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Novel Baseband Equivalent Models of Quadrature Modulated All-Digital Transmitters

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Abstract—In this paper an exact baseband equivalent model of a quadrature modulated all-digital transmitter is derived. No restrictions on the number of levels of a digital switched-mode power amplifier (SMPA) driving input, nor the pulse encoding scheme employed, are made. This implies a high level of generality of the proposed model. We show that all-digital transmitter (ADT) can be represented as a series connection of the pulse encoder, discrete-time Volterra series model of fixed degree and memory depth, and a linear time-varying system with special properties. This result suggests a new analytically motivated structure of a digital predistortion (DPD) of SMPA nonlinearities in ADT. Numerical simulations in MATLAB are used to verify proposed baseband equivalent model.

Index Terms—Digital predistortion, all-digital transmitter, baseband equivalent model.

I. INTRODUCTION

Behavioral modeling of nonlinearities in power amplifiers (PA), and their compensation, has been an active area of research for more than two decades (see [1]- [4] and references therein). Most of the work has focused on traditional transmitters employing linear PAs. All-digital transmitters (ADT), which use switched-mode power amplifiers (SMPA) instead of linear PAs, have recently gained significant importance due to their promising potential of providing high power efficiency (see [5]- [7] and references therein). Surprisingly, not much research has been done on behavioral modelling of all-digital transmitters. Neural networks based behavioral ADT models were presented in [8]. Main deficiency of such black box modeling is the lack of insight into structure and internal dynamics of the nonlinear system being approximated. An exact baseband equivalent model for a quadrature modulated ADT was given in [9], but only for 2 level pulse encoding scheme (taking precisely ± 1 values), and without an obvious extension to multi-level case. An analog baseband equivalent model was recently given in [10]. Effects of pulse encoder are completely ignored in the derivation of equivalent model, thus neglecting large amount of quantization noise in the PA input, which spectrally spreads into signal band once processed by the passband nonlinearity.

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Recently, in [11]-[12], authors showed that passband nonlinearities can be represented by an equivalent baseband model consisting of a series connection of a short memory nonlinear system followed by a special linear time-invariant system (LTI). They consider quadrature modulated transmitters in traditional setup, employing analog upconversion to carrier frequency and linear PAs. Assumption which enables such a compact system description is the zero-order hold digital-to-analog conversion of a PA driving signal. By recognizing similar form of the SMPA driving input, we extend that description to all-digital transmitters. Proposed ADT structure does not depend on the choice of pulse encoder (e.g. pulse-width modulation or delta-sigma modulation), nor does it depend on the number of its output levels. It exactly represents ADT when the passband nonlinearity can be represented by continuous-time Volterra series of fixed memory. Furthermore, it suggests a novel, non-obvious, analytically motivated DPD structure, which reduces computational and hardware complexity of a standard memory polynomial or pruned Volterra-series based DPD.

II. PROBLEM FORMULATION

Detailed block diagram of a quadrature modulated ADT is shown in the figure below. High resolution input se-

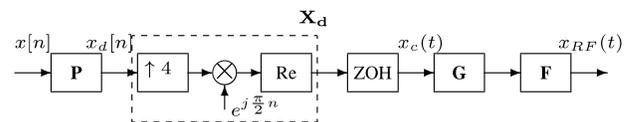


Fig. 1. Detailed block diagram of a quadrature modulated ADT.

quence $x = x[n]$, whose in-phase and quadrature components are denoted $i = i[n]$ and $q = q[n]$ respectively, is first processed with a pulse encoder, denoted \mathbf{P} , so to assume amplitude levels suitable for driving a low resolution SMPA. Here we assume that \mathbf{P} acts on i and q separately, and produces digital output signal $x_d = x_d[n] = i_d[n] + jq_d[n]$, where $i_d = \mathbf{P}i$, and $q_d = \mathbf{P}q$. Signal x_d is first upconverted to a digital carrier frequency, before being converted to continuous-time domain by a

zero-order hold (ZOH) digital-to-analog converter (DAC). Upconversion to digital frequency is usually done at the sampling rate of 4 times the carrier frequency. Under this assumption, mixing in digital domain becomes equivalent to interleaving the in-phase and quadrature components, together with their negative counterparts. We denote the digital upconversion system as \mathbf{X}_d (Fig. 1). Continuous-time (CT) pulsed signal $x_c = x_c(t)$ is fed into SMPA, which is denoted by \mathbf{G} in Fig. 1. We are particularly interested in the case when \mathbf{G} can be described by the general CT Volterra series model [13], with memory not larger than the sampling period of signal x_d .

