Linearisation Issues in Microwave Amplifiers

M. S. O'Droma[1], J. Portilla[2], E. Bertran[3], S. Donati[4], T. J. Brazil[5], M. Rupp[6], R. Quay[7]

[1] UL, Limerick, Ireland, (mairtin.odroma@ul.ie); [2]UPV/EHU, Bilbao, Spain; [3]UPC, Barcelona, Spain; [4]Politecnico di Torino, Italy; [5]UCD, Dublin, Ireland; [6]Technische Universitat Wien, Austria; [7]FhG-IAF, Freiburg, Germany

Abstract — **The European Union has established the TARGET network of excellence (NoE) to focus on microwave power amplifier (PA) technology research. It aims to integrate the research resources comprised of many research groups covering the full range of expertise in PA technology. TARGET'S linearisation expertise covers leading edge researchers in classical and new linearisation techniques, including feedforward, predistortion, feedback and envelope elimination and restoration (EER), adaptive and non-adaptive, digital and analog, baseband, IF and RF, together with device, circuit and system modeling and behavioural analysis techniques. This paper reviews key linearisation issues to be faced in evolving linearisation solutions for future complex PA systems destined for a wide range of advanced wireless systems.**

I. INTRODUCTION

Mobile wireless networks are evolving towards wider bandwidths, higher spectral efficiency (bits/Hz), using multi-level non-constant envelope modulation, NoCEM, schemes (e.g. M-QAM), at higher air-interface frequencies. Handsets, base stations, HAPs and satellites – all types of access nodes– are already being required to handle air interface modes with high signal envelope crest factors (high peak to average power ratio, PAPR), and this requirement is set to become more serious with the hope of having simultaneous multi-band, multi-mode, including ultra-wideband (UWB) modes, [1], utilising a common transmit PA. For reduced in-band distortion and out-of-band emissions, the linearity requirements grow, and this especially applies to the RF PA. Typically the PA consumes over 70% of available stored energy in today's mobile handsets at power added efficiencies (PAE) of the order of 50% and less. Hence PA linearisation techniques, in enabling amelioration of in-band and out-of-band nonlinear PA impairment effects, are becoming increasingly important.

Behaviourally non-linearity is gauged by (a) the interference caused in the adjacent channels, typically given as an adjacent channel power ratio (ACPR) measure, and (b) the deterioration in modulation fidelity (MF) of the transmitted signal, typically measured as an error vector magnitude (EVM). As the same PA nonlinearity is the source of both problems, specifications for one may override that for the other, e.g. [2].

The typical PAE curve shows poor PAE performance with PA operation in the linear region but 'takes off' roughly and usually along a raised sine (RS) shaped curve as it moves into the nonlinear region. Linear operation by operating point backoff will be at the expense of PAE. Hence a lineariser which enables operation more into or through the RS region of the PAE curve is likely to be attractive, assuming acceptable performance-, and manufacturability-, cost ratios.

The standard static memoryless or quasi-memoryless [3] PA and lineariser characteristic models are effective at setting upper bounds to, and to some extent at predicting real, composite PA-lineariser performance as a function of percentage linearisation (PL) [4] and input power backoff and PAE values.

However, apart from the problems arising from incorrectly tuned bias circuits [3], SSPAs are extremely sensitive to temperature with self-heating effects impacting on their RF performance. It has been found in certain SSPAs, where large PAPR drive signals are applied, that the signal envelope can modulate the operating temperature. Then characterization of the nonlinearity, and thus of the impairments caused by this nonlinearity, becomes a dynamic matter. Linearisers seeking to offset SSPA nonlinearities will need to adapt dynamically. As RF operating frequencies go higher, up to 100GHz, and signal bandwidths become greater (>50MHz per single mode channel with a demand for simultaneous multimode channels) the challenge to find solutions becomes more urgent. An early step in this work is research into accurate measurement of self-heating [5] so as to better understand and characterise these effects. Research goals of temperature, time and space resolution for these measurements in TARGET are 5K, 2ns and 2μm resp., [6].

