainstream technique in commercially available base station products [xil07], [int05], [sie07], [alt03].

Besides the power efficiency problem, coping with high speed envelope signals makes designers reconsider the degradation suffered from PA *memory effects*, since their impact is more relevant as signal bandwidth increases. Actually, the PA dynamics causes the amplified signal to be not only a function of the input signal amplitude at the same instant, but to be also dependent on the history of the input-output signals as well. Therefore, if we consider the use of PA linearizers it is necessary to consider not only the classic trade-off between linearity and efficiency, but also PA memory effects.

This Ph.D. thesis provides a contribution to the study of *digital predistortion linearization*, proposing a new DPD prototype whose characteristics and performance are presented and validated by means of simulation and experimental results. A more detailed description of the related topics concerning our particular objective is provided in the following subsection.

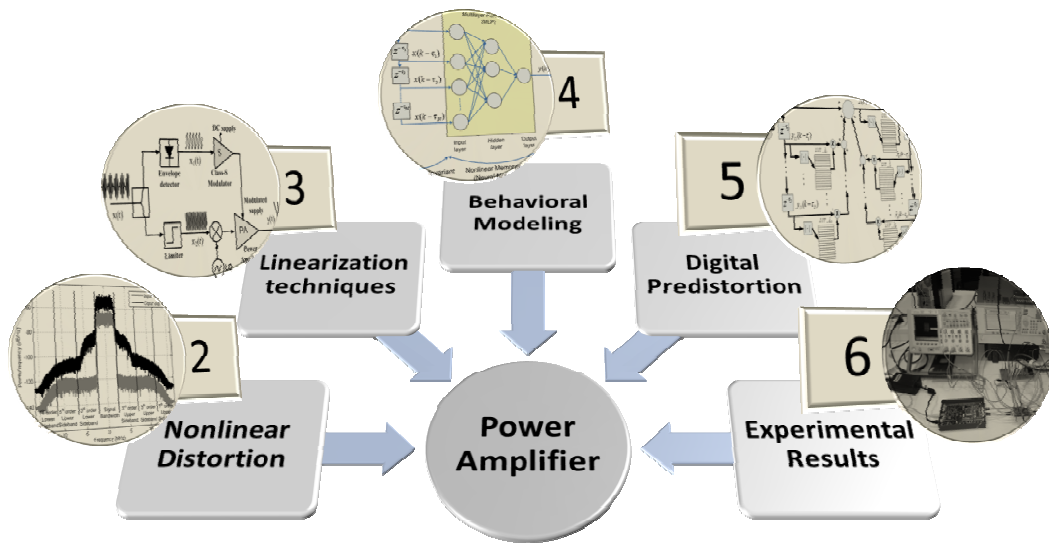


Figure 1.2: Overview of the main chapters of this thesis.

1.2 Outline of Thesis

This Ph. D. thesis covers different topics related to power amplifier linearization, from the problem statement to the implementation of a new multi-LUT based digital predistortion linearizer. The main body of this thesis is schematically depicted in Fig. 1.2.

In concrete, Chapter 1 describes the motivation of the work, the outline of the Ph.D. thesis and some research contributions in terms of the author's publications.

In Chapter 2 we present the problematic associated to PA nonlinear behavior. Power amplifier linearization is a well known problem extendedly presented in literature, but still open since it has to continuously handle with new communication scenarios where linear amplification is a must and power efficiency is an important figure of merit. In this Chapter the inherent nonlinear behavior associated to PA is exposed, including more recent issues regarding the degradation suffered in linearity performance due to PA memory effects.

Chapter 3 provides a survey of the state of the art in PA linearization techniques. The current allowance of high speed digital signal processors (DSP's) not only have revived classical analogue solutions, such as the Kahn's envelope elimination and restoration (EE&R) or the outphasing techniques, but also have facilitated new approaches to the linearization problem. A general overview covering from Black's classical feedback or feedforward to more recent contributions in digital predistortion are presented in this Chapter.

Focusing our contribution in the field of digital predistortion linearization, Chapter 4 presents an overview of PA behavioral models, a key issue towards a future DPD linearization. In this

Chapter we expose the basis and needs of PA behavioral modeling when it is oriented to a final DPD implementation. In addition, an overview of the most common structures used to model PA nonlinear dynamics is presented. At the end of this Chapter, our particular contribution to this topic, consisting in a nonlinear auto-regressive moving average (NARMA) PA model, is deeply explained. Additionally, we propose a technique to reduce models complexity which is also detailed within this Chapter.

Chapter 5 is specifically focused in presenting our particular contribution in DPD linearization. In this Chapter a first introduction of some basic concepts regarding LUT organization is provided, to continue exposing identification methods to extract the DPD function, in which we contribute presenting a new predictive extraction method. The DPD function derivation into a set of multiple LUTs, as well as different configurations for the DPD adaptation process are also discussed within this Chapter.