Output of the nonlinear system \mathbf{G} is passed through an analog bandpass filter \mathbf{F} , in order to produce the RF signal $x_{RF} = x_{RF}(t)$ to be radiated by antenna. Here we assume \mathbf{F} to be an ideal bandpass filter with bandwidth equal to the sampling rate of the input signal x , and centered at the carrier frequency f_c . This is to avoid modeling the whole range of the output signal's spectrum which would make the linearization bandwidth very large, and would put a significant burden on system design.

ADT, as a system, maps baseband DT signal x into passband CT signal x_{RF} . If baseband equivalent model is used for DPD design, it is more beneficial to find the map between x and the downconverted and sampled version of x_{RF} , which we denote as \hat{x} . Therefore, instead of considering the ADT system given in Fig. 1, it is natural to consider a system depicted in Fig. 2, and denoted \mathbf{S} . Here \mathbf{D} denotes an ideal demodulator, which runs at the sampling rate of baseband input signal $x[n]$, and \mathbf{M} is used to denote the ZOH converter.

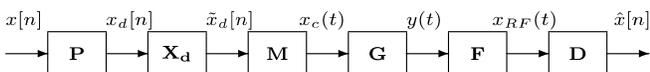


Fig. 2. Series connection of ADT and a demodulator system.

The SMPA driving signal x_c , i.e. input into \mathbf{G} , is a piecewise constant signal, which assumes only a finite number of amplitude levels corresponding to the choice of the pulse encoder \mathbf{P} . This is a consequence of the zero-order hold operation of digital-to-analog converter \mathbf{M} . It is now easy to see that series interconnection \mathbf{DFGM} , in Fig. 2, has very similar structure to the analogous one in [11]. The only difference is that sampling rates of the input and output signals are not equal. Signal \hat{x} runs at a sampling rate of the baseband signal x , while x_d runs at a higher sampling rate. Let K be the ratio of the sampling rates of x_d and x . It was shown in [11], that the equivalent of the composition system \mathbf{DFGM} can be represented as a series interconnection \mathbf{LV} of a Volterra type DT nonlinear system \mathbf{V} , and an LTI system \mathbf{L} . For the system shown in Fig. 2, the equivalent \mathbf{L} should be a time-varying system, due to the above mentioned mismatch

between input and output signal rates. In the following section we decompose this equivalent linear subsystem into a series interconnection of a multi-input single-output LTI subsystem \mathbf{L} and a downsampler.

III. MAIN RESULT

Under assumptions introduced in the previous section, we give a general description of an ADT system.

Complete characterization of system \mathbf{S} in Fig.2:

Let \mathbf{V} be a single-input multi-output system mapping a complex signal $x[n] = i[n] + jq[n]$ into a vector valued real signal $v[n] = [v_1[n] \dots v_N[n]]^T$, components of which are all Volterra monomials composed of $i[n]$ and $q[n]$, up to degree M and depths m_i and m_q . Let \mathbf{K} be a downsampling by factor of K subsystem, where K was defined in the previous section. System \mathbf{S} , as given in Fig. 2, can be decomposed into a series connection of systems \mathbf{P} , \mathbf{V} , \mathbf{L} and \mathbf{K} , as given in Fig. 3, where \mathbf{L} is a multi-input single-output LTI system with long memory, and good approximation by finite impulse response (FIR) filters (Proof is omitted due to space limitations.).

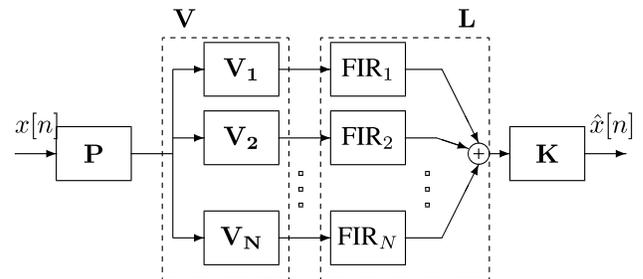


Fig. 3. Baseband equivalent model of \mathbf{S} .

