Weighted Polynomial Digital Predistortion for Low Memory Effect Doherty Power Amplifier

Sungchul Hong, Young Yun Woo, Jangheon Kim, Jeonghyeon Cha, Ildu Kim, Junghwan Moon, Jaehyok Yi, and Bumman Kim, *Fellow, IEEE*

***Abstract*—We have proposed a simple and effective weighted polynomial digital predistortion algorithm, which consists of weighting, least square polynomial fit, and de-weighting. The weighting factor is introduced to describe the signal distribution statistics and high harmonic generation at a high power region to improve accuracy of the error function. A low memory linear Doherty power amplifier (PA) has been realized with two 90-W peak envelope power LDMOSFETs using memory effect reduction techniques, and the proposed algorithm has been applied to the PA. For the forward-link wideband code division multiple access 3FA signal, the adjacent channel leakage ratio performance at 5-MHz offset is −56 dBc with power-added efficiency of 20.78% at an average power of 40 dBm. The proposed weighting polynomial algorithm provides a significantly reduced error power and superior convergence behavior with improved linearization capability than the conventional polynomial. Moreover, the low memory Doherty amplifier could be linearized for a wideband signal using the simple algorithm without any memory effect compensation.**

***Index Terms*—Digital predistortion (DPD), Doherty, linearization, memory effect, power amplifier (PA), weighted polynomial.**

I. INTRODUCTION

Modern wireless communication systems provide high-data-rate multimedia services to the numerous subscribers in time. In order to sustain these services, the power amplifier (PA) in the base station should transmit the multichannels of modulated signal without distortion. However, the PAs that amplify the wideband signals produce a severe memory effect and nonlinearities [1]. The memory effect especially restricts the linearization capacity of analog predistortion (PD) [2], and the recent digital predistortion (DPD) techniques can compensate the memory effect using finite impulse response (FIR) filters, Volterra series or memory polynomials, etc. [3]–[5].

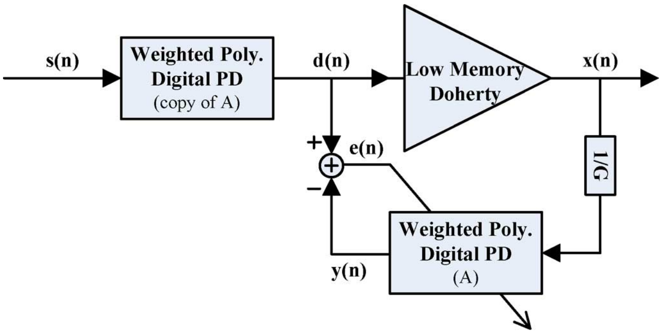


Fig. 1. Proposed weighted polynomial DPD with low memory Doherty PA.

There are two distinct methods to implement the DPD algorithm, i.e., a lookup table (LUT) and a polynomial. The polynomial DPD is more immune to noise and requires less memory storage than the LUT case. Moreover, the polynomial can operate with only a few collected data, while the LUT needs sufficient data to fill all the operation area. However, the conventional polynomial has inferior accuracy to the LUT case [6], and we have proposed a weighted polynomial technique that provides a considerable improvement in accuracy, especially at the peak power region. A weighting factor is introduced to describe the signal distribution statistics and high harmonic generation property at a high power region to improve accuracy of the error function. The proposed weighted polynomial utilizes the indirect learning architecture [7], as shown in Fig. 1. The algorithm forces the PA output $x(n)$ to converge to the linear output $G \cdot s(n)$, as the error $e(n)$ approaches zero.

In this study, we have implemented a Doherty PA whose memory effect has been minimized using the drain and gate envelope terminations in front of quarter-wavelength bias lines [8]. The weighted polynomial indirect DPD algorithm without a complex memory effect cancellation has been applied to the PA. For the forward-link wideband code division multiple access (WCDMA) 3FA signal, the ACLR performance at 5-MHz offset is −56 dBc, while maintaining power-added efficiency (PAE) of 20.78% at an average power of 40 dBm. The proposed simple algorithm has a good linearization capability with significantly reduced error power for the low memory effect Doherty PA, which is superior to the conventional nonweighting polynomial indirect DPD.

Manuscript received September 8, 2006; revised January 26, 2007. This work was supported in part by the Korean Ministry of Education under the BK21 Project and by the Center for Broadband Orthogonal Frequency Division Multiplexing Mobile Access, Pohang University of Science and Technology under the Information Technology Research Center Program of the Korean Ministry of Information and Communication, supervised by the Institute for Information Technology Advancement (IITA-2006-C1090-0603-0037).

S. Hong and Y. Y. Woo are with the Telecommunication Research and Development Center, Samsung Electronics Company Ltd., Suwon, Gyeonggi 442-742, Korea (e-mail: powings@postech.ac.kr).

