Adaptive Nulling Loop Control for 1.7-GHz Feedforward Linearization Systems

Eid E. Eid and Fadhel M. Ghannouchi, *Senior Member, IEEE*

***Abstract*—An adaptive analog control system is introduced for the nulling loop (first loop) of a 1.7-GHz feedforward linearization system. The sensitivity to temperature and frequency variations is experimentally shown for a conventional feedforward system, leading to the need for an adaptive control system. Two error signals based on detected power levels are introduced and used to control the nulling loop vector modulator to ensure cancellation of the main signal. Finally, the experimental performance of this system is presented.**

I. NTRODUCTION

MORE and more emphasis is being put on amplifier linearity in communication systems today with the use of new modulation patterns such as multilevel quadrature amplitude modulation (QAM) or code division multiple access (CDMA), etc. These modulation patterns require good amplifier linearity over a certain dynamic range, frequency bandwidth, or temperature range. Furthermore, even modulation patterns such as quadrature phase-shift keying (QPSK), which are relatively insensitive to nonlinearities in terms of bit error rate, can still have their occupied spectrum deteriorated by nonlinear amplifiers.

Although feedforward [1] is one of the most effective linearization methods, as it can ensure carrier-to-intermodulation ratios (C/I) of 40–60 dBc, it is very sensitive to variations such as temperature changes, channel frequency variations, or input power level changes. It is then necessary to provide the feedforward system with an appropriate control circuit to guarantee constant C/I performances despite these variations.

This paper presents an adaptive control for the nulling loop (first loop) of a feedforward system. This control is briefly described, an experimental implementation is shown, and results showing performance enhancement of the controlled system versus the open-loop system are presented.

II. THE FEEDFORWARD LINEARIZATION SYSTEM

A typical feedforward system is shown in Fig. 1. It consists of two cancellation loops; the first loop is the main signal nulling loop, and it is adjusted to provide exact out-of-phase cancellation of the main signal at the output of the nulling combiner. This leaves only the intermodulation products introduced by the main amplifier. This error signal then enters the error loop (second loop) where it is amplified, phase-shifted, and reinjected out-of-phase to cancel with the intermodulation products in the main signal path. The output signal is, hence, free of the unwanted intermodulation products. This results in an improvement of the C/I of the main amplifier.

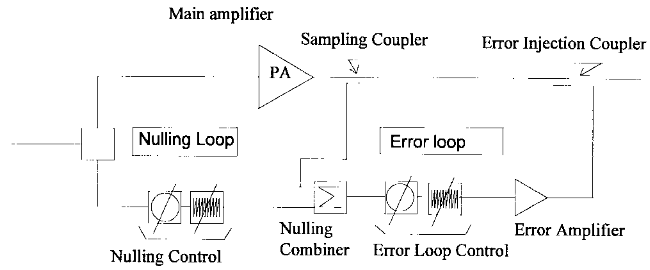

Fig. 1. A typical feedforward linearization system.

Our experimental setup was built in microwave integrated circuit (MIC) technology, at 1.7 GHz, and is designed to produce a 20-dB enhancement of the main amplifier C/I. The amplitude and phase controls in each of the two loops were implemented by one-quadrant vector modulators consisting of two controllable attenuators in quadrature. This setup is capable of producing up to 20-dB attenuation and $\pm 40°$ phase shift on the signal so as to ensure perfect out-of-phase cancellation. Under a two-tone test, the whole system was able to bring a Class A main amplifier C/I from 24 to 56 dBc, thus, producing a 32-dB enhancement of the C/I.

Figs. 2 and 3 show that even if feedforward systems have excellent performance for the conditions they were adjusted in, this performance tends to deteriorate sharply as operating conditions, notably the base plate temperature or the channel frequency change. This shows the need for an adaptive control system that guarantees that the vector modulators in either loop can follow these variations in order to maintain perfect cancellation [2].

On the other hand, performance degradation is an immediate consequence of the imperfect out-of-phase cancellation at each of the two loops' outputs. So, whatever the nature of the perturbation that affects the circuit, it always leads to an imperfect cancellation, and this is what deteriorates the circuit performance. Hence, an adequate control system would be one that detects an imperfect cancellation and acts on the vector modulators to correct this situation. Such a control system would be independent of the nature of the perturbation that affected the circuit. In the following section we present such an adaptive control for the nulling loop.

Manuscript received March 18, 1996; revised September 23, 1996. This work was supported by the Synergie Program.

