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SMALL SIGNAL GAIN DEGRADATION AND ITS CORRECTION BY FEEDFORWARD LINEARIZATION

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ABSTRACT

In this paper we propose a new measure of amplifier nonlinearity; namely, the small signal gain degradation due to large signal capture of the amplifier power. This new criterion for linearity evaluation is specially important in repeaters where received signals are not a priory known. A 5th order mathematical model is used to characterize this phenomenon. After a thorough comparison between different linearization techniques, we select the classical feed-forward linearization. We adapt the FF linearization circuit to the total input signal power at different conditions and simulate the small signal gain against a large input signal gain in each case. An interesting result was that the feed-forward linearization circuit adapted to the total input power, completely compensates the small signal gain degradation. Although the results are frequency dependent, we can find some average settings to correct the system performance within a certain frequency band. We propose the use of a general power detector and a set of look-up tables for system adaptation.

KEY WORDS

Small signal gain degradation, feed-forward, adaptive feed-forward, linearization, AM-AM conversion, AM-PM conversion, *Harmonic Distortion, Inter-modulation Distortion,* Gain Compression, phase Distortion, and adjacent Channel Interference.

NOMENCLATURE

ADS	Advanced design system
FF	Feed-Forward
IBIP	In-Band Inter-modulation Products
IMD_3	Third-order *Inter-modulation Distortion*
P_{1dB}	1 dB compression point
P_{IP3}	Third order Intercept point

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INTRODUCTION

RF and microwave power amplifiers are used in a wide variety of applications. All wireless transmitters contain RF amplifiers which are nonlinear to some degree. Nonlinearities cause imperfect reproduction of the amplified signal if the signal to be amplified has a non-constant envelope, such as for linear modulation schemes or for a multicarrier signals [1]. The most important nonlinear effects in a nonlinear power amplifier are *Harmonic Distortion, Inter-modulation Distortion IMD,* Gain *Compression, phase Distortion [phase deviation as a function of amplitude or power level], and Adjacent Channel Interference*.

When the envelope of the signal is clipped or phase rotated, the resulting IMD (Spectral Re-growth) causes out-of-band components in adjacent channels, thus causing interference to other users of the system. For this reason the IMD of digitally modulated signals are often specified as adjacent channel power ratio (ACPR) [2]. AM-AM conversion is the modification in the fundamental signal gain as the input amplitude is increased. AM-PM conversion is a phase change in the fundamental signal introduced by AM-PM dependence on signal amplitude

These nonlinear effects can be characterized by different criteria. The 1dB compression point P_{1dB} is the output power level, at which the gain has dropped by 1 dB compared to the linear gain [3]. The third order Intercept point P_{IP3} is the output power level corresponding to the intersection of the extrapolation of the fundamental, and the third order IMD [2].

In a signal repeater, such as a communication repeater or a repeater jammer, where the received signals are not a priory known, nonlinearity has another important effect that degrades the repeater performance. The characterization and compensation of this additional effect is the subject of this paper.

DESCRIPTION OF THE PROBLEM

1. Mathematical Formulation

Consider a nonlinear power amplifier modeled with an n^{th} order power series transfer characteristics

$$V_{out}(t) = \sum_{i=1}^{n} a_i V_{in}^{i}(t) \tag{1}$$

Consider a two-tone signal *x (t)* applied to this amplifier

$$x(t) = A_1 \cos(\omega_1 t) + A_2 \cos(\omega_2 t) \quad , \quad \omega_1 < \omega_2 \tag{2}$$