II. ONGOING LINEARISATION RESEARCH

Research work happening in this field, and in the process of being integrated within the TARGET network, includes the following -

a. General realisations of linearisation techniques, including integration of control components, into MMIC structures; some specific work in the 37-40GHz broadband is well underway in CoRiTeL. An efficient linearisation scheme, suited for MMIC implementation, has been demonstrated by the Politecnico di Torino (Polito), [7] providing nearly exact IM3 cancellation when linearising a 1W K-band PA.

b. The effect of device semiconductor characteristics (compound semiconductor, modulation-doped FET, electro-thermal effects in GaN-HEMTs etc.) on PA linearity, linearity memory effects, and efficiency is being investigated. It includes circuit level design methodologies such as those based on harmonic balance techniques**.** This effort is being led by the Fraunhofer Institute, the University of Stuttgart, and MiMEG - University of Rome (Tor Vergata).

c. Research into the design and realisation of adaptive linearisation schemes to match variations of PA characteristics manifesting transient memory effects due to adaptive power control techniques, operating temperature (including local and global self-heating), and ageing (a long term effect). This includes techniques such as digital adaptive predistortion, adaptive filters, neural networks, and Volterra series based methods. These digital techniques, by their nature, are realised at baseband and hold most promise in (the ever-broadening) narrowband systems. Headway is being made also for their use with the inclusion of compensation for memory effects, e.g. UMTS,[8]. Cross fertilisation in this field of research among TARGET partners such as Polito, University of Bologna (Unibo-DEIS), Technical University of Vienna (TUW-INTHFT), University College Dublin (UCD), Universitat Politecnica de Catalunya (UPC) and University of Limerick (UL) is underway.

d. Analytic techniques to assess impact of levels of linearisation on system parameters (UL) and general evaluation of classical lineariser structures – UPC, CNRS - LAAS, CoRiTeL and others.

III. TARGET REVIEW OF LINEARISATION

With a view to greater integration and focus of network resources, TARGET is supporting a comprehensive review of techniques, designs, models, and algorithms for linearisation systems, circuits and devices. This will contribute also to establishing clarity in respect of characterisation, memory and adaptability issues, and clear means of objective evaluation and comparison. The focus is proactive in that linearisation improvement goals over the lifetime of TARGET have been set down.

The theory, principles and techniques of PA linearisation have been evolving since the early days of wireless transmitters. Techniques include predistortion, feed-forward, direct and indirect feedback techniques, envelope elimination and restoration (EER), polar loop, Cartesian loop, and other cancellation methods. System and circuit attributes that have to be considered include – dynamic/static; adaptive/non-adaptive; baseband/RF; memoryless/memory-effects tracking and compensation. Other issues that have to be addressed include simulation and analysis, and performance measurement, at various levels (device circuit system, and behavioural); implementation issues – complexity, stability, robustness, reliability, energy efficiency, size, weight, thermal considerations and cost.

In general, there is no ‘best’ linearisation technique. The method used to linearise a PA should be the optimum for the particular system being designed taking into account frequency, modulation method and bandwidth. Internationally and within Europe much of the focus of linearisation research is on the first two techniques – predistortion and feed-forward - as holding promise for successful adaptation to upcoming advanced wireless communication systems. TARGET’s effort however will be to combine research strengths to seek linearisation solutions across a wide range of systems, but with special emphasis on wideband systems and solutions which respond to the dynamic characteristics encountered in new SSPA materials being investigated which manifest multifactorial transient effects, e.g. in self-heating and memory.

