# Digital Signal Processing Techniques to Compensate for RF Imperfections in Advanced Transmitter Architectures

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*Abstract*— **Evolution of wireless standards toward multi-communication pipe radios such as cellular, connectivity and broadcast pipes leads to technical challenges. On the transmitter point of view, the main difficulty is achieving standards linearity constraint while maintaining high efficiency of the power amplifier. After a presentation of the state of the art in transmitter architectures including their limitations in relation with modulation schemes, we present how digital signal processing can be implemented to compensate for RF imperfections. We demonstrate that the strategy for developing new transmitter architecture has to be based on a total interaction between digital signal processing and pure radio concepts.**

## I. Introduction

The rapid evolution of radiocommunication systems and the high data rate demand for data transmissions require efficient modulation schemes in order to optimize the spectral efficiency of these systems. The complexity of the modulation increased from Quadrature Amplitude Modulation (QAM) for 3G system, to Orthogonal Frequency Data Multiplex Modulation (OFDM) for 4G and DVB-T/H systems.

The choice of the TX architecture will be contingent upon the following modulation properties: peak to average power ratio (PAPR), bandwidth of both baseband signals and modulated RF signal. For an OFDM modulation (64 carriers, QPSK), the PAPR can be up to 12dB [1], whereas for a 16QAM modulation, the PAPR is about 6dB [2]. This PAPR directly constraints the linearity of the power amplifier (PA). Transmitter performances are evaluated in term of Error Vector Magnitude (EVM), output spectrum and Adjacent Channel Power Ratio (ACPR) or Adjacent Channel power Leakage Ratio (ACLR).

One can either choose a conventional architecture, such as zero intermediate frequency transmitter (ZIF), with additional digital signal processing to alleviate distortions, or alternative architectures such as polar modulation or digital transmitter. Nonetheless, these latter architectures suffer from other imperfections that would have to be tackled with signal processing algorithms. In the first part of the article, we give a state of the art in transmitter architecture and point out the main weaknesses of the different solutions. In the second part, we present few digital signal processing techniques that can be employed to improve the transmitter performances.

## II. Transmitter architecture

Wireless transmitters are mainly based on two different architectures: direct up conversion and polar modulation.

### A. Direct up conversion transmitter

*1) Classical I/Q transmitter:* The classical I/Q ZIF transmitter is presented on Fig. 1. The in phase and quadrature components of the baseband signals, digitally generated and converted into analog signals, are sent at the input of the I/Q modulator after low pass filtering. The local oscillator drives the mixer for RF modulation. The RF signal is then fed to the power amplifier, after preamplification and filtering. Although this architecture is very simple, it suffers from various imperfections: I/Q imbalance, noise floor and linearity of the power amplifier. The imbalance can be thwart by fine tuning of the modulator with either feedback or calibration techniques [3]. The output noise remains a weak point because it imposes a filter at the output of the mixer and according to the system, at the output of the PA (GSM case).

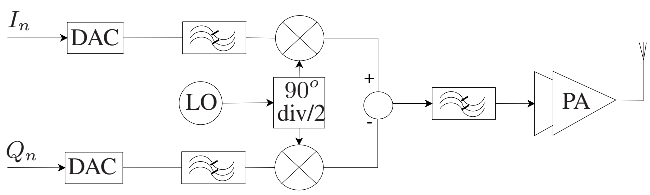


Fig. 1. I/Q ZIF transmitter

The roadblock is the power amplifier linearity, in terms of AM/AM and AM/PM distortions and memory effects. For non constant envelope modulations, the PA has to be backed off, at the detriment of the efficiency, in order to fulfill ACPR standards requirements. For the W-CDMA, this back off is on the order of 3-6dB, whereas for an OFDM modulation, its value increases to 8-10dB [4]. Otherwise, either correction or predistortion have to be employed, or alternative architectures can be chosen.

*2) Transmitters using $\Sigma\Delta$ modulators:* The development of silicon technologies allows the design of high efficiency switched PA. For non constant envelope modulations, one can consider the use of a RF class S power amplifier. The principle consists in transforming the RF signal into a Pulse Width Modulated (PWM) signal which is then amplified by the switched PA and filtered, as presented on Fig. 2. The PWM transformation is preferably proceeded with a $\Sigma\Delta$ modulator to reduce in-band spurious levels. Various architectures going by that principle are proposed, some based on bandpass RF Sigma Delta modulator [5], fully digital [6] or based on the multiplication of a phase modulated signal and a PWM coded envelope signal [7]. For all these versions, the limiting point is the output spectrum. Indeed, the $\Sigma\Delta$ modulator reshapes and rejects the quantification noise outside the bandpass of the signal and the spectrum is replicated (sampling system). The output has then to be strongly filtered outside the bandpass with as a drawback the filter losses. Consequently, these architectures move the constraint from the PA to the filter.

