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# Linear Power Amplifier Uses Mirror Predistortion

**By Khaled Fayed, Amin Ezzeddine, and Ho Huang, AMCOM Communications Inc., and Amir Zaghloul, U.S. Army Research Laboratory and Virginia Tech**

This article describes a hybrid power amplifier linearization method that combines analog predistortion and feedforward design concepts

Current wireless communication standards have been established to carry voice, data and video with high data rates. These high data rates require efficient modulation techniques such as OFDM 64 QAM, to allow transmission in a given finite bandwidth. With these types of modulation, there are probabilities that at certain times, the voltages of the multiple carriers are in phase and their amplitudes add up to create a very high peak to average ratio (PAR) that may reach 15 dB. This high PAR will drive a conventional PA into saturation; causing signal distortion and generating out-band interference. One way to solve this problem is to use a high power PA in Class A mode, with average power set at a back off (BO) of 10-12 dB. Unfortunately, this technique results in a very inefficient PA.

There are various linearization techniques that are used to increase the linearity of the PA allowing the use at lower BO values and consequently having higher efficiency. These techniques include *feedback*, *feedforward*, *digital predistortion* or *analog predistortion* [1, 2]. Amongst all, the analog predistortion (Figure 1) tends to provide a good compromise between complexity, bandwidth and linearity improvement.

Several methods are available to implement an analog predistorter circuit. One method is to use a simple diode circuit in front of the PA and to choose its size and bias to compensate for its AM-PM nonlinearity. Although this technique is simple and could be easily integrated with a PA in one package, the linearity improvement reported is very limited and does not track well with higher output power levels [3, 4]. Another way is to use Cuber Predistortion [5, 6] where higher improvement in $IMD_3$ could be achieved, but with an increase in the fifth and higher order nonlinearities. In [7, 9] the $IMD_3$ and $IMD_5$ are independently improved by using two Cuber Predistorter circuits but with an increased level of complexity. A simpler technique is suggested in [10] to improve both of $IMD_3$ and $IMD_5$ by using a new Cuber PD design.

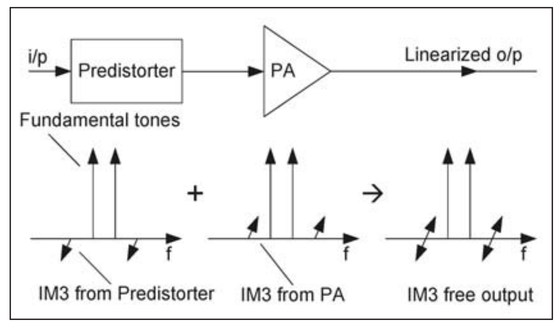

**Figure 1 · Intermodulation cancellation concept using a predistorter.**

All of the predistortion techniques require a full nonlinear characterization of the phase and magnitude of the $IM_3$ and $IM_5$ for both the predistorter circuit and the power amplifier. This characterization requires a special measurement techniques like those reported in [11, 12].

The feedforward linearization method provides higher levels of IMD improvement up to the amplifier's $P_{1dB}$ but requires the use of an additional Error Amplifier (EA) that is required to be very linear and consequently

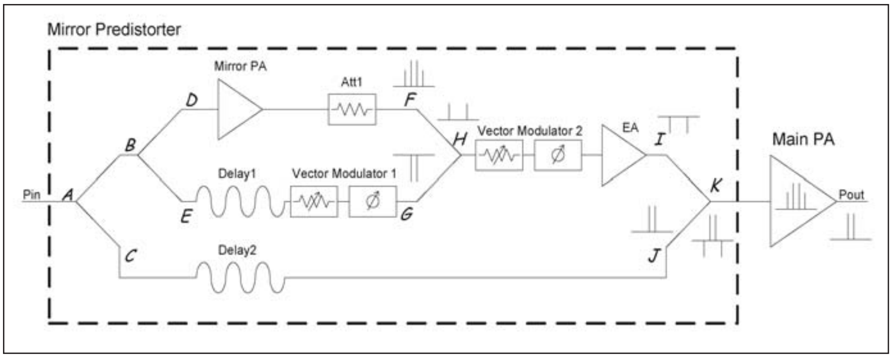


Figure 2 · Mirror predistortion linearization block diagram.