Only odd-order terms are responsible for the In-Band Inter-modulation Products (IBIP), while the even terms, are responsible for the out-of-band distortion products [3]. Considering terms up to the fifth-order and neglect higher-order terms due to their smaller weights in the output spectrum and simplify our analysis with acceptable accuracy. From (1) and (2), it is easy to derive an expression for the output spectrum of the amplifier. If we divide the coefficient of cos(ω_1t) by A_1 and that of cos(ω_2t) by A_2 we get the voltage gain for each of the two input signals :

$$\begin{aligned} g_1 &= a_1 A_1 + \frac{3a_3 A_1^2}{4} + \frac{3a_3 A_2^2}{2} + \frac{5a_5 A_1^4}{8} + \frac{15\, a_5 A_2^4}{8} + \frac{30\, a_5 A_1^2 A_2^2}{8} \\ g_2 &= a_1 A_2 + \frac{3a_3 A_2^2}{4} + \frac{3a_3 A_1^2}{2} + \frac{5a_5 A_2^4}{8} + \frac{15\, a_5 A_1^4}{8} + \frac{30\, a_5 A_1^2 A_2^2}{8} \end{aligned} \qquad (3)$$

Equal signals will have equal gain and equal pairs of spurious outputs symmetrically distributed around the two input frequencies.

If the amplitude of the first tone is much smaller than that of the second ($A_1 << A_2$), while the second signal is strong enough to drive the amplifier into compression, the in-band output of the PA can be approximated to

$$\begin{aligned} V_{out}(t) \cong & \left(a_1 A_1 + \frac{3a_3 A_1 A_2^2}{2} + \frac{15\, a_5 A_1 A_2^4}{8} \right) \cos(\omega_1 t) \\ & + \left(a_1 A_2 + \frac{3a_3 A_2^3}{2} + \frac{5a_5 A_2^5}{4} \right) \cos(\omega_2 t) \\ & + \left(\frac{3a_3 A_1 A_2^2}{4} + \frac{5a_5 A_1 A_2^4}{4} \right) \cos(2\omega_2 - \omega_1) t \end{aligned} \qquad (4)$$

And the two gains become:

$$\begin{aligned} g_1 &\cong \left(a_1 + \frac{3a_3 A_2^2}{2} + \frac{15\, a_5 A_2^4}{8} \right) \\ g_2 &\cong \left(a_1 + \frac{3a_3 A_2^2}{4} + \frac{5a_5 A_2^4}{8} \right) \end{aligned} \qquad (5)$$

We can notice the following:

- The coefficient of cos [($2\omega_1 - \omega_2$)t] contains powers of A_1 higher than one and can be neglected; which means that this inter-modulation frequency component will have a very small output power.
- All fifth (and higher order) inter-modulation products contain higher powers of A_1 and can be neglected.
- The gain of the power amplifier will not equally distribute on the two signals; i.e. g_2 is not equal to g_1.

At a first glance, g_2 seems smaller than g_1, but if we consider that for a saturated power amplifier, usually a_3 and a_5 are negative, or at least one of them. We understand how the power amplifier gain is captured by the strong signal.

This degradation of small signal gain due to the presence of large signal is the proposed measure of power amplifier nonlinearity. We can call this phenomenon *small signal gain degradation*, or simply *Gain Capture*. It degrades the performance of power amplifiers working at or near saturation, such as communication power amplifiers, where efficiency requirements force designers to bias the PA in classes C, D, E and even F. It degrades, also, wide-band saturated power amplifiers in jamming systems. Moreover, it affects wide-open receiving amplifiers in EW systems, where neither signal frequencies nor their levels are a-priori known. In such receivers, gain degradation can define the upper limit of dynamic range.

2. Verification by ADS CAD simulations

To verify the gain capture problem, using the nonlinear model of the Agilent Va-hp-MSA-0500 power amplifier at 1, 1.5, and 2 GHz, and a two-tone input signal with different tones power (weak signal and strong signal) at 2 [kHz] frequency spacing. The total input power is then:

$$P_{total} = 10 * \log\left(\frac{A_1^2 + A_2^2}{2R}\right) + 30 \qquad [dBm] \qquad (6)$$

Where A1 and A2 are the input signal amplitudes [v]
R is the system characteristic impedance [Ω]

Sweeping the strong signal power from -7 dBm to +5 dBm, while keeping the weak signal power at -20 dBm, and measure the signals gain in dB at each measurement. Simulation ensure that the weak signal gain is decreased rapidly as the level of the higher tone is increased, while the higher tone captured the gain of the amplifier receiving most of its power.

