Developments in Predistortion and Feedforward Adaptive Power Amplifier Linearisers

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Abstract — **Key issues in predistortion and feedforward linearisation solutions for future complex PA systems destined for a wide range of evolving advanced wireless systems are reviewed in this paper. In particular, digital techniques and adaptive schemes are discussed.**

I. INTRODUCTION

Signal integrity, together with low cost and low power consumption, is the bottleneck of wireless systems. In future, from a 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 [1]. 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.

The main focus on linearisation research is on the most intuitive techniques: predistortion and feedforward. Both approaches have the advantage of large bandwidth operation but, because they are open loop techniques, are sensitive to changes on the device behaviour over time, temperature drifts or, in general, change in any operating condition or even on the signal to be processed. Different digital and analogue solutions can be employed to control gain and phase, through specific feedback mechanisms, in order to improve distortion cancellation, in such a way that most of the solutions are, in fact, a hybrid combination of different techniques. The possibility of developing wideband advanced digital linearising structures, with feedback and adaptability attributes has become quite real.

II. DEVELOPMENTS ON PREDISTORTION LINEARISERS

RF predistortion techniques potentially offer broadband linearisation. Nevertheless, the achieved linearity results depend on a large number of different issues. The successful application of predistortion techniques relies on the accuracy of the PA characterisation and the generation of an equivalent cancelling characteristic. Techniques include RF, intermediate frequency (IF), baseband (BB) digital (in both signal and data predistortion approaches) and analogue predistortion, e.g. [2-3]. Some interesting MMIC oriented RF predistortion have been discussed in [15]. In regard to digital predistorters, most techniques proposed in recent years are based on memoryless models for both the PA and the distorter. In many instances, e.g. for narrowband signals, these can be sufficiently good approximations. However PAs do manifest memory effects, PA-memory. In fact as the PA characteristics will be dynamic in various ways (memory, thermal effects, aging, bias point), the use of fixed memoryless predistortion will show reduced and insufficient cancellation performance under various conditions. This PA-memory problem is growing in prominence as power requirements and capability grow higher, as operating bandwidth requirements grow ever wider and bandwidth efficiency higher – the latter leading to large instantaneous signal envelope crest factors (i.e. wide dynamic power ranges, or peak to average power ratios, PAPR). This bandwidth efficiency, e.g. through use of complex non-constant envelope modulation schemes (NoCEM) which require highly linear transmission paths, competes with power efficiency.

Approaches to building memory into predistortion devices are based on Volterra series, Wiener-Hammerstein models, memory polynomials or neural networks [e.g. 4-7]. Some of these PA-memory models have computationally efficient complex inverse functions and currently are mainly of academic interest. The model proposed in [6], consisting in a relatively simple baseband behavioural model that accommodates memory as well as nonlinear behaviour is regarded as quite effective. A memory polynomial model, e.g. presented in [7] as a Nonlinear Tapped Delay Line (NTDL) digital predistorter, has proven to be effective for predistortion of real PA under typical operating conditions [8].

In digital signal predistortion the coefficients of the predistorter polynomial, which are related to the PA distortion curves, are allocated in a look-up-table (LUT). Pre-computed coefficients are used in the non-adaptive approach; their values are continuously adjusted in the adaptive case. There are current research activities aimed at reducing computational time and memory requirements for effective derivation of the LUT's coefficients. Signal predistortion at IF or BB is preferred over RF it being independent of the final transmit frequency band. Also robustness of circuits and systems in respect of environmental parameters is inversely proportional to frequency. A drawback is the increasing linearity requirements since the up-conversion process can introduce additional distortion. The number of up- and down- converters (or I&Q modulators) may be reduced for predistortion at IF; software radio techniques may be used (i.e., the so called “IF sampling”), this benefit being offset by the increasing bandwidth requirements of new standards. For instance, the symbol rate specified in local multipoint distribution systems, LMDS, (IEEE 802.16) made questionable use of DSPs, as already some manufacturers are producing alternatives based on FPGAs.

Figure 1 shows the basic structure of BB adaptive signal predistorter. Based on the LUT approach three classifications are identified so far: mapping predistorters, polar predistorters and complex-gain based predistorters.

