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Broadband Linearisation of High-Efficiency Power Amplifiers

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Abstract

A feedforward-based amplifier linearisation technique is presented which is capable of yielding significant improvements in both linearity and power efficiency over conventional amplifier classes (e.g. class-A or class-AB). Theoretical and practical results are presented showing that class-C stages may be used for both the main and error amplifiers yielding practical efficiencies well in excess of 30%, with theoretical efficiencies of much greater than 40% being possible. The levels of linearity which may be achieved with such a system are well in excess of those which are required for most satellite systems, however if greater linearity is required, the technique may be used in addition to conventional pre-distortion techniques.

Introduction

Recent advances in solid state power amplifier design have led to smaller and more efficient designs appearing on the market. Such systems have made use of improved semiconductor technology and marginal improvements in classical design techniques in order to yield adequate linearity at the highest possible efficiency.

Efficiency is the key factor in all of these systems, no matter what frequency band they are required to operate in. A relatively modest improvement in efficiency can lead to significant weight savings in the spacecraft and these savings multiply due to a form of 'positive feedback': Any efficiency improvement leads directly to a reduction in the power supply requirements for the amplifier and also to a reduction in the size and amount of heat-sinking required. These in turn mean that a smaller area of solar panels is required and a smaller and hence lighter support structure is necessary. It also leads to a significant reduction in the required size of the back-up batteries and hence their charging circuitry. All of these factors lead to a reduction in the overall spacecraft size and weight and hence to a significant reduction in launch costs.

The fundamental problem with the techniques used at present is that the linearity requirement leads to a compromise in the maximum efficiency obtainable, and further improvements in semiconductor technology will only yield marginal improvements in efficiency.

Broadband Linearisation

This paper describes a technique for linearising a highly non-linear, and hence efficient, amplifier over a broad bandwidth. Potential efficiencies in the range 40-60% are possible using this technique with IMD performance of between 30 and 50dB (or more). It can be used in conjunction with simple linearisation schemes currently in operation, such as 3rd-order predistortion, but will provide a reduction of all orders of distortion if required. The technique is based on an adaptive form of feedforward which overcomes the classical disadvantages of this technique, in terms of its inability to monitor and correct its own performance. Significant simulation work has been

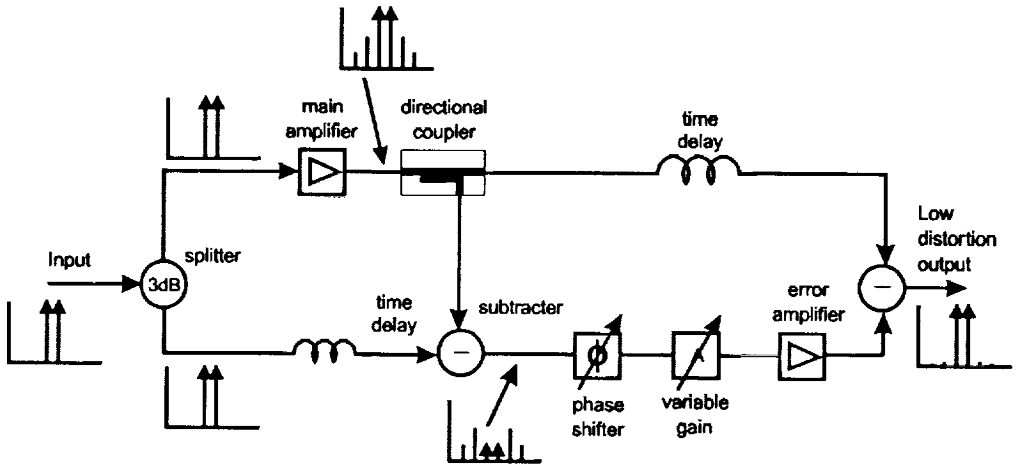


Figure 1: Simplified block diagram of a feedforward amplifier system.

performed on the system, yielding a detailed understanding of its operation, and demonstration systems have been built at VHF and UHF/SHF.

The system is based on the feedforward approach to amplifier linearisation shown in Figure 1 above. A two-tone test is shown for the purposes of illustration, however, any number of signals can be amplified simultaneously, with the only limitation being imposed by the overall peak envelope power (PEP) rating of the main amplifier.