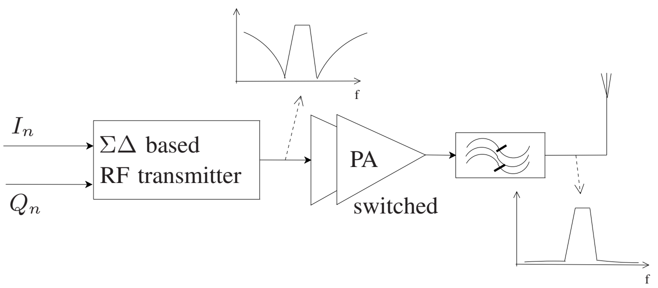


Fig. 2. Transmitters using $\Sigma\Delta$ modulators

### B. Polar modulation

*1) Polar transmitter:* Direct up conversion transmitters are based on the rectangular decomposition of the modulated complex signal whereas the polar modulation uses the expression of its magnitude and its phase. The phase component is translated to RF frequency using a PLL and the magnitude signal is restored through the power supply of the PA, see Fig. 3.

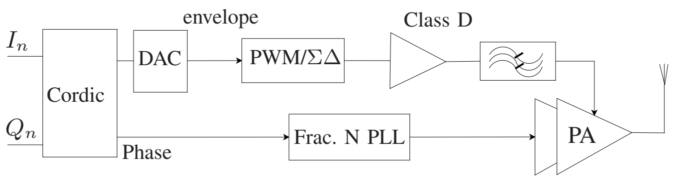


Fig. 3. Polar transmitter

This solution enables a high reduction of the power consumption of the transmitter (efficient PA) and alleviate the common linearity problem of the PA.

The polar decomposition of a complex signal, by opposition to the rectangular expression, widen the spectrum of both components. For the phase path, this often implies the use of a two point phase modulator in a $\Sigma\Delta$ controlled fractional N synthesizer [8].

The restoration procedure presents two difficulties. The first concern is the linearity of the restoration control on the PA through the voltage supply. Analog solutions of polar modulation require a feedback loop including an envelope detector and a comparator as demonstrated in [9]. A digital approach could be made using a predistortion of the envelope signal. The second tough concern in the envelope processing path is the design of the wide band modulated supply voltage, with either a DC-DC converter based on a class S amplification (classical PWM or $\Sigma\Delta$ PWM [10]) or switching regulator. The efficiency of the regulator is directly linked to the switching frequency that is a trade off between the bandwidth of the envelope signal and the allowed distortions. As an illustration of the complexity of the power supply generation for the W-CDMA, in term of sampling frequency, we can cite the PWM buck converter running at 50MHz [11]. To ease the conception of this supply voltage, crest factor reduction is employed, see section III-D.

An other highly sensitive point of this architecture is the signal paths desynchronization effect. This effect is linked to the fact that signals are differently processed. This delay mismatch which degrades both ACPR (ACLR) and EVM values, is mainly due to the passive filter (LC) inserted between the output of the supply modulated system and the supply pin of the RF PA. It is demonstrated in [12] that in the case of a 16QAM 64 subcarriers OFDM modulation, the disalignment as be to lower than $T_s/30$, $T_s$ being the symbol period, to limit ACPR. Thus, it is mandatory to compensate for these delays using either a production tuning or adaptive algorithms.

*2) Polar digital transmitter:* The development of advanced CMOS technology opens up the way to new architecture solutions, less analog, more digital. Digital transmitter architectures are issued from polar TX architecture well suited for CMOS implementation. Nevertheless, we shall mention that these solutions do not include the PA stage. The output signal is amplified by an external PA stage. The transmitter still requires the implementation of a linearization procedure.

A fully digital transmitter is demonstrated in [13] and is presented Fig. 4 (a). The heart of this solution is a Digitally Controlled Oscillator (DCO) based on $\Sigma\Delta$ controlled varactor banks in an frequency modulated all digital PLL (ADPLL). The envelope restoration is done through a Digitally controlled PA (DPA) made of a large array of MOS switches operating near class E mode. The RF amplitude is linked to the number of active switches.