In *Mapping Predistortion* (Fig.2) the complex input signal is decomposed into its real-valued components $i_{in} + jq_{in}$ so as to consider both amplitude (AM-AM distortion) and phase (AM-PM distortion) aspects. These signal components are mapped to other complex predistorted signal components, i_{out} and q_{out}, *i.e.* $i_{out} + jq_{out}$, where $i_{out} = i_{in} + f_i(i_{in}, q_{in})$ and $q_{out} = q_{in} + f_q(i_{in}, q_{in})$. Consequently, two bidimensional tables are used. These will be large tables related to the product of the quantisation range in each dimension. Because the values of both bidimensional tables must to be adjusted, the convergence time may be considerably high.

In *Polar Predistortion* (Fig.3) the input signal amplitude, R_{in}, is used to point and read a table whose output is a real predistortion factor, $R_{out} = F_R(R_{in})$. This factor is then used to modify the original input signal amplitude and for selecting the corresponding predistortion angle,$\Phi_{out} = F_{\Phi}(R_{out})$ which is applied to the signal after the amplitude predistortion is applied. Both tables are one-dimensional, so the access time and the memory requirements are reduced in respect to the previous Mapping Predistortion.

Complex Gain Predistortion (Fig.4) uses the power x_m of the source signal v_m ($x_m = |v_m|^2$) as an address to point to a unique table entry containing the complex values of a corresponding predistortion function $F(x_m)$. The output of this table is used to predistort v_m by computing $v_d = v_m \cdot F(x_m)$. The technique uses 7 or more bits quantisation, needing 128 or more complex digital words to be allocated in memory. This is a significantly reduced table memory resource as compared with Mapping Predistortion. As a consequence, convergence times, at start-up and for each adaptive cycle, are correspondingly reduced.

III. Developments on Feedforward Linearisers

Feedforward linearisers e.g. [2-3, 9] have reduced mathematical complexity in the control law design, and being an open loop structure in principle are unconditionally stable. Having fast time response makes them attractive and suitable for broadband applications (e.g. multicarrier modulations). The open loop nature also has limitations such as high sensitivity to loop maladjustments and device imperfections, which influence both PAE and the degree of linearity. Efficiency of feedforward linearisers depends on three main factors: loop imbalances, device losses and the kind of auxiliary amplifier, which is often also a power amplifier. As the auxiliary amplifier, AA, input signal is composed of distortion components, it exhibits a high PAPR. However operating it at low power levels will be sufficient to achieve cancellation of the main PA’s distortion components.

In order to achieve the signal or IMD suppression (in their respective loops within the lineariser structure) the signals in the reference and active paths must have equal amplitude and delay, and opposite phase. These are the key aspects for correct feedforward design, and they may be approached in two ways. The first and more basic approach is to use and adjust appropriate devices, mainly power combiners, subtracters and delay compensators, if it is possible. The second approach is at the system level, which may be adaptive or not. Combinations of feedforward with feedback or predistortion linearisers, as well as the use of multiple feedforward loops in a hierarchical structure, are typical system level solutions to mitigate feedforward weaknesses. Fig. 5 shows an adaptive monitoring and control scheme of a feedforward amplifier. Two feedback paths have been added to the error and the correction loops in order to correct gain and phase mismatches in its corresponding loop. Gain and phase adjustment components may not necessarily appear as presented in Fig. 5.

Digital adaptive compensation - LMS and other gradient based methods, correlative algorithm, and such like- aims to supervise system behaviour and, if required, to take corrective actions. Hence, performance quality can be maintained throughout the system lifetime. Besides the development of the theoretical support, issues include the effects of imbalances and imperfect cancellation, stability, loop controllers and optimising algorithms, e.g. [10]. Analogue implementations of adaptive loop controllers have been also proposed [11], normally based on analogue versions of the LMS algorithm. Reported IMD reductions (two tone tests) in feedforward amplifiers vary from 70dBc to 40dBc in PCN base-stations, and ACPR reductions over 30dBc have been obtained in EDGE modulations. A DSP-controlled feedforward system [12], closely related to the analogue version of Fig. 5, is shown in Fig. 6. Coefficients α and β are now controlled (adapted) by an algorithm implemented on a DSP. To do so, the signals $v_m(t)$, $v_e(t)$ and $v_o(t)$ are downconverted from the RF domain into BB or IF and digitised. If ADCs available are sufficient for IF operation, this allows avoidance of I&Q modulators and demodulators in the adaptive schemes and greater potential use of software radio techniques. Apart from the IF sampling routines, the rest of the procedures are similar to baseband processing. For both BB and IF schemes new values for α and β are calculated and used to control the vector modulators.

