Decomposition of generalized piecewise-polynomial model of digital predistorter to suppress power amplifier non-linearity

Elena Borisovna Solovyeva

Saint Petersburg Electrotechnical University "LETI", Professora Popova Street, 5, St. Petersburg, 197376, Russian Federation

Abstract. A decomposed generalized piecewise-polynomial model of a digital predistorter designed for linearization of power amplifier characteristics is suggested. The digital predistorter model is designed in such a way that its non-linear distortions compensate non-linear ones in the subsequent power amplifier. Decomposition of digital predistorter model is designed taking into account the dynamics of change of signal complex envelope module. This signal is transformed in power amplifier. The accuracy of the compensation of non-linear signal distortions in the power amplifier increases at decomposition of digital predistorter piecewise-polynomial model. The comparative analysis of different models of digital predistorters is performed under the conditions of linearization of the power amplifier Winner-Hammerstein model in GSM-signal class with four carriers.

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Introduction

Power amplifier (PA) is an integral part of many communication systems. PA is a non-linear device in which a transmitted signal is distorted, its spectrum broadens and moves beyond the transmission band of the used communication channel. As the result the distortions, created by the influence of the adjacent channels on each other, increases (we can observe the interchannel interference) [1]–[5].

Linearization of power amplifier characteristics is performed in order to prevent PA output signal spectrum expansion and to maintain a high level of amplifier energetic effectiveness (high coefficient of efficiency). One of linearization universal methods is a digital predistortion (precompensation) for which such features as robustness, simplicity of hardware implementation, high level of non-linearity suppression are characteristic [3]. The task of a precompensator (digital predistorter, DPD) is to linearise PA by means of predistortion which is used for compensation of non-linear distortions in a power amplifier. In broad-band communication channels dynamic non-linearity is characteristic of PA with high coefficient of efficiency and PA is described by a non-linear memory model. Consequently, DPD is a digital non-linear dynamic device [3], [4].

DPD models are different: non-recursive and recursive polynomial constructions, different types of neuron networks [3]. Precompensator model simplicity plays an important role in DPD hardware implementation, that's why the DPD synthesis on the basis of Volterra truncated series modifications, in particular the most simple of them: memory polynomial (MP) and generalized memory polynomial (GMP) remains promising [1]–[6]. The power amplifier linearization accuracy increases in the process of transfer from the MP model of DPD to the piecewise MP model (piecewise memory polynomial, PMP) [7]. The PMP input signal is a vector of complex signal which consists of sub-signals formed by the division of a complex domain of DPD scalar excitation into regions with assigned thresholds (radius).

In this paper the method of DPD synthesis on the basis of piecewise generalized memory polynomial (PGMP) is developed and the decomposition of the above mentioned model with regard to the dynamics of the change of a complex signal module transformed in PA with the purpose of increasing power amplifier linearization accuracy is suggested.

Decomposition of generalized piecewise-polynomial model of a digital predistorter

In the process of DPD model synthesis there appears the number K of areas (zones) of complex envelope $x(n)$ domain of DPD excitation. Thresholds (radius) of zones are set of values R_i, $i = 1, 2, ..., (K-1)$, where i — is the number of the zone, $R_1 < R_2 < ... < R_{K-1}$ [7]. Let's suppose $R_0 = 0$, $R_K = \infty$.

Independent non-linear operators in different zones are introduced according to the conditions:

$F_i[\boldsymbol{X}(n)]$ while $R_{i-1} < |x(n)| \le R_i$, $i = 1, 2, ..., K$, (1)

where n is the normalized discrete time, $\boldsymbol{X}(n)$ is the vector of DPD input signals which is formed, for example, by delay line with the length M, $\boldsymbol{X}(n) = [x(n), x(n-1), ..., x(n-M)]$.

