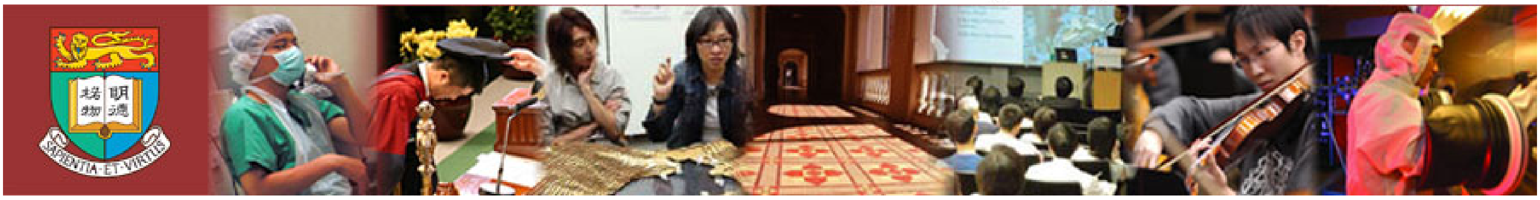

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Citation	The 12th IEEE International Conference on Communication Systems (ICCS 2010), Singapore, 17-19 November 2010. In Proceedings of 12th ICCS, 2010, p. 19-22
Issued Date	2010
URL	http://hdl.handle.net/10722/140280
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A 5^{th}-Order Analog Predistorter for NADC system

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Abstract— **This paper presents the design of a 5^{th}-order analog predistorter using the inband intermodulation (IM) signals for predistortion of base-station high power amplifiers (HPAs) for the North American Digital Cellular (NADC) system. The predistorter employs two mixers with same configuration to generate 3^{rd}-order intermodulation (IM3) products and 5^{th}-order intermodulation (IM5) products, to suppress the 3^{rd}-and 5^{th}-order intermodulation distortion products (IMDP3 and IMDP5) at the HPA output. The predistorter is implemented and tested using the pi/4-DQPSK signal of the NADC system at 2.2GHz in a practical 100W-HPA. The results show that, at the HPA output powers of 65.6, 56.2, 50 and 41.3 W, the predistorter can suppress the adjacent channel power ratio (ACPR) of the pi/4-DQPSK signal at ± 20 kHz from the center frequency by 15.16, 15.83, 16.17 and 15.17 dB, respectively.**

I. INTRODUCTION

In modern wireless communication systems, high-power amplifier (HPA) is one of the most nonlinear components. HPA nonlinearity introduces intermodulation distortion and causes interference to the adjacent channels, deteriorating the communication quality. The first generation digital cellular mobile system, IS-54, employs a spectrally efficient modulation scheme, pi/4-DQPSK. However, achieving spectral efficiency requires the use of a linear transmit power amplifier. Due to the inherent nature of RF HPAs, the amplification processes are always nonlinear. Therefore, HPAs have been widely used in conjunction with linearization techniques such as feed-back, feed-forward and predistortion [1-9]. Among these techniques, predistortion is extensively used in repeaters and base stations. When compared with its counterpart of digital predistortion (DPD), analog predistortion (APD) has a moderate linearity improvement with much simpler circuits and lower cost.

APD can be implemented by feeding the inband intermodulation (IM) signals [5], the difference-frequency signals (known as the difference-frequency technique) [6] or the harmonic-frequency signals (known as the harmonic-injection technique) [7] of the fundamental signal to the input of the nonlinear HPA. The difference-frequency signals have relatively low frequencies and the harmonic-frequency signals have relatively high frequencies, so the uses of these two techniques are limited to the HPAs with very wide bandwidths.

