Title	Green Communications: Digital Predistortion for Wideband RF Power Amplifiers
Authors(s)	Guan, Lei, Zhu, Anding
Publication date	2014-11-12
Publication information	Guan, Lei, and Anding Zhu. "Green Communications: Digital Predistortion for Wideband RF Power Amplifiers" 15, no. 7 (November 12, 2014).
Publisher	IEEE
Item record/more information	http://hdl.handle.net/10197/8638
Publisher's statement	© 2014 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works
Publisher's version (DOI)	10.1109/MMM.2014.2356037

Green Communications: Digital Predistortion for Wideband RF Power Amplifiers

I. Introduction or Background

WIRELESS communications has already shaped our daily life by providing seamless radio access worldwide. According to the latest ITU statistics [1], in 2013, mobile-cellular subscriptions will reach to 6.8 billion, which is almost equal to the world population. Having this subscription number in mind, realistically, wireless system design and manufacturing have already become the fastest growing section of the electronics industry. However, the incremental demand of providing better wireless connection services for more subscribers imposes several challenges in delivering the next-generation wireless radio access devices: subscribers need cheaper bundles with higher data rate, while operators need more efficient solution with wider bandwidth.

As a key physical media between subscribers and operators, wireless base station is the most expensive unit in a mobile network, and is the dominant power consumer compared to the other components in the network. Surprisingly, over 60% of the power is wasted in the form of heat rather than transmitting data. As an operator, think about how much extra cost you are spending for cooling down your base stations when transmitting user data. While as an end user, think about how many times you have to charge your smart phone per week when heavily using mobile wireless services. This low-efficient behavior is 1) environmentally undesirable due to more CO_2 generated, and 2) economically undesirable because of the increment of unnecessary capital expenditure (CAPEX) and operational expenditure (OPEX). So what happened then?

If we break down a base station, it is not difficult to find out power amplifiers (PAs) consume the majority power. Usually, nonlinear PAs operate in the peak-power (saturation) region to achieve maximum power efficiency. However, in this saturation region, PAs suffer from inherent nonlinear distortion causing in-band distortion and out-of-band spectral regrowth [2]. The in-band distortion will damage the signal quality, consequently degrading the overall communication performance within the user's own frequency band, while the out-of-band spectral regrowth can cause undesired interference, or even failure, of the other wireless systems running in the adjacent frequency bands. The traditional back-off concept does improve the linearity but with a compromised power efficiency. In orthogonal frequency division multiplexing (OFDM) based modern wireless systems such as DVB, WiMAX, and LTE, PAs use significant backed-off power due to the high peak-to-average power ratio (PAPR) of OFDM signals [3], resulting in very low power efficiency. Is there any approach that can allow PAs maintain high power efficiency and simultaneously keep reasonable linearity?

The answer is, absolutely, a YES! Over the past several decades, two design 'tricks' have emerged: 1) applying some *internal modification* on the PA physical architecture (circuit-level approaches), and 2) carrying out some *external modification* on a given type of PA without touching the PA architecture (system-level approaches). The first type of approaches deals with PA structures, such as a) Doherty power amplifiers [4], [5], [6], [7] that were based on linear transistor operation and utilized load modulation to keep efficiency high, and b) envelope tracking (ET) power amplifiers [8], [9], [10], which are also implemented based on linear transistor operation but employ drain voltage modulation to keep efficiency high. For high-power, wideband applications such as UMTS and LTE, those PAs do still suffer from nonlinear distortion, so we still need some kind of linearization. In the second trick, for a given PA operating near saturation, the linearity can be improved by signal processing techniques, PA linearization [11], using techniques such as a) feedback distortion compensation [12], [13], [14], [15], [16], using closed-loop regulators to reduce the nonlinear distortion, b) feedforward distortion compensation [17], [18], [19], [20], [21], which utilizes an additional error amplifier in the forward loop to compensate for the nonlinear distortion introduced by the main PA, and c) predistortion linearization [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], which uses a stand-alone module to pre-distort the input signal to the PA, improving the linearity at PA output. Due to its high flexibility and excellent linearization performance, digital predistortion (DPD) has become one of the most preferred choice for linearizing RF PAs, and tends to be an fundamental component in current and next-generation wireless communication systems.

A. Linearity Requirements for Wireless Transceivers

The linearity of wireless transceivers is specified in standards with two metrics: 1) in-band *error vector magnitude (EVM)*, characterizing the error level between ideal signal and actual transmitted signal, and 2) out-of-band *adjacent channel leakage ratio (ACLR)*, assessing the interference emission level outside of the transmission frequency band. Table I summarizes the linearity requirements in typical 3G and 4G systems. Since the numbers listed in this table are the recommendation values under some "realistic" assumptions, it is judicious to reserve at least 5 dB margins in the real applications.

Lei Guan (lei.guan@alcatel-lucent.com), Member of IEEE, is a Member of Technical Staff in Bell Laboratories, Alcatel Lucent Ireland, Blanchardstown, Dublin 15, Ireland.

Anding Zhu (anding.zhu@ucd.ie), Senior Member of IEEE, is with School of Electrical, Electronic and Communications Engineering, University College Dublin, Dublin 4, Ireland.

Table I
LINEARITY REQUIREMENTS IN TYPICAL 3G/4G BASE STATIONS

Standard	UMTS (Ref [37])	WiMAX (Ref [38])	LTE (Ref [39])	LTE-A (Ref [40])
Multiplexing Type	WCDMA	OFDMA	OFDMA	OFDMA
Single Channel Bandwidth (MHz)	5	1.25, 5, 10, 20	1.4, 3, 5, 10, 15, 20	20
Max. Aggregated Bandwidth (MHz)	60 (12-band)	20	20	100 (5-band)
In-band Rqm. EVM[a] (%)	< 12.5	< 6	< 12.5	< 12.5
Out-of-band Rqm. ACLR1[b] (dBc) ACLR2[c] (dBc)	< – 45 < – 50	< – 45 < – 50	< – 45 < – 45	< – 45 < – 45

a. Based on the 16-QAM modulation scheme;
b. Refers to the first adjacent channel leakage power ratio;
c. Refers to the second adjacent channel leakage power ratio;

B. DPD in Conventional Wireless Systems

As shown in Fig. 1 and omitting the antenna, a typical high performance wireless transmitter comprises three essential parts: 1) *baseband signal processor* for digital signal processing (DSP), such as coding/de-coding, modulation/demodulation and so on; 2) *transmitter RF chain (TX)*, which usually includes a digital-to-analog conversion (DAC) stage, an up-conversion (frequency-mixing) stage and a power amplifier stage; 3) *sampling receiver RF chain (SRX)*, which generally comprises an input attenuation stage, a low-noise amplifier (LNA) stage, a down-conversion (frequency-mixing) stage, a variable-gain amplifier (VGA) stage, and an analog-to-digital conversion (ADC) stage. Since the price of silicon devices is dropping year by year while the transistor density is increasing, plenty of headroom, both in terms of cost and silicon read estate, in the digital domain is available for adding in extra signal processing at baseband, such as DPD module.

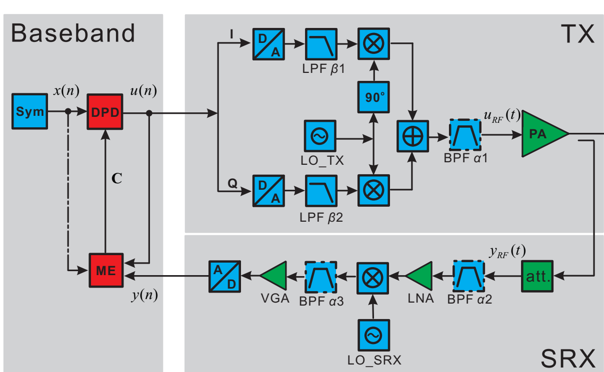

Figure 1. Simplified diagram of DPD-enabled wireless transmitter.

The DPD idea is very simple as illustrated in Fig. 2. A typical transfer function of a nonlinear PA is shown on the top right (with u as input and y as output). If the DPD unit can manipulate the signal with a proper inverse transfer function such as shown on the top left (with x as input and u as output), the final output y will be a linear signal with respect to original input x, as shown at the bottom of Fig. 2. Different from circuit-level nonlinearity compensation, DPD utilizes so-call "black-box"-based behavioral modeling techniques to characterize and pre-invert the PA behavior at the system level. Under this concept, we only need PA input and output to do PA linearization. This representation eliminates the need for understanding analog signal processing theory, and significantly relieves the burden of analog circuit design and debugging.

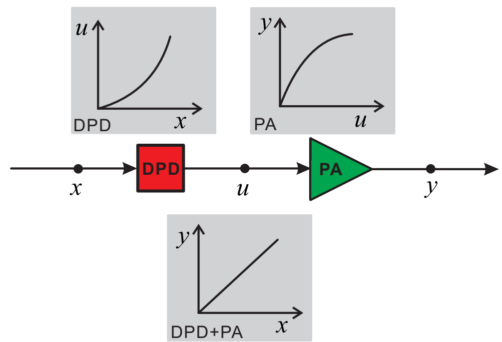

Figure 2. Basic concept of DPD.

