Digital Predistortion for Wideband High Efficiency RF Power Amplifiers for High Throughput Satellites

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ABSTRACT

In satellite communications, there is considerable increasing demand to support higher data throughput on necessarily pre-allocated bandwidth channels. In communication payloads, the DC-to-RF power conversion efficiency is crucial and most of the DC power is consumed by the RF Power Amplifier (PA). Thus, maximizing the PA efficiency while maintaining low distortion is key. Both power and bandwidth efficiency could be increased by employing digital pre-distortion (DPD). This paper focuses on state-of-the-art DPD techniques and possible developments to fit in satellite communications. The toleration of effects of temperature, supply voltage, and load mismatch variations, are investigated. This research suggests that there are benefits to be gained; employing spectrally efficient modulation techniques and transmitting a high fidelity signal to result in less expensive space and ground segment transmitters. A proof-of-concept by simulation is presented for ultra-wideband applications. A novel DPD system architecture is proposed where envelope tracking (ET) of the driver amplifier (DA) and load modulation of the PA are used to maximize the overall PAE while high PAPR signals can be used. To the best of the authors' knowledge, this is the first time that DPD has been proposed for large fractional bandwidth high PAPR signals for satellite communications.

INTRODUCTION

In future satellite communications links, a huge amount of data has to be transmitted due to the increase in the accuracy of the payload, number of subscribers or the need for transmission of a large volume of data within a limited period of time (maximum visibility). This could be achieved by employing a spectrally efficient modulation technique (SEMT), e.g. M-ary QAM, which necessarily has a non-constant envelope with increased information carrying ability per unit bandwidth. However, this leads to very high constraints on the linearity of the transmitter power amplifier (PA).

Linear PAs, although suitable for SEMTs, are the main source of power consumption in the transmitter. Their use results in low overall transmitter efficiency due to the wasted power as a heat which necessarily requires thermal management. In contrast, high efficiency PA is rather a complex nonlinear system (e.g. switch), and is not suitable for transmission of SEMTs.

On the one hand, due to variations in the amplitude of generated SEMT and saturated (i.e. power efficient) PA nonlinearities the transmitted SEMT occupies larger bandwidth (i.e. spectral regrowth) results in out-of-band distortion that disturbs the adjacent channels. This may cause noncompliance to relevant regulatory standards (e.g. International Telecommunications Union ITU) and may violate the predefined spectral mask constraint. On the other hand, SEMTs have a weak tolerance to amplitude disturbances that occur in the nonlinear amplification process since its information carrying ability depends on the signal amplitude. This may cause in-band distortion in the transmitted signal (i.e. error vector magnitude EVM) which consequently deteriorates the receiver performance in terms of bit error rate (BER). In addition, the overall transmitter power efficiency significantly deteriorates if a high peak-to-average power ratio (PAPR) signal is used where more power back-off is required. Therefore, high efficiency PAs should be used which, unfortunately, suffer from strong nonlinearities.

High efficiency PAs show a dynamic nonlinear behavior (memory effects) if a wideband fast varying envelope signal is used. In this case, the amplified signal depends on the current and past input symbols.

To satisfy PA linearity requirements as well as to improve overall system efficiency, it is necessary to undertake some linearization. Traditionally, PA static nonlinearity has been mitigated by compromising the PA DC-to-RF power conversion efficiency where output power back-off is required. However, power backing-off is not suitable for battery operated (on-board payload) or high running costs (ground segment) systems. Moreover, power back-off cannot cope with distortion due to memory effects, hence the need for a linearization approach that achieves low in-band and out-of-band distortion and high power efficiency simultaneously. Several linearization techniques, which are analog in essence, have been proposed to cope with the PA nonlinear behavior (e.g. Feedforward, RF predistortion and LINC). However, digital predistortion DPD has shown a good simultaneous efficiency and linearity improvements for a transmitter. In addition, DPD is implemented in on FPGA or ASIC, thus immune to components tolerance or aging.

In the following, DPD characterization, techniques, and suitability to fit in satellite communications are first presented. A proof of concept for wideband DPD by simulation and experimental results on a demonstration amplifier for band-limited DPD are shown. A novel DPD+PA architecture for wideband high PAPR signals is then proposed.