Instead of a DPA, a digital envelope demodulator is presented in [14], Fig. 4 (b), based on a thermometer-coded DAC principles. An array of transistors is driven by the phase modulated signal and the gates of the switched transistors are driven by a digital representation of the envelope signal.

## III. RF IMPERFECTION CORRECTION WITH DIGITAL SIGNAL PROCESSING

In the previous section, we presented the main transmitter architecture solutions, from analog to fully digital, and

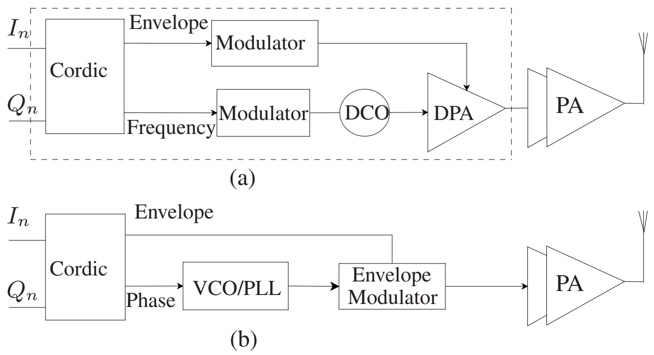


Fig. 4. Digital polar transmitters

highlighted their main weaknesses. We now describe that DSP techniques can be useful for correction and compensation of TX impairments. Therefore they can have a crucial impact on transmitter architectures viability. We show that in addition to digital implementation, adaptive algorithms are of high interest for unsupervised tuning. We begin with a presentation of a Least Mean Square (LMS) algorithm in the context of RF default compensation. Predistortion and polar transmitter delay correction principles are then exposed. Finally, solutions for crest factor reduction are mentioned.

### *A. Introduction to LMS algorithm*

Many correction algorithms are based on the minimization of the mean square error between two signals. Let us denote $X(t)$ the complex envelope of the first signal and $Z(t)$ the complex envelope second one. The general principle consists in finding the parameters $\alpha_i$ of a function $F(\bullet)$ in order to minimize the mean square of the error

$$e(t) = X(t) - F(Z(t)). \quad (1)$$

If $X(t)$ is the reference signal and $Z(t)$ the output signal, the procedure amounts to the correction of the defaults, whereas if $X(t)$ is the output and $Z(t)$ the input then the procedure solves an identification problem. The criteria is:

$$J(\alpha_1, ..., \alpha_n) = E\left[|e(t)|^2\right] = E\left[|X(t) - F(Z(t))|^2\right] \quad (2)$$

where $E(\bullet)$ is the statistical expectation operator.
It is often advantageous, since the exact solution to (2) can be either unpracticable or non explicit, to attain the solution thanks to a descent gradient algorithm. It consists in iterating the following formula for each $\alpha_i$:

$$\alpha_i(n+1) = \alpha_i(n) - \gamma_i(n) \left. \frac{\partial J(\alpha_1, ..., \alpha_n)}{\partial \alpha_i} \right|_{\alpha_i = \alpha_i(n)}, \quad (3)$$

with $\gamma_i$ the adaptation step of the algorithm that possibly depends on the iteration index $n$. This parameter impacts the convergence time and the stability of the algorithm.

Often, we will not have the mathematical expressions of statistical expectations involved and we have to resort to stochastic approximations of the theoretical recursions. A popular solution in adaptive filtering is the LMS algorithm that simply consists in omitting the statistical expectation. The LMS then involves the instantaneous gradient rather than the (correct) statistical average. Furthermore, the equations are updated at each new sample. This gives:

$$\alpha_i(n+1) = \alpha_i(n) - 2\gamma_i(n)\ Re\left\{ e(t) \left( \frac{\partial e(t)}{\partial \alpha_i} \right)^* \right\} \Bigg|_{t(n)}. \quad (4)$$

The two next sections present correction procedures that profits from the LMS approach.

### *B. Digital predistortion*

Digital predistortion algorithms aim to compensate for non linear and memory effects of the PA. This usually requires a feedback loop to adjust in real time the predistortion parameters as in Fig. 5. Different models can be considered from which we can quote: Volterra series, memory polynomial models [15] or block oriented model, referred to as the Wiener and Hammerstein nonlinear model.