Although the concept of DPD is quite simple, developing a high-performance and low-cost DPD unit for the modern transceiver is not that easy. Besides the critical requirement of accurate behavior modeling and efficient model parameter extraction, there are new challenges blocking the way forward.

C. Challenges in DPD for Future Wireless Communications

1) Wide-band DPD in High-power Base Stations: Evolved from GSM/EDGE systems, 3G/4G and beyond-4G systems promise faster data down/up links, which requires wider transmission bandwidth. For example, as shown in Table I, multi-carrier UMTS systems support up to 60-MHz transmission bandwidth, and LTE-A systems will utilize up to 100-MHz transmission bandwidth with flexible carrier aggregation techniques. If up-to 5th-order nonlinearity (dominant nonlinearity) is considered, 5 times the original bandwidth appears at the PA output; for example, a 100 MHz LTE-A signal will occupy 500 MHz bandwidth at the output of nonlinear PA, illustrating by Fig. 3. Though the price of silicon is getting down, we still need ultra high speed, high resolution data acquisition and DSP units to properly handle those wideband signals. The extra cost of deploying such wideband SRX pathes will dramatically reduce the overall economical attractiveness. DPD has to be running under band-limited situations (bandwidth of the SRX path is far less than 5 times signal bandwidth) in the wideband systems. Conventional DPD solutions could provide satisfactory linearization if the major nonlinear distortion (up-to 5th-order nonlinearity) was accurately captured, but the linearization performance will dramatically degrade under band-limited situations. It is a big challenge to develop a proper DPD module with reasonably good linearization performance under band-limited situations.

Providing wireless services with one continuous frequency band is not the only option. According to the carrier aggregation concept in the LTE-A standard [40], a wider frequency

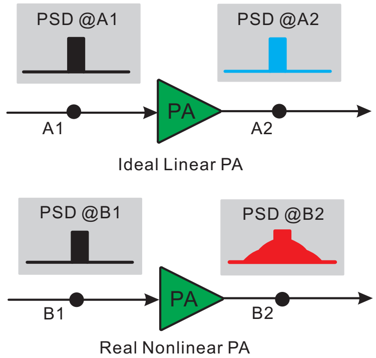

Figure 3. Spectrum regrowth due to nonlinear distortion.

band can be aggregated from several smaller frequency bands with or without gaps between sub bands. We treat this feature as one of the multi-band challenges.

2) Multi-band DPD in High-power Base Stations: The physical capacity of one frequency band is generally limited, so if no more data can be squeezed into the one frequency band, we may turn to a multi-band solution. Under this concept, multiple concurrent frequency bands can be used to transmit user data. Three DPD application scenarios should be considered when dealing with aggregation of concurrent bands: a) no gap between concurrent bands; b) narrow gaps between concurrent bands; and c) wide gaps between concurrent bands, as shown in Fig. 4.

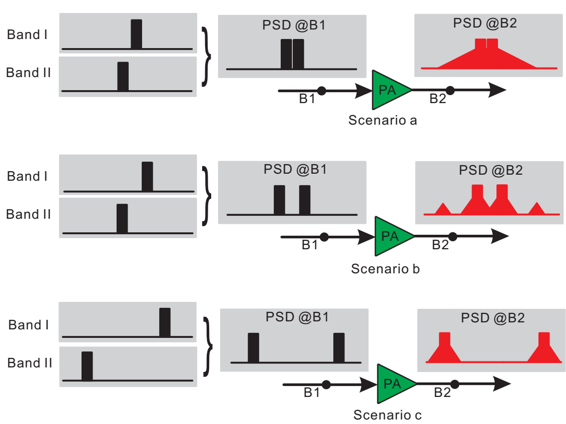

Figure 4. Examples of nonlinear distortion generated by multi-band systems.

In Scenario a, multiple frequency bands are actually aggregated as one single continuous wider frequency band; In Scenario b, multiple frequency bands are located very close to each others, therefore the spectral regrowth of different carriers will overlap with each other. Traditional DPDs are not capable of fully correcting nonlinear distortion in this scenario because the partial intermodulation terms are mixed together, and no proper mapping can be set up between the original PA inputs and the overlapped PA outputs. New DPD approaches are required to handle this high-demand multi-band linearization problem. In Scenario c, due to the wide gap between different bands, the in-band spectrum overlap may be eliminated. However, given the fact that the bandwidth of the transmitter SRX is generally limited (indicating by the grey block background in Fig. 4), only partial nonlinear distortion can be captured at the feedback path. This is similar to the wideband scenario with band-limited constraints. Proper DPD approaches for the band-limited scenario will be eventually required.

3) Cognitive DPD in Low-power Small Cells and Handsets: From the operator's perspective, logically deploying more small cells in the network will use the limited spectrum resource more efficiently. It is also helpful to have more than one antenna (MIMO system) to gain benefits from dynamic beam-forming to provide wireless access over different targeted areas. In order to further enhance spectrum utilization efficiency, the cognitive radio concept [41] was proposed, in which spectrum resources are smartly utilized according to dynamic resource detection and allocation policies. The wireless connection can then set up in different frequency bands from time to time. A cognitive DPD will be required to guarantee a linear RF output in those cognitive-radio-based small-cell systems. DPD approaches should have "smart" and fast adaptive capability to dynamically characterize and linearize PAs.

Since DPD algorithms are normally running in a baseband processor, extra power will be consumed for computing/updating DPD parameters and pipelining DPD outputs. For high power base stations (> 47 dBm output power, i.e., 50 W), a small additional baseband power consumption (less than 0.5 W, estimated by Xilinx Power Estimator according to the FPGA resource usage in [42] and [43]) by the DPD unit is worthwhile for obtaining more than 20% enhancement of the overall transceiver power efficiency. However, for low-power small cells or mobile handsets, the small amount of power consumed by the DPD unit cannot be ignored. Low-power-consumption DPD solutions will be in high demand, but, this is not a simple implementation issue: a proper behavioral model and an efficient parameter extraction scheme needs to be invented first, followed by the optimization of the hardware implementation.

II. DPD Verification Platforms

The DPD validation is a type of multi-step adjacent-channel-power (ACP) test of the RF transmitter, which includes:

1) *Data Pattern Generation*: generating a digital baseband data sequence with required sampling rate and PAPR value such as 4-carrier UMTS signal with 6.5 PAPR;
2) *Signal Up-Conversion*: up-converting baseband signal to the required RF frequency, for example 2.14 GHz, with proper power to drive a nonlinear RF PA;
3) *Feedback Signal Acquisition*: down-converting the output of the RF PA to the baseband or IF, and then capturing the baseband or IF analog signal with proper ADC-based digitizer;
4) *Time Alignment*: aligning the original input and captured PA output in the time domain so that the latency (sample delay) introduced by the system (transmitter and feedback path) can be characterized and compensated, thus obtaining matched/paired PA input and output;

5) *DPD Parameter Extraction and Updating*: calculating DPD parameters and then updating the parameters in the filter-like digital predistorter;
6) *Performance Assessment*: using spectrum analyzer to evaluate the frequency-domain linearization performance (ACLR) or capturing the signal again to assess the time-domain performance by calculating EVM;

For some PAs with strong nonlinear distortion and memory effects, it is necessary to train the DPD parameters over several iterations. In order to properly evaluate DPD performance, a robust testing platform is needed. Depending on different verification purposes and financial constraints, 3 types of DPD platforms have been reported in the literature (Table II).

Table II
DPD PLATFORM CATEGORIES

No.	Main Architecture
A	Simulation software / machine based DPD platforms
B	Commercial measurement Instruments based DPD platforms
C	Digital & analog HW evaluation board based DPD platforms

A. Simulation-machine-based DPD Platforms

DPD algorithm are inherently mathematical, and must be run on a processor with computational capability, therefore a simulation-based testing environment, such as MATLAB/Simulink, is recommended at the initial DPD algorithm development stage. It is helpful to have an idea of how the DPD works by performing simulation under different assumptions for the deterministic nonlinear distortion and statistical noise distribution (noiseless or noisy situations). For example, Fig. 5 illustrates a MATLAB/Simulink-based DPD simulation platform that was developed and used in [44]. Each module is described by a proper mathematical baseband-equivalent model for the corresponding function.

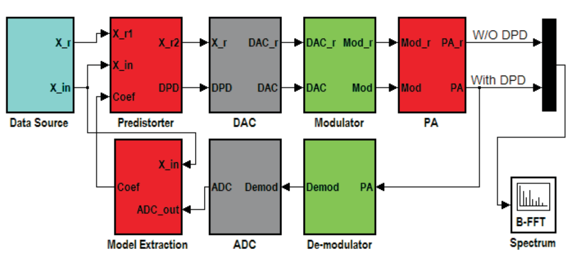

Figure 5. Example of a simulation-based DPD platform [44].