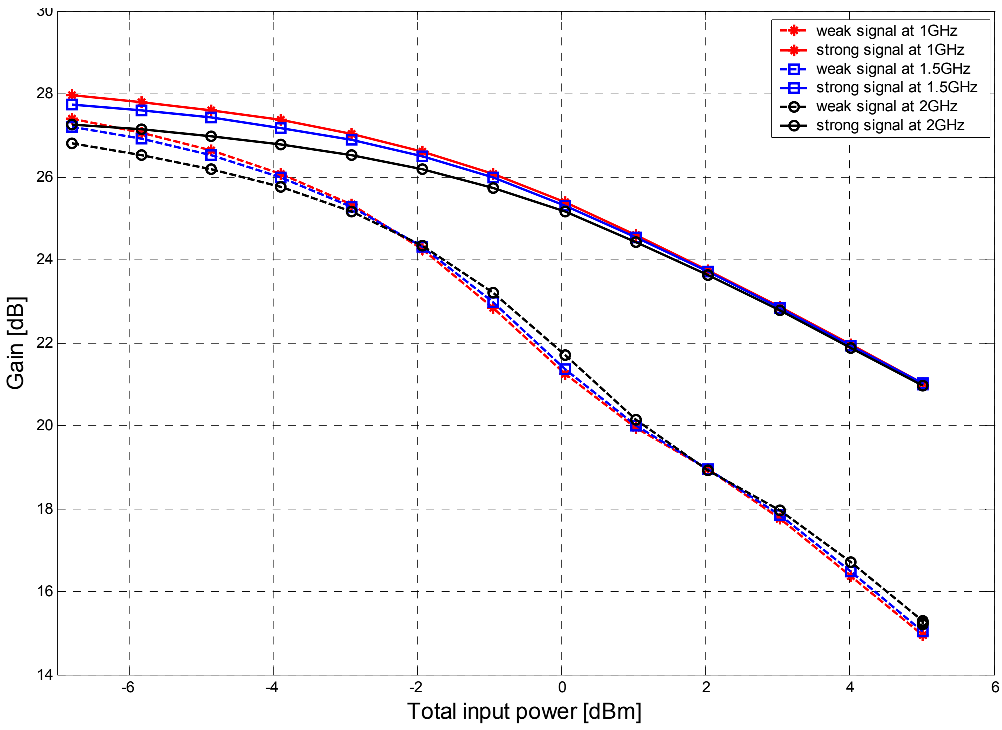

Figure 1: Gain Capture of the PA at 1, 1.5 and 2 GHz

As the input power level increase the gain difference between the large and the small signal increases and the gain difference for each signal at different frequencies decrease. As shown in figure 1.

SOLUTION OF THE GAIN CAPTURE PROBLEM

After describing the problem, and since the problem reason is amplifier nonlinearity, the solution is to linearize the power amplifier characteristics using external circuit.

1- Survey of different linearization techniques

Several linearization techniques exist. They were discussed in details in [2], [3] and [4]. Only the most common categories are briefly mentioned here.

Feedback techniques can suppress distortion as long as the feedback loop has sufficient incremental gain [1]. To increase the loop gain, base-band error amplifiers in Cartesian or polar form are commonly used. The necessary up and down conversions inside the loop increase noise sources and loop delays, limiting the stable bandwidth of the linearizer typically to below 100 kHz [3]. We cannot use feedback techniques to correct the gain capture problem for signal durations shorter than the feedback delay.

Predistortion based on expanding the signal before the power amplifier, so that the predistorter-amplifier pair appears as a linear circuit [3]. In principle, predistortion is a very power efficient and wideband linearization method, although it typically needs a slow feedback to adapt the predistortion function. A simple RF predistorter may consist of just a couple of biased diodes [1], or the predistortion signal can be generated in the digital baseband using adapted lookup tables. Predistortion techniques need a-priori knowledge of the signal spectrum and cannot be used in applications such as EW receivers or jammers.

