ANALYSIS AND DESIGN OF BROADBAND, HIGH EFFICIENCY FEEDFORWARD AMPLIFIERS

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Abstract

A novel analysis of feedforward linearizers providing design procedures for determining circuit parameters required for specified linearity and achieving high efficiency, is presented. Experimental results are reported for a C band feedforward linearized amplifier demonstrating a minimum of 20 dB intermodulation distortion suppression across the 5.9 - 6.4 GHz satellite band.

Introduction

Feedforward linearization is an effective technique for improving the nonlinearity of power amplifiers[1]. Due to its potential for excellent distortion suppression the method has been considered for phase array antenna applications[2] and mobile communication systems around 900 MHz[3]. However, the need for an auxiliary amplifier and the tight requirements for phase and amplitude balance impose restrictions on the bandwidth and the efficiency of the system which are overcome through a developed optimization method without compromising performance.

The novel analysis of feedforward linearizers developed permits evaluation of system performance as a function of specific circuit parameters and phase and amplitude imbalance. As a result, the auxiliary amplifier linearity required for specific performance can be calculated. The advantage of this approach is that it allows a lower power auxiliary amplifier to be used resulting in feedforward systems with significantly improved efficiency as opposed to the classic feedforward configuration which employs two identical amplifiers. The effectiveness of the developed approach is demonstrated experimentally for a feedforward linearizer designed to operate over the 5.9 - 6.4 GHz satellite band.

Theory

The principle of operation of a feedforward linearizer is illustrated in Fig.1. A portion of the nonlinear main amplifier output is compared with the reference signal in the second coupler producing an error signal proportional to the distortion of the power amplifier. This error signal is then amplified to the appropriate level by the auxiliary amplifier and is subtracted from the amplified distorted signal at the output coupler resulting in an error free signal at the linearizer output.

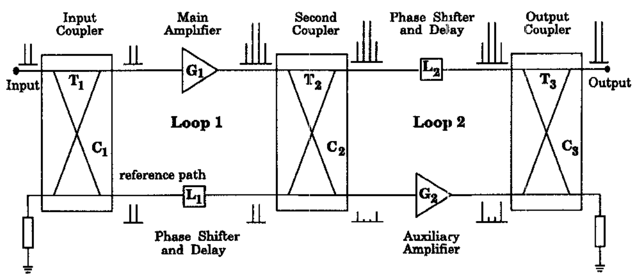

Fig.1 Feedforward linearizer block diagram

The operation of the feedforward linearizer circuit is based on the subtraction of two nearly equal signals and is, therefore, sensitive to amplitude and phase imbalance. The cancellation achieved by each independent feedforward loop is defined as the power ratio of the suppressed signal over the signal corresponding to the open loop configuration. It can be directly calculated by the vector subtraction of two signals[4] and is shown in Fig.2. Thus, the cancellation achieved independently by the first and second loops can be calculated by:

$$CANC_1 = 10 \log (1 + \alpha_1^2 - 2\alpha_1 \cos\theta_1) \text{ dB} \quad (1)$$

$$CANC_2 = 10 \log (1 + \alpha_2^2 - 2\alpha_2 \cos\theta_2) \text{ dB} \quad (2)$$

where α_1 , θ_1 and α_2, θ_2 are the amplitude and phase imbalance in the first and second loops.

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Imbalance in the second loop directly results in incomplete cancellation of the main amplifier distortion at the output of the linearizer. Imbalance in the first loop, however, has a more subtle effect leading to incomplete cancellation of the fundamental signals at the input of the auxiliary amplifier. Depending on the power handling capabilities of this amplifier, further distortion may be produced contributing to the overall system distortion. This effect is difficult to evaluate due to the complex behaviour of nonlinear systems which would require the development of complicated nonlinear CAD techniques. However, if the auxiliary amplifier distortion is assumed to add in phase with any residual distortion at the output of the linearizer, power series analysis can be employed to develop the required design equations for evaluating the overall circuit performance. In-phase addition of the distortion signals is the worst case situation which will provide the design criteria to set the safety margin for the performance requirements of the linearizer components.

