# Energy-Efficient Power Amplifier Techniques for TD-SCDMA and TD-LTE Multi-Standard Wireless Communications

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## Abstract

An energy-efficient concurrent dual-band Doherty power amplifier (PA) and its related digital predistortion (DPD) for TD-SCDMA and TD-LTE multi-standard wireless communications are investigated in this paper. Due to the proposed inter-modulation tuning technique, the PA efficiency and output power in concurrent operation mode are improved significantly. To alleviate the burden on hardware implementation, a low complexity two-dimensional digital predistortion (2D-DPD) is employed to compensate for the nonlinearities of the dual-band PA, the coefficients number is drasitically reduced. Experimental results show that the proposed dual-band Doherty PA achieves the output power of 38.1 dBm and the PAE of 42.1% in cocurrent mode, which could satisfy the requirement of multi-standard applications.

## 1. Introduction

To speed up the deployment of TD-LTE and achieve smooth evolution from TD-SCDMA to TD-LTE system, wireless communication systems should have the capability of multi-standard operating. Therefore, the radio frequency (RF) front-end in future systems should be able to support multiband operations. In this situation, a multiband PA is highly desirable, especially for the concurrent mode. To enhance the efficiency in the power backoff region, the Doherty PA has been studied extensively and adopted in base stations, many efforts have recently been carried out to realize concurrent multiband PAs [1-3]. Recently, some new techniques to design a Doherty PA that supports concurrent dual-band operation have been proposed by using dual-band transformers, however, these dual-band PAs often suffer from an efficiency deteriation in concurrent mode [2].

Recently, an attractive technique called as 2D-DPD was introduced in [1] to linearize the concurrent dual-band PA successfully. In the 2D-DPD technique, the cross-band modulation effects are taken into account in the 2D-DPD model, and both modulation signals in two different frequency bands are involved to the linearization of each band. This linearization technique had been tested for different signal scenarios, and the adjacent channel power ratio (ACPR) improvements were more than 10 dB in most cases. However, it should be also noticed that the 2D-DPD model shows quite high model complexity. Since three summations are employed in the model for each band, a large number of coefficients have to be required. This dramatically increases the model extraction burden, the run-time complexity and the cost of FPGA resources in practical applications.

## 2. IM-Tuning Concept for Multiband PA

In recent years, many PAs have been reported for dual-band or multiband applications. Most of the previously dual-band PAs can work well under non-concurrent stimulus at each band, however, under concurrent dual-band stimuli, many of them suffer from evident performance deterioration, frustrating the industrial application of dual-band transmitters. Fortunately, in recent months, an effort has been made to explain and solve such deterioration [3]. It has been revealed that the impedance matching at intermodulation (IM) frequencies can impact concurrent dual-band PA's concurrent performance obviously, leading to the new technique of intermodulation matching tuning (IM-Tuning) [3].

Taking concurrent dual-band PA as the example, the concept of IM tunings can be explained as following, which can be easily extended to multi-band cases. The structure and prototype of concurrent dual-band PA can be illustrated as Fig.1 (a) and (b). According to Fig.1 (a), in the case of concurrent dual-band PA, the stimulus and response can be written as (1) and (2) respectively.

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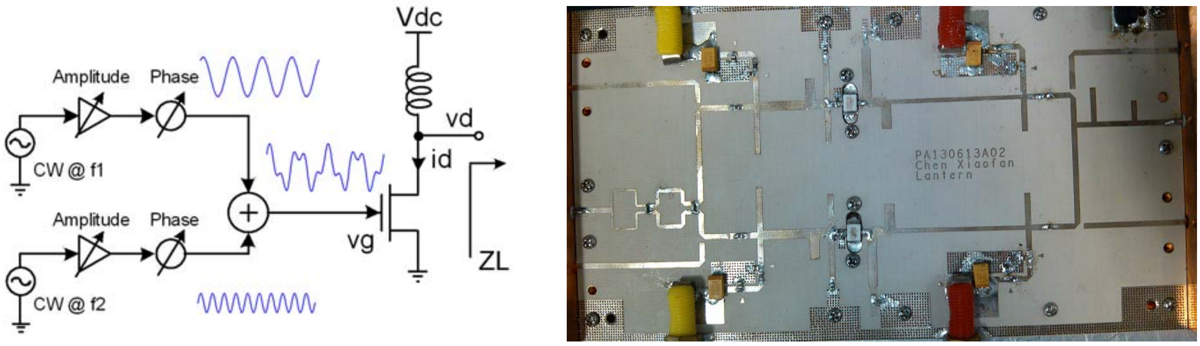