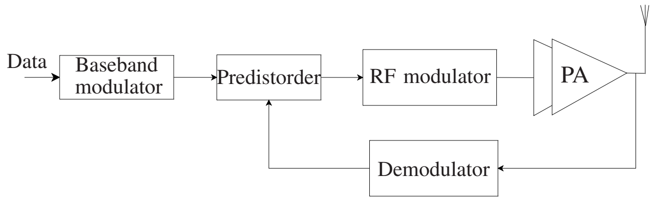


Fig. 5. Predistortion principle

The Hammerstein model is used as the representation of the PA nonlinear behaviors, with a memoryless distortion block followed by a linear subsystem $h(n)$ which represents the memory effect. The associated predistorder is the Wiener model formed by a linear subsystem followed by a predistortion memoryless system.

For the PA memoryless distortion, the predistortion can be implemented using a general power series or with a look-up table (LUT). For the polynomial model, the principle relies on the identification of a polynomial function which represents the inverse characteristic of the PA. The LUT predistorder consists in addressing a table which contains a quantified version of this inverse characteristic. The first solution suffers from curve fitting limitations whereas the second suffers from quantization aspects [16]. In both cases, as for memory polynomial model, the LMS algorithm is used. Concerning the nonlinear subsystem characterized by its impulse response, [17] proposes a frequency domain method for the identification of the Hammerstein model. The Wiener is then deduced from the identification.

### *C. Digital delay correction in polar transmitter*

As previously indicated, polar transmitter is very sensitive to delay mismatch between envelope and phase signals. An adaptive solution is proposed in [12] where the delays are adjusted by comparison between the output signal and the reference one. A point here is that instead of adopting very high sampling frequencies in order to get the required precision, digital interpolation is implemented. This is a more effective solution as it keeps reasonable sampling frequencies and save consumption. Interpolator filters are well suited for digital implementation using the Farrow structure. The effective performances of the algorithm for a 3G system are illustrated on Fig. 6 for an initial desynchronisation of 0.5 symbol period. The output spectrum ACPR is lowered to a residual noise floor corresponding to the interpolation error which is a function of both interpolator order and oversampling frequency.

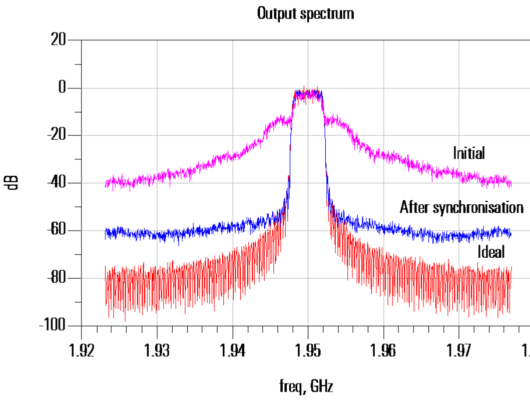


Fig. 6. Result of delay mismatch correction on the output spectrum

### *D. Crest factor reduction*

An other issue in digital signal processing is the reduction of the PAPR value also called crest factor. The crest factor is the ratio between the peak value of the signal and its rms value. Crest factor reduction can be applied on both cartesian or polar architectures. It is often implemented in the case of BTS transmitter where multichannel imply very high value of PAPR. An effective and simple solution is a peak limiter. Although the clipping level is chosen so as to lower the resulting degradations, this technique induces both spectral regrowths and discontinuities on the time domain signal. To reduce impacts of crest reduction, few analog or digital solutions can be employed. The technique adopted in [18] consists in subtracting a cancellation pulse from each time domain peak signal over a predefined threshold value, implying that N samples of the original signal are modified during the digital generation. The pulse is in fact spectrally shaped to unaffect the ACLR of the modulated signal. As a result, distortions only impacts the output EVM. An analog approach is presented in [19] for a polar modulation. A soft clipping is obtained by subtracting to the original signal the part of the signal over the threshold value multiplied by a smooth function, a Kaiser windowed sinc function for example.

## IV. Conclusions

In this article we presented both transmitter architectures and digital signal processing used to compensate for analog imperfections. We presented separately each DSP technique for enhancement of transmitters performances. Obviously, all these solutions have to be jointly optimized, eg. [20]. We highlight that in addition to digital integration of transceiver solutions, adaptive algorithms, which enable unsupervised calibration, are the key to fulfill system requirements. It is interesting to go further by tackling TX architecture as a whole, including both signal processing and RF parts, and see how far we can use signal processing concepts, as those employed in receiver part, to improve both integration and performances.

## References


[1] H. G. Myung, J. Lim, and D. J. Goodman, "Single carrier FDMA for uplink wireless transmission," *IEEE Vehicular Technology Magazine*, pp. 30–38, sept 2006.

