A new digital predistortion technique for analog beamforming systems

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Abstract: A digital predistortion (DPD) technique to linearize multiple power amplifiers (PAs) in analog beamforming systems is proposed. The analog beamforming system considered in this paper has one digital chain and multiple PAs/antennas controlled by phase shifters. Due to the system configuration, a single DPD should linearize the multiple PAs. To design the DPD, this paper introduces a cost function, squares of the sum of errors for all the PAs. The DPD solution minimizing the cost function is found by a recursive least squares (RLS) algorithm. Experimental results with commercial PAs show that the proposed DPD can effectively linearize multiple PAs.

Keywords: analog beamforming, power amplifier, digital predistortion, memory polynomial, nonlinear distortion

Classification: Microwave and millimeter wave devices, circuits, and systems

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1 Introduction

Multiple antenna systems have been proposed to exploit diversity gain and/or spatial multiplexing gain. However, their practical application requires separate radio frequency (RF) front ends and multiple data converter units, which lead to an increase in hardware cost, size, and power consumption. One well-known sub-optimal technique to reduce the number of RF and digital chains is using analog processing networks for linearly weighting the antennas, i.e., analog beamforming (BF). In [1], a phase shift processor, which uses active and passive weighting elements to change the phase at each antenna in the RF domain, is implemented.

Considering the transmitters in analog BF systems, there are multiple power amplifiers (PAs) and fewer (or single) digital chains. In general, PAs have nonlinear characteristics that cause spectral regrowth (or spectral broadening) and inband signal distortion. The former increases inter-channel interference and the latter degrades signal quality. To mitigate these problems, many linearization techniques, such as analog/digital predistortion, and feedforward/feedback methods, have been studied [2]. Among them, digital predistortion (DPD) is the most popular technique due to its excellent linearization performance and high power efficiency. DPD can compensate for the nonlinearity of a PA by making the combined characteristics of DPD and PA linear [3, 4, 5, 6, 7, 8]. Recently, a DPD technique for MIMO transmitters has been proposed [9]. However, DPD for analog BF systems has not yet researched. This paper addresses the DPD problem for analog beamforming systems with one digital/RF chain and multiple PAs/antennas. The DPD problem for these systems is not a trivial extension of existing DPD techniques, because one DPD should linearize multiple PAs simultaneously.

This paper proposes a new DPD technique for phased array BF systems by minimizing the square of the sum of errors for all the PAs. In this method, all the multiple feedback signals of the PAs are phase-synchronized by de-rotating the phases appropriately. This is possible, because the rotating phases from the phase shifters are known at the transmitter. Then, the phase-synchronized feedback signals are combined, and the DPD parameter is found based on the conventional indirect learning technique [9]. The performance of the proposed method is verified through experiment with commercial PAs. The results show that the proposed technique shows similar linearization performance for all the PAs, while the conventional method shows a large variation in linearization performances across the multiple PAs.
2 System model

The baseband equivalent system model for the analog beamforming transmitter is shown in Fig. 1. A transmitter with $M$ antennas and 1 digital chain is considered. The analog beamforming coefficients are multiplied in front of the PAs by using the phase shifters. The output of the $m$-th PA, denoted by $z_m(n)$, is $\varphi_m\exp(j\phi_m)y(n)$ where $\phi_m$ is the rotation phase of the $m$-th antenna and $\exp(j\phi_m)y(n)$ is the input of the $m$-th PA. The output of DPD, $y(n)$, is $\psi(x(n))$ where $x(n)$ is the transmitted signal. $\varphi(\cdot)$ and $\psi(\cdot)$ are the characteristic functions of PA and PD, respectively.

The DPD problem in the above analog BF system is different from that in conventional systems. In a conventional DPD problem for single-input single-output (SISO) [5] systems or multiple-input multiple-output (MISO) systems [9], one DPD block linearizes one associated PA. However, in our problem, one DPD should linearize $M$ PAs simultaneously. If the multiple RF paths and PAs are perfectly calibrated and have the same characteristics, constructing one feedback path among $M$ PAs should be enough to linearize $M$ PAs. In practice, however, $M$ PAs may have different responses so a new DPD design considering all the PAs needs to be developed.