In this paper, we propose to use the inband IM signals for predistortion of HPAs. The design of a 3^{rd}-order analog predistorter was described in [8]. In order to obtain high linearity performance at higher HPA output power, a higher order predistorter is needed to suppress the intermodulation distortion products (IMDPs). Here we propose the design of a 5^{th}-order predistorter which employs two IM generators with identical configuration to generate the 3^{rd}- and 5^{th}-order intermodulation (IM3 and IM5) products. The predistorter is implemented and tested using the pi/4-DQPSK signal of the North American Digital Cellular (NADC) system at 2.2GHz in a practical base-station 100W-HPA, HPA2100-085-SW01, manufactured by Bravotech Inc., China, at the output powers of 65.6 W, 56.2 W, 50 W and 41.3 W. The results are compared with those using a 3^{rd}-order predistorter. The results show that, as expected, at higher HPA output powers, the improvements by 5^{th}-order predistortion are more significant.

II. IM SIGNALS GENERATORS

The basic idea of using the inband IM signals for predistortion of base station HPAs can be found in [8]. In a 3^{rd}-order analog predistorter, the IM3 signals are generated using an IM3 signal generator, combined with the fundamental signal and then fed to the HPA to cancel the IMD3 at the output of the HPA [8]. When the HPA is operating in the more nonlinear region of the characteristic for higher efficiency, predistortion using higher order is required for better power linearity. Here we propose an IM signal generator to generate the IM3 and IM5 signals to cancel the IMDP3 and IMDP5 at the output of the HPA.

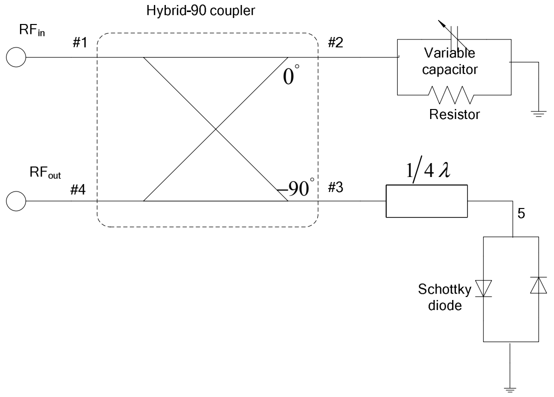

Fig. 1 Block diagram of IM signal generator

Figure 1 shows the block diagram of our proposed IM signal generator which consists of a 3-dB 90°-hybrid coupler, a pair of anti-parallel Schottky diodes, a λ/4-length transmission line at the frequency of 2.2 GHz, a variable capacitor and a resistor. RF_{in} and RF_{out} are the input and output ports, respectively, of

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the IM generator and also the coupler. The anti-parallel Schottky diodes circuit works like a mixer with its current flow given by [9]:

$$\begin{aligned} I(t) &= I_s\{\exp[kV(t)]-1\} - I_s\{\exp[-kV(t)]-1\} \\ &= I_s\{2kV(t) + \frac{[kV(t)]^3}{6} + \ldots + \frac{[kV(t)]^{2n+1}}{(2n+1)!} + \ldots\} \end{aligned} \tag{1}$$

where $V(t)$ is the signal voltage across the diodes at node 5, k is a constant and I_s is the saturation current of the diodes.

Let the input signal in Fig. 1 be a fundamental signal having two tones given by:

$$V_1(t) = a\cos\omega_1 t + a\cos\omega_2 t \tag{2}$$

Assume that $V_1(t)$ has a relatively low power level, so that only the 1st-order and 3rd-order terms in (1) are dominant and other higher order terms will have much lower levels and can be neglected. Thus the mixer produces mainly the IM3 signals and the fundamental signal at the output. By appropriately adjusting the values of the variable capacitor and the resistor in Fig. 1, we can have the reflected fundamental signals from both ports #2 and # 3 with the same magnitudes and a phase difference of 180° and hence cancelled off, leaving only a strong IM3 signal at the output. The generator is therefore an IM3 signal generator. This IM3 signal generated can be combined with the fundamental signal in (2) to produce the signal:

$$\begin{aligned} V_2(t) &= a\cos(\omega_1 t) + a\cos(\omega_2 t) + b\cos[(2\omega_1-\omega_2)t] \\ &\quad + b\cos[(2\omega_2-\omega_1)t] \end{aligned} \tag{3}$$