Every non-linear operator $F_i[\boldsymbol{X}(n)]$ from the set of zones (1) is approximated by polynomial model, in particular, by generalized memory polynomial (GMP) [1]–[3]. As a result, the output complex envelope $y(n)$ of the PGMP model is described by the equation

$$y(n) = \sum_{m=0}^{M} x(n-m)\left[\sum_{l=0}^{L}\sum_{k=0}^{(P-1)/2} a_{k,l,m}^{(i)} |x(n-m-l)|^{2k}\right] \cong F_i[\boldsymbol{X}(n)], \quad (2)$$

where i is the number of the zone set at the time moment n on the basis of conditions (1), P ($P \ge 3$) is the odd degree of polynomial, M is the PGMP memory length, L is the time delay of the input signal envelope, $a_{k,l,m}^{(i)}$ is the parameter of the model.

Let us perform the PGMP model decomposition by dividing every area into two sub-zones depending on the dynamics of change of the complex envelope $x(n)$ module. If the complex envelope $x(n)$ module in the area i decreases, i.e.

$$\Delta|x(n)| = |x(n)| - |x(n-1)| < 0, \quad (3)$$

the signal $x(n)$ relates to the 1st sub-zone ($g = 1$) of the area. In case of condition which is opposite to the inequation (3) the signal $x(n)$ relates to the 2nd sub-zone ($g = 2$) of the area i.

In the result of this division of areas into sub-zones DPD independent non-linear operators are introduced according to the following conditions:

$$F_{i,1}[\boldsymbol{X}(n)] \text{ while } R_{i-1} < |x(n)| \le R_i \text{ and } \Delta|x(n)| < 0,$$

$$F_{i,2}[\boldsymbol{X}(n)] \text{ while } R_{i-1} < |x(n)| \le R_i \text{ and } \Delta|x(n)| \ge 0, \quad i = 1, 2, ..., K, \quad (4)$$

where $\boldsymbol{X}(n) = [x(n), x(n-1), ..., x(n-M)]$.

The PGMP model decomposition gives the decomposed PGMP model (decomposed piecewise generalized memory polynomial, DPGMP) of the following type:

$$y(n) = \sum_{m=0}^{M} x(n-m)\left[\sum_{l=0}^{L}\sum_{k=0}^{(P-1)/2} a_{k,l,m}^{(i,g)} |x(n-m-l)|^{2k}\right] \cong F_{i,g}[\boldsymbol{X}(n)], \quad (5)$$

where i, g are the numbers of the zone and the sub-zone set at the time moment n on the basis of conditions (4), $a_{k,l,m}^{(i,g)}$, P ($P \ge 3$), M, L are the parameter, the odd degree, the DPGMP memory length and the signal envelope time delay respectively.

Thus, the DPGMP model reflects the fact that signal complex envelopes with increasing and decreasing modules are transformed in PA by different non-linear operators.

Parameters of PGMP (2) and DPGMP (5) models are resulted from training DPD which is performed according to direct or indirect structure [3]. The indirect structure is often used in practice. This structure is shown in Fig. 1, where G is the PA gain.

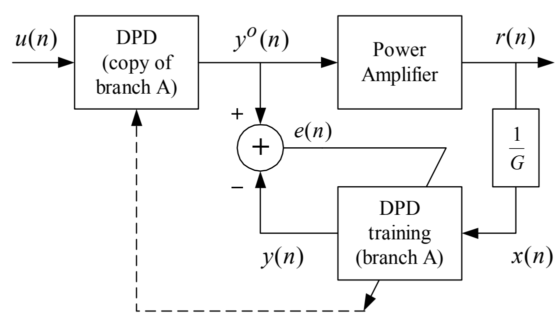

Fig. 1. Indirect structure of DPD training

In the DPGMP model (5) the optimal coefficient vector $\boldsymbol{A} = [\boldsymbol{a}_0, \boldsymbol{a}_1, ..., \boldsymbol{a}_m, ..., \boldsymbol{a}_M]^T$, where $\boldsymbol{a}_m = \left[a_{0,0,m}^{(i,g)}, a_{1,l,m}^{(i,g)}, ..., a_{(P-1)/2,l,m}^{(i,g)}\right]^T$, is defined by the iterative procedure fulfilled in accordance with the structure shown in Fig. 1. At every iteration in the root-mean-square metric it is required to solve the approximation task

$$\left\| y^o(n) - y(n) \right\| \Rightarrow \min_{n \in [0,\, N-1]},$$

where N is the number of signal samples taking part in DPD training.