A simple validation philosophy can be applied: if a potential DPD algorithm (including model architecture and parameter extraction) cannot achieve satisfactory linearization in ideal simulations, it will not be able to provide good linearization performance in a real physical system.

B. Measurement-instruments-based DPD Platforms

Commercial measurement instrument-based DPD testing solutions are widely used for their flexibility and multiple standards support capability. Agilent, for example, provides a DPD validation platform that includes a signal generator, spectrum analyzer with digitizer option, and PC with MATLAB [45], similarly solutions are also provided by Rohde & Schwarz [46]. Fig. 6 illustrates a typical instruments-based DPD platform. Test data can be initialized by an arbitrary waveform generator, and upconverted to the required RF frequency by tuning the signal generator (ESG 4438C). We can use spectrum analyzer (with proper digitizer option) to capture the PA output and down-convert to baseband. The DPD algorithms can be developed in Matlab on a PC.

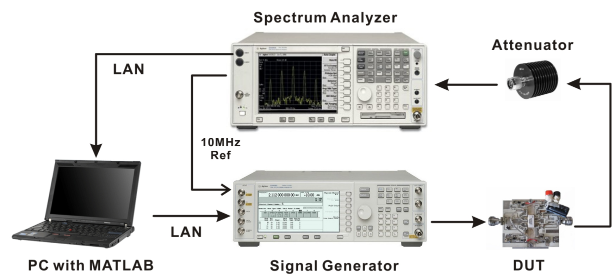

Figure 6. Example of commercial instruments-based DPD platform.

Those instruments are well designed for general measurement and testing purposes, and can be compatible with different wireless communication standards. Besides their high cost, the analysis bandwidth of spectrum analyzers is limited, with maximum available bandwidth of about 160 MHz. This bandwidth may not be sufficient to capture the 5th-order nonlinear distortion components for ultra wideband signal such as in 12-carrier UMTS signals with 60 MHz bandwidth.

C. Digital & Analog Evaluation-boards-based DPD Platforms

Another popular option for a DPD platform is to use DAC and ADC evaluation boards; those can be commercial ones or independently developed ones. Those boards usually have high performance DAC and ADC chips, (14-bit/16-bit, 500 - 1000 Mega samples per second (MSPS)), which are able to evaluate DPD with different transmitter architectures such as superheterodyne, digital IF, or direct up-conversion. Using high performance ICs will also be helpful in reducing the overall system noise floor and increase the spur-free dynamic range (SFDR) to provide better signal representation. Equipped with standardized industrial high-speed data interfaces, these high performance DAC/ADC evaluation boards have satisfactory physical connectivity and extension/upgrading capability. For example, the FPGA evaluation boards are preferred for use as baseband signal processing unit. It can be seamless upgraded to a higher performance FPGA board for better DSP performance, as long as it has the same data interface.

D. Summary of Typical DPD Platforms

Table III summarized the most popular DPD evaluation platforms that have been reported in the literature, in terms of the key specifications. Because of the potential wideband linearization capability (> 40-MHz linearization bandwidth), several DPD platforms are highlighted here, such as those developed by University of Calgary, Canada [47], Southeast University, China [48], and University College Dublin, Ireland [43]. Some commercial digital processor vendors, such as Xilinx and Altera also provide DPD solutions in the form of IP cores, and TI introduced the first industrial 3rd party hardware DPD chip [49]. It is helpful to promote DPD research by evaluating some commercial DPD solutions, however, commercial DPD performance standards are beyond the scope of this article.

III. DPD Behavior Models

PA nonlinearities can be categorized as follows: a) memoryless (static) nonlinearities, inherently induced by the device; b) linear memory effects, arising from time delays, or phase shift, in the matching networks; and c) nonlinear memory effects, coming from direct low-frequency dynamics, such as trapping effects and non-ideal bias networks. Experimental test result trends show the wider the bandwidth occupied by the transmitted signal, the stronger the memory effects that the PA suffers from, especially in the multi-carrier systems. In the DPD context, a proper behavioral model must be capable of characterizing the nonlinear distortion and memory effects.

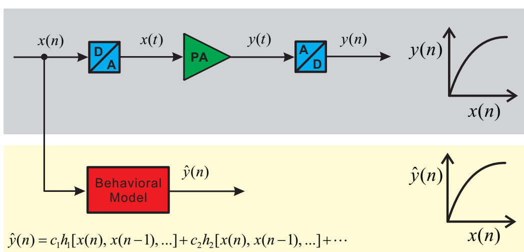

Figure 7. Basic concept of behavioral modeling.

Unlike circuit-level modeling, which is used to physically describe the nonlinear behavior, black-box-based behavioral modeling is carried out at the system level. Behavioral modeling uses a series of mathematical formulations to derive the relationship between input and output of the PA. As shown in Fig. 7, distortion will be found in $y\left(t\right)$ when the input $x\left(t\right)$ passes through the physical nonlinear RF PA. In order to characterize the nonlinearities, a set of the basis functions h_1, h_2, ..., can be applied to the digitized input and its delayed versions $\left[x\left(n\right), x\left(n-1\right), ...\right]$ to generate a series of nonlinear function: $h_1\left[x\left(n\right), x\left(n-1\right), ...\right]$, $h_2\left[x\left(n\right), x\left(n-1\right), ...\right]$, ... The summation of these functions when weighted by a set of coefficients $c_1, c_2, \cdots$, i.e., $\hat{y}\left(n\right)$, can be considered as an approximation of the real output $y\left(n\right)$, which is a digitized version of the analog PA output $y\left(t\right)$. The advantage of such behavioral modeling is that complicated knowledge of the physical RF circuits is not required, and so the nonlinear characterization procedure tends to be easier to quantify. Once the behavioral models are verified through cross validation, they can be easily applied in DPD applications.

We group the most useful behavioral models into two major categories: 1) *memory unaware (frequency-independent) models* and 2) *memory aware (frequency-dependent) models*. Although it has already been experimentally verified that most of distortion a PA suffers comes from nonlinear behaviors instead of memory effects [30], it does appear that a PA will be more affected by memory effects in wideband systems. With this in mind, we will put more effort in explanation of memory-aware models that are better suited for wideband DPD.

A. Memory-Unaware Models

a) *Generalized power series (GPS) model* [67]. Due to its clear model structure, the GPS model has been widely used for modeling nonlinear systems without memory effects, and is the simplest memoryless nonlinear model. In this model, different nonlinear-order terms indicate different levels of the nonlinearity, as shown in Fig. 8.

b) *Memoryless lookup-tables (ML-LUT) model* [22]. Another very popular memoryless nonlinear model is ML-LUT, in which the nonlinear weights are pre-calculated and stored in the form of lookup-tables. This compact implementation structure, as shown in Fig. 8, is suitable for real-time DPD applications. However, this model suffers from quantization error because only a limited number of LUT entries can be physically implemented.

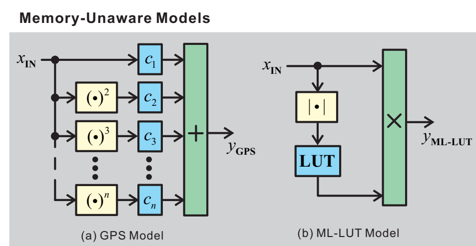

Figure 8. Memory unaware models implementation structures.

B. Memory-Aware Models

1) *Full Voterra (FV) model* [68]. Combining linear convolution and nonlinear power series, the Volterra series can be considered as a very good candidate for accurately modeling nonlinear systems with fading memory effects. However, the complexity of this model significantly increases as the nonlinear order and memory length increase. Simplification or truncation of the FV model is required to achieve a balance between model accuracy and model complexity. The FV model is mathematically represented as

$$y_{\text{FV}}\left(n\right)=\sum_{k=1}^{K}\sum_{m_1=0}^{M}\cdots\sum_{m_k=0}^{M}h_k\left(m_1,\cdots,m_k\right)\prod_{j=1}^{k}x\left(n-m_j\right) \quad (1)$$

2) *Memory polynomial (*MP*) model* [69], [27]. The MP model is a special case of the FV model or an extension of GPS model. Compared with the FV model, the complexity of the MP model is dramatically reduced as is its accuracy, but the MP model can still provide reasonable performance.