The operation of a feedforward system may be summarised as follows (with reference to Figure 1). The input signal is split to form a main signal path (top) and a reference path (bottom). The signals in the main path are amplified by the main amplifier and a small portion of the output signal coupled off and subtracted from the reference path. The resulting signal contains predominantly the distortion information of the main amplifier and hence constitutes an error signal. This error signal is appropriately weighted in gain and phase and then amplified to the required level before being fed in anti-phase to the output coupler where it cancels the distortion from the main amplifier. The resulting signal is therefore a linearly amplified version of the input signal; the bulk of the distortion from the main amplifier having been removed by the feedforward process.

Efficiency of a Feedforward Amplifier

The theoretical efficiency of a feedforward amplifier has been derived in the reference [1], and hence will not be reproduced here. However, the result of that derivation will be used in order to demonstrate the optimal coupling factors and peak theoretical efficiencies obtainable from a feedforward system. An extension to the derivation has also been performed and this incorporates the effects of loss in the delay element in the main (top) signal path, since this element can have a major effect on the efficiency obtainable from the system. Full details of this extension will be given in the literature [2] and only the results will be presented here.

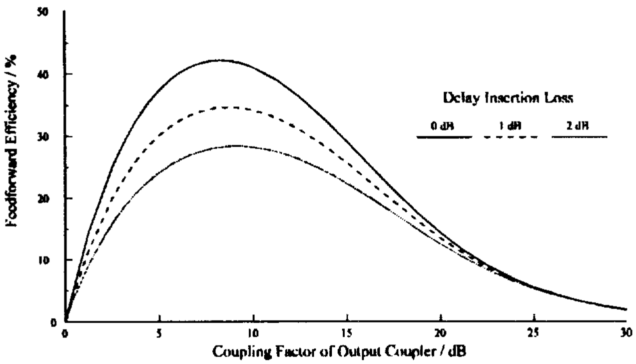


Figure 2: Feedforward efficiency characteristic using class-C main and error amplifiers and incorporating the effects of main path delay insertion loss.

Figure 2 shows the theoretical efficiencies which can be obtained from a feedforward system comprising of class-C main and error amplifiers and a main path delay element with varying degrees of loss. The class-C amplifiers are both assumed to have a DC to RF conversion efficiency of 60%. It can be seen that at an output coupling factor of a little under 10dB, the peak efficiency for a perfect system (no delay loss) is around 42%. As the delay loss increases, this efficiency is degraded until it reaches approximately 27% for a delay loss of 2dB. Note that the loss in the error coupler will be negligible due to its high value (30dB typically), and that the loss in the output coupler is already included in the derivation.

The variation of efficiency of the feedforward amplifier with the insertion loss of the delay element is shown in Figure 3, for values of insertion loss up to 3dB. This again demonstrates the marked effect of this loss on the overall efficiency of a feedforward system.

It is important therefore to attempt to minimise the delay loss in the feedforward system in order to maximise its efficiency and approach the 42% ideal. This can be achieved in a number of ways. If the delay is formed utilising coaxial cable, which may be the case at low frequencies, then the use of low-loss cables will obviously be of benefit. Alternatively, the delay may be etched onto a low-loss, high dielectric constant substrate. This also has the advantage of minimising the size of the delay element.

At higher frequencies the delay may be achieved in waveguide, although this may be bulky.

A much better approach would be to reduce the value of the delay element, and hence its loss, or eliminate it altogether.