J. Kim, I. Kim, J. Moon, and B. Kim are with the Department of Electrical Engineering, Pohang University of Science and Technology, Gyeongbuk 790-784, Korea (e-mail: bmkim@postech.ac.kr; jhmoon@postech.ac.kr).

J. Cha is with the XRONet Corporation, Seongnam, Gyeonggi 463-020, Korea.

J. Yi is with the Mobile Handset Research and Development Center, Telecommunication Equipment and Handset Company, LG Electronics Inc., Seoul 153-801, Korea.

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TMTT.2007.895167

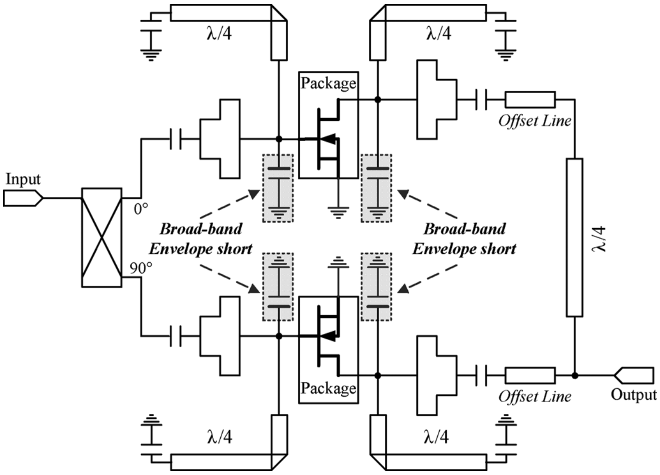


Fig. 2. Block diagram of the memory effect minimized Doherty PA.

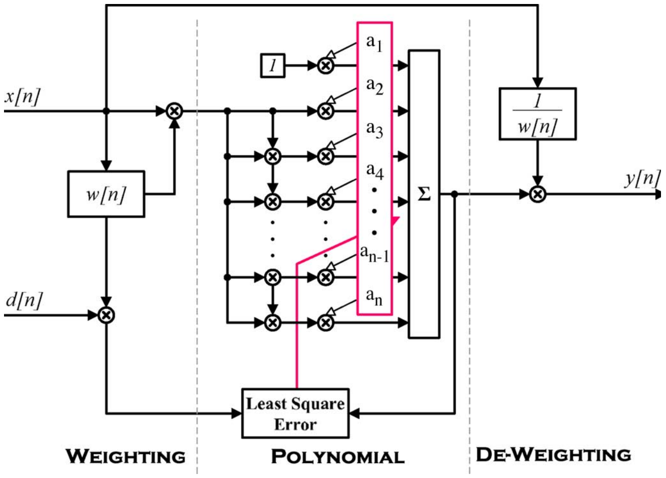


Fig. 3. Block diagram of the weighted polynomial DPD.

II. LOW MEMORY EFFECT DOHERTY PA

The major sources of memory effect are the envelope and second harmonic components at the device terminals, and they should be reduced by proper terminations. We have reported a matching topology for minimizing the drain and gate impedances across the broadband of the envelope and second harmonic frequencies, while maintaining matchable impedances at an RF signal frequency [8]. The broadband second harmonic termination can be easily achieved without any change of the bias topology using a quarter-wavelength transmission line.

The conventional wisdom for the envelope signal termination is to provide a short after or inside of the quarter-wave bias line [9]. However, the termination produces dispersion by the line, disturbing the broadband envelope termination. The envelope frequency short circuit should be attached at the gate and drain terminals in front of the quarter-wavelength line, as shown in Fig. 2. The envelope signal termination is realized by using a series LC circuit, which is composed of a large tantalum capacitor with a small parasitic inductor of the package. The inductance of approximately 1.2 nH is practically short at the envelope frequency for Freescale's MRF5S21090 LDMOSFET, while it is a high impedance at the fundamental frequency. Therefore, the realized series LC circuit provides a broadband envelope termination, and the Doherty amplifier has a considerably reduced memory effect, while maintaining good power performances.

III. WEIGHTED POLYNOMIAL DPD

As shown in Fig. 3, the proposed weighted polynomial algorithm consists of the weighting, polynomial, and de-weighting blocks. The weighting is introduced to get an ideal error function for the least square fit algorithm [10]. The weighting function describes the statistical characteristics of the modulation signal and the harmonic generation property of an amplifier at a high power level. The weighted polynomial PD signals are then generated by using a polynomial least square fit algorithm. Finally, the generated PD signals are de-weighted and applied to the PA. These procedures are iterated using the indirect learning architecture until we get the linear output [7].