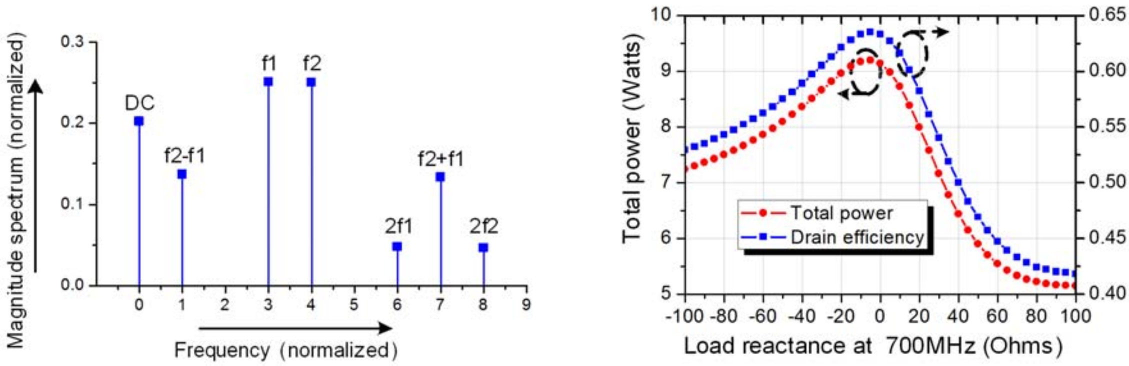

(a) (b)

Fig.1 (a) the structure of concurrent dual-band PA, (b) fabricated concurrent dual-band Doherty power amplifier.

$$v_g(t) = V_{s1}\cos(\omega_1 t + \theta_1) + V_{s2}\cos(\omega_2 t + \theta_2) \quad (1)$$

$$\begin{aligned} \bar{i}_d(v_g) &= v_g, 0 \le v_g(t) \le 1 - V_q \\ &= 0, v_g < -V_q \\ &= 1, v_g > 1 - V_q \end{aligned} \quad (2)$$

The spectrum of drain current (2) can be derived mathematically [3]. According to the calculated spectrum, the drain current contains significant intermodulation (IM) components in addition to fundamental and harmonic components, especially when the magnitudes of the two carriers are comparable. The spectrum of drain current is shown in Fig.2 (a) for a typical dual-band Class-B PA when $\omega_2/\omega_1 = 4/3$ and the two carriers share equal magnitude.




(a) (b)

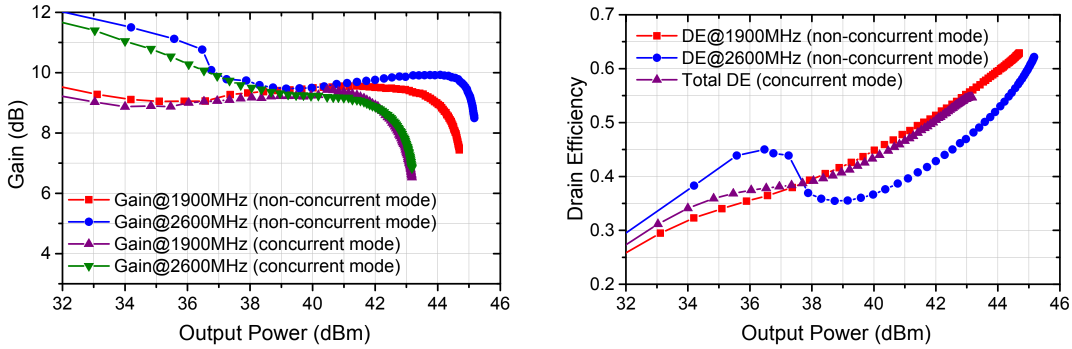
Fig.2. (a) spectrum of Class-B drain current. ($\omega_2/\omega_1 = 4/3$), (b) simulated concurrent performance versus the load reactance at lower second order IM frequency (f2-f1 = 700MHz).