In the following analysis the third order intermodulation products which are the most significant in multi-carrier systems, are considered. The power is expressed in watts and the gain of the amplifiers, the coupling factors and the losses are expressed as linear power ratios.

At the output of the main amplifier the power level $P_{MAIN,IM}$ of a third order intermodulation product is:

$$P_{MAIN,\,IM} = P_{MAIN} \left(\frac{C}{I} \right)^{-1}_{MAIN} \tag{3}$$

where $(C/I)_{MAIN}$ is the carrier to third order intermodulation ratio of the main amplifier for P_{MAIN} output power level per carrier.

At the output of the second coupler the carriers are suppressed and the level of the fundamental signals entering the auxiliary amplifier is:

$$P_{SUPP} = P_{MAIN}\, C_2\, CANC_1 \tag{4}$$

where C_2 is the coupling ratio of the second coupler and $CANC_1$ is the cancellation achieved in the first loop. The residual carriers at the output of the first loop produce further third order intermodulation products $P_{AUX,\,IM}$ at the output of the auxiliary amplifier:

$$P_{AUX,\,IM} = P_{SUPP}\, G_2 \left(\frac{C}{I} \right)^{-1}_{AUX} \tag{5}$$

where $(C/I)_{AUX}$ is the carrier to intermodulation ratio of the auxiliary amplifier for the specific

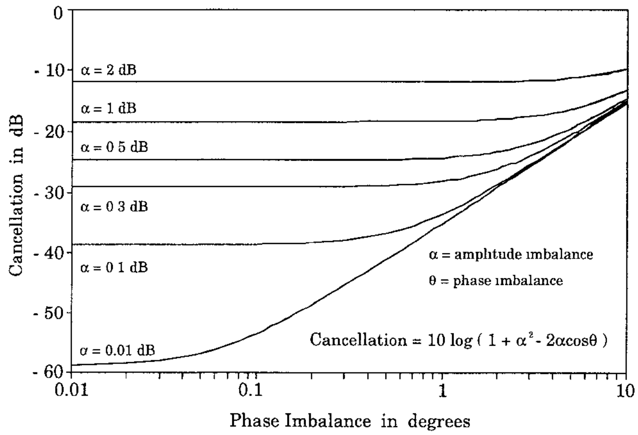

Fig.2 Cancellation as a function of phase and amplitude imbalance

output power level and G_2 is the gain of the auxiliary amplifier.

The carrier to third order intermodulation ratio (C/I) of an amplifier is related to the output power per carrier $P_{carrier}$ and the third order intercept point IP by[5]:

$$\left(\frac{C}{I} \right) = 2\,IP - 2\,P_{carrier} \quad dB \tag{6}$$

The cancellation achieved in the second loop is:

$$CANC_2 = \frac{P_{SUPP,\,IM}}{P_{MAIN,\,IM}\, T_2\, L_2\, T_3} \tag{7}$$

where T_2 and T_3 are the transmission loss of the second and output coupler, L_2 is the loss of the delay line of the second loop. $P_{SUPP,\,IM}$ is the level of the third order intermodulation products of the main amplifier suppressed at the linearizer output due to the corrective action of the second loop.

The effective cancellation of the overall feedforward linearizer is the power ratio of the level of all the intermodulation products at the output of the linearizer over the power level of the intermodulation products for the open loop configuration. Assuming in-phase addition of the intermodulation products of the main and auxiliary amplifiers:

$$CANC_{eff} = \frac{\left(\sqrt{P_{SUPP,\,IM}} + \sqrt{P_{AUX,\,IM}\, C_3} \right)^2}{P_{MAIN,\,IM}\, T_2\, L_2\, T_3} \tag{8}$$

where C_3 is the coupling ratio of the output coupler. Substituting eqns.3 - 7 into eqn.8 the effective cancellation of the intermodulation products at the output of the linearizer becomes:

$$CANC_{eff} = 20 \log \left(\sqrt{CANC_2} + \sqrt{CANC_1^3 \left(\frac{IP_{MAIN}}{IP_{AUX}} \right)^2 \frac{1}{C_3^2} \frac{T_2^2 L_2^2 T_3^2}{\alpha_2^3}} \right) dB \tag{9}$$

where the amplitude imbalance α_2 in the second loop is defined as the ratio of the power gain of the two paths:

$$\alpha_2 = \frac{T_2 L_2 T_3}{C_2 G_2 C_3} \tag{10}$$

Equations 1, 2 and 9 govern the cancellation of the third order intermodulation distortion that can be achieved with the feedforward correction for a specific level of phase and amplitude imbalance in any of the loops. The first term of eqn.9 depends on the balance that can be achieved in the second loop (eqn.2). The second term of eqn.9, however, depends on the balance that can be achieved in the first loop (eqn.1) as well as other circuit parameters. In particular, it depends on the linearity of the auxiliary amplifier compared to the linearity of the main amplifier, the loss ($T_2 L_2 T_3$) through the output power path and the coupling ratio C_3 of the output coupler. An auxiliary amplifier with too low power handling capabilities or too loose coupling at the output coupler increases the effect of the amplitude and phase imbalance of the first loop. As an example, the distortion cancellation for some representative values of the circuit parameters and two different auxiliary amplifiers is shown in Fig.3.

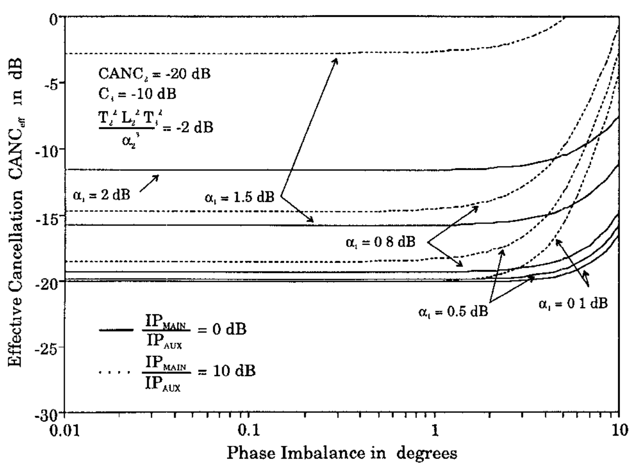

Fig.3 Effective cancellation as a function of first loop phase and amplitude imbalance

Phase and amplitude imbalances in the first loop which are expressed by the term $CANC_1^3$ result in a threefold deterioration of the overall cancellation, as opposed to imbalances in the second loop which directly affect the cancellation through the $CANC_2$ term. This dependence will be more critical if the auxiliary amplifier linearity and the coupling ratio of the output coupler are low. These results explain and support the findings of the CAD analysis of feedforward systems published in [6] which indicated that the simulated feedforward circuits were more sensitive to first loop imbalance. The system became more sensitive to imbalances of the first loop as the power handling capability of the auxiliary amplifier was reduced.

The equations presented here enable the calculation of the intermodulation distortion suppression for a given level of amplitude and phase imbalance in both loops and specific circuit parameters permitting, thus, the optimum design of circuit components for the desired reduction in distortion. In particular, the performance requirements of the auxiliary amplifier can be determined to allow lower power rating amplifiers to be used to achieve the highest system efficiency and minimize cost without compromising performance.

Experimental Results

A 1 W feedforward linearized class A amplifier operating over the 5.9 - 6.4 GHz band with auxiliary amplifier power rating half that of the main amplifier was designed employing a linear approach for the optimization. Schiffman and active quadrature phase shifters were used to adjust the amplitude and phase in each loop.