The generator can also be used as an IM5 generator as described as follows. The signal of (3) is used as the input signal to the IM signal generator of Fig. 1. Thus, the signal applied to the Schottky diodes, which has a half power of (3), can be represented as:

$$V_3(t) = c\begin{Bmatrix} a\left(\cos\omega_1 t + \cos\omega_2 t\right) \\ +b\left[\cos(2\omega_1-\omega_2)t + \cos(2\omega_2-\omega_1)t\right] \end{Bmatrix} \tag{4}$$

The output signal, obtained by substituting (4) into (1) and expanding the 3rd-order term, consists of the fundamental signal, IM3, IM5, IM7 and IM9 signals given by, respectively, :

$$\frac{I_s\cdot k^3}{6}\left(\frac{9}{4}a^3c^3 + \frac{9}{4}a^2bc^3 + \frac{9}{2}ab^2c^3 + \frac{12}{k^2}ac\right)\left(\cos\omega_1 t + \cos\omega_2 t\right) \tag{5}$$

$$\frac{I_s\cdot k^3}{6}\begin{pmatrix} \frac{9}{4}b^3c^3 + \frac{3}{4}a^3c^3 \\ +\frac{9}{2}a^2bc^3 + \frac{12}{k^2}bc \end{pmatrix}\left[\cos\left(2\omega_1-\omega_2\right)t + \cos\left(2\omega_2-\omega_1\right)t\right] \tag{6}$$

$$\frac{I_s\cdot k^3\cdot c^3}{6}\left[\frac{9}{4}(a^2b + ab^2)\right]\left\{\cos[(3\omega_1-2\omega_2)t] + \cos[(3\omega_2-2\omega_1)t]\right\} \tag{7}$$

$$\frac{I_s\cdot k^3\cdot c^3}{6}\left(\frac{9}{4}ab^2\right)\left\{\cos[(4\omega_1-3\omega_2)t] + \cos[(4\omega_2-3\omega_1)t]\right\} \tag{8}$$

$$\frac{I_s\cdot k^3\cdot c^3}{6}\left(\frac{3}{4}b^3\right)\left\{\cos[(5\omega_1-4\omega_2)t] + \cos[(5\omega_2-4\omega_1)t]\right\} \tag{9}$$

From (7)-(9), it can be seen that, if a is much larger than b, say 5 dB, then $a^2b >> ab^2 >> b^3$, the IM5 signals in (7) will be much larger than the IM7 signals in (8) and the IM9 signals in (9) which therefore can be neglected. Then again, by appropriately adjusting the values of the variable capacitor and the resistor in Fig. 1, we can cancel off either the fundamental signal of (5) or the IM3 signal of (6) at the output port using the signals reflected back from port #2. Note that we cannot cancel off both signals of (5) and (6) simultaneously because we cannot adjust the fundamental and IM3 signals separately in port #2. For example, if we make the adjustment to cancel the fundamental signal of (5) at port #4, the same adjustment cannot be used to cancel off the IM3 signal at port #4, and vice versa. Thus, only one of the signals can be cancelled off in an adjustment. In our design, we select to cancel the IM3 signals, so there will be a strong IM5 signal of (7) at the generator output. Regarding to the fundamental signal of (5) at port #4, there is no need to suppress it because the signals from the IM5 generator will be eventually combined with a very strong fundamental signal (and an IM3 signal) and then fed to the PA for predistortion. Thus, as far as our design is concerned, the generator in Fig. 1 can be used as an IM5 signal generator.

Figure 2 shows the block diagram of our proposed 5th-order predistorter which consists of the IM3 and IM5 signal generators.