A. PD Signal Generation Using the Least Square Polynomial Fit

We have used the least square error algorithm to get the polynomial coefficients of the PD signal that minimizes the error function of (1). The indirect PD signal polynomial can be generalized to a degree $n-1$, which has n coefficients, as shown in (2), as follows:

$$\text{least square fit error} = \sum_{i=1}^{L} \left[f(x_i) - d_i\right]^2 \tag{1}$$

$$f(x_i) = \sum_{k=1}^{n} p_k \cdot x_i^{k-1}. \tag{2}$$

In (3), the data points are raised to the $(n-1)$th-order powers and are constructed as an $L \times n$ "Vandermonde" matrix. The matrix is multiplied by an $n \times 1$ coefficient vector P, which produces the desired PD signal. The polynomial coefficients are the eigenvalues of (3) as follows:

$$\begin{bmatrix} 1 & x_1 & x_1^2 & \dots & x_1^{n-1} \\ 1 & x_2 & x_2^2 & \dots & x_2^{n-1} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & x_L & x_L^2 & \dots & x_L^{n-1} \end{bmatrix} P = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_L \end{bmatrix} \tag{3}$$

$$P = [p_1 \quad p_2 \quad \dots \quad p_n]^T \tag{4}$$

where L is the number of input (or output) training signal data points used to determine the polynomial coefficients number of n. Mathematically, L should be equal to or larger than n in order to solve (3). In this adaptation, we have used L of 1024, which is larger than n, to delineate the amplifier distortion more accurately. There are a number of methods that have been developed to find the roots of the polynomial, and we have used the well-known QR method, which solves the eigenvalues of the matrix using numerical calculation [11].

B. Statistical Analysis of WCDMA Signal and Weighting

The least square fit algorithm is employed to optimize the coefficients with a minimum square error given by (1) for a sequential ramp training signal. For the modulated signal, the error function (1) is not accurate since the occurrence of the

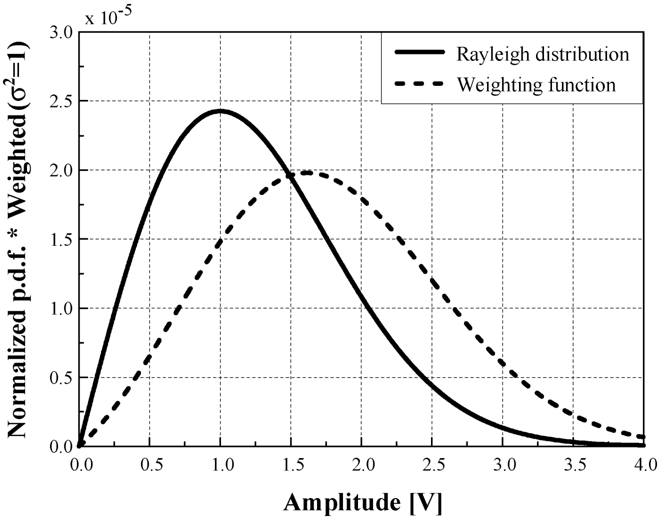


Fig. 4. p.d.f. of WCDMA signal and the weighting function.

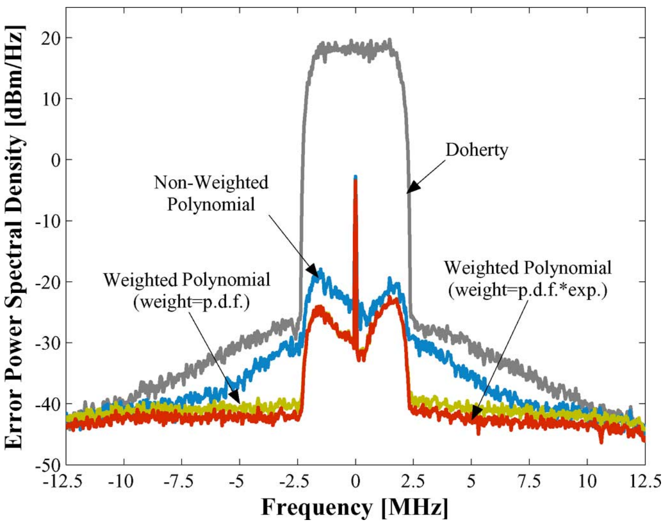


Fig. 5. Error power spectral densities for the model with each weighting function for the forward-link WCDMA 1FA signal at an average power of 43 dBm.

data point, i.e., probability density function (p.d.f.) is different. In case of the forward-link WCDMA signal, the p.d.f. of the amplitude response has the Rayleigh distribution, as expressed as follows in (5) and shown in Fig. 4:

$$\text{p.d.f}(x) = \begin{cases} \dfrac{x}{\sigma^2} \cdot e^{-x^2/2\sigma^2}, & \text{for } x \geq 0 \\ 0, & \text{for otherwise.} \end{cases} \tag{5}$$

We can estimate the overall error, which is sum of differences between modeled responses (y_i) and desired responses (d_i) of the modulated signal with the least square fit optimized polynomial coefficients. The overall error can be calculated by integrating the product of the average error distribution at each amplitude $(\text{error}_{\text{avg}}(x))$, which is determined by the least square fit model by the Rayleigh p.d.f. as follows:

$$\begin{aligned} \text{overall error} &= \sum_{i=1}^{N} \{y_i - d_i\} \\ &= N \times \int \{\text{error}_{\text{avg}}(x) \cdot \text{p.d.f.}(x)\}\, dx. \end{aligned} \tag{6}$$

The nonweighted ramp training signal has an uniform average error distribution, and it is not the optimum for the minimum overall error, given by (6), of the WCDMA signal. Therefore, the Rayleigh distribution weighting is applied to the least square fit error function of (1) for the ramp training signal.

