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# Linearity Improvement Techniques for Wireless Transmitters: Part 1

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This two-part article presents a wide range of techniques for amplifier linearization, along with historical notes to help us appreciate the creative work in their development

In modern telecommunication systems, it is very important to simultaneously achieve high efficiency and linear operation of the power amplifiers. There are several linearization techniques that provide linearization of both entire transmitter system and individual power amplifier. In this article, the major linearization schemes will be examined, with discussion of their various advantages and disadvantages.

*Feedforward*, *cross cancellation*, and *reflect forward* linearization techniques are available technologies for satellite and cellular base station applications, achieving very high linearity levels. The practical realization of these techniques is quite complicated and very sensitive to both the feedback loop imbalance and the parameters of its individual components.

*Analog predistortion* linearization technique is the simplest form of power amplifier linearization and can be used for handset application, although significant linearity improvement is difficult to realize. Different types of *feedback* linearization schemes, together with *digital predistortion* techniques, can potentially be used both in handset and base station applications. The choice of a linearity correction scheme depends on both performance tradeoffs and manufacturing capabilities.

## Feedforward Amplifier Architecture

In the middle of 1920s H. S. Black first proposed the method of suppressing even- and odd-order distortion components produced in nonlinear transmitting system [1]. However, interest in this invention was limited at that time due to success of the competing feedback approach (invented later by him), with its simplicity and effectiveness.

Almost three decades later, W. D. Lewis extended the feedforward approach to microwave frequencies by using waveguide sections for delay lines, branch-line hybrid junctions and directional couplers [2]. Since then, the interest in feedforward correction in RF and microwave applications has become significant to satisfy the simultaneous requirements of high output power, extremely high linearity, good long-term stability and broad bandwidths.

H. Seidel described in detail the application of a feedforward compensated circuit in which the amplified signal is compared with a time-shifted reference signal [3]. In this case, the error component, which includes both noise and distortion components introduced by the main amplifier, is then amplified by means of a high-quality linear subsidiary amplifier and added to the time-shifted amplified signal in such a phase as to minimize the error in the output signal. To minimize errors due to impedance mismatch in the amplifier circuit, hybrid-coupler power dividers can be used. At the same time, to minimize noise in the output signal due to the subsidiary amplifier, the portion of input signal coupled to the subsidiary amplifier must be larger than that coupled to the main amplifier. Most efficient utilization of the power in the amplified signal and the error signal can be realized by using a reactive three-port network to match the main signal path and the error signal path to the output load. As a part of a test to determine its applicability to coaxial repeaters, a feedfor-

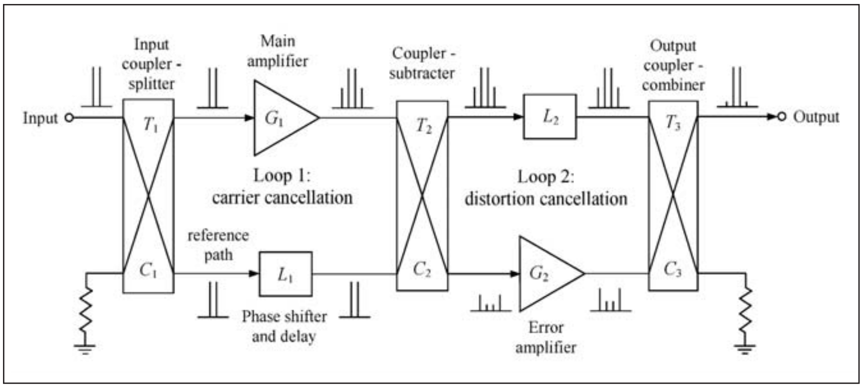


**Figure 1 · Basic structure and operation principle of feedforward amplifier linearization.**

ward error-controlled system was applied to a coaxial flat-gain amplifier operating in the frequency range of 0.5-20 MHz. As a result, a modulation product reduction of greater than 35 dB over a 40:1 bandwidth was achieved [4, 5]. The use of feedforward architecture could result in up to 20 dB distortion improvement in a feedback amplifier operating over the whole frequency decade 30-300 MHz [6]. In a practical 2.2 GHz feedforward amplifier system with a power gain of 30 dB and an output power of 1.25 W, the suppression of the intermodulation distortion products of at least 50 dB from the carrier level was achieved [7].