3) *Generalized memory polynomial (GMP) model* [28]. In order to expand the modeling capability of the MP model,

Table III
COMPARISON OF THE TYPICAL PROVEN DPD PLATFORMS

	Platform composition (3 parts)			Main Specification						
	Baseband Type	RF Type	PA Type	System Standard	Power (dBm)	BW (MHz)	ACLR1 (dBc)	EVM (%)	Ref.	Reported By
A	Matlab	Ideal / Model	PA Model	UMTS	-	15	-	-	[27]	
	Matlab	Ideal / Model	PA Model	8-tone	-	-	-	-	[50]	Widely Used
	PC with Matlab;	Signal Generator;	Class-AB	UMTS	40	15	–57	0.95	[51]	
		Spectrum Analyzer;	Doherty	UMTS	47	10	–55	-	[31]	
			Class-AB	UMTS	36	20	–51	-	[52]	Widely Used
B	PC with Matlab;	Signal Generator;	DLM[1] PA	UMTS	31	5	–45	-	[53]	Chalmers University
		Oscilloscope;	DLM PA	UMTS	31	5	–50	-	[54]	Sweden
	PC with Matlab;	Pattern Generator;	Class-AB	UMTS	40	5	–58	1.98	[30]	UCSD
	Logic Analyzer;	RF Board;	DLM PA	UMTS	25	5	–46	-	[55]	USA
	PC with Matlab;	DAC Eval. Board;	Class-AB	CDMA	45	15	–58	-	[28]	Bell Lab
		ADC Eval. Board;	Class-AB	UMTS	45	15	–56	-	[56]	USA
	GC5322EVM;	DPD RF-Card;	Doherty	UMTS	42	20	–51	9.2	[57]	Texas Instruments
	C6727-EVM;		Doherty	UMTS	46	10	–53	6.5		USA
	PC with Matlab;	DAC Eval. Board;	Class-AB	UMTS	40	20	–45	-	[58]	Ohio State University
	Stratix FPGA[4];	ADI MSDPD card;	Class-AB	UMTS	36	25	–52	1.21	[59]	USA
		Spectrum Analyzer;	Class-AB	LTE	36	10	–51	1.10		
	PC with Matlab	DSP Eval. Board;	Class-A/B	UMTS	40	5	–45	3	[60]	Technical University of
	Virtex 4 FPGA[5];	Mod/Demodulator;	Class-AB	UMTS	17	5	-	1.20	[61]	Catalonia, Spain
	-	OP6180-DEV	Doherty	GSM[2]	48	20	–70	-	[62]	Optichron[3]
	-	Evaluation Platform;	Doherty	UMTS	50	20	–59	-		NXP Semiconductor
	PC with Matlab;	Self-developped	Doherty	LTE-A	38	100	–50	-	[48]	Southeast University
C	Virtex 6 FPGA[5];	RF Board;	Doherty	LTE-A	40	100	–46	-	[63]	China
	PC;	Self-developped	Doherty	UMTS	-	40	–55	-	[47]	University of Calgary
	Stratix II FPGA[4];	RF Board;	Doherty	LTE	38	60	–51	-	[64]	Canada
	PC with Matlab;	Self-developped	Continuous	LTE	35	20	–53	1.05	[65]	
	Virtex 5 FPGA[5];	RF Board;	Class-F	UMTS	35	40	–49	1.44		University College Dublin
			Doherty	UMTS	40	40	–57	0.48	[66]	Ireland
			Doherty	LTE-A	37	100	–52	0.98	[43]	

1. DLM: Dynamic Load Modulation; 2. Refers to Class 1 multi-carrier GSM; 3. Merged with Broadcom; 4. Altera products; 5. Xilinx products;

local memory terms that are close to the current memory term are also taken into account when developing the GMP model.

4) *Nonlinear auto-regressive moving average (NARMA) model* [61]. Adding an IIR-filter-like nonlinear feedback path into the MP model forms a NARMA model. This recursive dynamic model structure on one hand may be able to capture the nonlinearity with reduced memory length, while on the other hand may cause an instability problem which requires an extra stability test when using it [70].

5) *Dynamic deviation reduction (DDR)-based Volterra model* [71], [30]. A practical and efficient pruning technique, called dynamic deviation reduction, was introduced to simplify the FV model. The 1st-order DDR-based Volterra model provides satisfactory performance when the PA has low-to-moderate memory effects, while the simplified 2nd-order DDR-based Volterra model (SDDR) [72] expands the model capability for strong memory effects, at the cost of adding in more cross memory terms.

6) *Artificial neural network (ANN) model*. This model is well known for its universal approximation capability, especially its global approximants for a strongly nonlinear system. However, there is no clear mapping relationship between the number of hidden neurons and the corresponding modeling performance. Moreover, the ANN model is not a linear-in-parameter model; consequently, the parameters have to be identified by a nonlinear training process. For illustration, two sub-types of commonly used ANN models are given, i.e., *Direct dynamic ANN (DD-ANN) model* [73], [74] and *Recursive dynamic ANN (RD-ANN)* [75], [33].

7) *Wiener model*. The original Wiener (OW) model [76] is a simplified DD-ANN model in terms of its mathematical representation, although it does not originally come from pruning an ANN model. This model has very clear physical meaning due to its two-part model architecture, a simple FIR filter followed by a static nonlinear basis (NLB) function. The OW model has a simple structure with limited capability

for modeling memory effects. By expanding the FIR part, an augmented Wiener (AW) model [77] was proposed to efficiently enhance the modeling accuracy and capability.

8) *Hammerstein model*. Another special case of DD-ANN is the original Hammerstein (OH) model [78]. Like the OW model, the OH model is not originally derived from the ANN model either; it is formed from a static nonlinear function followed by an FIR filter. The OH model uses a single filter that limits its modeling performance. In order to enhance the modeling performance, the augmented Hammerstein (AH) model [79], extended Hammerstein (EH) model [80] and Filter LUT (FLUT) models [81] have also been proposed, in which the filter blocks have been updated and modified.

Due to their nonlinear-in-parameter structure, the AW and AH models, as subsets of the ANN model, suffer from the similar problem of the nonlinear parameter identification process, which requires iterative nonlinear training/optimization and dramatically increases the computational complexity. This parameter identification process makes those nonlinear-in-parameter models not fully suitable for DPD requiring real-time parameter calculation and updating. If the PA under test is stable in terms of memoryless nonlinearity, memoryless distortion evaluation can be performed in advance by checking the AM-AM curve off-line. And then the Hammerstein model and its extended models can be simplified when the only parameters to be estimated are the coefficients of the corresponding FIR filters.

Table IV
SUMMARY AND COMPARISON OF MEMORY-AWARE DPD MODELS

No.	Model Name	Model Perf. 1	2	3	LIP	Ref.
1)	FV	E	H	S	√	[68]
2)	MP	S	L	M	√	[69], [27]
3)	GMP	E	M	M	√	[28]
4)	NARMA	R	M	M	√	[70], [61]
5)	DDR	S	L	M	√	[71], [30]
5)	SDDR	E	M	M	√	[72], [34]
6a)	DD-ANN	E	H	S	×	[73], [74]
6b)	RD-ANN	E	H	S	×	[75], [33]
7a)	OW	R	L	W	√	[76]
7b)	AW	S	M	M	×	[77]
8a)	OH	R	L	W	√	[78]
8b)	AH	S	M	M	×	[79]
8c)	EH	S	M	M	×	[80]
8d)	FLUT	S	M	M	×	[81]

1. Accuracy levels: Excellent (E), Satisfactory (S), Reasonable (R);
2. Complexity levels: High (H), Medium (M), Low (L);
3. Capability levels: Strong (S), Medium (M), Weak (W);

C. Summary of DPD models

How do we best judge the performance of DPD models? We recommend considering three concepts simultaneously (Table IV): model accuracy, complexity, and capability. For example, the FV model and NN models suffer from high computational complexity but can provide high modeling accuracy for strong memory-aware nonlinearities, while the simple OW model enjoys low computational complexity but can only be used for weak nonlinearities with limited modeling accuracy. Moreover, the linear-in-parameter (LIP) property is also important for physically achieving an efficient DPD.

Several advanced techniques are available for further improving model accuracy and capability, such as:

i) a signal (magnitude/vector) decomposition technique (SDT) that uses different basis functions in different magnitude ranges. For example, piecewising the basis function of the model can generate certain modified models with better performance such as the piecewise polynomial model [82], the vector threshold decomposition based Volterra model [83], and vector-switched model proposed in [84], which actually utilize different characterization parameters (local parameters) for different signal magnitude/vector ranges;

ii) a multiple-basis technique (MBT) that uses multiple basis functions in the same magnitude range to describe the nonlinearity and memory effects. For example, a separable-functions-based approach was proposed for DPD in [85] and its derivative approach, namely adaptive basis function was presented in [86]. Similar solutions were also given in [87], [88], where a LUT combined with an MP model was proposed to improve the model accuracy while considering computational complexity. These models use multiple basis functions in parallel to improve the overall model accuracy and corresponding DPD performance;

iii) a multiple-LUT technique (MLT) that uses multiple lookup tables to reduce the quantization error, consequently improving the model accuracy such as the approaches proposed in [60] and [42];

iv) a multi-input enhancement technique (MET), which uses a frequency harmonic analysis technique and corresponding harmonic mapping to enhance the overall performance, such as [54] for the ET system and [89], [52], [90], [35] for the multi-band systems;

v) a band-limited optimization technique (BLT) that deals with band-limited DPD problems using band-limited models [34]. The basic concept is to create a proper mapping between input and output of the PA under the band-limited constraints.