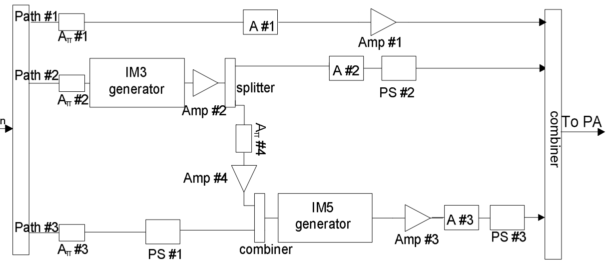


Fig. 2 Block diagram of 5th-order predistorter

At the input of the predistorter, the signal is divided into three paths, paths #1, #2 and #3, using two 2-way power splitters. Three π-resistive attenuators, A_π #1, A_π #2 and A_π #3, are used to control the input signal power levels in these three paths. The voltage-variable-attenuator, A #1, and the linear low power amplifier, Amp #1, in the main path, path #1, together is used to control the power level of the fundamental signal to the HPA and hence determine the operating point. (Note that Amp #1 is not adjustable, so the control of power to the HPA is done using the A #1). In path #2, the signal is adjusted by using A_π #2 and then fed to the IM3 signal generator. The IM3 signal generated is fed to a linear low power amplifier, Amp #2, to obtain a proper power level to a 2-way power splitter. One of the output IM3 signals from the splitter in path #2 is adjusted appropriately in amplitude and phase using the associated voltage-variable-attenuator (A #2) and phase shifter (PS #2), respectively, for predistortion. The other IM3 signal from the power spitter is adjusted by the pi-resistive attenuator, A_π #4, and then the amplifier, Amp #4, to obtain a proper power level suitable for the IM5 generator (the two-tone signal in (3)). In path #3, the signal is adjusted by A_π #3 and PS #1, combined with the IM3 signal from path #2 and then fed to the IM5 signal generator (i.e., the signal of (3)). The amplitude and phase of the IM5 signal are adjusted using the associated voltage-variable-attenuator A #3 and phase shifter PS #3. The resultants signals in paths #1, #2 and #3 are combined together and fed to the HPA for cancellation of the IMDP3 and IMDP5 at the output.

Note that although this is a 5th-order predistorter, if the attenuator A #3 is set to maximum, then it becomes a 3rd-order predistorter. Thus this design can give us a flexibility to compare the performances of 5th-order and 3rd-order predistorters.

III. EXPERIMENTAL RESULTS

The 5th-order predistorter of Fig. 2 has been fabricated on a PCB using Roger's RO4005C. The linear low power amplifiers (Amp #1-Amp4) used are RFMD's SBB5089, the attenuators (A #1-A #3) are Skyworks' AV103, the phase shifters (PS #1-PS #3) are Skyworks' PS214-315, the 2-way splitters and combiners are Skyworks' PD-22 and resistors in the π-resistive attenuators (A_π #1 to A_π #4) are 0603 mounting resistors. The IM3 and IM5 generators in Fig. 2 are as shown in Fig. 1, where the 3-dB 90^o hybrid couplers used are Anaren's JP503, the Schottky diodes are Avago-tech's HSMS 282X, the variable capacitors are Skyworks' SMV1245-011 and the resistors are 0603 mounting resistors. The predistorter has been optimised using the simulation tool ADS2009 and tested in a base-station 100W-HPA, HPA2100-085-SW01, manufactured by Bravotech inc. China, used in practical cellular mobile systems.

A two-tone signal centred at 2.2 GHz with 2 MHz spacing has been used to test the performances of the IM3 and IM5 generators and results are shown in Figs. 3 and 4. The result on the signal spectrum in Fig. 3 shows that the IM3 signal is more than 20 dB higher than the fundamental signal (i.e., the two-tone signal) and the other high-order IM signals. In Fig. 4, the result shows that the IM5 signal is more than 10 dB higher than the other high-order IM signals. The fundamental signal has a relatively high power level, for the reason described previously. However, results have shown that, in normal predistortion operation, the required signal level of the fundamental signal in the main path (i.e., path #1 of Fig. 2) is more than 20 dB higher than that of the fundamental signal from the IM5 generator. Hence the fundamental signal generated from the IM5 generator in Fig. 4 can still be neglected.