Figure 1 shows the basic structure and principle of operation of the feedforward amplifier. The linearization feedforward system consists of two cancellation loops and generally includes the main power amplifier, three couplers, two phase shifters and an auxiliary error amplifier. The operation of the feedforward linearization circuit is based on the subtraction of two equal signals with subsequent cancellation of the error signal in the amplifier output spectrum. Its operation principle can be seen clearly from the two-tone test spectra shown at various points in Fig. 1. The input signal is split by input coupler-splitter into two identical parts, although the ratio used in the splitting process does not need to be equal, with one part going to the main power amplifier while the other part goes to a delay element. The signal in the top path is amplified by the main amplifier whose inherent nonlinear behavior contributes to the intermodulation and harmonic distortion components that are added to the original signal. This signal is sampled and scaled by the coupler-subtracter before being combined with the delayed distortion-free portion of the input signal. The resulting error signal ideally contains only the distortion components provided by the main amplifier. The error signal is then amplified linearly by low-power high-linearity error amplifier to the level required to cancel the distortion in the main part, and is then fed to the output directional coupler-combiner, on the other input of which a time-delayed and out-of-phase main-path signal is forwarded. In an ideal case, the resulting signal at the feedforward linearization system output is an error-free signal, essentially an amplified version of the original input signal.

The operation quality of the feedforward amplifier system obviously depends significantly on cancellation accuracy at the coupler-subtracter and output coupler-combiner. The level of distortion reduction is determined by the cancellation occurring at the output coupler-combiner, while cancellation of the fundamental signals at coupler-subtracter is required to prevent subtraction of the fundamentals at the output coupler-combiner, and consequent gain loss. At the same time, cancellation of the fundamentals at the coupler-subtracter is also important in order to prevent large amplitude error signals from entering the error amplifier and possibly causing significant distortion. Generally, in the first carrier-cancellation loop, the precision in cancellation is required only to such a degree as to avoid any substantial degradation of linearity in the error amplifier [5]. On the other hand, since the second distortion-cancellation loop controls the entire linearity improvement of the feedforward system, the degree of its balance should always be at the highest level [7].

To analyze the effect of imperfect magnitude and phase equalization in the amplifier and delay line paths at any particular frequency, consider the signal in each upper and lower paths of the first cancellation loop to be cosinusoidal in the form of

$$v_1 = V\cos\omega t \tag{1}$$

$$v_2 = \left(V \pm \Delta V\right)\cos\left(\omega t \pm \theta\right) \tag{2}$$

where $\Delta V$ is the amplitude imbalance and $\theta$ is the phase imbalance.

After subtraction of these signals in a coupler-subtracter, we have in a normalized form

$$\begin{aligned} \frac{\Delta v}{V} &= \cos\omega t - \left(1 \pm \frac{\Delta v}{V}\right)\cos\left(\omega t \pm \theta\right) \\ &= \left(1 - \alpha\cos\theta\right)\cos\omega t \pm \alpha\sin\theta\sin\omega t \end{aligned} \tag{3}$$

where $\Delta v = v_1 - v_2$ and

$$\alpha = 1 \pm \frac{\Delta V}{V} \tag{4}$$

As a result, for a total imbalance magnitude,

$$\frac{|\Delta v|}{V} = \sqrt{(1-\alpha\cos\theta)^2 + (\alpha\sin\theta)^2} \tag{5}$$

Since cancellation achieved by the second loop can be analyzed ideally in a similar way, the cancellation result achieved by the first and second loops independently can be rewritten in the corresponding forms of

$$CANC_1 = 10\log_{10}\left(1+\alpha_1^2 - 2\alpha_1\cos\theta_1\right)\text{ dB} \tag{6}$$

$$CANC_2 = 10\log_{10}\left(1+\alpha_2^2 - 2\alpha_2\cos\theta_2\right)\text{ dB} \tag{7}$$

where $\alpha_1$ and $\theta_1$ are the amplitude and phase imbalance in the first loop, and $\alpha_2$ and $\theta_2$ are the amplitude and phase imbalance in the second loop, respectively [8].