Another point is that the PD signal at the peak power region, which is dominant for harmonic generation, should to be emphasized more than the other power regions. Therefore, we have implemented an increasing exponential weight to improve accuracy at the peak power region and to describe the harmonic generation property accurately as follows:

$$e^{a \cdot x_i} = 1 + a \cdot x_i + \frac{1}{2}a^2 \cdot x_i^2 + \frac{1}{6}a^3 \cdot x_i^3 + \cdots. \tag{7}$$

Equation (7) shows that it can represent the harmonic generation property of an amplifier, and as "a" becomes large, the high-order terms have more weighting than the low-order terms. As a consequence, the exponential function raises the accuracy at a higher power region, and $a = 1$ provides a good weighting function.

As shown in Fig. 5, we have examined the error power spectrums for the models with the weighed polynomials to verify the effect of weights. At the first step, we have used the Rayleigh p.d.f. weighting to minimize the in-band error that contributes mostly to the overall model error. We then add the exponential weight and adjust the coefficient "a" to model the nonlinearity more precisely. Consequently, we can get the optimum weighting function, as shown in Fig. 4, and minimized both in- and out-band errors. The data in Fig. 5 clearly show that the weighting function is very effective to reduce the error power. The optimum weighting and the error functions of the system becomes

$$\text{weight}(x_i) = e^{a \cdot |x_i|} \cdot \text{p.d.f}(x_i) \tag{8}$$

$$\text{least square fit error} = \sum_{i=1}^{L} \{\text{weight}(x_i) \cdot [f(x_i) - d_i]\}^2. \tag{9}$$

For implementation of the weighted PD algorithm, the input signal is weighted at the input and the signal is de-weighted before the indirect PD signals are applied to the nonlinear PA (see Fig. 3). The procedures are iterated until the indirect learning algorithm converges to the linear output.

IV. IMPLEMENTATION AND EXPERIMENTAL RESULTS

We have applied the indirect learning algorithm with the weighted least square polynomial fit to the low memory effect Doherty PA. In order to confirm the reduced memory effect of the proposed PA, we have tested the intermodulation distortions (IMDs) for various spacing two-tone signals and the ACLR characteristics for a forward-link WCDMA 4FA signal with 20-MHz bandwidth. The proposed optimum weighting polynomial algorithm has been compared for the linearization capability and convergence behavior with those of the Rayleigh

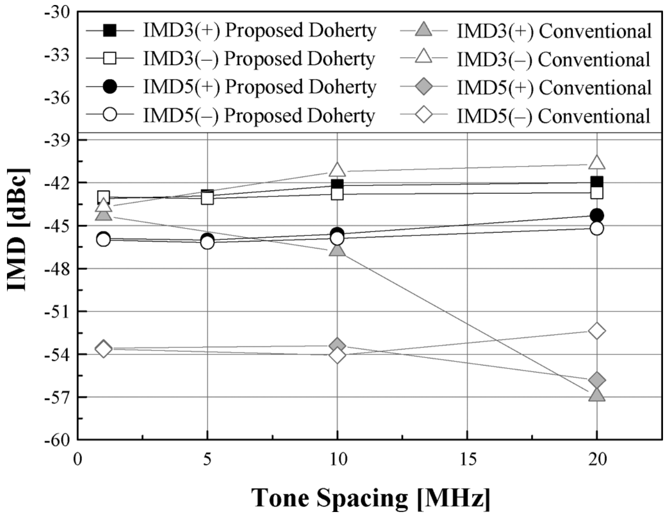


Fig. 6. Comparison of the measured IMDs of the low memory effect Doherty PA and conventional Doherty PA for the two-tone signals at an average power of 40 dBm.