[2] I. Hibon, C. Berland, D. Pache, *et al.*, "Linear transmitter architecture using a 1-bit $\Sigma\Delta$," in *Proc. European Microwave Week 2005 / ECWT*, CNIT La Défense, Paris, Oct. 2005, pp. 321–324.

[3] E. E. Tsui and J. Lin, "Adaptive IQ imbalance correction for ofdm systems with frequency and timing offsets," in *Proc. IEEE Global Telecommunications Conference GLOBECOM '04*, vol. 6, CNIT La Défense, Paris, Nov. 2004, pp. 4004 – 4010.

[4] J. Groe, "Polar transmitters for wireless communications," *IEEE Communications Magazine*, pp. 58–63, sept 2007.

[5] A. Jayaraman, P. F. Chen, G. Hanington, *et al.*, "Linear high-efficiency microwave power amplifiers using bandpass sigma delta modulators," *IEEE Microwave and Guided Wave Letters*, vol. 8, pp. 121–123, mar 1998.

[6] A. Jerng and C. G. Sodini, "A wideband $\Sigma\Delta$ digital-RF modulator for high data rate transmitters," *IEEE J. Solid-State Circuits*, vol. 42, no. 8, pp. 121–123, aug 2007.

[7] C. Berland, I. Hibon, J. F. Bercher, *et al.*, "A transmitter architecture for nonconstant envelope modulation," *IEEE Trans. Circuits Syst. II*, vol. 53, no. 1, pp. 13–17, jan 2006.

[8] Y. Huang, J. H. Mikkensen, and T. Larsen, "Investigation of polar transmitters for WCDMA handset applications," in *Proc. 24th Norchip Conference*, nov 2006, pp. 155–158.

[9] K. Kunihiro, K. Takahashi, S. Yamanouchi, *et al.*, "A polar transmitter using a linear-assisted delta-modulation envelope amplifier for WCDMA applications," in *Proc. European Microwave Week 2006*, Manchester, UK, Sept. 2006, pp. 136–140.

[10] J. Zhang, B. Shi, and Y. Lina, "Performance evaluation on polar transmitters uninsg delta and delta-sigma modulations," in *Proc. 6th International Conference on Information, Communications & Signal Processing*, dec 2007, pp. 1–4.

[11] J. H. Chen, P. Fedorenko, and J. S. Kenney, "A low voltage W-CDMA polar transmitter with digital envelope path gain compensation," *IEEE Microwave and Wireless Component letters*, vol. 16, no. 7, jul 2006.

[12] J. F. Bercher and C. Berland, "Envelope and phase delays correction in an EER radio architecture," *Analog Integrated Circuits and Signal Processing*, vol. 55, no. 1, pp. 21–35, apr 2008.

[13] R. B. Staszewski, J. L. Wallberg, S. Reseq, *et al.*, "All-digital PLL and transmitter for mobile phones," *IEEE J. Solid-State Circuits*, vol. 40, no. 12, pp. 2469–2482, dec 2005.

[14] P. T. M. V. Zeijl and M. Collados, "A digital envelope modulator for a WLAN OFDM polar transmitter in 90nm cmos," *IEEE J. Solid-State Circuits*, vol. 40, no. 10, pp. 2204–2211, oct 2007.

[15] P. Varahram and Z.Atlasbaf, "Adaptive digital predistortion for high power amplifiers with memory effects," in *Proc. Microwave Conference, Asia-Pacific Conference*, vol. 3, dec 2005.

[16] H. H. Chen, C. Lin, P. C. Huang, *et al.*, "Joint polynomial and look-up-table predistortion power amplifier linearization," *IEEE Trans. Circuits Syst. II*, vol. 53, no. 8, aug 2006.

[17] T. Wang and J. Ilow, "Compensation of nonlinear distortions with memory effects in digital transmitters," in *Proc. 2nd Annual Conference on Communication Networks and Services Research*, may '2004, pp. 3–9.

[18] A. Wegener, "High-performance crest factor reduction processor for W-CDMA and OFDM applications," in *Proc. IEEE Radio Frequency Integrated Circuits (RFIC) Symposium*, jun 2006.

[19] J. H. Chen and J. S. Kenney, "A crest factor reduction technique for W-CDMA polar transmitters," in *Proc. IEEE Radio and Wireless Symposium*, jan 2007, pp. 345–348.

[20] R. Sperlich, Y. Park, G. Copeland, *et al.*, "Power amplifier linearization with digital pre-distortion and crest factor reduction," *Proc. IEEE MTT-S International*, vol. 2, pp. 669–672, June 2004.