IV. DPD PARAMETER EXTRACTION SCHEMES

A generalized architecture of parameter extraction for DPD is shown in Fig. 10. A feedback link $\mathbf{L_Y}$ is required to capture the nonlinear output of the PA, and, depending on the extraction algorithm, up to two more links (input $\mathbf{L_X}$ and output $\mathbf{L_U}$) are needed. Table V lists different type of parameter extraction architectures with given examples.

Due to its simple architecture and reasonable performance, the Arch. I-based (See Table V for definitions of architecture types) parameter extraction approach is widely used for deriving the DPD parameters. However, in a real system, the observed signals may be "corrupted" due to the limited bandwidth of the feedback loop and measurement noise in the data acquisition process. With those effects in play, it is

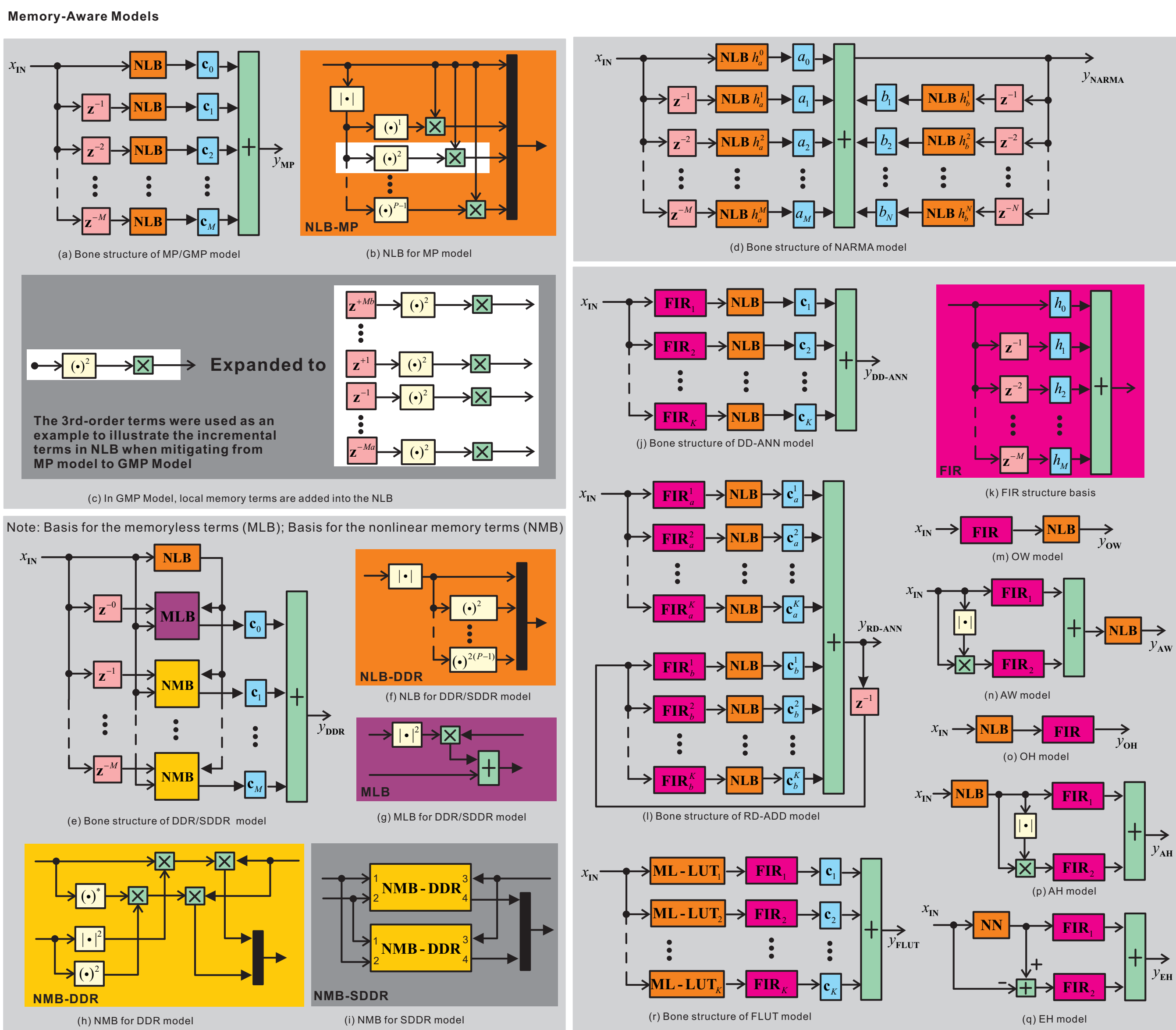

Figure 9. Memory-aware models implementation structures.

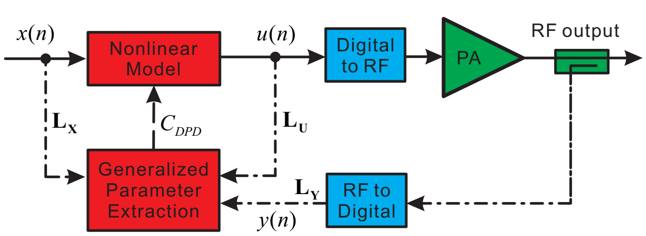

Figure 10. Generalized DPD parameter extraction architecture.

Table V
PARAMETER EXTRACTION ARCHITECTURES.

	Architecture Type	Examples
Arch. I	Feedback $\mathbf{L_Y}$ + Output $\mathbf{L_U}$	pth-order Inverse; Indirect Learning
Arch. II	Feedback $\mathbf{L_Y}$ + Input $\mathbf{L_X}$	Direct Learning; Model Reference
Arch. III	Feedback $\mathbf{L_Y}$ + Input $\mathbf{L_X}$ & Output $\mathbf{L_U}$	Optimized Dual-loop

difficult to accurately obtain DPD parameters by Arch. I-based parameter extraction. Alternatively, Arch. II uses a feedback signal together with the original input to extract parameters by directly comparing the original input and the observed output of the PA. This approach only works well for PAs with weak nonlinearities such as if the residual distortion between the nonlinear PA output and the original signal is small, otherwise, the coefficient adaptation may diverge [31]. Another optimized dual-loop model parameter scheme was also proposed for enhancing the single-loop parameter extraction performance at a cost of slightly increasing the complexity [92].

Table VI summaries the main contributions in the litera-

Table VI
EXPERIMENTAL COMPARISON OF PARAMETER-EXTRACTION SCHEMES FOR LINEAR-IN-PARAMETER MODELS.

Example	Model	Parameters Estimation		PA Excitation		DPD Performance	
Reference	Used	Method	Architecture	Signal	Bandwidth	ACLR 1	EVM/NRMSE
[28]	GMP	Standard LS	Arch. I	11-Carrier CDMA	15 MHz	–57.6/–56.2 dBc	-
[30]	DDR	Standard LS	Arch. I	UMTS	5 MHz	–60.6/–61.2 dBc	1.76%
[91]	GMP+MET	Standard LS	Arch. I	2-band UMTS	5 MHz	–55.8/–53.1 dBc	-
[64]	LUT	QR-RLS	Arch. I	3-Carrier LTE	60 MHz	–50.7/–50.1 dBc	-
[61]	NARMA+MLT	Standard LMS	Arch. I	OFDM	5 MHz	-	1.20%
[31]	ML-LUT+MP	Modified LMS	Arch. II	2-Carrier UMTS	10 MHz	–55.1/–54.3 dBc	-
[92]	DDR	Standard LS	Arch. III	8-Carrier UMTS	40 MHz	–57.5/–56.9 dBc	0.39%
[93]	MP & DDR	Modified LS	Arch. I	2-Carrier UMTS	10 MHz	–55.0/–55.0 dBc	-
[66]	SDDR	Optimized LS	Arch. I & III	1-Carrier LTE	20 MHz	–60.5/–60.4 dBc	0.65%
[94]	GMP	Newton-type	Arch. II	2-Carrier UMTS	10 MHz	–59.7/–59.8 dBc	-

ture regarding DPD parameter extraction, including parameter estimation algorithms and extraction architectures. Standard least-squares (LS) are widely utilized in DPD model extraction [28], [30], [91] because of their well-known performance in estimating the coefficients of linear-in parameter models. In order to reduce the standard LS complexity and computational latency for physical real-time coefficient extraction and updating, several approaches are also reported in the literature, such as QR-RLS [64] for LUT-based DPDs, the optimized LS [66] for behavior-model-based DPDs, and adaptive basis function based DPD [86]. As the signal bandwidth increases, extracting the DPD parameters using reduced bandwidth becomes a challenging problem. Several helpful approaches can be used to efficiently derive DPD parameters in this band-limited situation, such as using reduced memory correction approach [95], direct learning with reduced bandwidth feedback [94], bandwidth-constrained least squares [96] and dual-loop parameter optimization [92].