Let us use the precompensator DPGMP model (5) for linearization of the power amplifier Winner-Hammerstein model [8].

Linearization of the power amplifier Winner-Hammerstein model

PA of AB class is described by the low-frequency Winner-Hammerstein model which includes the following equations of cascade blocks [8]:

— difference equation of the linear dynamic circuit

$$v(n) = u(n) + 0{,}5u(n-2) + 0{,}2v(n-1),$$

where $u(n)$, $v(n)$ is the input and output signals of the circuit correspondingly;

— equation of memory less nonlinearity

$$w(n) = b_1 v(n) + b_3 v(n)|v(n)|^2 + b_5 v(n)|v(n)|^4,$$

where $b_1 = 1{,}0108 + 0{,}0858j$, $b_3 = 0{,}0879 - 0{,}1583j$, $b_5 = -1{,}0992 - 0{,}8891j$;

— difference equation of the linear dynamic circuit

$$r(n) = w(n) - 0{,}1w(n-2) + 0{,}4r(n-1),$$

where $w(n)$ is the input signal of the linear circuit, and $r(n)$ is the PA output signal.

The excitation $u(n)$ of the PA low-frequency model is a complex envelope of GSM signal with four carriers in the frequency band of 20 MHz, which is situated relative to the central frequency of $1{,}845$ GHz. Sampling frequency of the GSM signal envelope is $184{,}32$ MHz.

Normalized non-linear amplitude characteristic of the described PA is $|\tilde{r}|_n(|\tilde{u}|_n)$, where

$$|\tilde{r}|_n = \frac{|r(n)|}{\max\limits_{n \in [0,\, N-1]} |r(n)|},$$

$$|\tilde{u}|_n = \frac{|u(n)|}{\max\limits_{n \in [0,\, N-1]} |u(n)|}.$$

This characteristic is shown in Fig. 2.

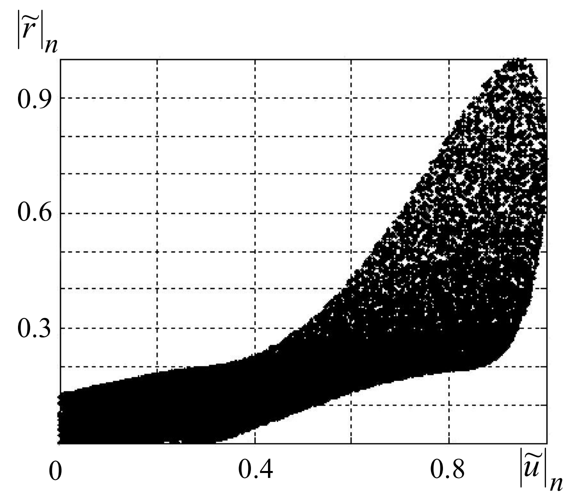

Fig. 2 Normalized non-linear amplitude characteristic of the PA

For described PA linearization by predistorter PMP, PGMP and DPGMP models with memory $M = 4$, and degrees $P = 3$ and $P = 5$ were used.

Normalized mean-square error, dB (NMSE) of PA linearization was calculated using the following formula

$$\mathrm{NMSE} = 10\log_{10}\left(\frac{\sum\limits_{n=0}^{N-1} |u(n) - x(n)|^2}{\sum\limits_{n=0}^{N-1} |u(n)|^2} \right),$$

where $x(n) = r(n)/G$, G is the PA gain. Input signal $u(n)$ had the length $N = 106\,339$ of samples.