Two problems in the analogue realisation of feedforward adaptation are circumvented by the digital solution. Firstly, in an analogue feedforward system, bandpass correlation of the corresponding RF signals to produce a lowpass result is implemented using analogue mixing. Carrier couplings, DC offsets and 1/f noise in the mixers may cause convergence to incorrect values, thereby degrading IM suppression. In contrast to the analogue solution, the digital solution performs correlation in the digital domain and thus, the mentioned problems are reduced. Secondly, analogue implementation of the correction loop results in long time constants and thus in slow convergence due to the presence of the strong signal at the input of the correction loop, which really acts as a disturbance. This problem can be solved by the use of a digital filter, which suppresses the strong signal component from the sampled output $v_o(t)$.

Further improvements in feedforward amplifiers have been achieved by shifting several analogue components to the digital regime. Fig. 7 shows a feedforward transmitter setup as proposed in [13]. Here the error loop is composed of a behavioural model of the main amplifier and a subtracter. On the one hand, as the calculation of the auxiliary amplifier input signal is decoupled from the main amplifier output signal $v_{MA}(t)$, it can be evaluated in advance. Thus the time delay located after the main amplifier can be avoided. This fact leads to a significant improvement of the efficiency of the whole setup. On the other hand, a control algorithm is needed to parameterise and track the main amplifier model. This model information can further be used to predistort the main amplifier input signal and to reduce the distortion generated by this amplifier. Other improvements come from enhanced control algorithms. In the classical concept two separate loop controllers are used to balance the loops of a feedforward amplifier. Larose and Gannouchi [14] showed that further linearity improvements can be achieved by a 4-dimensional control algorithm which simultaneously tunes both loops in order to maximise the correlation between the input and the feedforward output signal.

IV. Conclusion

Linearisation techniques play a key role for modern evolving advanced wireless transmitters from embedded mobile and handheld terminals, to base stations, HAPs and satellites. A key driver is competing requirements of improved signal fidelity and PA system PAE in contexts of single and multicarrier NoCEM air-interface modes to simultaneous multimode transmitter systems. Especially the ever-widening signal bandwidth is causing a lot of PA linearisation research efforts to be focussed on predistortion and feedforward linearization solutions. At present, solutions –these two and others– offer finite though modest linearity behavioural improvements. The level of benefit available is a function not just of the degree of linearization achieved but also of the air-interface mode(s). Their adequacy depends on the context but they can help achieve linearity goals when working together with other options. Nevertheless, different practical PA 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 the potential performance. Development of lineariser adaptivity is the response to such problems. Realising such adaptivity effectively, robustly efficiently in modern designs of feedforward and predistortion linearization schemes is a significant research challenge and is as important for the continued evolution of wireless communications as the invention of the appropriate high power, high frequency, broad band PAs.

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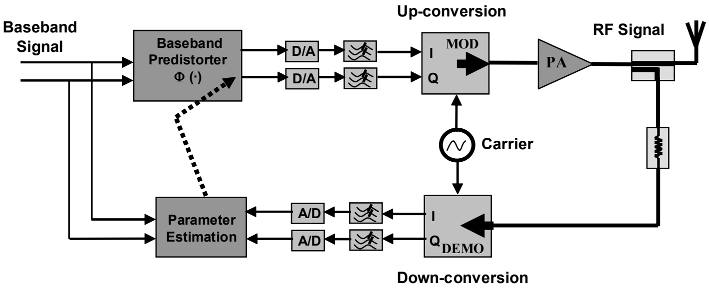