The predistorter in Fig. 2 has been tested using the pi/4-DQPSK signal of the NADC system centred at 2.2 GHz in the same practical 100W-HPA. To see the improvements provided by the predistorter, the signal spectrum without predistortion was first studied using a spectrum analyser. The signal spectrum obtained via a 45-dB coupler in the HPA module for an output power of 65.6 W is shown in Fig. 5(a). Then, with 3rd-order predistortion, i.e. setting the attenuator A #3 to the maximum value to stop any IM5 signal from going through, the attenuator A #2 and phase shifter PS #2 at the output of IM3 generator were adjusted to reduce the regrowth of the spectrum, while maintaining the HPA output at 65.6 W. The signal spectrum is shown in Fig. 5(b). For 5th-order predistortion, both A #2 and PS #2 in path #2 and A #3 and PS #3 in path #3 were adjusted to reduce the regrowth of the spectrum, while again maintaining the HPA output at 65.6 W. The result is shown in Fig. 5(c). It can be seen that in Fig. 5 that, without predistortion, the average power level at ±20 kHz from the center frequency is -48.7dBm. With 3rd-order predistortion, the average power levels at the same frequencies ±20 kHz from the center frequency are reduced to about -56.5dBm. With 5th-order predistortion, the average power levels at the same frequencies were reduced to -63.8 dBm, achieving a further reduction of 7.3 dB. Thus the 5th-order predistorter has reduced the adjacent channel power ratio (ACPR) by 15.1 dB at ±20 kHz from the center frequency. TABLE I shows the improvements of the ACPR at different HPA output power levels. It can be seen that at a low output power of 41.3 W, the further improvement by using 5th-order predistortion, instead of 3rd-order predistortion, is only 2.7 dB. This is because, at a low output power, the HPA is already operating in a relatively linear region, so 5th-order predistortion does not provide much further improvement. However, at higher output power levels, the HPA is more nonlinear and so higher order predistortion is more effective.