The fact that the drain current contains significant IM components indicates that the IM components must be matched properly to reduce the drain voltage swings to obtain satisfactory performance. It can be proven that among all the IM components, the impedance matching at the lower second-order IM frequency (lower IM2) $\omega_2$-$\omega_1$ is most important. The simulated performance versus varied lower IM2 load impedance is shown in Fig.2 (b) for a 1.9-2.6GHz dual-band PA, showing the significance of IM tuning. The concept of IM tuning can be easily extended to multiband PAs, which will be published in our future papers and will not be discussed in detail here for simplicity.

## 3. High-Efficiency Concurrent PA Design

Based on the concept of IM-Tuning, concurrent dual-band/multiband PA with high-efficiency performance can be realized utilizing matching networks exhibiting proper fundamental, harmonics, and IM impedance tuning. A 1.9-2.6GHz example concurrent dual-band Doherty power amplifier is designed and fabricated using Cree's 10-Watts GaN HEMT CGH40010, which is shown in Fig.1 (b).

The fabricated Doherty power amplifier is measured in both non-concurrent and concurrent mode and the measured performance is shown in Fig.3 (a) and (b). According to the measured results, the fabricated power amplifier exhibits satisfactory performance in both non-concurrent and concurrent modes. As shown, the power utilization factor is significantly enhaned as compared to conventional designs.




(a) (b)

Fig.3 (a) measured power gain in non-concurrent and concurrent mode, (b) measured drain efficiency in non-concurrent and concurrent mode.

## 3. Low Complexity DPD for Multi-Standard PA

The motivation of the adaptive basis functions selection algorithm is to prune the existing memory polynomial (MP) model iteratively with the captured input and output signals of PAs, as a result, the coefficients number and computation complexity can be reduce effectiely. In this way, the characteristic of PA can be utilized to select the model basis functions, so as to remove the redundant terms and make the model compact as possible. To determine the fate of each coefficient in MP model, the basis vector $\mathbf{\Phi}$ is initialized as:

$$\mathbf{\Phi}^{(0)} = \{\phi_1^{(0)},...\phi_k^{(0)},..,\phi_K^{(0)}\} \tag{3}$$

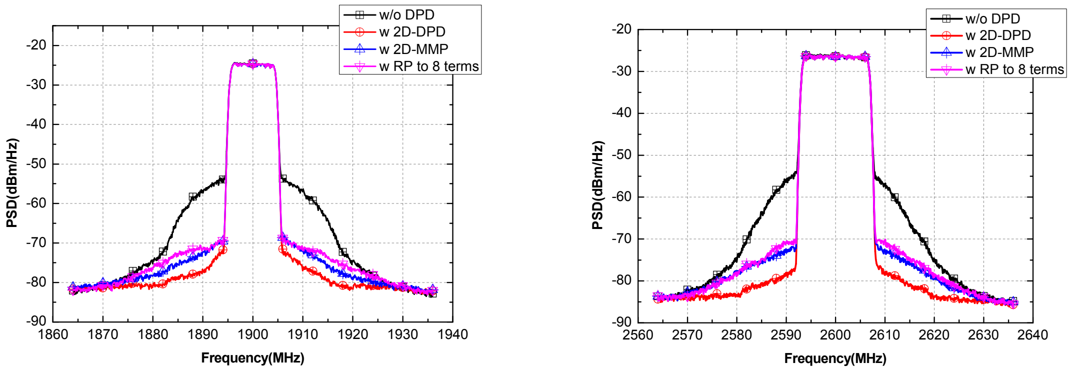
where $\mathbf{\Phi}^{(i)}$ is a vector of all selected terms of the model in the ith iteratioin. $\phi_k^{(i)}$ is the kth term in $\mathbf{\Phi}^{(i)}$, and K is the number of the terms in the seeding model. Two other vectors are also initialized as blank vectors and marked as $\mathbf{PRECISION}^{(0)}$ and $\mathbf{LABEL}^{(0)}$. In the following procedure, $\mathbf{PRECISION}^{(i)}$ and $\mathbf{LABEL}^{(i)}$ will be used to save the calculated precision and pruned terms in the $i^{th}$ iterations, which are evaluated by the loss of normalized mean square error (NMSE).