Chapter 6 addresses the hardware implementation of the new DPD linearizer proposed in Chapter 5. This Chapter is aimed at validating the functioning of the proposed DPD in terms of nonlinear distortion compensation and linearity enhancement. Moreover, it provides an insight view of some issues related to DPD implementation in digital signal processors, such as DPD reliability in the adaptation process, power consumption and the overall system efficiency.

Finally, Chapter 7 concludes the thesis and proposes possible future lines of research.

1.3 Research Contributions

The main contribution of this Ph.D. thesis consists in the design of an adaptive DPD based in a new recursive PA behavioral model. To show its good linearization performance, the DPD has been implemented and experimentally validated.

In the following, the research contributions are organized by chapters according to their contents.

Chapter 3

Some previous contributions in system level linearization, concretely in Feedforward and Cartesian Feedback with reference model linearizers, have been published in one book chapter and four conference papers:

- P. L. Gilabert, E. Bertran, G. Montoro, and J. Berenguer, "Study on the Robustness of a 22 MHz Bandwidth Feedforward Amplifier at the 2.4 GHz ISM-Band," *Proc. 15th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC'04)*, vol. 1, pp. 186-190, Barcelona, Spain, Sept. 2004.

- G. Montoro, P. L. Gilabert, and E. Bertran, "Linealización por Realimentación Cartesiana con Modelo de Referencia," *XIX Simposium Nacional de la Unión Científica Internacional de Radio (URSI 2004)*, Barcelona, Spain, Sept. 2004.
- P. L. Gilabert, E. Bertran, G. Montoro, and J. Berenguer, "On the Efficiency of Feedforward Amplifiers for WiFi Applications," *Proc. XI Electronic and Electromagnetic Technologies for Space Applications*, Orvieto, Italy, April 2005.
- G. Montoro, E. Bertran, M. O'Droma, P. L. Gilabert, and J. Berenguer, Characterization and Modelling Approaches for Advanced Linearisation Techniques, Chap. 8, Design of RF power amplifier linearisers using H-Infinity control theory, pp. 159-183, Research Signpost, Kerala, 2005.
- M. O'Droma, E. Bertran, M. Gadringer, S. Donati, A. Zhu, P. L. Gilabert, and J. Portilla, "Developments in Predistortion and Feedforward Adaptive Power Amplifier Linearizers," *Gallium Arsenide and Other Semiconductor Application Symposium (GAAS'05)*, pp. 337-340, Paris, France, Oct. 2005.

Chapter 4

The main contributions in this chapter regarding the design and simplification of PA behavioral models for digital predistortion, have been published in one book chapter, one journal paper, six conference papers and one international workshop presentation:

- P. L. Gilabert, G. Montoro, and E. Bertran, "On the Wiener and Hammerstein Models for Power Amplifier Predistortion," *Proc Asia-Pacific Microwave Conference (APMC'05)*, vol. 2, pp. 4-7, Suzhou, China, Dec. 2005.
- P. L. Gilabert, and G. Montoro, "Predistorsión Digital y Adaptativa de Amplificadores de RF con Modelos de Hammerstein," *Proc. XX Simposium Nacional de la Unión Científica Internacional de Radio (URSI'05)*, Gandía, Spain, Sept. 2005.
- P. L. Gilabert, G. Montoro, and E. Bertran, "Linealización de Sistemas por Predistorsión Digital y Adaptativa Mediante Modelos de Hammerstein," *Proc. I Seminario de Aplicaciones Industriales de Control Avanzado (SAICA'05)*, Madrid, Spain, Oct. 2005.
- P. L. Gilabert, G. Montoro, and E. Bertran, "A methodology to model and predistort short-term memory nonlinearities in power amplifiers", *Proc. International Workshop on Integrated Nonlinear Microwave and Millimeter-Wave Circuits (INMMIC'06)*, pp. 142-145, Aveiro, Portugal, Jan. 2006.

- P. L. Gilabert, E. Bertran, and G. Montoro, “Baseband Power Amplifier Equivalent Models for Digital Predistortion,” *Workshop on Modelling for TX System Level Analysis, European Microwave Week (EMW’06)*, Manchester, UK, Sept. 2006.
- P. L. Gilabert, D. D. Silveira, G. Montoro, and G. Magerl, “RF-Power Amplifier Modeling and Predistortion Based on a Modular Approach,” *Proc. European Microwave Integrated Circuits Conference (EuMIC’06)*, pp. 265-268, 10-13, Manchester, UK, Sept. 2006.
- D. D. Silveira, H. Arthaber, P. L. Gilabert, G. Magerl, and E. Bertran, “Application of Optimal Delays Selection on Parallel Cascade Hammerstein Models for the Prediction of RF-Power Amplifier Behavior,” *Proc Asia-Pacific Microwave Conference (APMC’06)*, vol. 1, pp. 283-286, Yokohama, Japan, Dec. 2006.
- P. L. Gilabert, D. D. Silveira, G. Montoro, M. E. Gadringer and E. Bertran, “Heuristic Algorithms for Power Amplifier Behavioral Modeling”, *IEEE Microwave and Wireless Components Letters*, vol 17, n^o. 6, pp. 715-717, Oct. 2007.
- P. L. Gilabert, G. Montoro, E. Bertran et al., “Nonlinear Auto Regressive Moving Average Models”, section 5.4 of the Chapter 5 entitled *Nonlinear Models with Nonlinear Memory*, of the book entitled *RF Power Amplifier Behavioural Modeling*, Cambridge University Press (to be published).