Assuming that the PA is described by a memory polynomial model, the $m$-th feedback signal can be written as

$$a_m(n) = \frac{\varphi_m\exp(j\phi_m)y(n)}{K} = \sum_{l=0}^{L_a} \sum_{p=1}^{P} h_{1,p,m}|e^{j\phi_m}y(n-l)|^{2(p-1)}e^{j\phi_m}y(n-l)$$

$$= e^{j\phi_m} \sum_{l=0}^{L_a} \sum_{p=1}^{P} h_{1,p,m}|y(n-l)|^{2(p-1)}y(n-l)$$

(1)

where $K$ is the PA gain, $L_a$ is the memory depth, and $2P-1$ is the maximum nonlinear order of the PA. In addition, we select a memory polynomial model to characterize the DPD function. The DPD output can be expressed as

$$y(n) = \psi(x(n)) = \sum_{l=0}^{L_p} \sum_{q=1}^{Q} w^*_l x(n-l)|^{2(q-1)}x(n-l)$$

$$= w^T x(n)$$

(2)

where $2Q-1$ is the maximum polynomial order of DPD. $w$ is the polynomial coefficient vector given by $w = [w_0^1, w_0^2, \cdots, w_0^P, w_1^1, \cdots, w_1^P, w_2^1, \cdots, w_2^P]^T$, and $x(n) = [x(n), x(n)|x(n)|^2, \cdots, x(n)|x(n)|^{2(Q-1)}, x(n-1), \cdots, x(n-L_p)|x(n-L_p)|^{2(Q-1)}]^T$.

The number of coefficients to be found is $Q(L_p+1)$. The problem is to find $w$ that linearizes all the PAs, i.e., $\varphi_m\exp(j\phi_m)\psi(x(n)) = Ke^{j\phi_m}x(n)$ for $m = 1, \cdots, M$.

3 Proposed DPD

To design the DPD, the indirect method, one of the popular DPD techniques [9], is used. In this technique, instead of finding the DPD parameter directly, the post-distorter is first found by linearizing the PA–post-distorter chain. The post-distorter parameter is then copied to the DPD as shown in Fig. 1. The post-distorter has the
same polynomial structure as the DPD. To design the post-distorter that linearizes $M$ PA–post-distorter chains, we introduce a least squares (LS) criterion of the sum of errors. The cost function is written as

$$
E = \sum_{n=1}^{N} \lambda^{N-n} |y(n) - e^{-j\phi_m} w^H a_1(n) + \cdots + y(n) - e^{-j\phi_M} w^H a_M(n)|^2
$$

where $a_m(n) = [a_m(n), a_m(n)|a_m(n)|^2, \cdots, a_m(n)|a_m(n)|^{2(L_p-1)}, a_m(n-1), \cdots, a_m(n-L_p)]$, $\lambda \in [0, 1]$ is a forgetting factor, and $a(n) = e^{-j\phi_m} a_1(n) + \cdots + e^{-j\phi_M} a_M(n)$. Referring to the PA output in (1), it is noted that multiplying $e^{-j\phi_m}$ with $a_m(n)$ removes the phase rotation by the analog BF at the $m$-th feedback signal. The polynomial coefficient vector $w$ that minimizes $E$ in (3) is the proposed DPD solution considering all the PAs and not only a specific PA.

The solution can be found via the recursive least squares (RLS) algorithm [10] summarized in Table I. $N$ is the training length and should be sufficiently large for a reliable solution. In our experiment, several thousand samples were sufficient. According to [10], the proposed RLS algorithm converges if the following relation holds: $y(n) = e^{-j\phi_m} w^H a_m(n) + e_o(n)$ for $m = 1, \cdots, M$ where $e_o(n)$ is a measurement noise. The relation depends on the PA characteristics, the DPD polynomial order $L_p$ in (2) and the DPD memory depth $Q$ in (2). Thus, for convergence of the RLS algorithm, selection of proper $L_p$ and $Q$ for the PA being used is important.