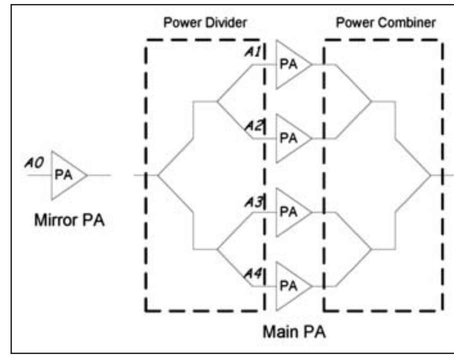


Figure 3 · Realizing a Mirror PA that has the same nonlinear characteristics as the main PA.

consumes a lot of power, resulting in reduction in the overall efficiency of the PA. This article describes a pseudo-predistortion linearization technique that mitigates the deficiencies of both analog predistortion and feedforward techniques.

We suggest using a low power PA in front of the main high power PA. This low power PA has identical construction as the main PA and, therefore, has the same distortion characteristics, but at a lower power level. Because this low power PA's third and higher order nonlinearities mirror those of the main PA in magnitude and phase, we call this low power PA a "Mirror Predistorter." The nonlinearities generated by the mirror PD are properly fed to the input of the PA, so that they appear at its output in the same magnitude but out of phase with the internally generated PA nonlinearities, resulting in IM cancellation as shown in Figure 1.

## Circuit Implementation

In order to prove the concept of the proposed mirror PD, we have designed a mirror predistortion PA. Figure 2 shows the block diagram of the proposed mirror PD linearization technique. The intermodulation terms coming from the mirror PD must be fed to the input signal of the PA so that they cancel the intermodulation products generated at the output. So the magnitudes of paths *ABDFHIK* and *ACJK* must be equal, but with the phases shifted by 180°. Both the magnitude and the phase are controlled by Vector Modulator 2, whereas Delay 2 is used to equalize the time delay of the two paths.

Also, it is necessary to cancel the carrier coming out from the mirror PA. This is done by adding path *EG* to path *DF* with the same delay and magnitude, but with a 180° phase shift. Again, this is controlled by using Vector Modulator 1 and Delay 1 to get broadband cancellation. Any carrier leakage at point *H* will result in reduced gain since paths *ABDFHIK* and *ACJK* are 180° out of phase, and also will result in non-optimum predistorter tracking to the AM-AM and AM-PM of the PA.

The main advantage of the Mirror PD over feedforward linearization is that the size of the Error Amplifier (EA) could be much smaller in terms of size and power consumption because the EA is in the input (low power) side. This is accomplished by feeding the intermodulation terms at the input of the PA rather than its output. So the power requirement of the EA is lower by an amount that is equal to the gain of the main PA. Moreover by changing the coupling ratio of coupler *IKJ* we can further decrease the requirement on the output power of the EA. However by doing so, the total loss of the PD will increase. For instance if we are using a 10 dB coupler instead of a 3 dB coupler, the total loss of the predistorter will be 7 dB greater.

If necessary, the total gain of the PA with the predistorter could be boosted by using a low power driver amplifier before the predistorter.

The mirror PA is an AMCOM MMIC PA, AM204437WM-BM. It has 30 dB gain with 36 dBm output power from 2.0 to 4.4 GHz. The main PA combines of four of the same MMICs as shown in Figure 3. Therefore, the DC power consump-

| | |
|---|---|
| **AMCOM AM204437WM-BM (used for Main and Mirror PA)** | |
| **Features:** | Wide bandwidth from 2.0 to 4.4 GHz |
| | High output power, $P_{sat}$ = 37 dBm |
| | High gain, 30 dB |
| | Fully matched; 50-ohm input/output impedance |
| | Ceramic package, RoHS compliant |
| **AMCOM AM304031WM-BM (used for EA)** | |
| **Features:** | Wide bandwidth from 2.6 to 4.6 GHz |
| | High output power, $P_{1dB}$ = 32 dBm |
| | High gain, 31 dB |
| | Fully matched; 50-ohm input/output impedance |
| | Ceramic package, RoHS compliant |

Table 1 · Specifications of the Main, Mirror and Error amplifier MMICs.