Figure 2 shows the distortion cancellation as a function of amplitude and phase imbalance. From these curves it follows that, to obtain a high degree of cancellation, it is necessary to maintain an extremely small degree of amplitude imbalance. For example, 40 dB of cancellation would require a phase imbalance of less than 1° and an amplitude imbalance of less than 0.1 dB. However, a demand for a high degree of linearity improvement will cause the system to become sensitive to circuit parameter variations due to temperature change. To achieve temperature stability in a practical system, the degree of linearity improvement should be kept at a reasonably low level. For example, a 30 dB of cancellation would require only an amplitude imbalance of 0.25 dB and a phase imbalance of 1.8°. To improve the temperature stability characteristic, it is better to realize both main and error amplifiers using the same technology, similar components and assembly techniques. However, if a higher degree of balance is to be maintained at all times, an automatic adaptive control system must be employed. Besides, an additional transmission-line delay mismatch can be taken into account when using transmission lines in high-frequency feedforward linearization systems. For example, if the difference in wavelength between the transmission lines in upper and lower paths at the centre bandwidth frequency $f_0$ is equal to $0.1\,f_0$, then, in order to obtain a 30 dB of cancellation with 30 MHz bandwidth at 800 MHz for $\alpha$ = 0.1 dB, the phase imbalance should be maintained within approximately 1.0° [9].

It is important for a telecommunication system to minimize its nonlinear distortion level, and the main indicator of its linearity is the level of the third-order intermodulation products at the system output. In this case, consider the cancellation provided by both the first and second loops through the parameters of the feedforward system [10]. At the output of the coupler-subtracter with suppressed carrier $P_{\text{supp}}$, the cancellation of the first loop is defined as

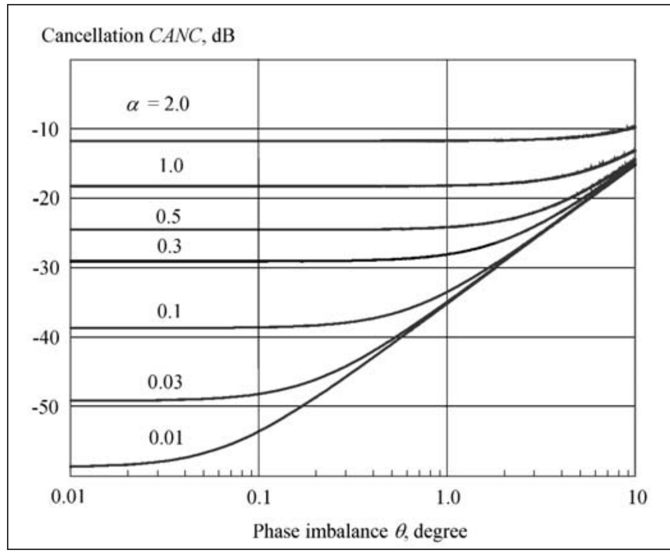


**Figure 2 · Cancellation as function of amplitude and phase imbalance.**

$$CANC_1 = \frac{P_{\text{supp}}}{C_2 P_{\text{main}}} \tag{8}$$

where $C_2$ is the coupling coefficient of the second coupler-subtracter and $P_{\text{main}}$ is the carrier power level of the main amplifier. On the other hand, the cancellation achieved in the second loop is

$$CANC_2 = \frac{P_{\text{IM3supp}}}{P_{\text{IM3main}}}\frac{1}{T_2 L_2 T_3} \tag{9}$$

where $P_{IM3\text{main}}$ is the power level of the third-order intermodulation component, $P_{IM3\text{supp}}$ is the power level of the third-order intermodulation component of the main amplifier suppressed at the linearizer output due to the corrective action of the second loop, $L_2$ is the delay-line loss in the second loop, $T_2$ and $T_3$ are the transmission losses in the coupler-subtracter and output coupler-combiner, respectively.