Elimination of the main path delay in a feedforward system

A further derivation has been performed to assess the effects, both in terms of efficiency and overall distortion cancellation, of the reduction or removal of the main path delay element. This derivation will

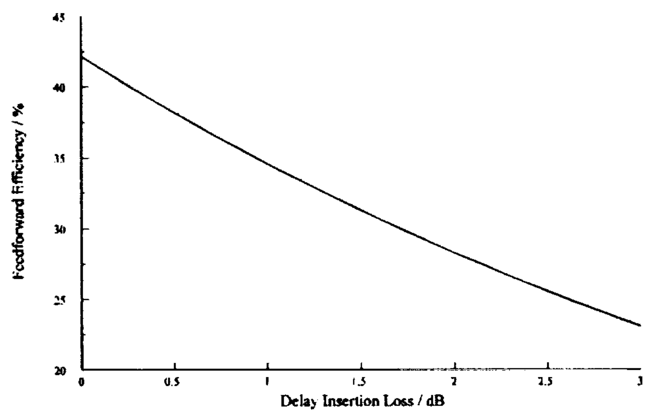


Figure 3: Maximum feedforward efficiency using class-C main and error amplifiers with main path delay insertion loss. This figure assumes that the optimum value of output coupling factor is being used.

be published in the literature [3] and so, again, only the significant results will be presented here.

Reduction (in value and hence size) of the delay element will result in a reduction in its insertion loss and also in an (unwanted) reduction in the level of distortion cancellation which can be achieved. However, if this reduction in cancellation is acceptable, *i.e.* it still allows the required specification to be met, then the reduction in loss can

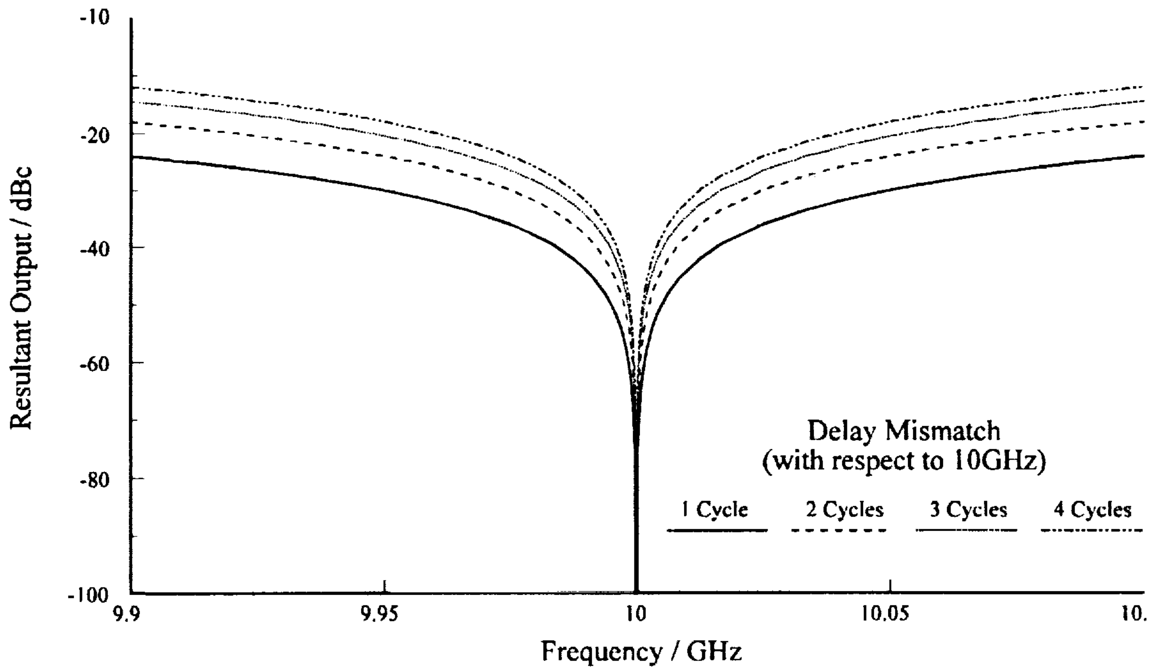


Figure 4: Distortion suppression which can be achieved across a 200MHz bandwidth at 10GHz with one cycle of delay mismatch.

be exploited as an improvement in overall efficiency of the linearised amplifier.

The level of cancellation which can be achieved across a 200MHz span at 10GHz is shown in Figure 4. Since the system is assumed to be set up on the centre frequency, perfect cancellation is achieved at this frequency. However, greater than 20dB of cancellation is achieved across the whole 200MHz span.