Here we emphasize some consequences of this result. Block diagram representation of \mathbf{S} in Fig. 3, stresses parallel structure in the \mathbf{LV} part of the system. Each \mathbf{V}_k in Fig. 3 describes one Volterra monomial, e.g. $(V_k x)[n] = i[n]i[n-1]q[n]^2$. Therefore, subsystems \mathbf{V}_k are relatively easy to implement since they only involve delays and multiplication operations. Attention should be paid to possible delays that can appear in subsystems \mathbf{V}_k . It can be shown that if continuous-time Volterra kernel has maximal memory τ (over all variables), then its corresponding discrete-time analog (group of monomials \mathbf{V}_k), has memory $\lceil \frac{\tau}{T} \rceil$, where $\lceil \cdot \rceil$ is a ceil function. Frequency responses of components of \mathbf{L} , depend heavily on the passband nonlinearity, but they have a common feature: they are smooth over the spectral band of interest. This makes them well approximable in spectral domain, by e.g. polynomials. Moreover, finding coefficients of those polynomials can be done by simple least squares optimization.

It is important to emphasize that due to bandpass filtering of the PA output, long memory dynamic behavior

is now present, which makes band-limited models fundamentally different from the conventional baseband models. This implies that traditional modeling methods, such as memory polynomials or dynamic deviation reduction-based Volterra series modeling, might be too general to define this new structure, and also not well suited for practical implementations due to long memory requirements (of the nonlinear part) which would require exponentially large number of coefficients. Therefore, the structure proposed in this paper does not suffer from issues of long memory of nonlinear subsystem, but rather has memory depth equivalent to that of the passband nonlinearity. Long memory requirements are forwarded to the linear subsystems \mathbf{L}_k , taking complexity burden off the nonlinear part.

Now we discuss potential impact, of the above result, on digital predistortion design for all-digital transmitters. DPD design can be seen as a process of finding the inverse of \mathbf{S} (when it exists). In most applications, with an appropriate scaling and time delay, the system \mathbf{S} to be inverted can be viewed as a small perturbation of identity, i.e. $\mathbf{S} = \mathbf{I} + \mathbf{\Delta}$. Using Neumann's series, assuming $\mathbf{\Delta}$ is small in an appropriate sense, the inverse of \mathbf{S} can be well approximated by $\mathbf{S}^{-1} \approx \mathbf{I} - \mathbf{\Delta} = 2\mathbf{I} - \mathbf{S}$. Hence the result of this paper suggests a specific structure of the compensator $\mathbf{C} \approx 2\mathbf{I} - \mathbf{S}$. As pointed out in [11], this implies that plain Volterra monomials structure is, in general, not enough to model \mathbf{C} , as it lacks the capacity to implement the long memory effects caused by bandpass filtering. Instead, \mathbf{C} should be sought in the form $\mathbf{C} = \mathbf{I} - \mathbf{K}\mathbf{L}_0\mathbf{XVP}$, where \mathbf{P} is the pulse encoder, \mathbf{V} is the system generating all Volterra series monomials of a limited depth and limited degree, \mathbf{L}_0 is a fixed LTI system with a long time constant, \mathbf{X} is a matrix of coefficients to be optimized to fit the data available, and \mathbf{K} is a downsampler. Elements of the coefficient matrix \mathbf{X} can be easily obtained by applying simple least squares optimization on the set of input output pairs of \mathbf{S} .