IV. TYPES OF LINEARISATION

Negative feedback has been widely employed at low frequencies but can also provide linearisation if applied directly to the amplifier in the form of RF feedback, envelope feedback or harmonic feedback e.g.[9, 10]. The use of negative feedback at high frequencies has been limited by unavoidable parasitic and time-delay effects, leading to instability problems. This problem can be effectively circumvented for narrow bandwidth applications with careful design. However for wider band modern and future systems feasibility, stability and robustness problems will slow and constrain the evolution of feedback linearisation [9, 11].

Detection, and avoidance of, undesired instabilities is possible in medium-power PAs working under different bias, frequency or power conditions. For instance techniques have been reported [12], which help optimise the feedback loop, thus avoiding spurious oscillations and opening up new perspectives for feedback linearisation strategy design. Preliminary studies on the application of stability analysis techniques to the design of a L-band medium-power bipolar amplifier with passive feedback have demonstrated encouraging results [13]. Fig.1 shows the ACPR improvement provided by the optimisation of the passive feedback loop, guaranteeing the amplifier stability over its whole power range. The excitation is a QPSK signal and different symbol rates have been considered. Simulations show improvements for symbol rates not exceeding 20MHz.

Circuit-level predistortion and feedback: H-infinity design optimization theory applied to feedback linearisers is another new approach, [14], presently being found to improve classical feedback results. The linearisation systems are designed according to the model reference structure, have good closed loop robustness, and do not require detailed information about the PA, rather only a simple bound on the nonlinearities is necessary.

Hyper-stable design of linearisers, implementable in analog circuitry or through DSP, [15], is another new technique under investigation within TARGET capable of tolerating significant PA parameter variations.

Other feedback linearisation issues include dynamic power supply, active bias and thermal compensation; the former being more directed at power efficiency rather than linearisation.

Feedforward techniques [16, 17] for the most part rely

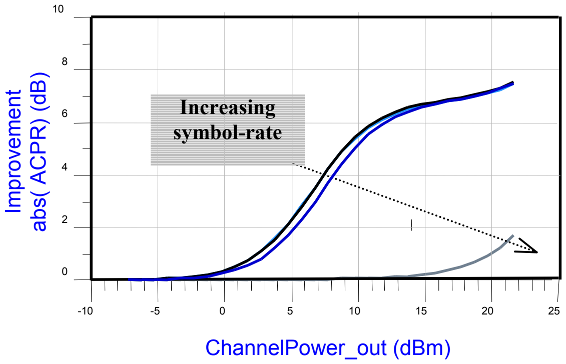

Fig.1 ACPR improvement on a L-Band bipolar PA using passive feedback under QPSK excitation with symbol rates: 10, 20 and 30MSymbols/s.

on automatic compensation loops based on analog solutions, and digital adaptive compensation - LMS and gradient-like based methods, correlative algorithm, and such like. Besides development of the theoretical support, issues include the effects of imbalances and imperfect cancellation, stability, controller loop and optimising algorithm, e.g. [18-20].

Predistortion techniques are viewed as of greatest importance because of their likely wideband application [21]. The success of predistortion relies on the accuracy of the PA characterization and the generation of an equivalent cancelling characteristic. To date the approach has been to assume quasi-static and memoryless approximations for the PA characteristics. Generally the interaction between the nonlinearities present in both the predistorter and amplifier, and the noticeable memory effects, make the design and optimisation of the predistorter an involved and critical task. Techniques include RF, IF, baseband digital and analogue predistortion, e.g. [11, 22]. Of key importance here is achieving real-time inverse adaptable dynamical modeling of the PA, with memory effects accounted for, whether they be based on Volterra, (e.g. [23, 24]) Wiener, Chebyschev, Bessel, Taylor, Saleh, or on other models.