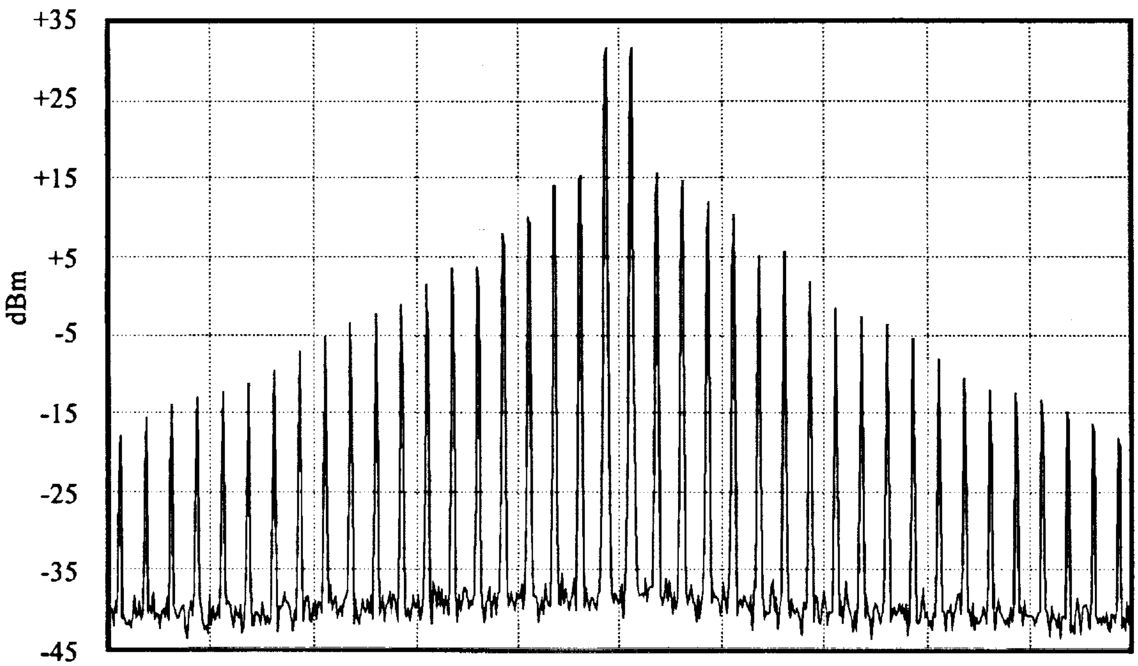
This translates in practice to a third-order intermodulation level of less than 35dB with respect to the tones in a two-tone test, when considering a class-C main amplifier with an intermodulation level of -15dB before compensation.

Decreasing the delay further, to a total of three cycles, will still yield a performance level equating to that of a good class-A amplifier (-30dB IMD products), for the above scenario. This amount of delay reduction should at least halve the loss in the delay element, if not completely eliminating it altogether.

Practical Results

A 'proof of concept' system has been built to verify the above theoretical results. A mid-VHF frequency band was chosen due to the relative ease of fabricating class-C amplifiers at this frequency and the ready availability of couplers etc. at a reasonable cost. The results, in terms of percentage bandwidths etc., are scaleable to any frequency, although efficiencies will generally decrease above a few GHz and losses in couplers and delay lines will increase. The theoretical characteristics can be modified by inserting the required practical values (for a particular frequency band) in the empirical relationships derived in references [2] and [3].

The open-loop (uncompensated) response of the class-C main amplifier is shown in Figure 5. The spacing of the two tones is 50kHz and the third-order IMP is around 15dB below the level of the tones. Figure 6 shows the response of the complete feedforward system, utilising the main amplifier whose response is shown in Figure 5. Five cycles of delay mismatch are present in the main path of this system and this is



Centre Freq: 221 MHz Span: 2 MHz
Res. B/W: 1 kHz Video B/W: 1 kHz Sweep: 6 s

Figure 5: Open loop (uncompensated) spectrum of the VHF class-C main amplifier.

achieved by completely removing the main path delay, and hence completely eliminating its loss.

It can be seen that the linearity performance of this complete system is still very good and comparable with that of a good class-A amplifier. The largest third-order IMP is now almost 32dB down on the tones, an improvement of over 16dB.