The effective cancellation of the overall feedforward linearization system is the ratio of the power level of all intermodulation components at the feedforward system output over the power level of the intermodulation products for open-loop configuration. As a result, for in-phase addition of the intermodulation components of the main and error amplifiers, the effective cancellation can be expressed by

$$CANC_{eff} = 20\log_{10}\left[\sqrt{CANC_2} + \sqrt{CANC_1^{\,3}\left(\frac{IP_{3\text{main}}}{IP_{3\text{error}}}\right)^2 \frac{T_2^2 L_2^2}{\alpha_2^3}\left(\frac{T_3}{C_3}\right)^2}\,\right]\text{ dB} \tag{10}$$

where the amplitude imbalance $\alpha_2$ is defined as the ratio of the power gains of the two paths

$$\alpha_2 = \frac{T_2 L_2 T_3}{C_2 G_2 C_3} \tag{11}$$

where $G_2$ is the power gain of the error amplifier, $C_3$ is the coupling coefficient of the output coupler-combiner, $IP_{3main}$ and $IP_{3error}$ are the third-order intercept points of the main and error amplifiers, respectively. The first term in Eq. (10) depends on the balance level achieved in the second loop, whereas the second term defines the possible imbalance created by the first loop and some other feedforward circuit parameters. In particular, an error amplifier with sufficiently low power capabilities having too small value of $IP_{3error}$ or too big coupling coefficient $C_3$ of the output coupler-combiner, and loss ($T_2L_2T_3$) through the main path increases the effect of the amplitude and phase imbalance.

The relationship between the overall feedforward system efficiency $\eta$ and the efficiencies of the two amplifiers, $\eta_{main}$ for main amplifier and $\eta_{error}$ for error amplifier, when the losses ($T_2L_2T_3$) through the main path are considered negligible, can be written as

$$\eta = \frac{\eta_{main}\eta_{error}C_3\left(1 - C_3\right)}{\eta_{error}C_3 + \eta_{main} f_{main}\left(1 - C_3\right)} \tag{12}$$

where $\log_{10} f_{main} = -\,(C/I)_{main}/10$, $(C/I)_{main}$ is the ratio of carrier to third-order intermodulation product of the main amplifier [11, 12]. Provided the optimum value of $C_3$, which maximizes the overall efficiency $\eta$ when the other system parameters are fixed, the maximum $\eta_{max}$ can be obtained by

$$\eta_{max} = \eta_{main} \Bigg/ \left(1 + \sqrt{\frac{\eta_{main}}{\eta_{error}} f_{main}}\right)^2 \tag{13}$$

which shows the efficiency degradation due to the linearization system [13]. For example, with a typical 10 dB coupling ratio of the output coupler-combiner, only 10 percent of the power from the error amplifier reaches the load, which means that the error amplifier must produce ten times the power of the distortion products in the main amplifier. In this case, it should operate in an inefficient linear mode in order not to disturb the error signal. As a result, the DC power consumed by the error amplifier can represent a significant part of that of the main amplifier. We need to take into account the fact that, despite its excellent distortion cancellation property, the feedforward amplifier system requires well-equalized circuitry and is generally characterized by substantially increased complexity and cost.