Chapter 5

The main contributions in this chapter are oriented at presenting our particular digital predistorter and have been published in two journal papers, two conference papers and two international workshop presentations:

- P. L. Gilabert, E. Bertran, and G. Montoro, “Multiple Lookup Table Predistortion for Adaptive Modulation,” *Proc. of the European Microwave Association*, vol. 1, pp. 304-311, Dec. 2005.
- P. L. Gilabert, G. Montoro, and A. Cesari, “A Recursive Digital Predistorter for Linearizing RF Power Amplifiers with Memory Effects,” *Proc. Asia-Pacific Microwave Conference (APMC’06)*, vol. 2, pp. 1043-1046, Yokohama, Japan, Dec. 2006.
- P. L. Gilabert, “Linear Power Amplifier Design & Wireless Systems: Digital Predistortion”, 3rd *TARGET Summer School*, Castelldefels, Spain, July 2006.
- G. Montoro, P. L. Gilabert, E. Bertran, A. Cesari, and D.D. Silveira, “A New Digital Predictive Predistorter for Behavioral Power Amplifier Linearization,” *IEEE Microwave and Wireless Components Letters*, vol. 17, n^o. 6, pp. 448-450, June 2007.

- P. L. Gilabert, G. Montoro, and E. Bertran, “An Overview on Digital Baseband Predistortion for Linearising RF Power Amplifiers,” *Workshop on Wireless Transmitter Design for Future Wireless Systems, European Microwave Week (EMW’07)*, Munich, Germany, Oct. 2007.
- G. Montoro, P. L. Gilabert, E. Bertran, A. Cesari and J. A. García, “An LMS-Based Adaptive Predistorter for Cancelling Nonlinear Memory Effects in RF Power Amplifiers,” *Proc. Asia-Pacific Microwave Conference (APMC’07)*, Bangkok, Thailand, Dec. 2007.

Chapter 6

Experimental results regarding our proposed adaptive digital predistorter presented in this chapter have been published in three conference papers and one paper submitted to a journal:

- A. Cesari, J. M. Dilhac, P. L. Gilabert, G. Montoro, and E. Bertran, “A FPGA-Based Platform for Fast Prototyping of RF PA Predistortion Linearizers,” *Proc. IEEE Topical Symposium on Power Amplifiers for Wireless Communications*, Long Beach, USA, Jan. 2007.
- A. Cesari, P. L. Gilabert, E. Bertran, G. Montoro, and J. M. Dilhac, “A FPGA Based Digital Predistorter for RF Power Amplifiers with Memory Effects,” *Proc. 2nd European Microwave Integrated Circuits Conference (EuMIC’07)*, Munich, Germany, Oct. 2007.
- P. L. Gilabert, G. Montoro, A. Cesari, J. A. García, and E. Bertran, “Implementación con Procesadores Digitales de Señal de un Predistorsionador Capaz de Compensar Efectos de Memoria no lineales en Amplificadores de RF,” *XXII Simposium Nacional de la Unión Científica Internacional de Radio (URSI’07)*, Tenerife, Spain, Sept. 2007.
- P. L. Gilabert, A. Cesari, G. Montoro, E. Bertran, and J. M. Dilhac, “Multi Look-Up Table FPFA Implementation of an Adaptive Digital Predistorter for Linearizing RF Power Amplifiers with Memory Effects,” *IEEE Tran. on Microwave Theory and Techniques*, will be published in the February 2008 issue of the journal.

Other

Other publications not directly related to the main topic of this thesis are:

- P. L. Gilabert, and P. Dini, “Estudio de un Escenario Híbrido para Comunicaciones Aeronáuticas de Banda Ancha” *Proc. XVIII Simposium Nacional de la Unión Científica Internacional de Radio (URSI’03)*, Sept. 2003.

- E. Bertran, J. Berenguer, G. Montoro, P. L. Gilabert and A. Cidronalli "Improvement of Up-Converters Linearity for Ka-Band Operation" *Proc. Asia-Pacific Microwave Conference (APMC'07)*, Bangkok, Thailand, Dec. 2007.
- E. Bertran, M. O'Droma, P. L. Gilabert, G. Montoro, "Performance Analysis of Power Amplifier Back-off Levels in UWB Transmitters" *IEEE Transactions on Consumer Electronics*, will be published in the November 2007 issue of the journal.