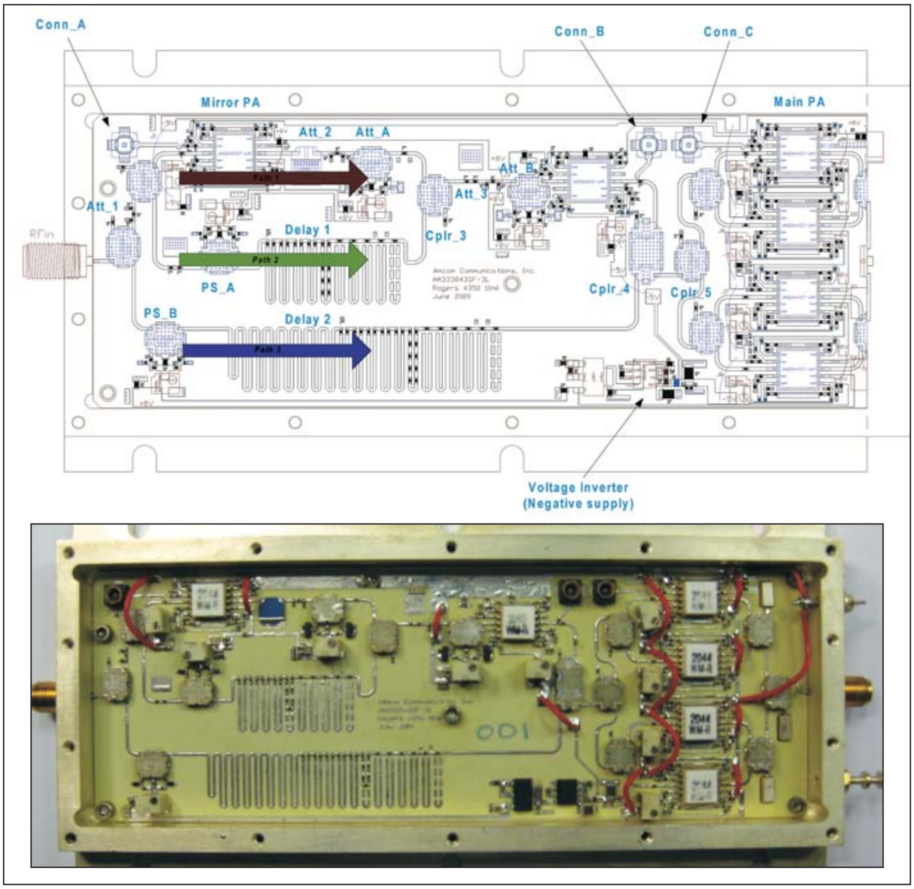


**Figure 4 · Layout diagram and photo of the implemented hybrid module.**

tion of the mirror PA is only 1/4 of the main PA. The overall efficiency can be improved if the main PA is implemented by combining eight MMICs. The input power of the MMIC used in the mirror PA must be equal to the input power of each of the same MMICs used in the main PA ($P_{A0} = P_{A1\text{-}4}$), otherwise the nonlinear performance will be different. This could be adjusted by an additional fixed attenuator in front of the mirror PA according to the coupling factors of the different couplers used in the design. Table 1 shows the key specifications of the MMIC amplifier modules used in the PA.

The mirror predistortion PA was integrated in a hybrid module that is 6.1” × 2.9” (Figure 4). A low power AMCOM MMIC AM304031WM-BM was used as the EA and consumes only 22% of the mirror PA DC power, which is just 5.5% of the main PA power. Surface mount 3 dB hybrid couplers with a frequency band of 3.3 to 3.7 GHz were used everywhere in the design except for coupler *IKJ* where a 10 dB coupler was used to lower the output power from the EA at the expense of higher PD loss. The vector modulators consist of analog voltage attenuators and analog phase shifters. Both of them were designed using 3 dB hybrid coupler and two PIN diodes for the variable attenuator, plus two varactors for the variable phase shifter by using the reflective topology as described in [7].