The authors are with the Ampli Project, Poly-Grames Research Center, Electrical and Computer Engineering Department, Ecole Polytechnique de Montreal, Montreal, P. Q., H3C 3A7, Canada.

Publisher Item Identifier S 0018-9480(97)00269-X.

0018–9480/97$10.00 © 1997 IEEE

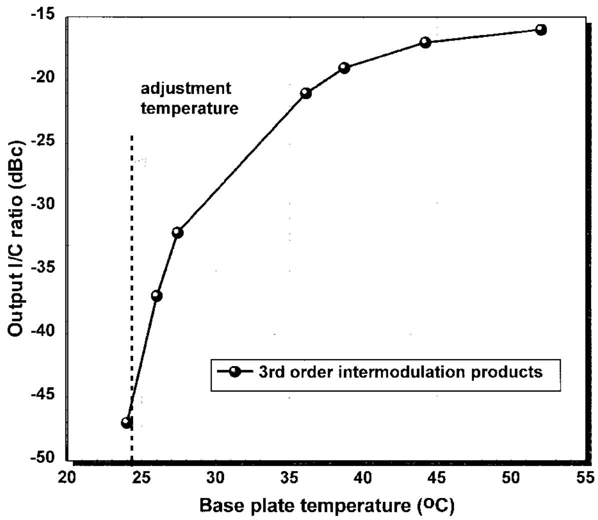

Fig. 2. Output I/C versus temperature variations.

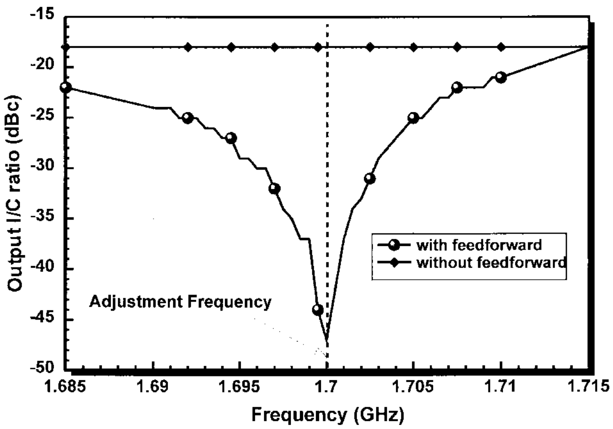

Fig. 3. Output I/C versus frequency drifts.

III. Adaptive Control for the Nulling Loop (First Loop)

Fig. 4 shows a detailed view of the nulling combiner, with the signal spectrum at each of the ports. The combiner consists of a branch-line hybrid combiner followed by a Wilkinson-type in-phase combiner. With such a configuration, if the signal at port 2 has exactly 180° phase shift with respect to the signal at port 1, only the intermodulations remain at port 4, with 3-dB attenuation. If the cancellation is perfect, total RF power at port 1 must be equal to the sum of the RF power levels at ports 2 and 4 (the latter being corrected for the 3-dB attenuation). This condition, if not satisfied, gives an error signal that can be used to control the system. A detailed explanation follows.

If we denote by P_i the power level (in watts) at port i, the error signal mentioned above then has the following expression:

$$\alpha = P_1 - (P_2 + 2P_4). \tag{1}$$

Let A denote the main signal amplitude at port 1 at a given instant (we can assume a null phase without loss of generality). Also, let B denote the amplitude of the intermodulation products at port 1 at the same instant. At port 2, we have a signal whose amplitude is $A_2 = (A + \delta A)$ and whose phase is $(\pi + \delta\phi)$, where δA and $\delta\phi$ represent the amplitude and phase errors that affect the cancellation [see Fig. 5(a)]. At port 4, we have the intermodulation products whose amplitude is $B_4 = B/\sqrt{2}$ and the main signal components whose amplitude is $A_4 = A^*/\sqrt{2}$, where A^* is the amplitude of the geometric sum of the main components at ports 1 and 2. The $\sqrt{2}$ factors account for the 3-dB attenuation mentioned above. We have, by application of a simple geometric relationship

$$A^{*2} = A^2 + (A + \delta A)^2 - 2A(A + \delta A)\cos\delta\phi. \tag{2}$$

The power levels at each port can be written as follows:

$$\begin{aligned} P_1 &= 2\left(\frac{A^2}{2} + \frac{B^2}{2}\right) = A^2 + B^2 \\ P_2 &= 2\frac{(A+\delta A)^2}{2} = (A + \delta A)^2 \\ P_4 &= 2\left(\frac{A_4^2 + B_4^2}{2}\right) = \left(\frac{A^*}{\sqrt{2}}\right)^2 + \left(\frac{B}{\sqrt{2}}\right)^2 \\ &= \frac{1}{2}(A^{*2} + B^2) \end{aligned}$$

where α becomes equal to

$$\alpha = -2(A + \delta A)[A(1 - \cos\delta\phi) + \delta A]. \tag{3}$$

It can be clearly seen that this quantity equals zero if the errors are null. Furthermore, if we consider that the errors are small enough, some approximations $(\delta A \ll A, \ \cos\delta\phi \approx 1)$ can be made, which lead to

$$\alpha \cong -2A\,\delta A. \tag{4}$$

This signal thus gives an indication of the amplitude error. The control circuit must bring the value of α to zero, which happens when $\delta A = 0$, i.e., when the amplitudes are perfectly matched.

However, the vector modulator consists of two controllable attenuators in quadrature and needs two control signals. Since the signal α does not give any significant indication on the phase error (the factor with $\cos\delta\phi$ is neglected and does not reflect the sign of the phase error), it is necessary to introduce a branch-line combiner to generate the second error signal. The latter is denoted by β and has the following expression:

$$\beta = P_1 + P_2 - 2P_3. \tag{5}$$

The signal at port 3 consists of main signal components whose amplitude is A_3 and intermodulation products whose amplitude is $B_3 = B/\sqrt{2}$. An expression for A_3 can be deduced similarly to that of A_4 by replacing $\cos\delta\phi$ with $-\sin\delta\phi$. It is obtained by $A_3 = A'/\sqrt{2}$, where A' is the amplitude of the sum of two vectors at port 3, and the relative geometric relationship is shown in Fig. 5(b)

$$A'^2 = A^2 + (A + \delta A)^2 - 2A(A + \delta A)\cos\left(\frac{\pi}{2} + \delta\phi\right). \tag{6}$$

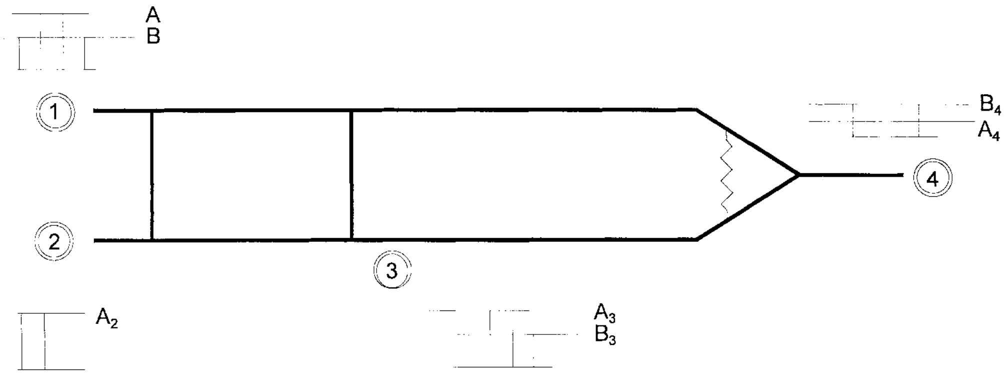

Fig. 4. Nulling combiner.

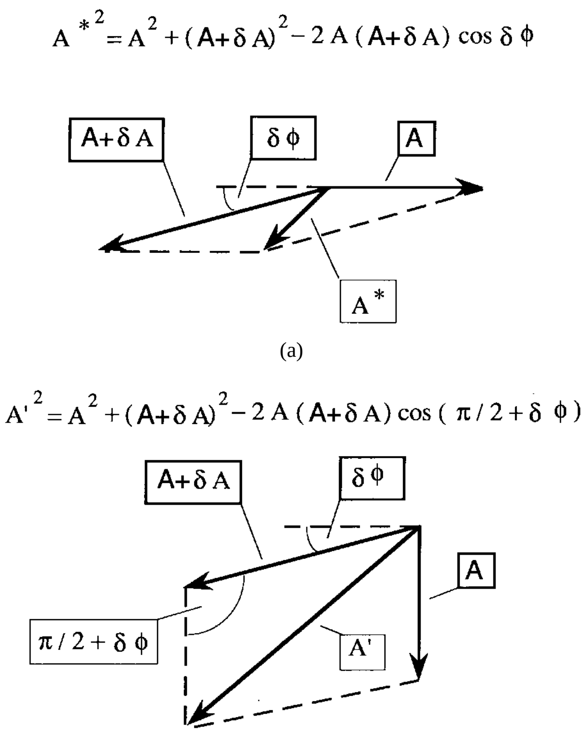

Fig. 5. Geometric sum of two out-of-phase vectors.