V. OPEN ISSUES AND FUTURE DIRECTIONS

In Table III, Table IV and Table VI, we outlined the three fundamental aspects of the surveyed DPD techniques. As seen in the tables, most of the DPD solutions are proposed for medium-to-high power amplifiers, which are normally utilized in middle-to-large-size base stations. For small base stations, mobile handsets, the forthcoming small-cells-based wireless networks, low-power amplifiers still suffer from lower efficiency because of the use of power back-off to control the inherent nonlinear distortion. Those small-size devices and associated equipment may use different power levels under different situations. Therefore, another open issue is how to perform low-power real-time DPD that can significantly enhance the power efficiency and prolong the battery life of these small wireless systems.

Carrier aggregation, one of the key shining features of LTE-advanced, calls for novel cognitive DPD solutions. These new solutions should be aware of the status of the various carrier aggregation modes in different transmitting periods, and perform corresponding adjustment and DPD coefficient updating. This will define a new direction for DPD research and development.

Advanced transceiver architecture will benefit the emerging multi-protocol wireless systems. Software defined radio (SDR) techniques enable end-user devices such as mobile phone the ability to change radio protocols in real time. An optimal SDR system requires a wideband analog front-end with a highly efficient switch-mode wideband RF PA. However, due to its square-wave-like transmission mechanism, switch-mode PAs suffer from very strong nonlinear distortion, which is another open issue for DPD research in terms of new behavioral model development and corresponding parameter-extraction schemes.

VI. CONCLUSIONS

The RF PA as one of the most essential components in any wireless system suffers from inherent nonlinearities. The output of PA must comply with the linearity requirement specified by the standards. Due to its satisfactory linearization capability, DPD has been widely accepted as one of the fundamental units in modern and future wideband wireless systems. With the help of this flexible digital technology, the inherent linearity problem of PAs operating in the saturation region can be significantly improved, which enables us, the wireless engineers, to create more suitable RF transceiver architectures to provide wireless access with better user experience (linearity perspective) and less power waste (power efficiency perspective). This moves us one more step towards the ultimate green communications.

In this article, we discussed the DPD techniques in the context of linearizing nonlinear RF PAs. As the computing-horsepower and the transistor-density of digital IC increases while the cost per transistor decreases, the concept that uses digital enhancement techniques to eliminate active analog imperfects will gain more attention from both industry and academia.

REFERENCES

[1] International Telecommunication Union, *The World in 2013: ICT Facts and Figures*. ITU, 2013.

[2] S. C. Cripps, *RF Power Amplifiers for Wireless Communications*. Norwood, MA: Artech House, 2006.

[3] L. Guan and A. Zhu, "Gaussian pulse-based two-threshold parallel scaling tone reservation for PAPR reduction of OFDM signals," *International Journal of Digital Multimedia Broadcasting*, vol. 2011, pp. 1–9, 2011.

[4] W. H. Doherty, "A new high efficiency power amplifier for modulated waves," *Proceedings of the Institute of Radio Engineers*, vol. 24, no. 9, pp. 1163–1182, 1936.

[5] F. H. Raab, "Efficiency of Doherty RF power-amplifier systems," *IEEE Trans. Broadcast.*, vol. BC-33, no. 3, pp. 77–83, 1987.

[6] 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. Microw. Theory Techn.*, vol. 50, no. 3, pp. 814–826, 2002.

[7] B. Kim, I. Kim, and J. Moon, "Advanced Doherty architecture," *IEEE Microw. Mag.*, vol. 11, no. 5, pp. 72–86, 2010.

[8] F. H. Raab, "Efficiency of envelope-tracking RF power ampifier systems," in *Proc. of RF Expo East*, Nov. 1986, pp. 303–311.

[9] F. Wang, A. H. Yang, D. F. Kimball, L. E. Larson, and P. M. Asbeck, "Design of wide-bandwidth envelope-tracking power amplifiers for OFDM applications," *IEEE Trans. Microw. Theory Techn.*, vol. 53, no. 4, pp. 1244–1255, 2005.

[10] C. Hsia, A. Zhu, J. J. Yan, P. Draxler, D. F. Kimball, S. Lanfranco, and P. M. Asbeck, "Digitally assisted dual-switch high-efficiency envelope amplifier for envelope-tracking base-station power amplifiers," *IEEE Trans. Microw. Theory Techn.*, vol. 59, no. 11, pp. 2943–2952, 2011.

[11] J. Wood, *Behavioral Modeling and Linearization of RF Power Amplifiers*. Norwood, MA: Artech House, 2014.

[12] M. Faulkner, "Amplifier linearization using RF feedback and feedforward techniques," *IEEE Trans. Veh. Technol.*, vol. 47, no. 1, pp. 209–215, 1998.

[13] J. L. Dawson and T. H. Lee, "Automatic phase alignment for a fully integrated Cartesian feedback power amplifier system," *IEEE J. Solid-State Circuits*, vol. 38, no. 12, pp. 2269–2279, 2003.

[14] S. Pipilos, Y. Papananos, N. Naskas, M. Zervakis, J. Jongsma, T. Gschier, N. Wilson, J. Gibbins, B. Carter, and G. Dann, "A transmitter IC for TETRA systems based on a Cartesian feedback loop linearization technique," *IEEE J. Solid-State Circuits*, vol. 40, no. 3, pp. 707–718, 2005.

[15] P. Adduci, E. Botti, E. Dallago, and G. Venchi, "PWM power audio amplifier with voltage/current mixed feedback for high-efficiency speakers," *IEEE Trans. Ind. Electron.*, vol. 54, no. 2, pp. 1141–1149, Apr. 2007.

[16] Y. Y. Woo, J. Kim, J. Yi, S. Hong, I. Kim, J. Moon, and B. Kim, "Adaptive digital feedback predistortion technique for linearizing power amplifiers," *IEEE Trans. Microw. Theory Techn.*, vol. 55, no. 5, pp. 932–940, May. 2007.

[17] K. J. Parsons and P. B. Kenington, "The efficiency of a feedforward amplifier with delay loss," *IEEE Trans. Veh. Technol.*, vol. 43, no. 2, pp. 407–412, 1994.

[18] P. A. Warr, P. B. Kenington, and M. A. Beach, "Feedforward linearization in high dynamic range receivers," in *ACTS Mobile Summit*, no. 839-844, Oct. 1997.

[19] K.-J. Cho, J.-H. Kim, and S. P. Stapleton, "A highly efficient Doherty feedforward linear power amplifier for W-CDMA base-station applications," *IEEE Trans. Microw. Theory Techn.*, vol. 53, no. 1, pp. 292–300, 2005.

[20] R. N. Braithwaite, "Positive feedback pilot system for second loop control in a feedforward power amplifier," *IEEE Trans. Circuits Syst. I, Reg. Papers*, vol. 55, no. 10, pp. 3293–3305, 2008.

[21] A. Gokceoglu, A. ghadam, and M. Valkama, "Steady-state performance analysis and step-size selection for LMS-Adaptive wideband feedforward power amplifier linearizer," *IEEE Trans. Signal Process.*, vol. 60, no. 1, pp. 82–99, 2012.

[22] J. K. Cavers, "Amplifier linearization using a digital predistorter with fast adaptation and low memory requirements," *IEEE Trans. Veh. Technol.*, vol. 39, no. 4, pp. 374–382, 1990.

[23] M. Faulkner and M. Johansson, "Adaptive linearization using predistortion-experimental results," *IEEE Trans. Veh. Technol.*, vol. 43, no. 2, pp. 323–332, 1994.

[24] A. N. D'Andrea, V. Lottici, and R. Reggiannini, "RF power amplifier linearization through amplitude and phase predistortion," *IEEE Trans. Commun.*, vol. 44, no. 11, pp. 1477–1484, 1996.

[25] J. K. Cavers, "Optimum table spacing in predistorting amplifier linearizers," *Vehicular Technology, IEEE Transactions on*, vol. 48, no. 5, pp. 1699–1705, 1999.

[26] N. Naskas and Y. Papananos, "Neural-network-based adaptive baseband predistortion method for RF power amplifiers," *IEEE Trans. Circuits Syst. II, Exp. Briefs*, vol. 51, no. 11, pp. 619–623, 2004.

[27] L. Ding, G. T. Zhou, D. R. Morgan, Z. Ma, J. S. Kenney, J. Kim, and C. R. Giardina, "A robust digital baseband predistorter constructed using memory polynomials," *IEEE Trans. Commun.*, vol. 52, no. 1, pp. 159–165, Jan. 2004.