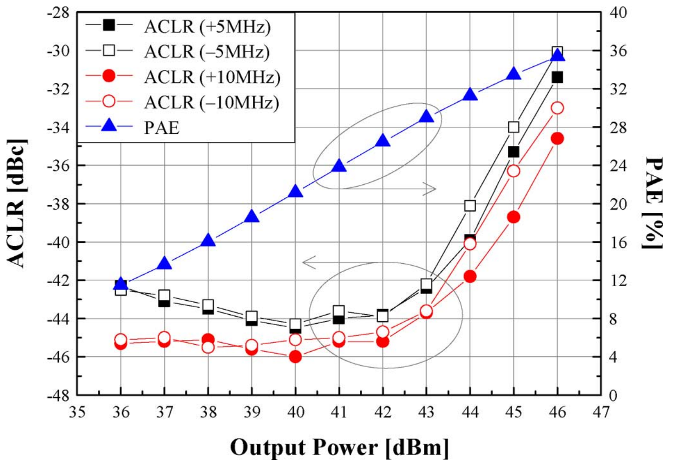


Fig. 7. Measured ACLR and PAE of the low memory effect Doherty PA for a forward-link WCDMA 4FA signal.

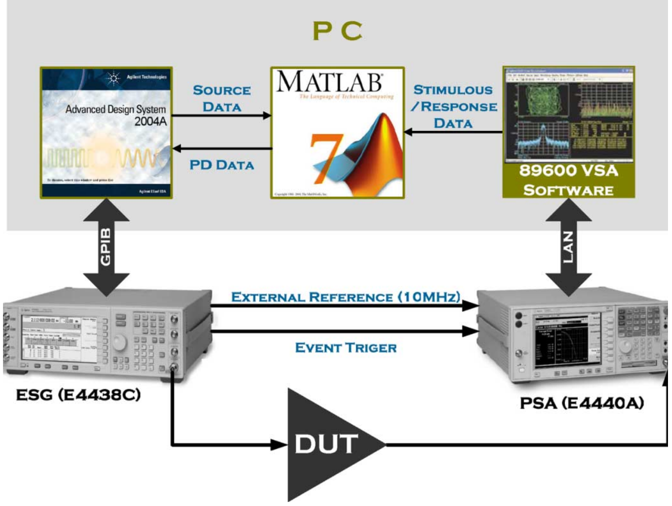


Fig. 8. Test setup for DPD algorithm.

p.d.f. weighting and the nonweighting polynomial cases for WCDMA 1FA and 3FA signals.

A. *Low Memory Effect Doherty PA*

For experimental demonstration, we have implemented the low memory effect Doherty PA using two Freescale MRF5S21090 LDMOSFETs. The broadband envelope and second harmonic terminations are attached at the gate and drain, which are introduced in Section II. The bias points of the carrier and peaking cells are adjusted to operate at class AB and C modes, respectively. The quiescent drain current of the carrier cell is 850 mA and the gate voltage of the peaking cell is set to 2.01 V.

Fig. 6 shows the third-order intermodulation distortions (IMD3s) and fifth-order intermodulation distortions (IMD5s) of the low memory Doherty PA and a conventional Doherty PA for two-tone signals with various tone spacings. The asymmetry of less than 1 dB is obtained for the signal with up to 20-MHz tone spacing, proving that the proposed PA has a considerably reduced memory effect. For a forward-link WCDMA 4FA signal, the measured ACLR at 5-MHz offset is −42.2 dBc with the low memory and the PAE is 28.3% at an average power of 43 dBm, as shown in Fig. 7. It especially has an asymmetry of less than 0.4 dB over the broad power levels up to 43 dBm for the forward-link WCDMA 4FA signal, which has the peak to average ratio (PAR) of 11 dB and the instantaneous bandwidth of 20 MHz. Compared with the test results at an average output power of 40 dBm for the low memory class AB PA implemented in a previous study [8], it is an improvement of the ACLR of 5.8 dB and efficiency of 11.6%.

B. *Weighted Polynomial DPD*

We have used the test setup in Fig. 8 for the demonstration of the weighted polynomial DPD. The digital signal processing core has been substituted by a PC with MATLAB software. The Agilent's ESG Signal Generator (E4438C) and PSA Spectrum Analyzer (E4440A) have been used for a generation of the PD signal and a collection of the PA response by use of Agilent's Advanced Design System (ADS) and Vector Signal Analyzer (VSA) softwares through networking with the PC [5], [12].

In Fig. 9, the linearization performance of the optimum (Rayleigh p.d.f. and exponential) weighted polynomial DPD algorithm is compared with those of the Rayleigh p.d.f. weighted and nonweighting polynomial for the forward-link WCDMA 1FA signal with PAR of 9.8 dB. For the experimental verifications, the algorithms have been implemented using the same polynomial order of 11 and loaded on the indirect learning architecture. The proposed optimum weighted polynomial algorithm cancels the ACLR approximately 12 dB more than that of the nonweighted polynomial PD up to an average power of 44 dBm, and 2 dB more than that of the Rayleigh p.d.f. weighted polynomial PD up to an average power of 43 dBm, which is the backed-off point by the amount of the PAR from the peak power. However, if the proposed algorithm is applied to the operation more than average output power of 43 dBm, which is insufficiently backed off, the convergence behavior of the proposed optimum weighted algorithm is similar to that of the p.d.f. weighted polynomial. The reason is that the PD signal