Hence

$$P_3 = \frac{1}{2}(A^2 + (A + \delta A)^2 + 2A(A + \delta A)\sin\delta\phi + B^2).$$

The expression for β then becomes

$$\beta = -2A(A + \delta A)\sin\delta\phi \tag{7}$$

and with the approximations $\delta A \ll A$ and $\sin\delta\phi \cong \phi$

$$\beta \cong -2A^2\delta\phi. \tag{8}$$

This quantity must be brought to zero by the control circuit, and in this case, $\delta\phi = 0$ and the phase shifts are perfectly matched independently of the signal level A.

The two error signals shown here, α and β, are linear combinations of power levels at various points in the circuit. The power levels are detected with diode detectors sufficiently attenuated to operate them in the square law region, where a linear combination of radio frequency (RF) power levels can be represented by a linear combination of dc voltages. Using approximately identical detectors, one can write that the voltages V_α and V_β associated with α and β are, respectively,

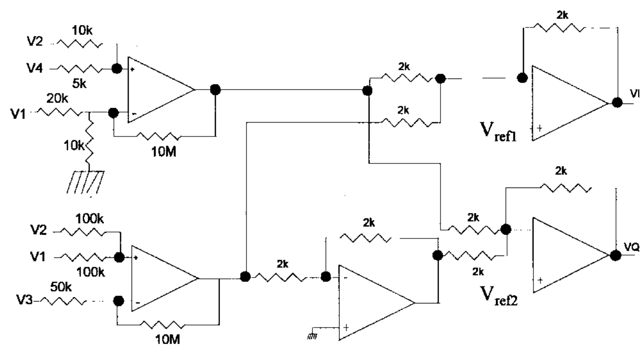

Fig. 6. Adaptive control circuit.

$$V_\alpha = V_1 - V_2 - 2V_4 \cong K\alpha \tag{9}$$

$$V_\beta = V_1 + V_2 - 2V_3 \cong K\beta \tag{10}$$

where K is a scalar function of the characteristics of the diode detectors that monitor P_1, P_2, P_4, or P_3.

These linear voltage combinations can be generated by classical op amp summing circuits as shown in Fig. 6. The output voltages of the first two op amp are $-C_1V_\alpha$ and C_2V_β, respectively, where coefficients C_1 and C_2 depend on the resistors of the operational amplifiers.

Finally, the vector modulators are controlled in rectangular mode (I, Q) while the error signals generated are polar (A, ϕ). Knowing that δA and $\delta\phi$ are small values and the system is in closed loop, it is possible to determine the perturbation control voltages δV_I and δV_Q of the vector modulator along I and Q axes by the difference and summation of α and β with weighting factors:

$$\delta V_I = M\alpha - N\beta \tag{11}$$

$$\delta V_Q = M\alpha + N\beta. \tag{12}$$

Different factors M and N are necessary, since α and β have different proportionality factors relative to δA and $\delta\phi$, as shown in (4) and (8). The operational amplifier summing circuits given in Fig. 6 are designed to implement the above

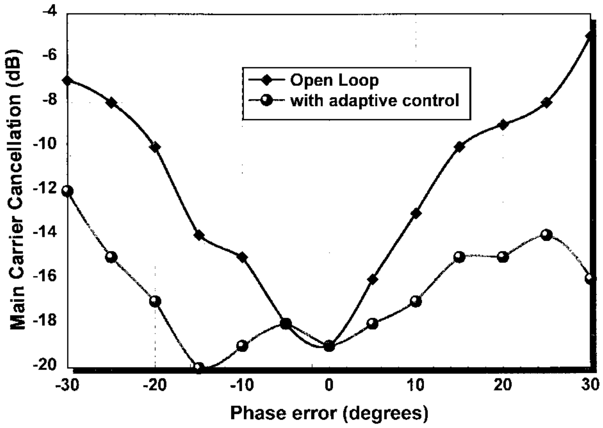

Fig. 7. Correction of phase errors.