After initialization, the model is calculated and pruned iteratively. In the iteration, the model with selected terms in $\mathbf{\Phi}^{(i)}$ is extracted with LS method, and evaluated with testing signals. The NMSE between the simulated output and measured output is calculated as a criterion of the model's precision. Once the algorithm converges to an acceptable level and preset value, we may exit out of the loop and output the final model for linearization. The detailed flow chart of the adaptive process can be referred to [4].

## 4 Performance Evaluations with Modulated Signals

The PA is designed to work at 1.9GHz and 2.6GHz for TD-SCDMA and TD-LTE multi-standard applications and its saturation output power could reach 11W under concurrent dual band CW stimulus. Two LTE signals are used to drive the DUT, which are with 10MHz and 15MHz bandwidth, respectively. Signals on both the two bands are clipped into PAPR 7dB. While operating, the PA is with 35.1dBm and 35.9dBm output power on each band, which is 38.1dBm in total. ACPRs in higher and lower band before DPD are -32.51dBc and -34.05dBc, respectively.

The adaptive pruning algorithm is applied to the proposed dual-band Doherty PA and compared with the state-of-the-art two-dimensional digital predistortion methods. The linearized performance and comparison are presented in Fig.4 and Tab.I. As shown in Fig.4, the adaptive pruning algorithm approximate the 2D-MMP with only 8 coefficients. Although its performance is a little bit worse than 2D-DPD, but they are sufficient for wireless commucation. It also can be seen that the proposed dual-band Doherty PA after low complexity DPD achieves the output power of 38.1dBm and the PAE of 42.1%, which are good specifications for real applications.




(a) (b)

Fig.4 Measured spectra of the PA output (a) lower band (b) upper band

Tab.I Modulated Performance

| | *Technology* | *Device(s)* | *Bands (GHz)* | *Signal* | *Power (dBm)* | *ACPR (dBc, L/H)* | *Total Power (dBm)* | *PAE (%)* |
|---|---|---|---|---|---|---|---|---|
| [2] | Doherty | 15W GaN HEMT × 2 | 1.8 | 10 MHz LTE 7dB PAR | N/A | -46.3/-47.9 | 33.2 | 35.3 |
| | | | 2.4 | 10 MHz LTE 7dB PAR | N/A | -49.4/-47.7 | | |
| This work | Doherty (with IM tuning) | 13W GaN HEMT × 1 | 1.9 | 10 MHz LTE 7dB PAR | 35.1 | -49.4/-48.7 | 38.1 | 42.1 |
| | | | 2.6 | 15 MHz LTE 7dB PAR | 35.9 | -47.9/-45.4 | | |

## 5. Conclusion

An energy-efficient dual-band Doerhty PA and low complexity DPD techiques are demonstrated in this paper, and good performances are achieved due to the proposed IM-Tuning and adaptive pruning methods. These techinques will provide ideal solutions for the upcoming multi-standard wireless communications.

## 6. Acknowledgments

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## 7. References

1. Wenhua Chen, S. A. Bassam, X. Li, Y. Liu, K. Rawat, M. Helaoui, F. M. Ghannouchi, Z. Feng, "Design and Linearization of Concurrent Dual-Band Doherty Power Amplifier with Frequency-Dependent Power Ranges", *IEEE Transactions on Microwave Theory and Technology*, Vol. 59, No.10, Part 1, Oct., 2011, pp.2537-2546.

2. P. Saad, P. Colantonio, L. Piazzon, F. Giannini, K. Andersson, and C. Fager, "Design of a concurrent dual-band 1.8–2.4-GHz GaN-HEMT Doherty power amplifier." *IEEE Transactions on Microwave Theory and Techniques*, Vol.60, No.6 , June. 2012, pp.1840-1849.

3. X. Chen, W. Chen, F.M. Ghannouchi, Z. Feng, and Y. Liu, "Enhanced Analysis and Design Method of Concurrent Dual-Band Power Amplifiers With Intermodulation Impedance Tuning." *IEEE Transactions on Microwave Theory and Techniques*, Vol. 61, No. 12, Dec. 2013, pp.4544-4558,.

4. Silong Zhang, Wenhua Chen, Fadhel M. Ghannouchi, Yaqin Chen, "An iterative pruning of 2-D digital predistortion model based on normalized polynomial terns," *International Microwave Symposium*, Seattle, June, 2013, pp.1-4.