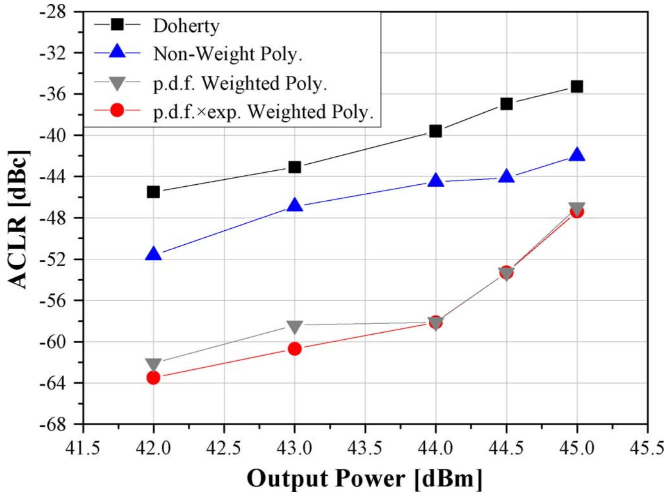


Fig. 9. Comparison of the measured ACLRs of the low memory effect Doherty with various linearization weighting modes for the forward-link WCDMA 1FA signal.

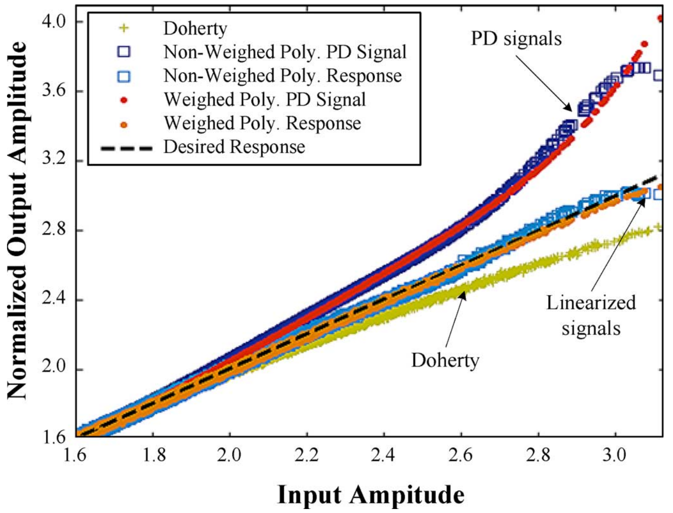


Fig. 11. Comparison of the AM/AM characteristics between weighted polynomial (filled) and nonweighting polynomial (empty) for the forward-link WCDMA 1FA signal at an average power of 43 dBm.

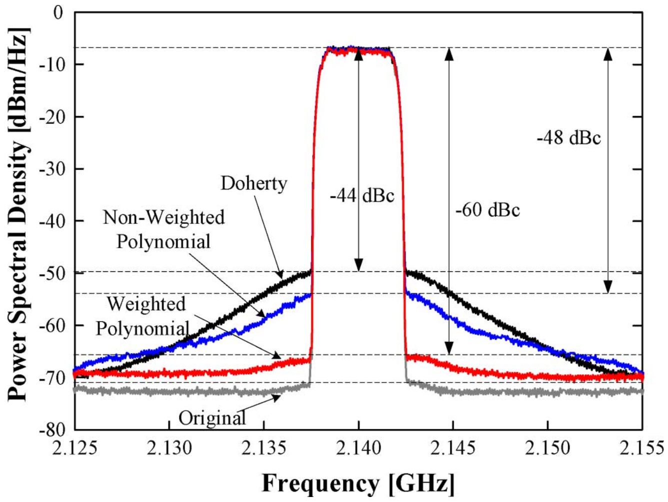


Fig. 10. Comparison of the measured power spectral densities of the low memory effect Doherty for the forward-link WCDMA 1FA signal at an average power of 43 dBm.

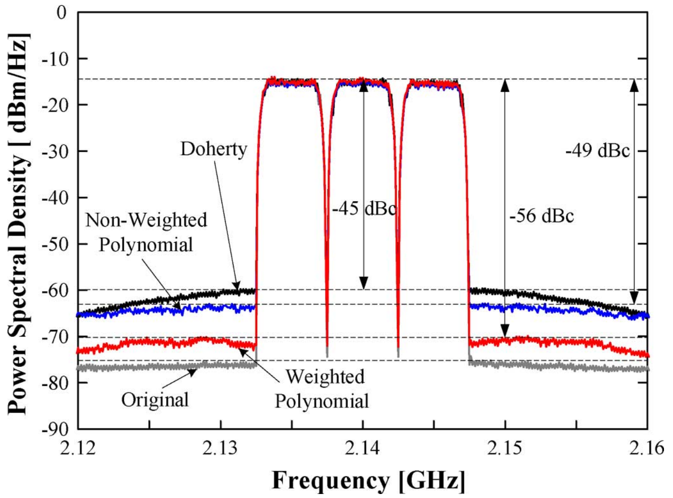


Fig. 12. Comparison of the measured power spectral densities of the low memory effect Doherty for the forward-link WCDMA 3FA signal at an average power of 40 dBm.

near the peak power level has been clipped out by the amplifier and the exponential weighting has no effect on the linearization performance.