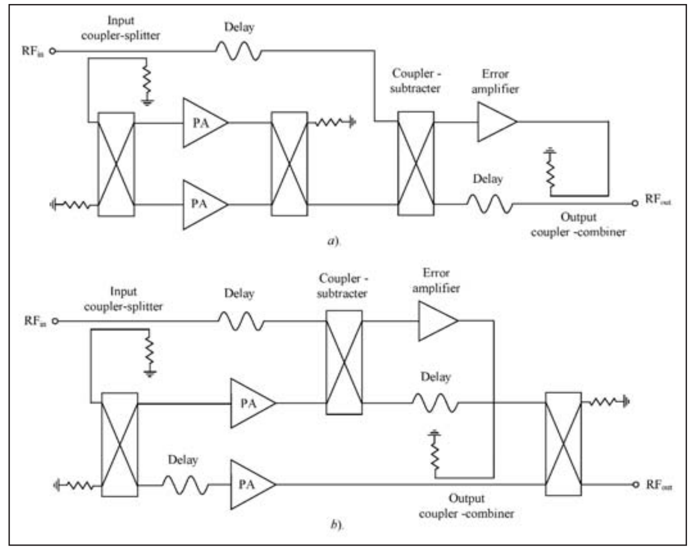


**Figure 3 · Balanced feedforward amplifier topologies.**

The efficiency of the conventional feedforward linearization system using a balanced configuration in the main amplifier shown in Figure 3(a) can be improved by providing some restructuring of the system. As a result, the modified feedforward system consists of three major loops shown in Figure 3(b): carrier cancellation loop, balanced power amplifier loop and error-injection loop [14]. In this case, the carrier cancellation loop extracts the error signal from the amplified signal at the output of the top power amplifier, whereas the error-injection loop provides an injection of the amplitude-adjusted and properly phased distortion into the output of the bottom power amplifier. Finally, the amplified signals in balanced paths are combined in the output hybrid combiner with corresponding distortion cancellation. Unlike the conventional feedforward system, in its balanced version each power amplifier sees only one coupler, either coupler-subtracter or output coupler-combiner, which means that there is no additional insertion loss due to output coupler-combiner as in the conventional feedforward system. As a result, for a four-carrier WCDMA signal with peak-to-average ratio of 10 dB, there is an efficiency improvement of 2% at an average output power of 40 dBm, with an improvement in *ACLR* (5 MHz offset) of about 18.6 dB by cancellation at the center bandwidth frequency of 2.14 GHz.

However, it is a serious problem for the conventional feedforward linearization system to maintain the necessary accuracy in amplitude and phase balance over time, temperature, supply voltage, or input source and load variations. In practice, some form of gain and phase adjustment are essential to achieve acceptably low level of intermodulation distortion. Figure 4(a) shows a block schematic of the analog adaptive feedforward linearization system which includes a feedback network for adap-

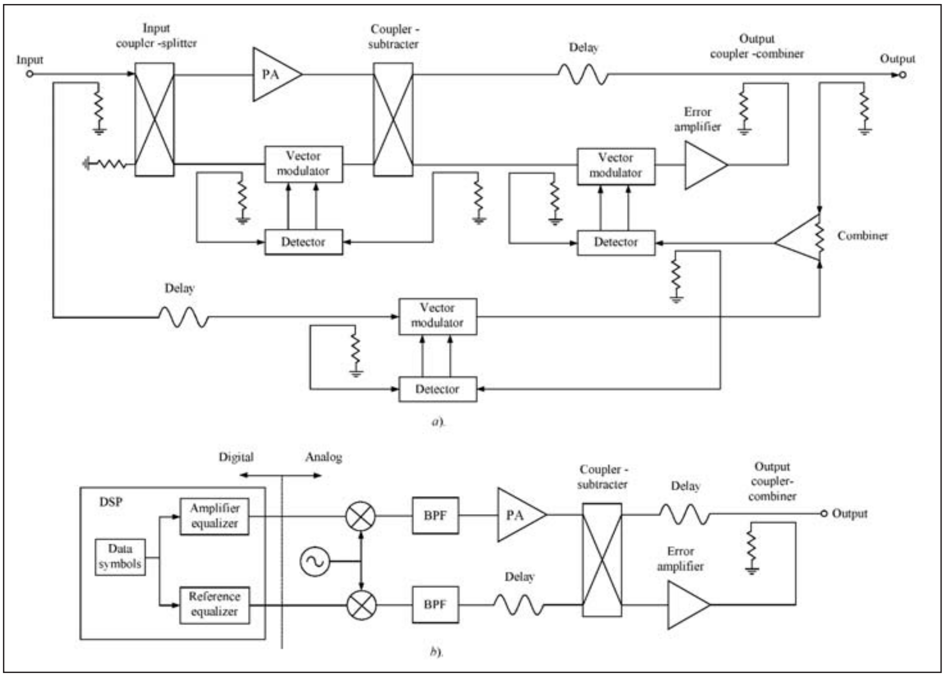


Figure 4 · Adaptive analog and digital feedforward amplifier linearizers.