Feedforward linearization (FF), is the most effective and popular technique for improving the linearity of power amplifiers, due to its potential for excellent distortion suppression [3], it is commonly used in wideband amplifiers. The distortion generated in the main amplifier is extracted by canceling the linear signal from the output of the main amplifier. This distortion signal is amplified by an auxiliary amplifier and finally subtracted from the PA output. As this arrangement does not contain a feedback loop, it has no stability limitations, but still the bandwidth of the power combiners and phase shifters limits the cancellation bandwidth. Feedforward linearization has advantages in speed, stability due to its open-loop nature. Another advantage is the operating bandwidth; generally, it is used with very wide bandwidth multi-carrier applications [6]. Although a classical method, it seems to be the most suitable technique for our problem. We apply Feedforward linearization with some sort of real-time adaptation to solve the gain capture problem. A short comparison between common linearization techniques is present in Table 1.

Table 1: Comparison between different linearization techniques

	Feedback	**Feedforward**	**Predistortion**
Bandwidth	Narrow	Wide	Wide
Efficiency	Low	medium	High
Complexity	Low	High	Intermediate
Stability	There is stability problems	Unconditionally stable	Can overcome stability problems
Cost	Low	High	Intermediate

2- Simulation of Feedforward Linearization Technique

The proposed linearized amplifier system, shown in Figure 2**,** consists of a two-stage power amplifier, the first stage is a 20 dB linear amplifier (A_1), and the second stage is a nonlinear power amplifier (A_2) with a typical 8.5 dB gain, a feedforward linearization circuit, and a digital control circuit. The linearizer consists of two loops, the first is the *signal cancellation loop*, and the second is the *error cancellation loop*. In the signal cancellation loop, a portion of the power amplifier input is fed, through a10-dB directional coupler, to the reference path, where it is delayed to compensate for the PA group delay and then attenuated if necessary, to be subtracted from an attenuated sample of the PA output to suppress the original signal and get a pure *spurious signal*. This spurious signal is amplified and subtracted from the PA output to get a spur-free output.

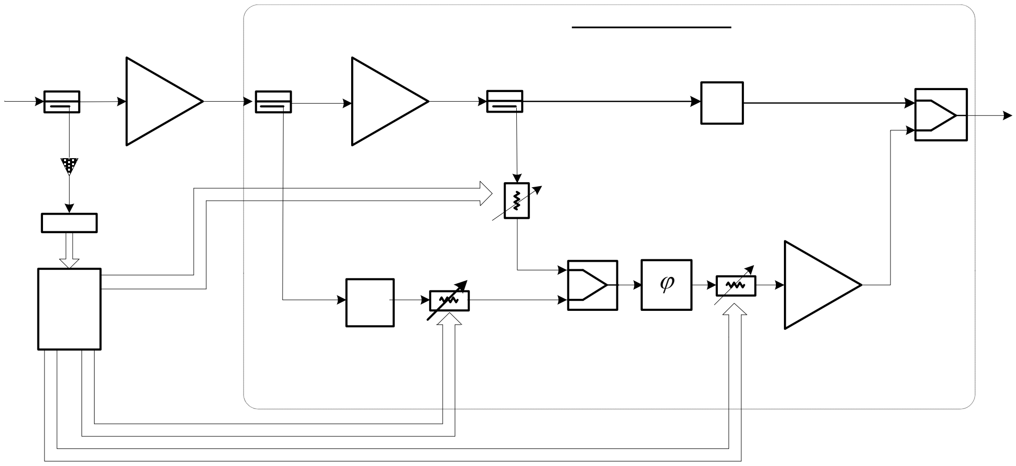

Figure 2: Adaptive Feedforward system block diagram

The function of the digital control circuit is to adjust the values of the set of attenuators for perfect cancellation performance at each power combiner, which in this case will work as a subtractor. For every different total input power level, each attenuator will require a specific value. We run a two-tone ADS simulation, with equal two-tone input to calculate the accurate attenuation values at each different level of the total input power. The attenuators were set in each case to obtain the maximum possible IM3 reduction. These attenuator settings were stored in a Look-up table (LUT). The power sensor at the input coupled port of the system, together with the