DIGITAL PREDISTORTION

DPD is adopted in terrestrial communications where baseband data are manipulated digitally to reverse the effect of the PA nonlinear behavior, Figure 1. The first DPD was proposed in [1] to compensate for static nonlinear amplification of a memoryless narrowband PA.

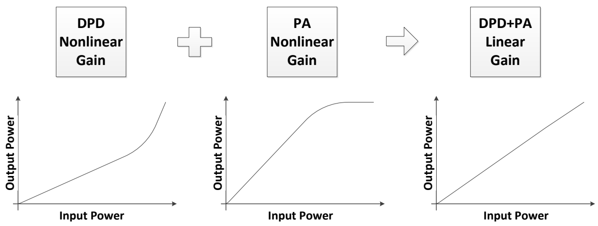

Figure 1 DPD Linearization Effect on PA Output

In small fractional bandwidth systems, it is not feasible to filter out the out-of-band spectral regrowth due to the required high-Q filter. PA DPD-based linearization is achieved by digitally processing the in-phase (I) and quadrature (Q) baseband data so that frequency components are generated within a bandwidth equal to that of the spectral regrowth (normally 5 times the modulated signal bandwidth) to compensate for the distortion due to PA nonlinearities. Thus, a wideband transmitter should be used. This digital "pre-processing" allows the PA to be operated up to saturation point and mitigates the in-band and out-of-band distortions due to nonlinear behavior. Hence, the output power back-off is significantly reduced.

DPD Hardware Test Setup

Figure 2 shows a block diagram for a typical DPD+PA hardware test setup. What follows is a description of the DPD model coefficient extraction procedure. The I and Q data of the test signal are generated in Matlab then downloaded on an arbitrary waveform generator (AWG). These data modulates an RF carrier in a Vector Signal Generator (VSG) where the signal upconversion is achieved. The modulated RF carrier feeds the PA and a driver amplifier (DA) may be used for high power PAs (HPA). A Vector Signal Analyzer (VSA) downconverts then demodulates the RF modulated carrier. This allows extraction of the DPD model coefficients (in a PC) by comparing the demodulated I and Q data of the original (PA is removed) and distorted signal (i.e. amplified signal by the PA). DPD+PA performance is verified by downloading the predistorter I and Q data on the AWG and measure the PA output.

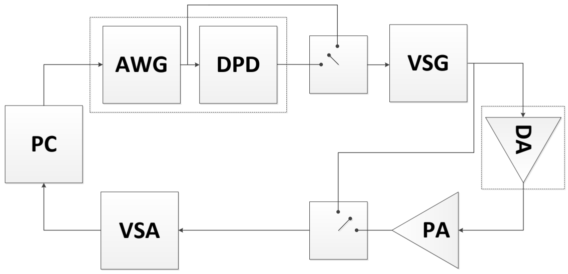

Figure 2: Typical DPD System Hardware Test Setup

Characterization of PA Nonlinearity Inverse Function

In this section, some DPD linearization models are presented. The Volterra series is first proposed in [2] to characterize nonlinear systems. Extensive research was done to develop a DPD using Volterra series and examples can be found in [3] and [4]. Nevertheless, Volterra series has a large number of coefficients, thus complex in terms of implementation. In contrast, a simplified Volterra series version could be used with less implementation complexity while satisfactory nonlinearity characterization is achieved as shown in [5].

The MP DPD model based on nonlinear auto-regressive moving average (NARMA) structure has been proposed in [6]. NARMA is built by a set of basic predistortion cells (BPC) which consists mainly of complex multiplier and LUT and is found to be suitable for FPGA implementation. A heuristic algorithm is used to examine the proper nonlinear function order and the memory depth [7].

Some DPD Techniques

A DPD by injection is explained in [8] where an iterative computational algorithm is used to inject, in baseband, a number of complex frequency components. These frequency components compensate for the intermodulation (IM) distortion. However, this technique is not suitable for wideband signals due to the expected huge number of these frequency components that lead to a very complex implementation. Moreover, no implementation on a standalone platform was proved.

To maintain linear amplification for high PAPR signals using linear PAs, two power back-offs should be done; the first to avoid nonlinear part of the gain curve and the second which is equal to the PAPR as shown in Figure 3. Even if DPD is used to alleviate the 1st back-off, either supply or load modulation could only mitigate the 2nd back-off to achieve acceptable overall power added efficiency (PAE).