NMSE error at the 6th iteration of PA linearization (errors were changing insignificantly on the following iterations), as well as the number K of areas and the number Q of parameters of DPD models at different degree P are represented in Table 1.

Table 1. PA linearization error, number of areas and parameters in DPD models

Model	P=3			P=5		
	NMSE	K	Q	NMSE	K	Q
PMP (L=0 in (2))	–65,793	32	352	-70.011	16	352
PGMP (L=1 in (2))	-69.274	32	672	-82,079	32	1152
DPGMP (L=1 in (5))	-74.237	16	672	-84.002	16	1152
DPGMP (L=2 in (5))	-77.773	24	1728	-86.256	8	1056

Fig. 3 shows the PA normalized amplitude characteristic which corresponds to the one shown in Fig. 2 and get at the 6th iteration of the amplifier linearization with the help of precompensator DPGMP model.

The comparative analysis of Fig. 2 and Fig. 3 shows that precompensator DPGMP model carries out PA linearization with a high accuracy.

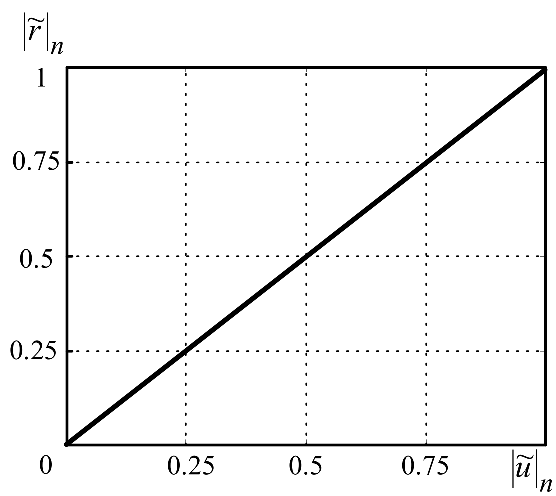

Fig. 3 Normalized amplitude characteristic of the PA after its linearization with the help of DPGMP precompensator

Conclusion

Basing on the analysis of Table 1 and Fig. 3 we can conclude that the precompensator DPGMP model provides higher precision of linearization of the PA Winner-Hammerstein model comparing to the similar DPDs.

DPGMP and PGMP models have similar complexity at the similar time delay of the input signal envelope ($L = 1$), however the decomposed model is more accurate than the PGMP model.

The PMP model of DPD provides the least accuracy of PA linearization.

Report

The statement that non-linear power amplifiers transform signal complex envelopes by different ways according to increase or decrease of the envelope module was taken into account at synthesis of the precompensator DPGMP model. Taking into account the PA mentioned property in the DPGMP model contributes to increase in PA linearization precision in comparison to linearization fulfilled by PGMP and PMP models of DPD.

The advantage of the DPGMP model over the PGMP model of DPD at suppression of non-linearity of the AB class power amplifier Winner-Hammerstein model is observed at similar complexity of the said DPD models (from Table 1 the number $Q = 672$ of parameters in the model (2) and (5) at $L = 1$, $P = 3$; the number $Q = 1152$ of parameters in the model (2) and (5) at $L = 1$, $P = 5$).

There is the fact that the bigger value L (time delay of the input signal envelope) in the predistorter DPGMP model, the higher precision of PA non-linearity compensation.

The method of DPD piecewise-polynomial model decomposition is independent of the form of the inner polynomial, that's why it is possible to increase the accuracy of PA linearization by using more complicated mathematical construction [9]-[12] in the DPD decomposed model, than generalized memory polynomial (DPGMP) in the model (5).

Corresponding Author:
Dr. Solovyeva Elena Borisovna
Saint Petersburg Electrotechnical University "LETI"
Professora Popova Street, 5, St. Petersburg, 197376, Russian Federation

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