For wideband systems RF predistorters based on diode or transistor devices [8, 9, 11] seem likely candidates. Focusing on third-order intermodulation distortion (IMD3) in a combined predistorter-PA, three main mechanisms contribute to the final result: *envelope*, *second harmonic* and *third degree* [24]. The pure *third degree* contribution is the obvious way to generate third-order intermodulation products. The *envelope* mechanism refers to the mixing of two fundamental frequencies in a given even-degree nonlinear element followed by a new mixing with a fundamental in other even-degree nonlinearity. The *second harmonic* mechanism involves the generation of the second harmonic of a fundamental frequency in an even-degree nonlinearity and a new even-degree mixing with another, different, fundamental. Most of the nonlinearities present in the devices contain even-degree components and, as a consequence of the *envelope* and *second harmonic* mechanisms, the linearisation performance depends not only on the in-band behaviour of both amplifier and predistorter, but also on the out-of-band impedances, thermal and trap effects, etc.,[24, 25].

In conclusion, the complex nonlinear phenomena and short- and long-term memory effects are issues to be considered carefully in order to optimise the lineariser performance. For instance optimisation of the predistorter circuit and low-frequency impedances in both the predistorter and PA needs to be carried out in order to improve the IMD3 performance over a broad frequency band. Figure 2 shows measurement results on a L-band bipolar PA, using two different diode-based predistorter circuits, c.f.[24].

Other techniques, which some might categorise among the types already mentioned, include EER, linear amplification using nonlinear components (LINC), combined analogue-locked loop universal modulator (CALLUM). Data predistortion, displays good in-band results but still needs further research to analyse ACI effects. There are also pseudo-linearisation techniques e.g. power combiners and Doherty amplifiers, [26].

V. ADAPTIVITY

To get the most benefit from the lineariser it should be matched to the particular amplifier. However the amplifier characteristics will vary - intended e.g. with bias point under transmit power control protocol, or unintended e.g. the self-heating effects mentioned above or PA tolerances in their fabrication. Adaptability of the linearisation characteristics to match PA variations, and the capturing of suitable control signals for this adaptation, is an important area of research. (Linearisers that do not adapt or adapt poorly could of course add to the nonlinearity problem rather than ameliorate it!) Here all the challenging issues of measurement of device characteristics, especially of memory and thermal effects, together with their multi-level model design are present, e.g. [3, 7]). As an example of modeling work in this context, a solution of the coupled electrical and thermal model has been demonstrated in the frequency domain through harmonic balance simulations [7]: Fig. 3 shows the DC thermal collapse of a power HBT with one input tone at different frequencies. A dispersive effect is visible in the nonlinear device behavior. Similar analysis can be carried out with multiple tones.

VI. EVALUATION CRITERIA AND STANDARDS

Linearisation evaluation criteria and standards also need to be looked at with a view to establishing some harmonious benchmarking techniques. Common measures of nonlinearity include 1dB compression point, and 2nd and 3rd order intercept points. From the behavioural viewpoint, deterioration of EVM of the MF of digitally modulated signals and the level of ACI, usually measured as ACPR, are key measures. Lately, new relative measures of linearisation, PL and percentage linearisation area (PLA) have been introduced and linked to the behavioural measures. These enable comparison between different linearisation techniques as well as the setting of design goals for linearised PAs.

VII. CONCLUSIONS

TARGET sees linearisation techniques at circuit and system levels as having become today a key research

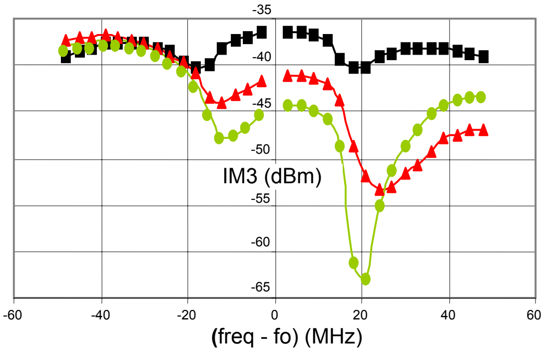

Fig 2. IM_3 Vs offset frequency w.r.t. the carrier, for PA alone (■), and with 1- diode (▲) and 2-diode (●) predistorters.