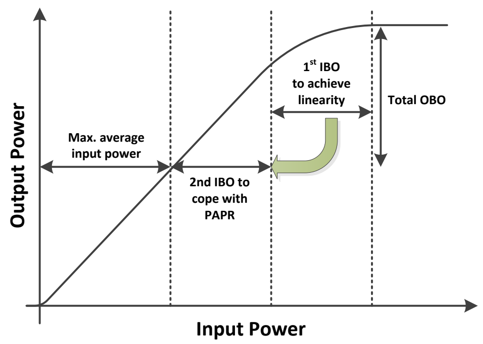

Figure 3 PA OBO for High PAPR Signal

Slow envelope dependent DPD for envelope tracking (ET) PAs is proposed in [9] where an envelope amplifier (EA) modulates the supply of the PA. The slew-rate constraint on the EA limits its capability to track the signal envelope. Thus, a band limited version of the signal envelope is generated to meet the EA requirements. This causes distortion at the PA output. Accordingly, the nominal and slow version of the signal envelope is accounted for in the DPD model.

Varactors based load modulation is shown in [10]. The PA load impedance is dynamically controlled via a varactor. The load-pull data is used to shape the control signal with no bandwidth limitation (compared to ET) to achieve maximum PAE. For high power PAs, parallel varactors could be used.

Adaptive versus Non-Adaptive DPD

In mobile communications, PA electrical characteristics are mainly dependent on fast time-varying ambient and circuit parameters including supply voltage, temperature, and load mismatch. Consequently, real-time adaptation for the user handset is of great importance to maintain compliance to the spectral emissions and reliable reception of the information [11]. This is done at the expense of additional power and hardware overhead to downconvert and demodulates, with accurate time alignment, a wideband RF signal with spectral regrowth. Fortunately, users are allocated a narrow bandwidth which although has a small fractional bandwidth does not suffer from memory effects. Therefore, memoryless DPD models may cope with the static nonlinearity and are usually implemented using updatable LUTs [12].

In contrast, in satellite communications these time-varying ambient and circuit parameters does not exist or has a negligible effect. Firstly, a regulated power supply (< 1%) is used onboard. Secondly, reflection from a nearby object does not exist, so mainly there is no load mismatch to due reflecting objects. Next, although the temperature variation range is between -10^{o} to +80^{o} in which the PA gain varies by several dBs, a PA with on-chip temperature compensation circuit could be used to reduce this gain variation to approximately 1dB [13]. Finally, the aging effect should be taken into consideration. Industrial constraints consider that a reliable PA should have less than 10% of characteristics variation after ten years of operation. As a result, approximately 0.5dB gain decrease is expected [14].

Having reviewed the above mentioned slow and fast time-varying PA dependent parameters onboard, the authors concludes that non-adaptive DPD could tolerate these slow varying parameters.

Band-limited DPD for Large Fractional BW Signals

The Band-limited DPD best fits large fractional bandwidth signals where spectral regrowth can be filtered out easily and the predistortion fixes only the in-band distortion. This has been proposed in [15] and [16]. In [15], the filtered PA output was measured to extract the conventional DPD model coefficients. On the other hand, filters are added to the DPD structure to filter out the bandwidth spreading at the DPD output, [16], where in-band distortion improvement is achieved.

Future high throughput satellites, where a large fractional bandwidth is expected, could benefit from adopting band-limited-DPD. These benefits, compared to using a conventional DPD, could be: less hardware complexity and less processing power as a result of processing a bandwidth comparable to the original modulated signal bandwidth compared to 5 times bandwidth in conventional DPD.