[28] D. R. Morgan, Z. Ma, J. Kim, M. G. Zierdt, and J. Pastalan, "A generalized memory polynomial model for digital predistortion of RF power amplifiers," *IEEE Trans. Signal Process.*, vol. 54, no. 10, pp. 3852–3860, 2006.

[29] S. Hong, Y. Y. Woo, J. Kim, J. Cha, I. Kim, J. Moon, J. Yi, and B. Kim, "Weighted polynomial digital predistortion for low memory effect Doherty power amplifier," *IEEE Trans. Microw. Theory Techn.*, vol. 55, no. 5, pp. 925–931, May. 2007.

[30] A. Zhu, P. J. Draxler, J. J. Yan, T. J. Brazil, D. F. Kimball, and P. M. Asbeck, "Open-loop digital predistorter for RF power amplifiers using dynamic deviation reduction-based Volterra series," *IEEE Trans. Microw. Theory Techn.*, vol. 56, no. 7, pp. 1524–1534, Jul. 2008.

[31] R. N. Braithwaite and S. Carichner, "An improved Doherty amplifier using cascaded digital predistortion and digital gate voltage enhancement," *IEEE Trans. Microw. Theory Techn.*, vol. 57, no. 12, pp. 3118–3126, Dec. 2009.

[32] F. M. Ghannouchi and O. Hammi, "Behavioral modeling and predistortion," *IEEE Microw. Mag.*, vol. 10, no. 7, pp. 52–64, Dec. 2009.

[33] M. Rawat, K. Rawat, and F. M. Ghannouchi, "Adaptive digital predistortion of wireless power amplifiers/transmitters using dynamic real-valued focused time-delay line neural networks," *IEEE Trans. Microw. Theory Techn.*, vol. 58, no. 1, pp. 95–104, 2010.

[34] C. Yu, L. Guan, E. Zhu, and A. Zhu, "Band-limited Volterra series-based digital predistortion for wideband RF power amplifiers," *IEEE Trans. Microw. Theory Techn.*, vol. 60, no. 12, pp. 4198–4208, Dec 2012.

[35] J. Kim, P. Roblin, D. Chaillot, and Z. Xie, "A generalized architecture for the frequency- selective digital predistortion linearization technique," *IEEE Trans. Microw. Theory Techn.*, vol. 61, no. 1, pp. 596–605, Jan 2013.

[36] B. Fehri and S. Boumaiza, "Baseband equivalent Volterra series for digital predistortion of dual-band power amplifiers," *Microwave Theory and Techniques, IEEE Transactions on*, vol. 62, no. 3, pp. 700–714, 2014.

[37] "Universal Mobile Telecommunications System (UMTS); Base Stations (BS) radio transmission and reception (FDD)," *ETSI Standard TS 125 104 V11.5.0*, 2013.

[38] "Air interface for broadband wireless access systems," *IEEE Standard 802.16*, 2012.

[39] "E-UTRA Base Station (BS) radio transmission and reception, Release 11," *3GPP Standard TS 36.104 V11.4.0*, 2013.

[40] "E-UTRA Radio Frequency (RF) system scenarios, Release 11," *3GPP Standard TR 36.942 V11.0.0*, 2012.

[41] J. Mitola and G. Q. Maguire, Jr., "Cognitive radio: making software radios more personal," *IEEE Pers. Commun.*, vol. 6, no. 4, pp. 13–18, 1999.

[42] L. Guan and A. Zhu, "Low-cost FPGA implementation of Volterra series-based digital predistorter for RF power amplifiers," *IEEE Trans. Microw. Theory Techn.*, vol. 58, no. 4, pp. 866–872, April 2010.

[43] L. Guan, R. Kearney, C. Yu, and A. Zhu, "High-performance digital predistortion test platform development for wideband RF power amplifiers," *International Journal of Microwave and Wireless Technologies*, vol. 5, no. 02, pp. 149–162, Apr 2013.

[44] L. Guan, "High Performance Digital Predistortion for Wideband RF Power Amplifier," Ph.D. dissertation, Univeristy College Dublin, Ireland, Jan. 2012.

[45] http://cp.literature.agilent.com/litweb/pdf/5990-8883EN.pdf.

[46] Rohde&Schwarz. [Online]. Available: http://www.rohde-schwarz.com/.

[47] A. Kwan, O. Hammi, M. Helaoui, and F. M. Ghannouchi, "High performance wideband digital predistortion platform for 3G+ applications with better than 55dBc over 40 MHz bandwidth," in *IEEE MTT-S International Microwave Symposium Digest (MTT)*, 2010, pp. 1082–1085.

[48] H. J. Wu, J. Xia, J. F. Zhai, L. Tian, M. S. Yang, L. Zhang, and X.-W. Zhu, "A wideband digital pre-distortion platform with 100 MHz instantaneous bandwidth for LTE-advanced applications," in *Workshop on Integrated Nonlinear Microwave and Millimetre-Wave Circuits (INMMIC)*, 2012, pp. 1–3.

[49] R. Sperlich and J. Quintal, "Designing a High-Efficiency WCDMA BTS Using TI GC5322 Digital Pre-Distortion Processor," *Application Report, Texas Instrument*, 2010.

[50] H.-H. Chen, C.-H. Lin, P.-C. Huang, and J.-T. Chen, "Joint polynomial and look-up-table predistortion power amplifier linearization," *IEEE Trans. Circuits Syst. II, Exp. Briefs*, vol. 53, no. 8, pp. 612–616, Aug. 2006.

[51] J. Kim, Y. Y. Woo, and J. M. B. Kim, "A new wideband adaptive digital predistortion technique employing feedback linearization," *IEEE Trans. Microw. Theory Techn.*, vol. 56, no. 2, pp. 385–392, Feb 2008.

[52] S. A. Bassam, M. Helaoui, and F. M. Ghannouchi, "Channel-selective multi-cell digital predistorter for multi-carrier transmitters," *IEEE Trans. Commun.*, vol. 60, no. 8, pp. 2344–2352, Aug 2012.

[53] H. Cao, H. M. Nemati, A. S. Tehrani, T. Eriksson, J. Grahn, and C. Fager, "Linearization of efficiency-optimized dynamic load modulation transmitter architectures," *IEEE Trans. Microw. Theory Techn.*, vol. 58, no. 4, pp. 873–881, Apr 2010.

[54] G. Haiying Cao, H. M. Nemati, A. S. Tehrani, T. Eriksson, and C. Fager, "Digital predistortion for high efficiency power amplifier architectures using a dual-input modeling approach," *IEEE Trans. Microw. Theory Techn.*, vol. 60, no. 2, pp. 361–369, 2012.

[55] C. D. Presti, F. Carrara, A. Scuderi, P. M. Asbeck, and G. Palmisano, "A 25 dBm digitally modulated CMOS power amplifier for WCDMA/EDGE/OFDM with adaptive digital predistortion and efficient power control," *IEEE J. Solid-State Circuits*, vol. 44, no. 7, pp. 1883–1896, Jul 2009.

[56] L. Ding, Z. Ma, D. R. Morgan, M. Zierdt, and J. Pastalan, "A least-squares/Newton method for digital predistortion of wideband signals," *IEEE Trans. Commun.*, vol. 54, no. 5, pp. 833–840, May 2006.

[57] H. Gandhi, "A flexible Volterra-based adaptive digital predistortion solution for wideband rf power amplifier linearization." *Texas Instrument, Palo Alto, USA*, 2010.

[58] P. Roblin, S. K. Myoung, D. Chaillot, Y. G. Kim, A. Fathimulla, J. Strahler, and S. Bibyk, "Frequency-selective predistortion linearization of RF power amplifiers," *IEEE Trans. Microw. Theory Techn.*, vol. 56, no. 1, pp. 65–76, Jan 2008.

[59] C. Quindroit, N. Naraharisetti, P. Roblin, S. Gheitanchi, V. Mauer, and M. Fitton, "FPGA implementation of orthogonal 2D digital predistortion system for concurrent dual-band power amplifiers based on time-division multiplexing," *Microwave Theory and Techniques, IEEE Transactions on*, vol. 61, no. 12, pp. 4591–4599, 2013.

[60] P. L. Gilabert, A. Cesari, G. Montoro, E. Bertran, and J.-M. Dilhac, "Multi-lookup table FPGA implementation of an adaptive digital predistorter for linearizing RF power amplifiers with memory effects," *IEEE Trans. Microw. Theory Techn.*, vol. 56, no. 2, pp. 372–384, 2008.

[61] P. L. Gilabert, G. Montoro, and E. Bertran, "FPGA implementation of a real-time narma-based digital adaptive predistorter," *IEEE Trans. Circuits Syst. II, Exp. Briefs*, vol. 58, no. 7, pp. 402–406, 2011.

[62] AN10921, "BLF7G20LS-200 Doherty 1.805 to 1.88 GHz RF power amplifier," *NXP Semiconductors*, 2010.