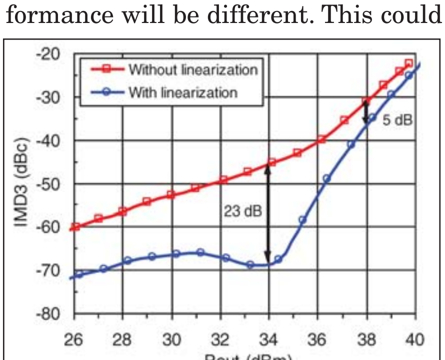


**Figure 5 · $IMD_3$ vs. output power with and without linearization.**

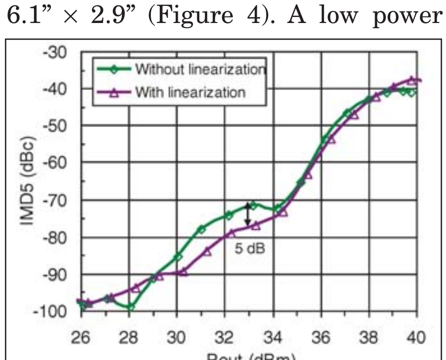


**Figure 6 · $IMD_5$ vs. output power with and without linearization.**

## Experimental Results

Figures 5 and 6 show the $IMD_3$ and $IMD_5$ versus two-tone total output power for this mirror predistortion PA, with and without linearization. The linearization is being activated and deactivated by turning on and off the EA. The frequency separation of the two tones is 10 MHz. We are able to optimize the performance at different back off levels by controlling the vector modulators. For the results shown, the performance is optimized at 34 dBm, which is 7.5 dB back off from the output 1 dB compression power of 41.5 dBm. At a two-tone total output power of 34 dBm, the $IMD_3$ is –46 dBc where the $IMD_5$ is –72 dBc when the linearization is deactivated. The $IMD_3$ is –69 dBc and the $IMD_5$ is –75 dBc when the linearization is activated. This represents $IMD_3$ and $IMD_5$ improvements of 23 dB and 3 dB, respectively.

Since the main purpose of linearization is to operate the PA at lower BO values with the same linearity, we plot the efficiency and output power of the PA versus the $IMD_3$ level with and without linearization as shown in Figure 7. We notice that for higher levels of linearity requirements, i.e. $|IMD_3| > 60$ dBc, the increase in efficiency is more than

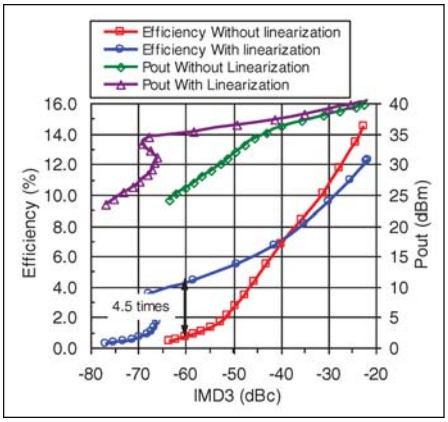


**Figure 7 · Efficiency and $P_{out}$ vs. $IMD_3$ with and without linearization.**

four times. This means that we can get output power that is four times higher for the same DC input power. At an $|IMD_3|$ value of 40 dBc the efficiency values with and without linearization are equal. This is because the amount of improvement in linearization at that level is not high enough to justify for the use of extra PAs for the mirror and the EA.

The reason that the linearity improvement degrades with higher power levels could be explained as follows: Although the mirror and the main PA are tracking each other, Vector Modulator 1 is not tracking the mirror PA when it starts compressing, so the carrier cancellation at *H* is imperfect. This resulting carrier leaks and arrives at the input of the PA out of phase with the main input carrier causing non optimum PD performance and consequently lower linearity improvement.

The measurements were repeated with different frequency separations: 1 MHz, 10 MHz (as shown in Figs. 5, 6, 7), and 20 MHz where the same performance was achieved, indicating broadband capability. This possible because equalizing Delay 1 and Delay 2 for high bandwidth could be achieved depending on the gain and phase flatness of the different components and on the bandwidth of the couplers. A bandwidth of 20 MHz is enough for a WiMAX channel.