IV. SIMULATION RESULTS

Validation of the above model of system \mathbf{S} is done for two cases of passband nonlinearity \mathbf{G} . In the first case we assume a simple third order analog nonlinearity, consisting of a linear term and one CT Volterra monomial, as given below

$$(Gx)(t) = x(t) - \delta_1 x(t - \tau_1)x(t - \tau_2)x(t - \tau_3). \quad (1)$$

Time delays in the above expression are taken as $\tau_1 = 1.2T$, $\tau_2 = 2.3T$, $\tau_3 = 0.4T$, where T is a sampling time of a digitally upconverted DT signal \tilde{x}_d (see Fig. 2). Parameter δ_1 is varied in the interval $[0.001, 0.2]$. This parameter roughly dictates the amount of passband distortion or equivalently the level of linearity of the

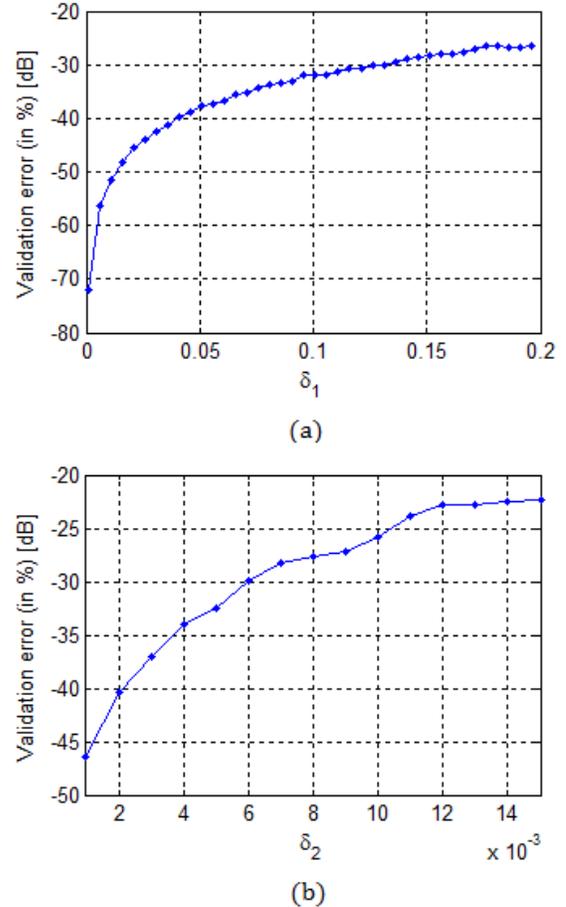


Fig. 4. Model Validation Error: (a) Example 1; (b) Example 2.

transmitter circuit. In the second case we assume

$$(Gx)(t) = x(t) - \delta_2 \int_0^t h(\tau_1, \tau_2)x(t - \tau_1)x(t - \tau_2)d\tau_1d\tau_2, \quad (2)$$

where kernel $h = h(t_1, t_2)$ is of memory less than $4T$, and is separable, i.e. $h(t_1, t_2) = h_1(t_1) \cdot h_2(t_2)$, with $h_1(t_1) = \exp(-0.95t_1)$ and $h_2(t_2) = \exp(-0.91t_2) \cos(\pi/5t_2)$. In this case, parameter δ_2 takes values from $[0.001, 0.015]$. In both cases, delta-sigma modulator (DSM) of first order and 5 output levels, was used as pulse encoder. System \mathbf{S} is modeled as given in Fig. 3. In both cases, systems \mathbf{V}_k are Volterra monomials of maximal degree 3, and digital memory of up to 4 samples (due to maximal memory of passband nonlinearity equal to $4T$). Coefficients of the FIR filters are obtained by fitting this model on a training data of 40960 input-output pairs.

Model validation results are depicted in Fig. 4. Very good modeling error (below 0.1% or -20dB) is achieved in both cases, though an upward trend in error (as $\delta_{1/2}$ is increased) is noticeable from Fig. 4. This is due to the error in approximating FIR filters, which gets enhanced as level of distortion increases.

V. CONCLUSION

In this paper, we propose a novel structure of the baseband equivalent model of a quadrature modulated ADT, under assumption that the passband nonlinearity is of Volterra series type of fixed memory. It was shown that ADT can be represented as a series connection of the pulse encoder, discrete-time Volterra series model of fixed degree and memory depth, and a linear time-varying system with special properties. Model does not assume any particular pulse encoding method, nor does it put constraints on the number of its output levels. Results suggest a novel, analytically motivated DPD structure, which can potentially reduce computational and hardware complexity compared to traditional DPD design techniques.

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