The efficiency of this complete, practical system is around 33%, an improvement over the 27% efficiency which is achievable with the correct main path delay value.

Incorporation of Pre-distortion

The main amplifier in a feedforward system can incorporate RF or IF pre-distortion in order to initially improve its linearity, before further improvement by use of the feedforward system.

The use of pre-distortion will generally only eliminate low-order distortion and this is unacceptable in some circumstances. The use of feedforward will, in general, eliminate all orders of distortion by the same amount and hence can be used to improve upon the performance of a purely pre-distorted system.

The use of pre-distortion in conjunction with feedforward also benefits the feedforward technique as it allows significantly higher efficiencies to be achieved. It is also possible to use class-A error amplifiers, to obtain an improved distortion performance, without significantly affecting overall efficiency, since the power required from such amplifiers is now small. Overall efficiencies of up to 60% are achievable using this technique (in conjunction with class-C amplifiers) and pave the way for true high-efficiency satellite amplification.

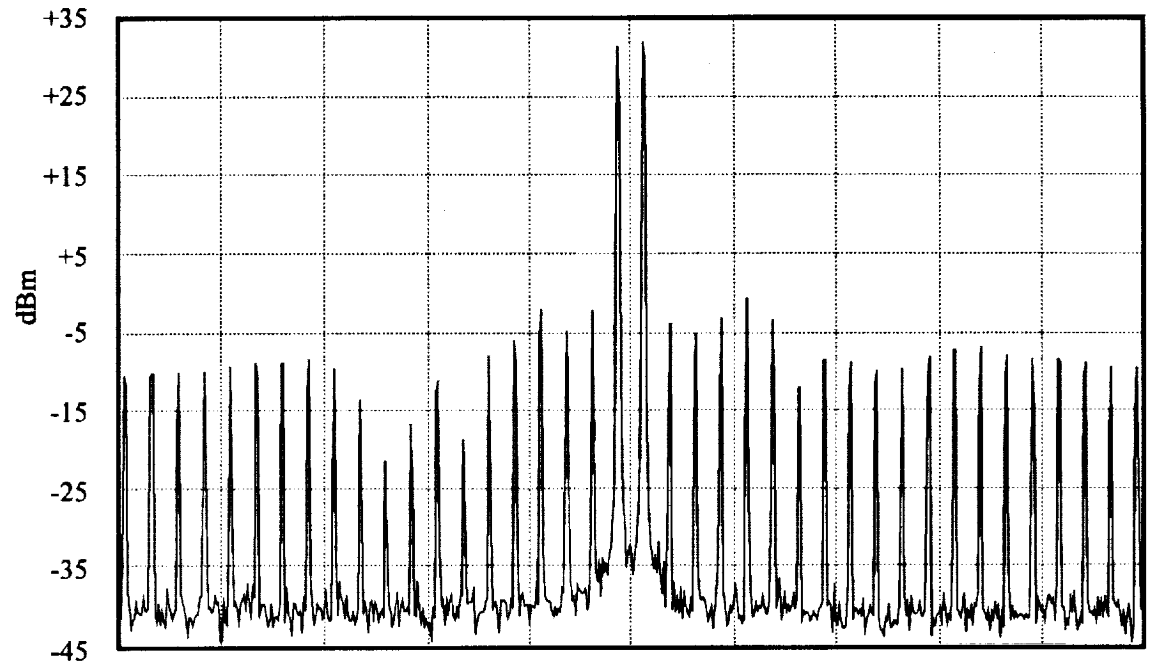


Figure 6: Linearised output from the VHF class-C feedforward system.

Conclusions

This paper has suggested the use of the feedforward amplifier linearisation technique for use in fabricating highly-efficient satellite amplifiers. Theoretical efficiencies in excess of 40% are possible purely by the use of feedforward, with efficiencies approaching 60% being possible with a combination of adaptive pre-distortion and feedforward.

The problems of loss in the main path delay have been highlighted and potential solutions suggested which yield practical efficiencies significantly better than those possible with current techniques.

Finally, the complete removal of the main path delay has been highlighted as a method of improving efficiency in some circumstances.

Acknowledgements

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Session 3
Regulatory and Policy Issues

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