SIMULATION AND EXPERIMENTAL RESULTS

In this section, a proof of concept by simulation is presented followed by experimental results for different bandwidth signals. NARMA-based DPD model is used and is characterized by Equation 1 to 5, [6].

$$\hat{y}_A(k) = \sum_{i=0}^{N} \hat{f}_i(x_A(k-\tau_i)) - \sum_{j=1}^{D} \hat{g}_j(y_A(k-\tau_j)) \qquad (1)$$

$$\hat{f}_i(x_A(k-\tau_i)) = \sum_{p=0}^{P} \alpha_{pi}.x_A(k-\tau_i)|x_A(k-\tau_i)|^p \qquad (2)$$

$$\hat{g}_i(y_A(k-\tau_j)) = \sum_{p=0}^{P} \beta_{pj}.y_A(k-\tau_j)|y_A(k-\tau_j)|^p \qquad (3)$$

where P is the nonlinear functions order, α_{pj} and β_{pi} are the nonlinear functions coefficients, and N and D are the memory depths for the nonlinear functions of the NARMA model, i.e. f_i and g_i. A least squares (LS) solution for the above equations is shown in equation 4:

$$\hat{\delta} = (Q^H Q)^{-1} Q^H y_A \qquad (4)$$

where $\hat{\delta}$ is a matrix that contains all coefficients. The cost function to be minimized to obtain NARMA model parameters is the normalized means square error (NMSE), Equation 5:

$$J(k) = |\bar{e}(k)|^2 = |(y(k) - \delta^H Q)/y(k)|^2 \qquad (5)$$

DPD+PA Simulations

A NARMA-based DPD model for 1GHz 1024-QAM ultra wideband signal modulated on a 4GHz carrier using MGA-545P8 PA model on Agilent ADS© software. Three iterations are done to attain further ACPR improvement. Figure 4 shows the original signal spectrum (green), PA distorted output (blue), and DPD+PA output for the three iteration (red, yellow, and green, respectively). The vertical and horizontal axes are set to 0 to -110 dBm and 1 to 7 GHz, respectively. Approximately 12 dB improvement in ACPR is achieved while -23dB NMSE is maintained.

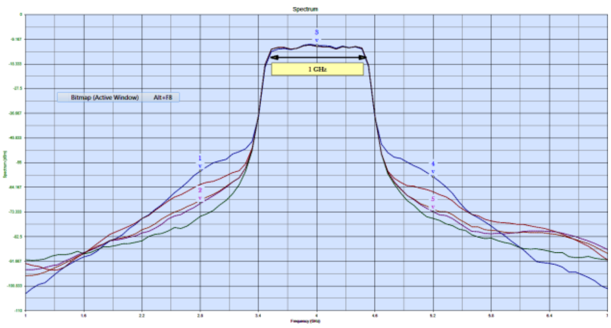

Figure 4 DPD+PA ACPR Improvement

DPD+PA Implementation on Test Platform

A demonstration low noise amplifier (ZFL-500LN+ Mini-Circuits©) is used to demonstrate the effect of band limited DPD on the DPD+PA performance. The following equipment are used, Figure 5:

- Agilent© N5182B MXG RF VSG.
- Agilent© N9030A PXA VSA.
- TTi EL302Tv triple power supply.

The VSG and VSA are connected through a network switch for control and data exachnge via a PC. Syncronization is establisthed by properly connecteing a 10 MHz refernece, trigger, and event ports.

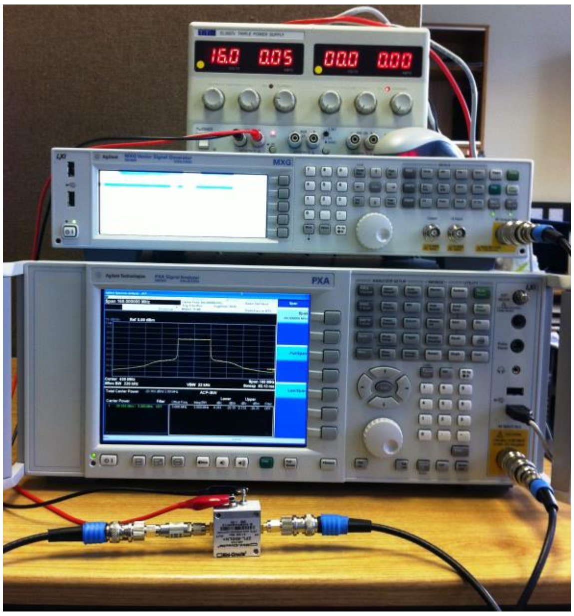

Figure 5 Hardware Test Setup for DPD+PA

Figure 6 to Figure 8 show the measured spectra of original signal, distorted PA output, and NARMA based DPD+PA for three different modulated test signals:

- 10MHz LTE DL (QPSK)
- 32 MHz 1024-QAM
- 50 MHz 1024-QAM

The ACPR and NMSE for DPD+PA are measured for each modulated signal and are summarized in Table 1. It is to be noted that a good NMSE could be achieved in all cases while a good ACPR is achieved only for the 10 MHz BW signal. This is justified as follows; due to the limited analysis bandwidth at the PA output, i.e. 60 MHz, no sufficient information about the spectral regrowth arrives to the DPD. Thus, the ACPR gets worse as the signal bandwidth becomes larger. However, DPD still cope with the in-band distortion.

Table 1 Measured ACPR and NMSE for DPD+PA

	ACPR (dB)	NMSE (dB)
10 MHz LTE DL	-25	-36
32MHz 1024 QAM	-10	-33.54
50 MHz 1024 QAM	-4	-33.52

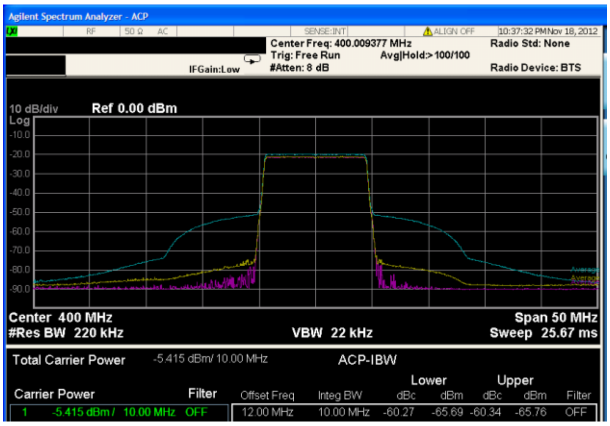

Figure 6 Measured Spectra for 10 MHz LTE DL

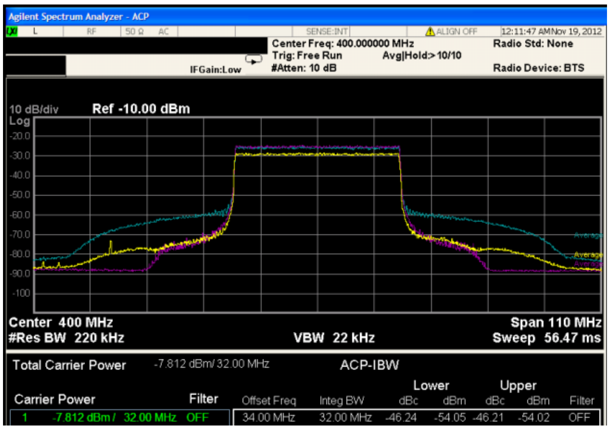

Figure 7 Measured Spectra for 32 MHz 1024-QAM

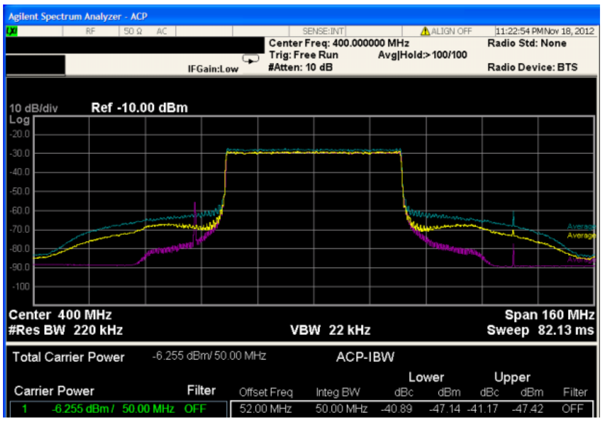

Figure 8 Measured Spectra for 50 MHz 1024-QAM

PROPOSED DPD+PA ARCHITECTURE FOR WIDEBAND HIGH PAPR SIGNALS

Broadband transmission is currently investigated for future satellite communication links. Fortunately, as the fractional bandwidth gets larger (e.g. broadband channels in L-Band) filtering of the spectral regrowth at the PA becomes feasible. In the light of that, DPD is no longer required to mitigate out-of-band distortion but rather it should cope with the expected in-band distortion due to severe memory effects impact at the PA output in response to a wideband signal. As a result, a band-limited DPD could relax the DPD bandwidth constraint to a comparable bandwidth of the original modulated signal. This means much less power consumption for DPD (i.e. FPGA and DAC) and a wideband transmitter to cope with the 5th order intermodulation products is no longer required. This agrees to the simulation results in [15] and the experimental results in Figure 8 and Table 1.