The design method is based on the nonlinear technique reported in [7] but has been further developed to allow the use of linear CAD. Each loop is designed independently and optimized for minimum output power over the full bandwidth. Eqn.9 with simulated loop cancellation values will provide the achievable overall cancellation. This approach allows the active elements to be treated as black boxes represented by small signal measured s-parameters avoiding, thus, the need for accurate nonlinear modelling. The method has, also, been employed to optimize the practical circuit to compensate for fabrication tolerances and different operating conditions. The measured signal cancellation for the first and second loops were 24 dB and 20 dB respectively. The theoretical design equation (eqn.9) with the above results predicted an effective cancellation of 20 dB. Some of the measured results for the system performance are presented in Figs 4 & 5 for a range of output power for the main amplifier and input signal combinations. A minimum of 20 dB improvement in the level of the intermodulation products is apparent at output power 0.5 dB below saturation.

Conclusions

Experimental results on a C band feedforward linearizer system demonstrated a minimum of 20 dB reduction of the intermodulation signals across the full operating band, allowing the linearized amplifier to achieve carrier to intermodulation ratios of 55 dB for output power 0.5 dB below saturation level. A linear design method has been developed for system optimization. Design equations have, also, been developed for optimization of linearizer components to meet specific system requirements. The required performance specifications for the auxiliary amplifier can, thus, be determined in order to optimize efficiency and achieve the desired linearity improvement. The measured results corroborate well with the theoretical predictions and indicate that feedforward linearization is a promising solution for satellite communication systems.

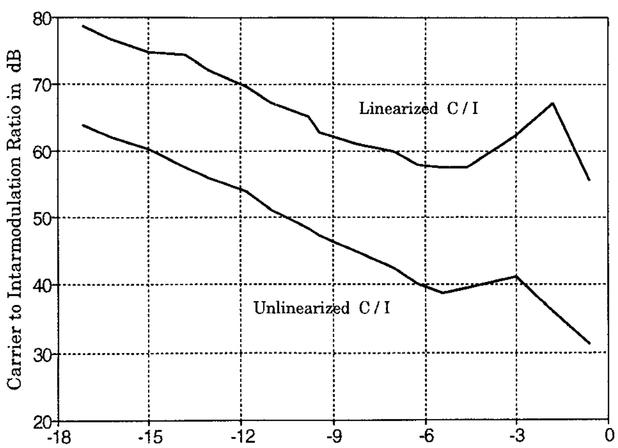

Fig.4 Carrier to third order intermodulation ratio with and without linearization

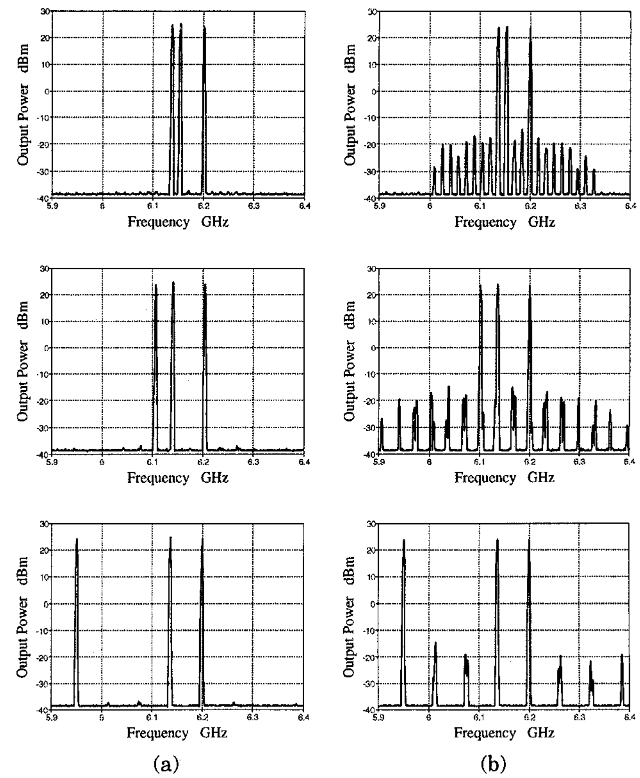

Fig.5 Output power spectra (a) with and (b) without linearization

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