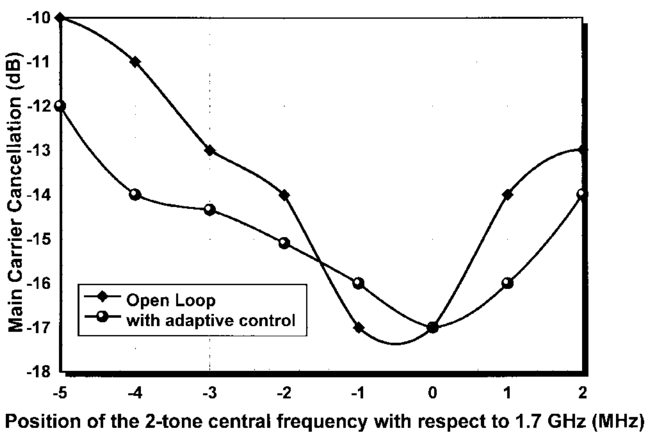

Fig. 8. Corrections during slight frequency drifts.

relations at its final output ports, with $M = C_1K$ and $N = C_2K$.

This analog control circuit is used to control the nulling loop vector modulator. It is worth noticing that this control system nulls the carriers to zero at port 4. This approach is different from the method of simply tracking the minimum power reading at this port. The latter method simply brings the carriers slightly lower than the intermodulation products level. Hence, an advantage of our method is that it brings the error signals α and β to zero rather than simply finding a minimum with an unknown value.

IV. Experimental Results

The nulling loop adaptive control system performance is illustrated by its action on the quality of the main signal cancellation at the output of the nulling combiner. In the adjustment position, for given working conditions, both the open-loop system and the controlled systems are tuned in order to have the best signal cancellation. Then different perturbations are applied to the circuit, and the signal cancellation is measured for the two systems. Figs. 7 and 8 show that the controlled system is capable of maintaining a better signal cancellation than the open-loop system.

V. Conclusion

An adaptive nulling loop control for a 1.7-GHz feedforward system has been presented in this paper. After a brief discussion of the RF feedforward system, the need for an adaptive control has been discussed and experimentally illustrated. Then, two error signals useful for controlling the nulling loop were introduced. The use of these signals maintains the signal cancellation quality over a wider range of values than the open-loop system, as shown in the experimental results presented.

Acknowledgment

The authors would like to thank A. Rich and G. Zhao for their valuable assistance in the completion of this work, as well as J. Gauthier and M. Bouchard for technical support.

References

[1] S. Kumar, "Power amplifier linearization using MMIC's," *Microwave J.*, pp. 96–104, Apr. 1992.

[2] A. K. Talwar, "Reduction of noise and distortion in amplifiers using adaptive cancellation," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 1086–1087, June 1994.

Eid E. Eid received the B.Eng. degree in electrical engineering from École Polytechnique de Montreal, in 1993. He then joined the Microwave Research Laboratory of École Polytechnique de Montréal for the M.Sc.A. studies, which he completed in August 1995.

He is a Registered Junior Engineer in P.Q., Canada. His research interests are in power amplifier linearization techniques as well as in six-port reflectometers measurements.

Fadhel M. Ghannouchi (S'84–M'88–SM'93) received the DEUS degree in physics/chemistry in 1980 from the University of Tunis, Tunis, Tunisia. He received the B.Eng. degree in engineering physics in 1983 and the M.Eng. and Ph.D. degrees in electrical engineering in 1984 and 1987, respectively, from École Polytechnique de Montréal, Montréal, P.Q., Canada.

He is currently an Associate Professor with the Electrical Engineering Department at École Polytechnique de Montréal where he has been teaching electromagnetics and microwave theory and techniques since 1984. He also acted as an Invited Professor at several universities in Europe. His research interests are in microwave/millimeter-wave instrumentation and measurements. He extended the six-port techniques from standard S-parameter measurements to multiharmonic load–pull and pulse measurements of microwave-active devices and to the control and calibration of phased-array antennas. His other research interests are in the area of nonlinear characterization and modeling of microwave and millimeter-wave transistors (MESFET's, HEMT's, and HBT's) and in the CAD of nonlinear microwave circuits, in particular, solid-state power amplifier design. At present he is also conducting an extensive work in collaboration with the industry to develop ultralinear amplifiers using, in particular, feedforward techniques for PCS and satellite applications.

Dr. Ghannouchi is a Registered Professional Engineer in Que'ebec, Canada. He is a member of the editorial boards of IEEE Transactions on Microwave Theory and Techniques and IEEE Transactions on Instrumentation and Measurement. He served on the technical committees of several international conferences and symposiums and provides consulting services to a number of microwave companies.