A/D converter, are responsible for choosing the required attenuation setting at each new value of the total input power. Again, we run the simulation at 1, 1.5 and 2 GHz to cover an octave frequency band, and the overall results were stored in three look-up tables, one for each frequency

3- Adaptive FF linearization as a gain capture correction technique

After adjusting the attenuation values for maximum IMD cancellation at a certain value of total input power, two different signals with the same power sum were applied to the system input, such that

$$10\log(P_S + P_L) = 10.\log P_{TT} + 3dB \qquad (7)$$

Where P_S, P_L and P_{TT} are the small, large and two-equal tone signals, respectively.

Simulation results showed that the linearization system was capable of completely correcting the gain capture effect for a certain total input power when the attenuators are set to cancel the two-equal tone spurs for the same total input power. At the output, both small and large signals get equal gains. Figures 2, 3 and 4 show the simulation results at 1, 1.5, and 2 GHz respectively.

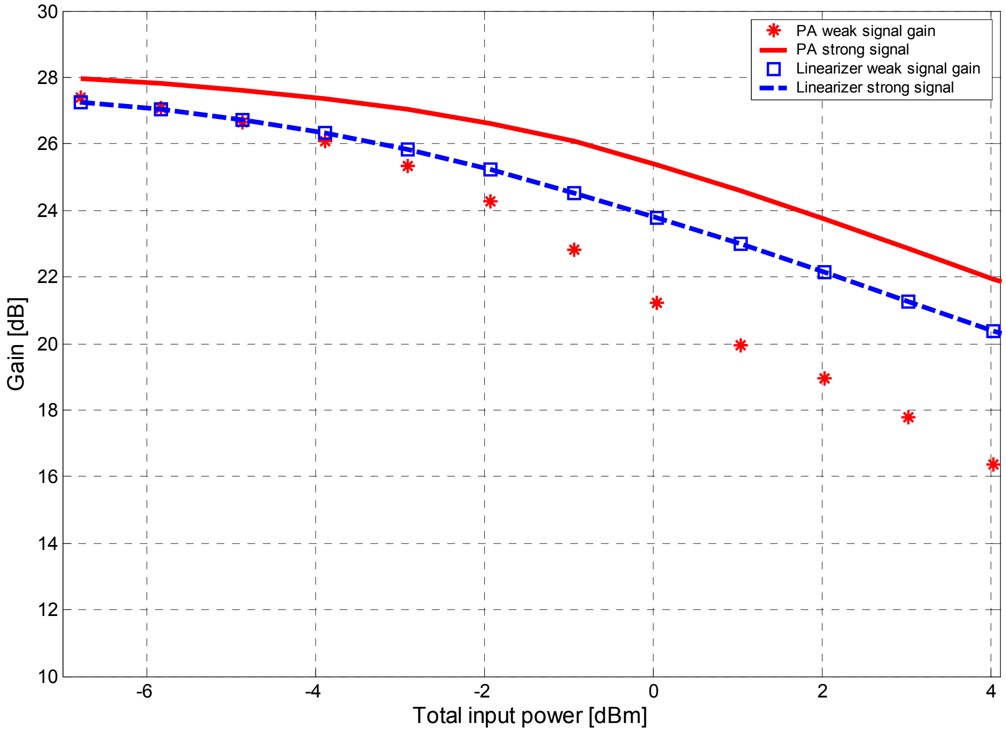

Figure 3: small and large signal gains before and after linearization at 1 GHz

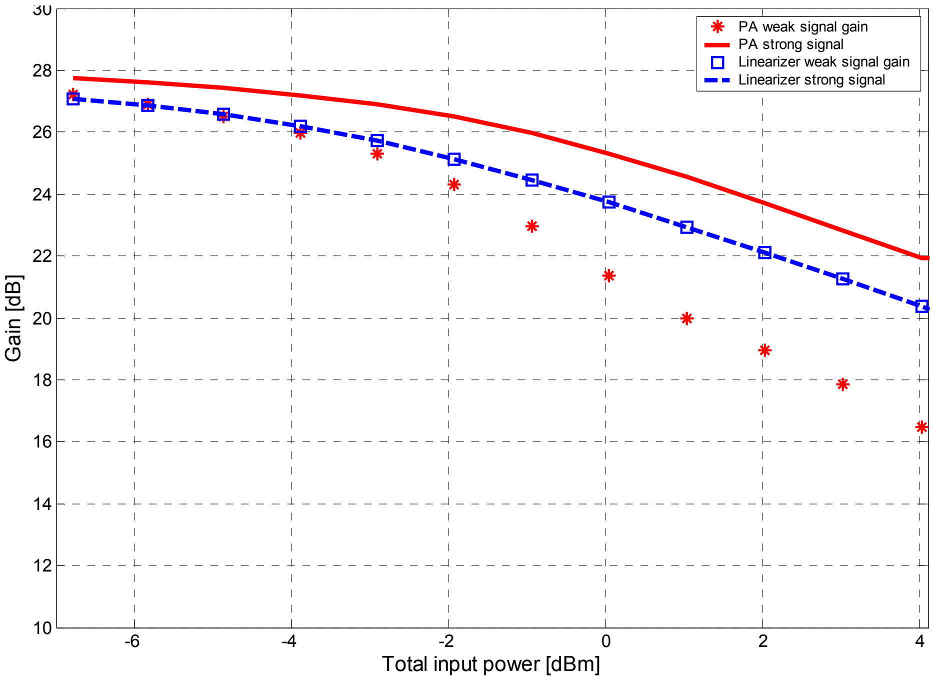

Figure 4: small and large signal gains before and after linearization at 1.5 GHz

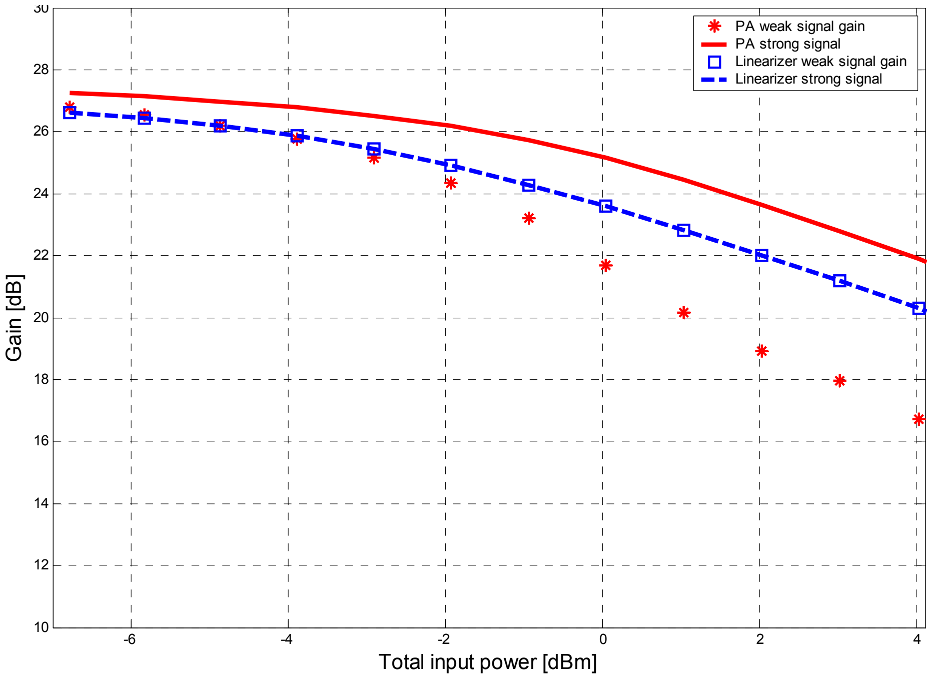

Figure 5: small and large signal gains before and after linearization at 2 GHz

4- System Adaptation on an octave frequency band.