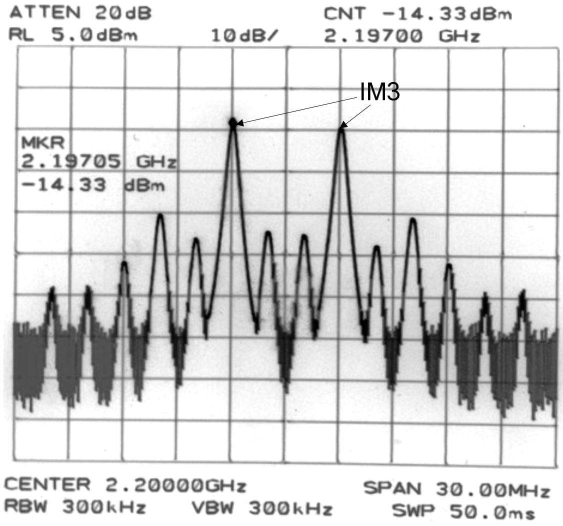


Fig. 3 Output spectrum from IM3 signal generator

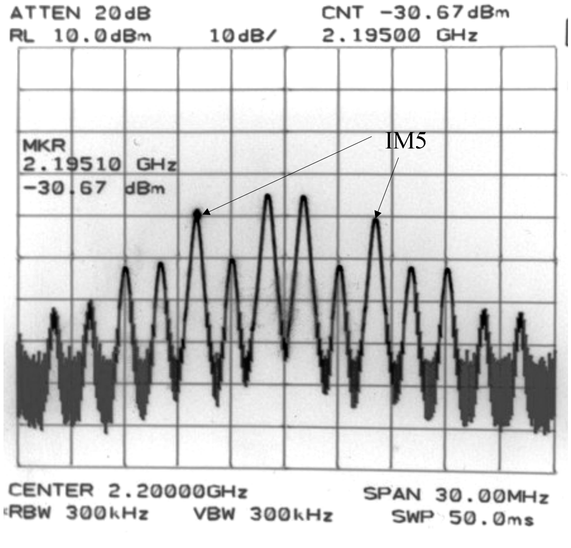
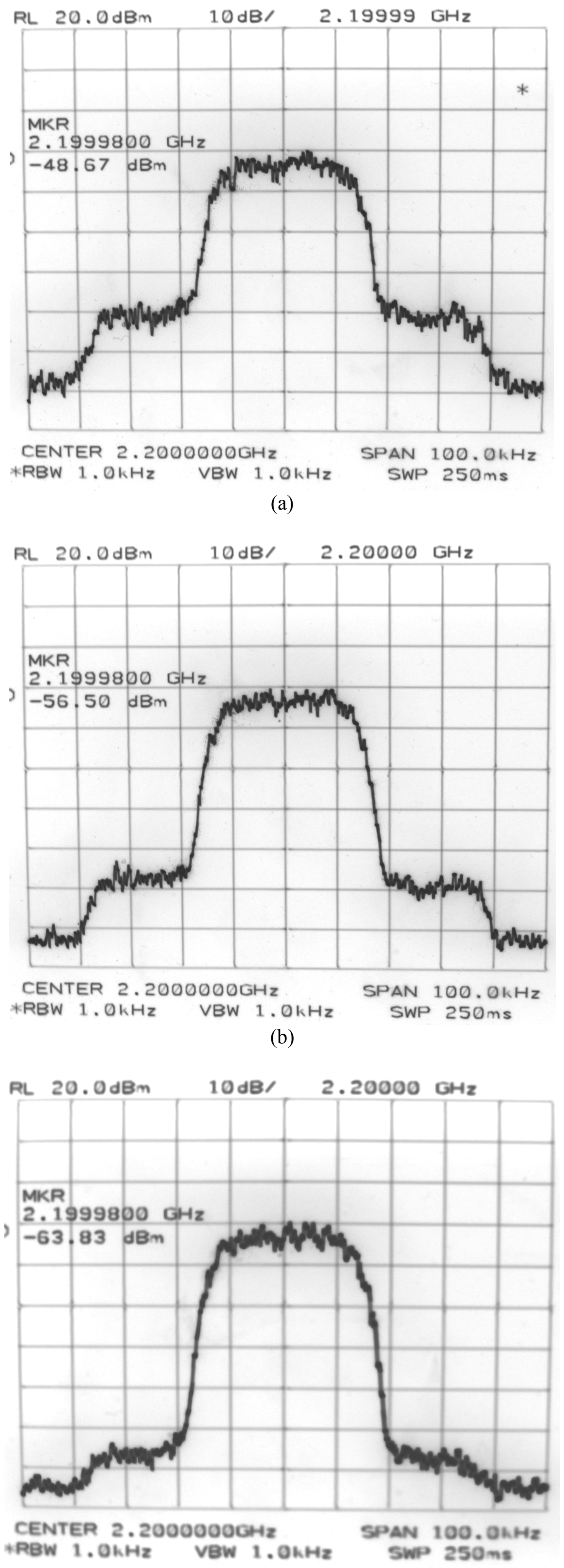


Fig. 4 Output spectrum from IM5 signal generator



(a)

(b)

(c)

Fig. 5 NADC test at output power=65.6W: (a) without predistortion, (b) with 3rd-order predistortion and (c) with 5th-order predistortion.

TABLE I. MEASUREMENT RESULTS

HPA Output Power	**Average power (dBm) at 2.2 GHz ± 20 kHz**			**Improvement (dB)**	
	Without Predistortion	***With 3rd-order Predistortion***	***With 5th-order Predistortion***	***3rd -order***	***5th-order***
41.3 W	-53.5	-66.0	-68.7	12.5	15.2
50.0 W	-52.0	-63.5	-68.2	11.5	16.2
56.2 W	-49.2	-59.0	-65.0	9.8	15.8
65.6 W	-48.7	-56.5	-63.8	7.8	15.1

IV. CONCLUSIONS

A 5th-order analog predistorter has been proposed and designed using an IM3 and IM5 signal generators with the same configuration. The predistorter has been implemented and tested in a practical 100W-HPA. Results of the tests using the pi/4-DQPSK signal of the NADC system have shown that, at the HPA output powers of 41.3, 50.0, 56.2 and 65.6 W, the predistorter can suppress the ACPR by 15.2, 16.2, 15.8 and 15.1 dB at the ± 20 kHz from the center frequency of 2.2 GHz.

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