## Conclusion

We have proposed a "new" predistortion linearization concept that mitigates the deficiencies of regular analog predistortion and feedforward linearization techniques. We call this "Mirror Predistortion Linearization." We have reduced this concept to practice by developing a Mirror Predistortion PA that achieved an $IMD_3$ of –69 dBc, a 23 dB $IMD_3$ improvement at back off of 7.5 dB.

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### Tuning the Amplifier

The main advantage of the Mirror PD linearization technique, as compared to the other predistortion techniques, is that no measurement of the nonlinear AM-AM and AM-PM of the PA and the PD circuits is necessary. Instead we follow a straight forward procedure to tune the circuit to the best linearization performance. This is done by the use of variable attenuators and phase shifters, variable delay lines Delay 1 and Delay 2, and SMT connectors Conn_A, Conn_B and Conn_C as shown in Figure 4.

So first of all we want to start with a close estimate of the values for the fixed attenuators and the delay lines. This is done by running linear *S*-parameter simulation of the module before we build it. In this simulation *S*-parameter files for the different components were used to simulate the magnitude, phase, and delay of different paths in order to determine the values of different components (delays and attenuators).

After the module was built, a vector network analyzer (VNA) was used, before doing any nonlinear measurement, to tune the performance by measuring the *S*-parameters of different sections. Note that each path from paths 1, 2, & 3 could be disconnected or connected by using a zero ohm resistor in series in each path. To disconnect a path we remove that resistor and connect two 50 ohms resistors at each end to avoid reflections from either ends. The following tuning steps were followed:

1. While disconnecting paths 2 & 3, measure and record $S_{21}$ for path 1 from the input to Conn_B.

2. While disconnecting paths 1 & 3, measure and record $S_{21}$ for path 2 from the input to Conn_B.

3. Compensate for the difference in delay by tuning Delay 1 making sure that the phase difference between paths 1 & 2 should be 180º in order to cancel the carrier, Also compensate for the magnitude difference by changing Att_2.

4. Now while path 3 is disconnected, measure $S_{21}$ again between the input and Conn_B to make sure that the compensation of the carrier is now working, where the magnitude of $S_{21}$should now be smaller than any of paths 1 or 2 by at least 30 dB over the band of operation.

5. Measure $S_{21}$ between the input and Conn_A. Then do the same thing between the input and Conn_C through path 3 (paths 1 & 2 disconnected) and make sure that both magnitudes are equal to ensure that both the mirror PA and every unit of the main PA are operating at the same input power level. Change the attenuation of Att_1 if necessary to compensate for any difference in magnitude.

6. The last thing we need to do is to make sure that the intermodulation terms arrive at the correct magnitude, phase and delay at the input of the main PA. This is done by repeating steps 1-4 but by doing the measurement between the input and Conn_C and for paths 1 and 3 while path 2 is disconnected. Any necessary tuning could be done by changing Att_3 and Delay 2.

Note that in the previous steps we try to keep any fine tuning elements in the middle of their tuning ranges for ease of final adjustments during the nonlinear measurements.

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## Author Information

Khaled Fayed received his Masters Degree in EE from Virginia Tech in 2009 and currently is a senior design engineer at AMCOM Communications Inc. in Maryland, where he develops MMIC and hybrid module power amplifiers for broadband, high power, and high linearity applications. He can be reached at khaled@amcomusa.com

Amin Ezzeddine is the Executive Vice President, Chief Engineer and co-founder of AMCOM Communications, Inc. He received his Bachelor of Science from Ain-Shams University, Cairo, his Masters Degree in EE and Doctor of Science degree from MIT. He has over 28 years experience designing MMIC and MIC components.

Ho-Chung Huang is President of AMCOM Communications Inc. He received his MS and Ph.D. EE from Cornell University. Dr. Huang has 12 patents and over 100 technical publications in the microwave area.

Amir I. Zaghloul received his M.A.Sc. and Ph.D. from University of Waterloo, Canada, and the B.Sc. from Cairo University, Egypt. He is currently with the US Army Research Laboratory on an IPA agreement with Virginia Tech.