Fig. 1 Basic structure of a base-band adaptive predistorter

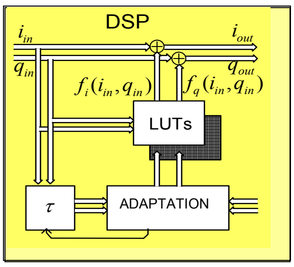

Fig. 2. Mapping Predistortion

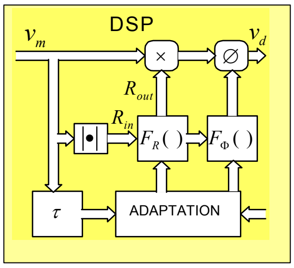

Fig. 3. Polar Predistortion

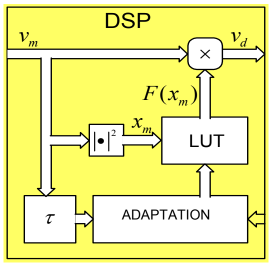

Fig. 4. Complex-Gain Predistortion

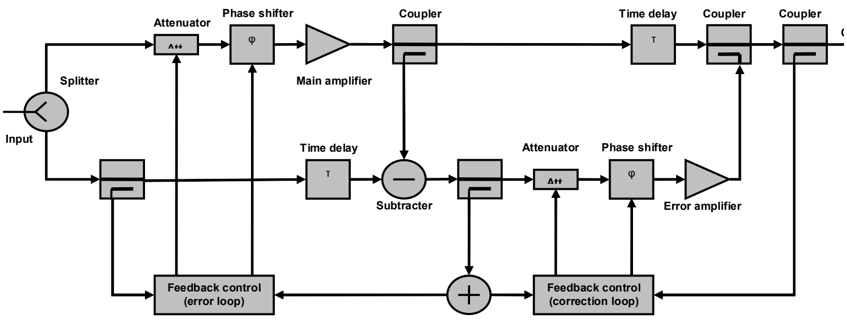

Fig. 5. Adaptive monitoring and control of a feedforward amplifier

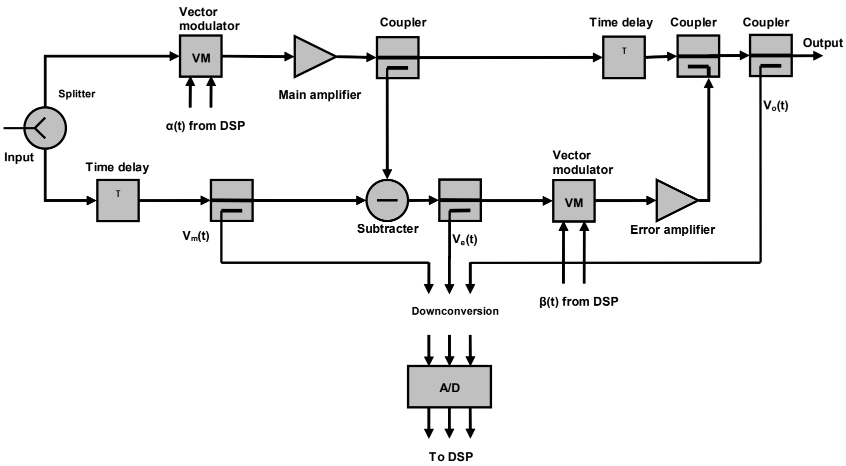

Fig. 6. DSP controlled adaptive feedforward amplifier

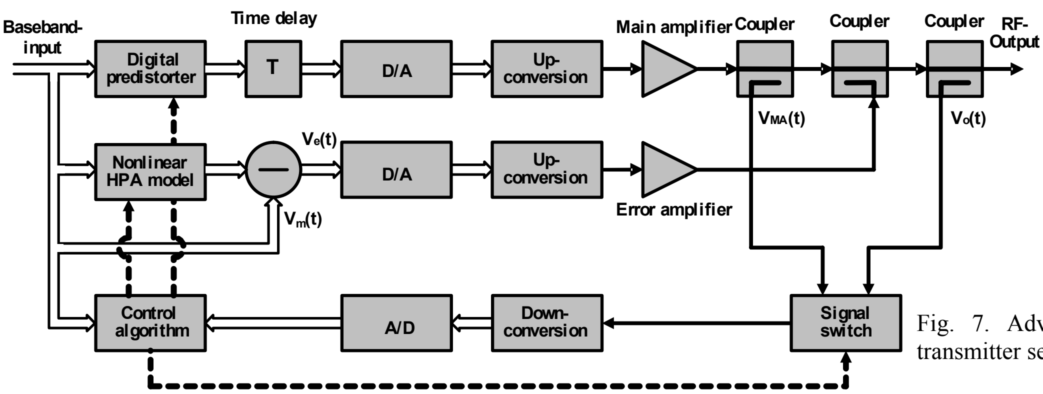

Fig. 7. Advanced feedforward transmitter setup