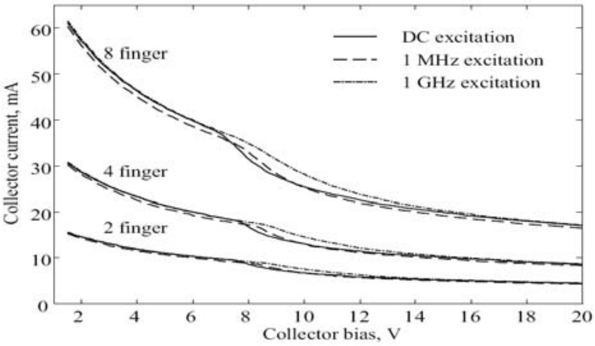

Fig. 3 Dispersive effects due to thermal coupling on the DC HBT output characteristics and on the HBT thermal collapse.

issue for modern evolving advanced wireless transmitters from embedded mobile and handheld terminals, to base stations, HAPs and satellites. A key driver is competing requirement of improved signal fidelity and PA system PAE in contexts of single and multicarrier NoCEM air-interface modes to simultaneous multimode transmitter systems. At present, solutions offer finite though modest linearity behavioural improvements, which are a function of the air-interface mode. Their adequacy depends on the context but they can help achieve linearity goals when working together with other options. Nevertheless, different practical problems –many of which have yet to be fully understood and characterised such memory effects, self-heating effects, interaction between non-linearities and stability issues– reduce potential performance.

ACKNOWLEDGEMENTS

TARGET network of excellence project, European Union, EU-FP6-IST-2004-507893, www.target-net.org, especially colleagues in TARGET's linearisation evaluation map workpackage.

REFERENCES

[1] M. S. O'Droma, "Wireless, Mobile and Always Best Connected," *IEEE Communications Magazine & GCN*, vol. 42, pp. 29-2, 2004.

[2] M. O'Droma and N. Mgebrishvili, "On quantifying the benefits of SSPA linearisation in UWC-136 systems," *To be published in IEEE Trans. on Signal Processings*, 2004.

[3] W. Bosch and G. Gatti, "Measurement and simulation of memory effects in predistortion linearizers," *IEEE Trans. MTT*, vol. 37, pp. 1885-1890, Dec. 1989.

[4] M. O'Droma, N. Mgebrishvili, and A. Goacher, "New percentage linearization measures of the degree of linearization of HPA nonlinearity," *IEEE Communications Letters*, vol. 8, pp. 214-216, 2004.

[5] P. Bianco, S. Donati Guerrieri, G. Ghione, M. Pirola, C. U. Naldi, C. Florian, G. Vannini, A. Santarelli, F. Filicori, L. Manfredi, "Optimum design of a new predistortion scheme for high linearity K-band MMIC power amplifiers", *GAAS 2001*, pp. 689-692, London, UK, Sep. 2001.

[6] G. Magerl, M. S. O'Droma, F. Giannini, T. J. Brazil, G. Manes, A. Cidronali, A. Mediavilla, R. Makri, W. Richter, J. P. Teyssier, M. Mayer, P. Colontonio, D. Schreurs, et al., "Top amplifier research group in a European team (TARGET) - NoE Description of Work. Annex I". EU-FP6-IST-2004-507893, www.target-net.org. 2004.

[7] F. Cappelluti, F. Bonani, S. D. Guerrieri, G. Ghione, M. Peroni, A. Cetronio, and R. Graffitti, "A new dynamic, self-consistent electro-thermal model of power HBTs and a novel interpretation of thermal collapse loci in multi-finger devices," *IEEE Conference on Custom Integrated Circuits*, pp. 397-400, May 2001.

[8] J.Kim and K.Konstantinou, "Digital predistortion of wideband signals based on power amplifier model with memory,"*Electronics Letters*, vol.37, pp.1417-1418, Nov. 2001.