Using a look-up table for each frequency requires a frequency measurement device to determine the signal frequency and select the suitable table. This is a complex design requirement. Moreover, in case of simultaneous input signals with different frequencies it becomes impossible. We tried to solve this problem and simplify the system adaptation by using only one look-up table with average values of attenuator setting covering the total frequency band.

Simulation results using the average attenuation settings, showed a maximum of 0.4 dB deviation in the system performance between using accurate and average attenuation settings. This deviation decrease as the input power level increases. Figures 6, 7 and 8 show the results for 1, 1.5, and 2 GHz.

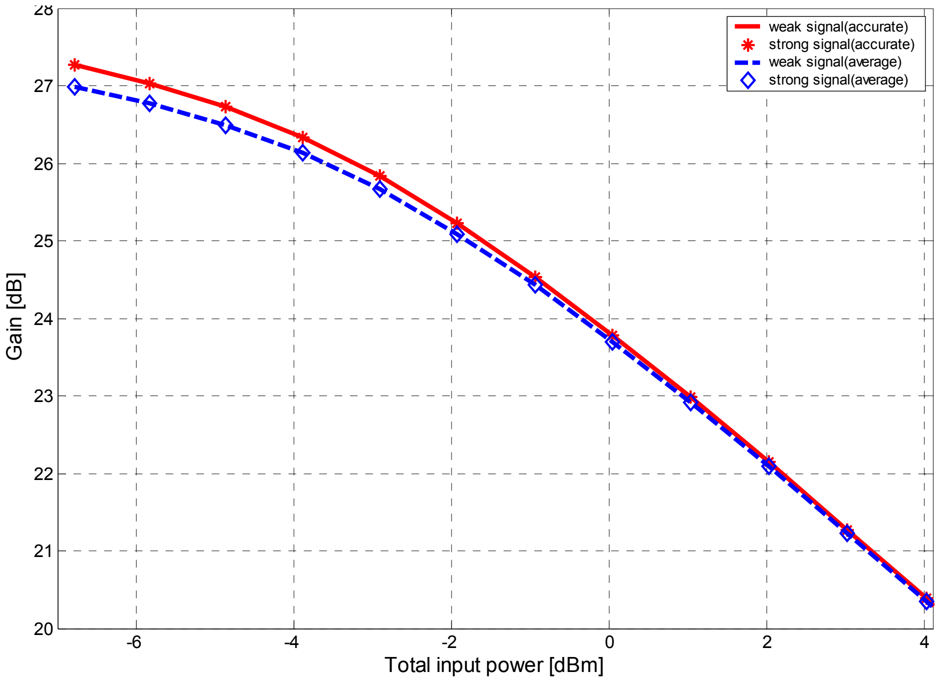

Figure 6: Comparison between the system correction at 1 GHz, using accurate and average attenuation settings