[63] J. F. Zhai, L. Zhang, J. Zhou, X.-W. Zhu, and W. Hong, "A nonlinear fitler-based Volterra model with low complexity for wideband power amplifiers," *IEEE Microw. Compon. Lett.*, vol. Has been accepted, 2014.

[64] A. Kwan, F. M. Ghannouchi, O. Hammi, M. Helaoui, and M. R. Smith, "Look-up table-based digital predistorter implementation for field programmable gate arrays using long-term evolution signals with 60 mhz bandwidth," *IET Science, Measurement & Technology*, vol. 6, no. 3, pp. 181–188, 2012.

[65] N. Tuffy, L. Guan, A. Zhu, and T. J. Brazil, "A simplified broadband design methodology for linearized high-efficiency continuous Class-F power amplifiers," *IEEE Trans. Microw. Theory Techn.*, vol. 60, no. 6, pp. 1952–1963, Jun 2012.

[66] L. Guan and A. Zhu, "Optimized low-complexity implementation of least squares based model extraction for digital predistortion of RF power amplifiers," *IEEE Trans. Microw. Theory Techn.*, vol. 60, no. 3, pp. 594–603, Mar 2012.

[67] P. J. Lunsford, II, G. W. Rhyne, and M. B. Steer, "Frequency-domain bivariate generalized power series analysis of nonlinear analog circuits," *IEEE Trans. Microw. Theory Techn.*, vol. 38, no. 6, pp. 815–818, 1990.

[68] M. Schetzen, *The Volterra and Wiener Theories of Nonlinear Systems*. reprint Krieger, Malabar, Florida, 2006.

[69] J. Kim and K. Konstantinou, "Digital predistortion of wideband signals based on power amplifier model with memory," *Electronics Letters*, vol. 37, no. 23, pp. 1417–1418, 2001.

[70] G. Montoro, P. L. Gilabert, E. Bertran, A. Cesari, and D. D. Silveira, "A new digital predictive predistorter for behavioral power amplifier linearization," *IEEE Microw. Compon. Lett.*, vol. 17, no. 6, pp. 448–450, 2007.

[71] A. Zhu, J. C. Pedro, and T. J. Brazil, "Dynamic deviation reduction-based Volterra behavioral modeling of RF power amplifiers," *IEEE Trans. Microw. Theory Techn.*, vol. 54, no. 12, pp. 4323–4332, 2006.

[72] L. Guan and A. Zhu, "Simplified dynamic deviation reduction-based Volterra model for Doherty power amplifiers," in *Proc. Workshop Integrated Nonlinear Microwave and Millimetre-Wave Circuits (INMMIC)*, 2011, pp. 1–4.

[73] J. Wood, D. E. Root, and N. B. Tufillaro, "A behavioral modeling approach to nonlinear model-order reduction for RF/microwave ICs and systems," *IEEE Trans. Microw. Theory Techn.*, vol. 52, no. 9, pp. 2274–2284, 2004.

[74] T. Liu, S. Boumaiza, and F. M. Ghannouchi, "Dynamic behavioral modeling of 3G power amplifiers using real-valued time-delay neural networks," *IEEE Trans. Microw. Theory Techn.*, vol. 52, no. 3, pp. 1025–1033, 2004.

[75] F. Mkadem and S. Boumaiza, "Physically inspired neural network model for RF power amplifier behavioral modeling and digital predistortion," *IEEE Trans. Microw. Theory Techn.*, vol. 59, no. 4, pp. 913–923, Apr 2011.

[76] S. Hyun Woo Kang, Y. S. Cho, and D. H. Youn, "Adaptive precompensation of Wiener systems," *IEEE Trans. Signal Process.*, vol. 46, no. 10, pp. 2825–2829, 1998.

[77] T. Liu, S. Boumaiza, and F. M. Ghannouchi, "Deembedding static nonlinearities and accurately identifying and modeling memory effects in wide-band RF transmitters," *IEEE Trans. Microw. Theory Techn.*, vol. 53, no. 11, pp. 3578–3587, 2005.

[78] P. L. Gilabert, G. Montoro, and E. Bertran, "On the Wiener and Hammerstein models for power amplifier predistortion," in *Proc. Asia-Pacific Microwave Conference (APMC)*, vol. 2, 2005.

[79] T. Liu, S. Boumaiza, and F. M. Ghannouchi, "Augmented Hammerstein predistorter for linearization of broad-band wireless transmitters," *IEEE Trans. Microw. Theory Techn.*, vol. 54, no. 4, pp. 1340–1349, 2006.

[80] F. Mkadem and S. Boumaiza, "Extended hammerstein behavioral model using artificial neural networks," *IEEE Trans. Microw. Theory Techn.*, vol. 57, no. 4, pp. 745–751, 2009.

[81] P. Jardin and G. Baudoin, "Filter lookup table method for power amplifier linearization," *IEEE Trans. Veh. Technol.*, vol. 56, no. 3, pp. 1076–1087, May 2007.

[82] W.-J. Kim, K.-J. Cho, S. P. Stapleton, and J.-H. Kim, "Piecewise pre-equalized linearization of the wireless transmitter with a Doherty amplifier," *IEEE Trans. Microw. Theory Techn.*, vol. 54, no. 9, pp. 3469–3478, 2006.

[83] A. Zhu, P. J. Draxler, C. Hsia, T. J. Brazil, D. F. Kimball, and P. M. Asbeck, "Digital predistortion for envelope-tracking power amplifiers using decomposed piecewise Volterra series," *IEEE Trans. Microw. Theory Techn.*, vol. 56, no. 10, pp. 2237–2247, 2008.

[84] S. Afsardoost, T. Eriksson, and C. Fager, "Digital predistortion using a vector-switched model," *IEEE Trans. Microw. Theory Techn.*, vol. 60, no. 4, pp. 1166–1174, 2012.

[85] H. Jiang and P. A. Wilford, "Digital predistortion for power amplifiers using separable functions," *IEEE Trans. Signal Process.*, vol. 58, no. 8, pp. 4121–4130, 2010.

[86] X. Yu and H. Jiang, "Digital predistortion using adaptive basis functions," *IEEE Trans. Circuits Syst. I, Reg. Papers*, vol. 60, no. 12, pp. 3317–3327, 2013.

[87] O. Hammi and F. M. Ghannouchi, "Twin nonlinear two-box models for power amplifiers and transmitters exhibiting memory effects with application to digital predistortion," *IEEE Microw. Compon. Lett.*, vol. 19, no. 8, pp. 530–532, 2009.

[88] M. Younes, O. Hammi, A. Kwan, and F. M. Ghannouchi, "An accurate complexity-reduced 'PLUME' model for behavioral modeling and digital predistortion of RF power amplifiers," *IEEE Trans. Ind. Electron.*, vol. 58, no. 4, pp. 1397–1405, 2011.

[89] R. N. Braithwaite, "Digital predistortion of a power amplifier for signals comprising widely spaced carriers," in *Microwave Measurement Symposium (ARFTG), 2011 78th ARFTG*, 2011, pp. 1–4.

[90] Y. Liu, W. Chen, J. Zhou, B. Zhou, and F. Ghannouchi, "Digital predistortion for concurrent dual-band transmitters using 2-D modified memory polynomials," *IEEE Trans. Microw. Theory Techn.*, vol. 61, no. 1, pp. 281–290, 2013.

[91] S. A. Bassam, M. Helaoui, and F. M. Ghannouchi, "2-D digital predistortion (2-D-DPD) architecture for concurrent dual-band transmitters," *IEEE Trans. Microw. Theory Techn.*, vol. 59, no. 10, pp. 2547–2553, Oct 2011.

[92] L. Guan and A. Zhu, "Dual-loop model extraction for digital predistortion of wideband RF power amplifiers," *IEEE Microw. Compon. Lett.*, vol. 21, no. 9, pp. 501–503, Sep. 2011.

[93] Y.-J. Liu, W. Chen, J. Zhou, B.-H. Zhou, F. M. Ghannouchi, and Y.-N. Liu, “Modified least squares extraction for Volterra-series digital predistorter in the presence of feedback measurement errors,” *IEEE Trans. Microw. Theory Techn.*, vol. 60, no. 11, pp. 3559–3570, Nov 2012.

[94] L. Ding, F. Mujica, and Z. Yang, “Digital predistortion using direct learning with reduced bandwidth feedback,” in *Microwave Symposium Digest (IMS), 2013 IEEE MTT-S International*, 2013, pp. 1–3.

[95] R. N. Braithwaite, “Wide bandwidth adaptive digital predistortion of power amplifiers using reduced order memory correction,” in *IEEE MTT-S International Microwave Symposium Digest*, 2008, pp. 1517–1520.

[96] L. Guan, C. Yu, and A. Zhu, “Bandwidth-constrained least squares-based model extraction for band-limited digital predistortion of RF power amplifiers,” in *Integrated Nonlinear Microwave and Millimetre-Wave Circuits (INMMIC), 2012 Workshop on*, 2012, pp. 1–3.