tively adjusting the performance of the overall feedforward system to compensate for uncontrolled variations of its component parameters [15]. The feedback network provides a control of the carrier and distortion cancellation loops by comparing the signals sampled at their inputs and outputs and adaptively adjusts the corresponding vector modulators to minimize the amplitude and phase imbalance when it is necessary. Different adaptation algorithms using optimization techniques can be implemented to improve the cancellation results for an analog adaptive feedforward linearization system [16].

Digital signal processing (DSP) creates a good opportunity to provide a baseband level correction in the amplitude and phase imbalance in the feedforward linearization system, thus making this procedure more predictable and faster, while overcoming problems with mixer DC offset and masking of strong signals by weaker ones that can compromise analog adaptive implementations [17]. To compensate for the component frequency response and the non-adaptive nature of the delay lines, a hybrid of the conventional feedforward linearizer and a digital signal processor can be used, as shown in Figure 4(b), where both the amplifier input signal and the reference signal are generated by DSP [18]. The reference signal is then used to cancel the linearly amplified component of the distorted amplifier output signals, leaving an error signal containing only the main amplifier distortion. By generating the reference signal in the DSP, rather than using an analog splitter, some of the analog hardware can be moved into a simpler digital implementation, with independent control of the main amplifier and reference signals by using equalizers. In this case, the amplitude and reference equalizers correct the phase shift, time delay and non-ideal response of the analog components to achieve the proper distortion cancellation. By improving the cancellation of the first loop, a more accurate error signal is generated that consists only of the distortion from the main amplifier. Generally, the use of amplifier and reference equalizers in the first loop has an advantage in that the tuning, previously done manually, has now been moved back into the DSP where it can be done adaptively.

## Cross Cancellation Technique

An alternative approach was proposed in the middle 1930s which provides higher efficiency: Distortion in nonlinear power amplifiers can be eliminated by using an auxiliary amplifier in which a fraction of the main-amplifier input signal, combined with a fraction of the distorted main-amplifier output signal, produces a correcting component which, combined with the total output, restores this to the same shape as the input [19, 20]. The approach is now known as the cross cancellation technique which combines the high efficiency of a parallel or balanced power amplifier with the capabilities of the predistortion linearizers.

The basic cross cancellation scheme shown in Figure 5(a) includes the two identical power amplifiers connect-

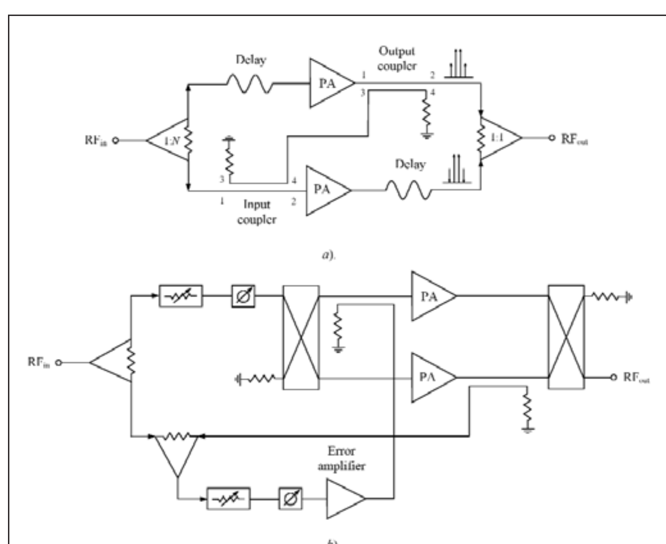


Figure 5 · Cross cancellation linearizer diagrams.