Fig. 10 shows the measured power spectral densities obtained using the proposed optimum weighted polynomial algorithm and the nonweighted polynomial algorithm. The proposed optimum weighting algorithm could deliver a good ACLR of -60 dBc at an average power of 43 dBm, which is a cancellation of 16 dB with PAE of approximately 29%, while the nonweighted polynomial case has a poor ACLR cancellation of 4 dB at the same average power. Fig. 11 shows AM/AM curves with the optimum weighting algorithm and the nonweighting case. These results show clearly the improved accuracy of the optimum weighted polynomial fit.

The ACLR data for the forward-link WCDMA 3FA signal with a PAR of 12 dB is shown in Fig. 12. The ACLR performance of the proposed optimum weighting algorithm at 5-MHz offset is -56 dBc with 11-dB cancellation while maintaining PAE of 20.78% at an average power of 40 dBm, which is a improvement ACLR of 7 dB more than that of the nonweighted polynomial case. The low memory Doherty PA could be linearized for the wideband signal using the proposed simple algorithm without any memory effect compensation methods.

V. CONCLUSIONS

In order to reduce the memory effect of a PA, we have implemented a new matching topology to minimize the drain and gate envelope impedances in front of the quarter-wavelength bias line, and the improved results have been verified using a Doherty amplifier for the two-tone and WCDMA 4FA signals. The amplifier has been linearized using a DPD. To improve the algorithm, we have introduced the weighting function. The Rayleigh distribution function to cover the statistical characteristics of the forward-link WCDMA signal and the exponential function to model the large harmonic generation at a high power region have been employed as a weighting function of the error extraction using the least square fit algorithm. The new algorithm achieves far better ACLR cancellation and superior convergence behavior than the conventional nonweighted polynomial case. We have demonstrated the good performances for linearizing the Doherty PA using WCDMA 1FA and 3FA signals. The ACLR at 5-MHz offset is -56 dBc while maintaining the PAE of 20.78% at an average power of 40 dBm for WCDMA 3FA signal. These results are achieved without using any memory reduction method. Therefore, the low memory Doherty amplifier with the weighted polynomial algorithm can be a very simple solution for the improved transmitter system of next-generation base-station applications.

ACKNOWLEDGMENT

The authors would like to express their gratitude to the reviewers for their comments and suggestions.

REFERENCES

[1] 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 Tech.*, vol. 50, no. 3, pp. 814–826, Mar. 2002.

[2] J. Cha, J. Yi, J. Kim, and B. Kim, "Optimum design of a predistortion RF power amplifier for multi-carrier WCDMA applications," *IEEE Trans. Microw. Theory Tech.*, vol. 52, no. 2, pp. 655–663, Feb. 2004.

[3] L. Ding, G. T. Zhou, D. R. Morgan, Z. Ma, J. S. Kenney, J. Kim, and C. R. Giardina, "Memory polynomial predistorter based on the indirect learning architecture," in *IEEE GLOBECOM*, Nov. 2002, vol. 1, pp. 967–971.

[4] W. Woo and J. S. Kenney, "A predistortion linearization system for high power amplifiers with low frequency envelope memory effects," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Jun. 2005, pp. 1545–1548.

[5] T. Liu, S. Boumaiza, and F. M. Ghannouchi, "Augmented Hammerstein predistorter for linearization of broadband wireless transmitters," *IEEE Trans. Microw. Theory Tech.*, vol. 54, no. 4, pp. 1340–1349, Jun. 2006.

[6] J. Sirois, S. Boumaiza, M. Helaoui, G. Brassard, and F. M. Ghannouchi, "A robust modeling and design approach for dynamically loaded and digitally linearized Doherty amplifiers," *IEEE Trans. Microw. Theory Tech.*, vol. 53, no. 9, pp. 2875–2883, Sep. 2005.

[7] C. Eun and E. J. Powers, "A new Volterra predistorter based on the indirect learning architecture," *IEEE Trans. Signal Process.*, vol. 45, no. 1, pp. 223–227, Jan. 1997.

[8] J. Cha, I. Kim, S. Hong, B. Kim, J. S. Lee, and H. S. Kim, "Memory effect minimization and wide instantaneous bandwidth operation of a base station power amplifier," *Microw. J.*, accepted for publication.

[9] A. Rabany, L. Nguyen, and D. Rice, "Memory effect reduction for LDMOS bias circuits," *Microw. J.*, vol. 46, no. 2, pp. 124–130, Feb. 2003.