[9] F. H. Raab, P. Asbeck, S. Cripps, P. B. Kenington, Z. B. Popovic, N. Pothecary, J. F. Sevic, and N. O. Sokal, "Power amplifiers and transmitters for RF and microwave," *IEEE Trans. on Microwave Theory and Techniques*, vol. 50, pp. 814-826, March 2002.

[10] C. S. Aitchison, M. Mbabele, M. R. Moazzam, D. Budimir, and F. Ali, "Improvement of third-order intermodulation product of RF and microwave amplifiers by injection," *IEEE Trans. on Microwave Theory and Techniques*, vol. 49, pp. 1148-1154, 2001.

[11] S. Cripps, *Advanced techniques in RF power amplifier design*. Artech House, 2002.

[12] A. Anakabe, J. M. Collantes, J. Portilla, J. Jugo, A. Mallet, L. Lapierre, and J.-P. Fraysse, "Analysis and elimination of parametric oscillations in monolithic power amplifiers," *IEEE MTT-S International Microwave Symposium Digest*, vol. 3, pp. 2181-2184, June 2002.

[13] D. Gil, J. Jugo, et al., "Eliminación de distorsión en amplificadores de RF mediante realimentación pasiva," *URSI, Spanish Chapter, A Coruña*, Sept. 2003.

[14] E. Bertran and G. Montoro, "Model Reference Linearization Based on H-infinity Control," *New Trends in Design of Control Systems, NTDCS, IFAC, S. Kozak, Ed. Smolenice: Pergamon Press*, pp. 77-82, 1997.

[15] A. J. Zozaya and E. Bertran, "Passivity Theory Applied to the Design of Power Amplifier Linearizers," *IEEE Trans. Veh. Tech.*, vol. (accepted for publication:, July 2004).

[16] P. Kenington, *High Linearity RF Amplifier Design*. Artech House, 2000.

[17] N. Pothecary, *Feedforward Linear Power Amplifiers*. Artech House, 1999.

[18] M. E. Gadringer, H. Arthaber, and G. Magerl, "Loop controller for a feedforward amplifier minimizing the measured power signal," *Proc. RAWCON'03*, pp. 281-284, 2003.

[19] P. B. Kenington, P. A. Warr, and R. J. Wilkinson, "Analysis of instability in feedforward loop," *Electronics Letters*, vol. 33, pp. 1669 - 1671, (Sept 25) 1997.

[20] A. J.Zozaya, E. B.Albertí, and J.Berenguer-Sau, "Adaptive feedforward amplifier lineariser using analog circuitry," *Microwave Journal*, vol. 44, pp. 102-114, July 2001.

[21] J. Vuolevi, J. Manninen, and T. Rahkonen., "Cancelling the memory effects in RF power amplifiers," Proc. *IEEE ISCAS*, vol. 1, pp. 57-60, May 2001.

[22] J. Yi, Y. Yang, M. Park, W. Kang, and B. Kim, "Analog predistortion linearizer for high-power RF amplifiers," *IEEE Trans on Microwave Theory and Techniques*, vol. 48, pp. 2709-2713, Dec. 2000.

[23] A. Zhu and T. J. Brazil, "Adaptive Volterra-based predistorter design for RF high power amplifiers," *6th IEEE HFPS Colloquium*, pp. 100-105, 2001.

[24] L. León and J. Portilla, "Predistorsión a diodo en amplificadores bipolares bajo régimen débilmente no lineal," *URSI, Spanish Chapter. A Coruña*, Sept. 2003.

[25] W. Kim and S. Kang, "Analysis of nonlinear behaviour of power HBTs," *IEEE Trans on Microwave Theory and Techniques*, vol. 50, pp. 1714-1722, 2002.

[26] J. R. Gajadharsing, O. Bosma, and P. V. Westen, "Analysis and Design of a 200W LDMOS Based Doherty Amplifier for 3G Base Stations," Proc. IEEE *IMS. Fort Worth*, pp. 529-532, 2004.