ed in parallel configuration under equal input drive conditions. Balancing the signal levels in both amplifying paths is only possible by employing an input divider with unequal division ratio, with greater power going to the lower amplifying path, where the sampled output signalfrom the upper amplifying path's output directional coupler is delivered through the input directional coupler with proper coupling coefficient. To equalize the signal phases in both amplifying paths, phase delay elements are included in the input and output circuits of the corresponding signal paths. As a result, the lower power amplifier is operated as a predistorted power amplifier with the predistortion signal created by the upper power amplifier. In this case, distortion neutralization is obtained by the injection of the distortion components to the lower amplifying path in such a manner that they will be 180 degree out of phase with those being created by the upper power amplifier at the input of the output combiner.

To derive some analytical relationships between parameters of the cross cancellation linearization system shown in Fig. 5(a), consider an idealized approach where the system parameters are normalized to the input power and power ratio of the input unequal divider is equal to 1:$N$. Then, the output powers of lower and upper amplifying paths at the corresponding inputs of the output combiner can be written as

$$\begin{aligned} &G_P(1-C_{31})+IM \\ &=\left[N(1-C_{31})-(G_P+IM)C_{31}^2\right]G_P+IM \\ &=\left[N(1-C_{31})-G_PC_{31}^2\right]G_P+\left(1-G_PC_{31}^2\right)IM \end{aligned} \tag{14}$$

where $G_P$ is the operating power gain of each power amplifier (PA), *IM* is the intermodulation distortion introduced by each PA, and $C_{31}$ is the coupling factor of each directional coupler is calculated as the ratio of power at the output port 3 relative to the input port 1, equal to the coupling factor $C_{24}$ of the input directional coupler when its port 4 becomes an input port. From a comparison between the left- and right-hand sides of Eq. (14) it follows that the out-of-phase conditions for intermodulation components at the corresponding inputs of the output inphase combiner can be obtained when

$$G_PC_{31}^2 = 2 \tag{15}$$

resulting in

$$N = \frac{3-C_{31}}{1-C_{31}} \tag{16}$$

As an example, if the power gain of each PA is $G_P$ = 200 or 23 dB, then from Eq. (15) it follows that it is necessary to choose the input and output directional couplers with coupling factor $C_{31}$ = 0.1 or –10 dB and the input power divider with $N$ = 3.2 (about 5 dB) resulting then from Eq. (16). In this case, the power gain of the overall system reduces to 19.5 dB. However, it was found that the linearity improvement is not as high as in a feedforward linearizer where the distortions are subtracted at its output. This is because the amplifying paths are not really identical. To make the cross cancellation system more symmetrical, it is necessary to equalize the insertion losses in the output circuits of both amplifying paths by introducing a required attenuation in a lower path which in turn results in reduced system efficiency. Generally, in practical applications, with varying input drive levels and temperature, it is necessary to use phase shifters and variable attenuators that are controlled by a power-minimization loop controller, which serves to minimize the distortion components in a composite output signal [21].

Figure 5(b) show the cross cancellation technique based on a balanced power amplifier configuration where the distortion generated in one balanced path, which is identical to the other path, are used to cancel the distortions generated by the whole balanced power amplifier [22]. This approach provides a control of the error signal separately, as in the feedforward technique. However, the main difference between these two techniques is that the error signal is added to the input of the amplifying path, not to the output, thus improving the system efficiency. In this case, samples of the signal and distortion from lower amplifying path are combined with a portion of the reference signal delivered from the input splitter such that the linear components of these two signals are cancel each other leaving the distortion components only from the sampled path of the balanced power amplifier. The gain and phase of the distortion are then adjusted using a variable attenuator, phase shifter and linear error amplifier so that, when it is coupled into the input of the other path of the balanced power amplifier, the distortions generated by both paths of the balanced power amplifier are cancelled.

*This article will be continued in the next issue. Topics include reflect-forward linearization, predistortion techniques, and feedback methods. The complete list of references will follow the final part of the article.*

## Author Information

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