[10] V. Guruswami and M. Sudan, "Improved decoding of Reed–Solomon and algebraic-geometry codes," *IEEE Trans. Inf. Theory*, vol. 45, no. 6, pp. 1757–1767, Sep. 1999.

[11] R. J. Schilling and S. L. Harris, *Applied Numerical Methods for Engineers*. Thousand Oaks, CA: Brooks/Cole, 2000.

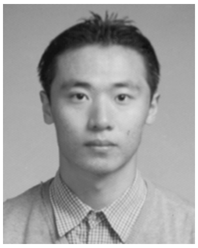
[12] W.-J. Kim, S. P. Stapleton, J. H. Kim, and C. Edelman, "Digital predistortion linearizes wireless power amplifiers," *IEEE Micro*, vol. 6, pp. 54–61, Sep. 2005.

Sungchul Hong received the B.S. degree in electrical and electronic engineering from Yonsei University, Seoul, Korea, in 2003, and the Master degree in electrical engineering from the Pohang University of Science and Technology (POSTECH), Pohang, Korea in 2007.

In 2007, he joined the Samsung Electronics Company Ltd., Suwon, Gyeunggi, Korea. His research interests include design of PAs, DPD techniques, and highly efficient transmitter systems.

Young Yun Woo received the B.S. degree in electrical and computer engineering from Han-Yang University, Seoul, Korea, in 2000, and the Ph.D. degree in electrical engineering from the Pohang University of Science and Technology (POSTECH), Pohang, Korea, in 2007.

In 2007, he joined the Samsung Electronics Company Ltd., Suwon, Gyeunggi, Korea. His current research interests include RF PA design, linear power amplifier (LPA) system design, and DPD techniques for linearizing high PAs.



Jangheon Kim received the B.S. degree in electronics and information engineering from Chon-buk National University, Chonju, Korea, in 2003, and is currently working toward the Ph.D. degree at the Pohang University of Science and Technology (POSTECH), Pohang, Korea.

His current research interests include highly linear and efficient RF PA design, memory effect compensation techniques, and linearization techniques.

Jeonghyeon Cha received the B.S. degree in electronics and information engineering from Chon-buk National University, Chonju, Korea, in 2001, and Ph.D. degree in electrical engineering from the Pohang University of Science and Technology (POSTECH), Pohang, Korea, in 2007.

In 2007, he joined the XRONet Corporation, Seongnam, Gyeunggi, Korea. His current research interests include RF PA design, linearization techniques, and efficiency-improving techniques.

Ildu Kim received the B.S. degree in electronics and information engineering from Chon-nam National University, Kwangju, Korea, in 2004, and is currently working toward the Ph.D. degree at the Pohang University of Science and Technology (POSTECH), Pohang, Korea.

His current research interests include RF PA design and linearity and efficiency improvement techniques.

Junghwan Moon received the B.S. degree in electrical and computer engineering from the University of Seoul, Seoul, Korea, in 2006, and is currently working toward the Ph.D. degree at the Pohang University of Science and Technology (POSTECH), Pohang, Gyeongbuk, Korea.

His current research interests include highly linear and efficient RF PA design.

Jaehyok Yi received the M.S. and Ph.D. degrees in electronics and electrical engineering from the Pohang University of Science and Technology (POSTECH), Namgu, Pohang, Korea, in 1999 and 2005, respectively.

In 2005, he joined the LG Electronics Company Ltd., Seoul, Korea. His research interests include the design and simulation of the behavior of linear RF PAs and linearization techniques.

Bumman Kim (S'77–M'78–SM'97–F'07) received the Ph.D. degree in electrical engineering from Carnegie–Mellon University, Pittsburgh, PA, in 1979.

From 1978 to 1981, he was engaged in fiber-optic network component research with GTE Laboratories Inc. In 1981, he joined the Central Research Laboratories, Texas Instruments Incorporated, where he was involved in development of GaAs power field-effect transistors (FETs) and monolithic microwave integrated circuits (MMICs). He has developed a large-signal model of a power field-effect transistor (FET), dual-gate FETs for gain control, high-power distributed amplifiers, and various millimeter-wave MMICs. In 1989, he joined the Pohang University of Science and Technology (POSTECH), Pohang, Gyeongbuk, Korea, where he is currently a Namko Professor with the Department of Electrical Engineering, and Director of the Microwave Application Research Center, where he is involved in device and circuit technology for RF integrated circuits (RFICs). He was a Visiting Professor of electrical engineering with the California Institute of Technology, Pasadena, in 2001. He has authored over 200 technical papers.

Dr. Kim is a member of the Korean Academy of Science and Technology and the Academy of Engineering of Korea. He was an associate editor for the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES and a Distinguished Lecturer of the IEEE Microwave Theory and Techniques Society (IEEE MTT-S).