In the research done so far, the DA efficiency and its impact on the overall DPD+PA system were neglected. This might not be valid for broadband high PAPR signal transmission using HPA. The authors proposes the DPD+PA architecture shown in Figure 9 aiming at increasing the overall average PAE while minimizing the distortion in the DA stage. Load modulation is applied at the PA output using a varactors-based matching network where varactors could be placed in parallel to cope with high PA output power. The bandwidth through path DPD1, upconverter, DA, and PA is limited to the original modulated signal bandwidth. ET is applied to the DA using an EA with additional DPD block (DPD2) to compensate for nonlinearities at EA output. Switching between the DA and PA could be considered for low input power which further improves the average PAE.

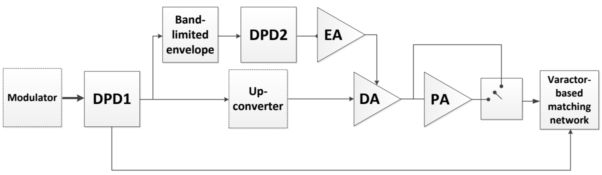

Figure 9 Proposed DPD+PA

Figure-of-Merit for the Proposed DPD+PA

As explained earlier in this paper, the spectral regrowth can be filtered out for large fractional bandwidth signals (e.g. in L-Band). For this reason, ACPR constraint is significantly relaxed.

To allow reliable reception of the transmitted signal over a satellite communication link a link budget-determined ratio of the signal energy over the spectral noise density, i.e. E_s/N_o, has to be maintained at the receiver side assuming perfect signal transmission. EVM at the transmitter side decreases this ratio and has to be kept at minimum by employing DPD.

As a result of the heritage in space technology, nonlinear (switch) PAs, although power efficient, are not commonly used whereas linear PAs (power inefficient) are used. Thus high spectral density modulation techniques are avoided. This paper highlights the fact that using DPD plus load and supply modulation (i.e. the proposed architecture) on space and ground segments guarantees efficient usage of power. Moreover, more throughput could be pushed into the link assuming the same power budget for a transmitter.

The figure of merit for the proposed DPD+PA should be achieving a lower EVM and high throughput with fixing the power consumption.

Using a Training Sequence to Update the DPD model

In X-band payloads, the transmitter is on for a short period of time to transfer data when the satellite is in the visibility zone of the station. However, this does not necessarily happen for each orbit. Consequently, one of the orbits can be freed to transmit a training sequence to the data reception station. This received data could be compared, offline, to the ideal training sequence and an update for the DPD model coefficient could be extracted. This updated coefficient could be transmitted to the satellite through the TT&C transponder and used to configure the DPD model onboard. In other words, an offline adaptation could be made to cope with any unexpected very slow time variation of the PA. To the best of the authors' knowledge, this is the first time an offline adaptation for X-band payload is proposed.

CONCLUSIONS

DPD techniques for terrestrial communications were reviewed and suitability for application to satellite communications was investigated. A DPD for an ultra-wideband 1GHz 1024-QAM signal modulating a 4GHz carrier was simulated for proof-of-concept purpose. A figure of merit for a DPD suitable for satellite communications was identified and could be used to compare different architectures. A novel DPD+PA system architecture is proposed where ET of the driver amplifier and load modulation of the PA are used to maximize the overall PAE while high PAPR signals can be used. To the best of the authors' knowledge, this is the first time that DPD has been proposed for wideband (approximately 20% fractional bandwidth) high PAPR signals for satellite communication links. A technique for an off-line adaptation for X-band transmitter was introduced. This paper suggests that there are benefits to be gained whilst still complying with relevant regulatory standards; increasing the link throughput and allowing less expensive (in terms of volume, mass, and cost) space and ground segment transmitters.

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