![Fig. 1. Digital predistortion structure in analog beamforming systems](image)

### Table I. Summary of RLS algorithm

| Initialization: | For time $n = 1, 2, \cdots, N$, compute |
|-----------------|----------------------------------------|
| $w = 0_Q(L_p+1)$ | $b = Pa(n)$ |
| $P = \delta^{-1}I_Q(L_p+1)$ | $c = b/(\lambda + a^H(n)b)$ |
| $(\delta$: a small positive constant) | $\zeta(n) = My(n) - w^H a(n)$ |
| $w = w + c\zeta(n)$ | $w = w + c\zeta(n)$ |
| $P = \lambda^{-1}P - \lambda^{-1}cw^H(n)P$ | |

### 4 Experimental results

The proposed DPD was verified by experiments using commercial PAs. The experimental setup is shown in Fig. 2. The number of antennas is 2 ($M = 2$). A
PC generates a 20 MHz long-term evolution (LTE) downlink waveform, and the signal generator (AWG710 by Tektronix) converts the digital waveform to analog. The center frequency of the waveform is 900 MHz. The following bandpass filter (BPF) removes the image spectra and spurious in the signal generator output. The analog waveform is divided into two signals by the power divider and supplied to the commercial PAs. To implement phase shifters, we used two cables with a different length of about 10 cm. Denoting $\Delta \theta$, $\Delta l$, and $\gamma$ as the phase difference, the cable length difference, and the wavelength, respectively, we have $\Delta \theta = 2\pi \Delta l/\gamma$. Therefore, our experiment environment provided a 120° phase difference between the two paths. For the PAs, we used ZKL-2R7+ by Mini-Circuits. The PA has a 24 dB gain, and the P1 dB is +13 dBm. The BPFs at the PA outputs attenuate the harmonics. The BPF outputs were directly sampled by the digital oscilloscope (TDS7254 by Tektronix) and supplied to the PC. At the initial phase, the DPD was bypassed and its parameters were obtained from the Tx waveform and the PA output waveform via the adaptive algorithm described in Section 3. Next, the DPD parameters were applied to the DPD block, and the spectra were observed at the PA outputs.

![Fig. 2. Digital predistortion structure in analog beamforming systems](image)

Fig. 3 shows the PA output spectra. Yellow, blue, and purple represent the spectra without DPD, with conventional DPD and with proposed DPD, respectively. The conventional DPD constructs one feedback path for PA 2 and finds the DPD parameter for PA 2 (neglects PA 1). In the right spectrum, the conventional DPD shows the best performance. The proposed DPD can reduce spectral regrowth by about 8 dB, while the conventional DPD can reduce it by over 10 dB. In contrast, the proposed DPD performs better in the left spectrum while the conventional DPD reduces the regrowth by only 5 dB. According to the results, the proposed DPD can successfully linearize the two PAs simultaneously, and the spectral regrowths are lowered by over 8 dB. However, the conventional DPD can show a large variation in linearization performance across the PAs.

Next, the DPD performances for various PA output powers were observed. The peak-to-average power ratio (PAPR) of the LTE signal is around 10 dB. Therefore 10 dB output back-off from the PA saturation power is suitable. We observed the adjacent channel leakage ratio (ACLR) at 15 MHz offset by changing the output...
back-off of both PAs. The results are summarized in Table II. For large back-off, the ACLR improvement is insignificant since the PA is already driven in its linear region. When the back-off is smaller than the signal’s PAPR, the ACLR is degraded as well because significant portion of the signal falls into saturation region.

We also observed the performance of the proposed DPD by increasing the variation of two PAs’ gains. To make gain difference between two PAs, a variable step attenuator was inserted at the PA1’s input. Table III shows the ACLR improvement for the PA gain difference. As the gain difference increases, the ACLRs of both PAs are degraded. Those results indicate that the proposed DPD is effective when the variation between multiple PAs are small.

Table II. ACLR of proposed DPD for output back-off

| Output Back-off of both PAs (dB) | 13  | 12  | 11  | 10  | 9   | 8   | 7   |
|----------------------------------|-----|-----|-----|-----|-----|-----|-----|
| ACLR improvement (dB)            | 2.86| 4.02| 5.55| 7.55| 6.11| 4.17| 2.56|

Table III. ACLR improvement for variation of PA characteristics

| PA gain difference (dB) | 0    | 1    | 2    | 3    |
|-------------------------|------|------|------|------|
| ACLR improvement for PA1 (dB) | 10.01| 8.90 | 3.28 | 0.45 |
| ACLR improvement for PA2 (dB) | 7.22 | 6.38 | 4.53 | 3.68 |

5 Conclusion

In this study, a DPD technique for analog beamforming systems was proposed. The proposed DPD can linearize multiple PAs simultaneously. The experimental results confirmed that the proposed DPD is effective when the output back-off of the PA is the signal’s PAPR and the variation of multiple PAs are small.
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