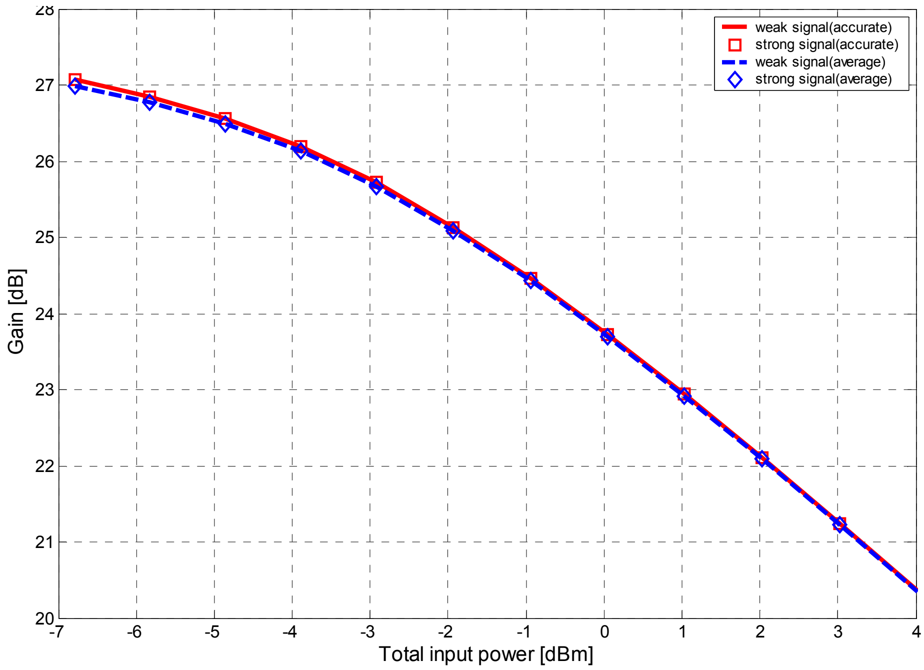

Figure 7: Comparison between the system correction at 1.5 GHz, using accurate and average attenuation settings

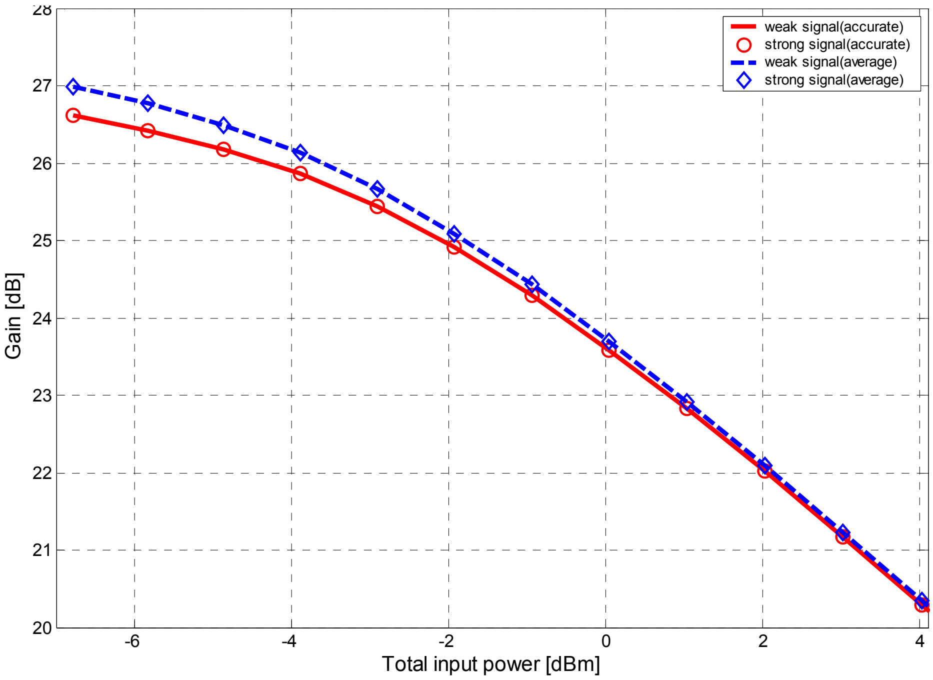

Figure 8: Comparison between the system correction at 2 GHz, using accurate and average attenuation settings

CONCLUSION

1. The concept of ***gain capture*** as a criterion for amplifier linearity evaluation is introduced.
2. It is possible to correct the gain capture effect at different levels of input signals using classical Feed-Forward linearization technique, by proper setting of system attenuators and delay lines.
3. The attenuation settings used to minimize IMD_3 in the equal two-tone model for a certain total input power can completely correct the gain capture effect for the same total input power.
4. It is possible to find a set of attenuator settings to correct the gain capture effect on a certain frequency band without the need to measure signal frequencies.

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