# Development of an Envelope Tracked High Power Amplifier for COFDM

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**Abstract**

An envelope tracking (supply bias) modulator is developed using a combination of a switched mode converter and Class A/B linear amplifier to achieve natural diplexing between high and low modulation frequencies. It is tested in conjunction with a balanced LDMOS amplifier working at 450 MHz with a mean power output of 8W. The overall DC-RF efficiency was increased from 37.1% to 46.7%, with ACLR reduced from 31.5 to 29.0 dB.

## 1 Introduction

A long-standing problem for traditional radio frequency power amplifiers (RFPAs) is the low efficiency achieved when amplifying envelope modulated signals with a high peak-to-mean power ratio. Excluding switching mode RF amplifiers, and envelope restoration methods, load line considerations show that the problem must be tackled either by bias supply modulation, also known as "envelope tracking", i.e. reducing the supply rail voltage when the instantaneous signal envelope is small, or by modulating the effective device load impedance, as occurs in Doherty, Chireix and other variable impedance configurations [1]. This paper presents a case study of the bias modulation technique.

## 2 Modulator Design Principles

To be viable, the modulator itself must be very efficient, and this implies a switched mode circuit. The most obvious choice is a classical buck converter (Fig. 1) containing one switching device and one diode [2]. This is conventionally switched at a fixed frequency and variable mark-space ratio, allowing the output voltage to be varied from 0 to nearly $V_{supply}$, minus the forward voltage of the switch. Such a circuit can be very efficient but obviously has limited speed of response to changes in mark-space ratio. Modulating its output at megahertz rates, as is required in most communications systems, requires excessive switching frequency and this results in high switch losses. This is of course a familiar trade-off in power electronic converters.

The key to a practical modulator is to recognise that most of the power in the modulation envelope waveform is carried in low frequency components. The required operating principle is to supply these components from the switched mode converter and to fill-in the high frequency region using a nominally linear Class A/B amplifier. For maximum efficiency, as much supply rail power as possible should be supplied from the switched mode converter.

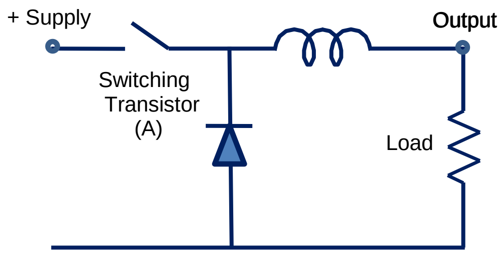


*Figure 1 Elementary buck converter*

If the load on the buck converter can be modelled approximately as a resistor, which could be non-linear, it is obvious that the switch in Fig. 1 can be controlled by connecting the output node to a threshold detector (comparator) with hysteresis. This can be described as a bang-bang controller whose set point, approximately the mean threshold, is set equal to the desired output voltage. With a memoryless load, the output voltage obviously switches stably between the upper and lower threshold levels. Both its switching frequency and mark-space ratio will vary.

For enhancing high frequency response, the naïve approach of using a diplexing filter to separate the envelope signal into low and high frequency regions is very cumbersome and it can be circumvented using the arrangement shown in Fig. 2. A fast Class A/B amplifier with low output impedance is attached to the output node, and a fast feedback loop is provided which 'forces' the output node voltage to follow closely the set-point which is the rail voltage that the RF power amplifier requires to work efficiently at the instantaneous level of the signal envelope. In the simplest arrangement, the set-point is a linear function of the measured envelope with appropriate offset and gain, so that the rail voltage varies between the

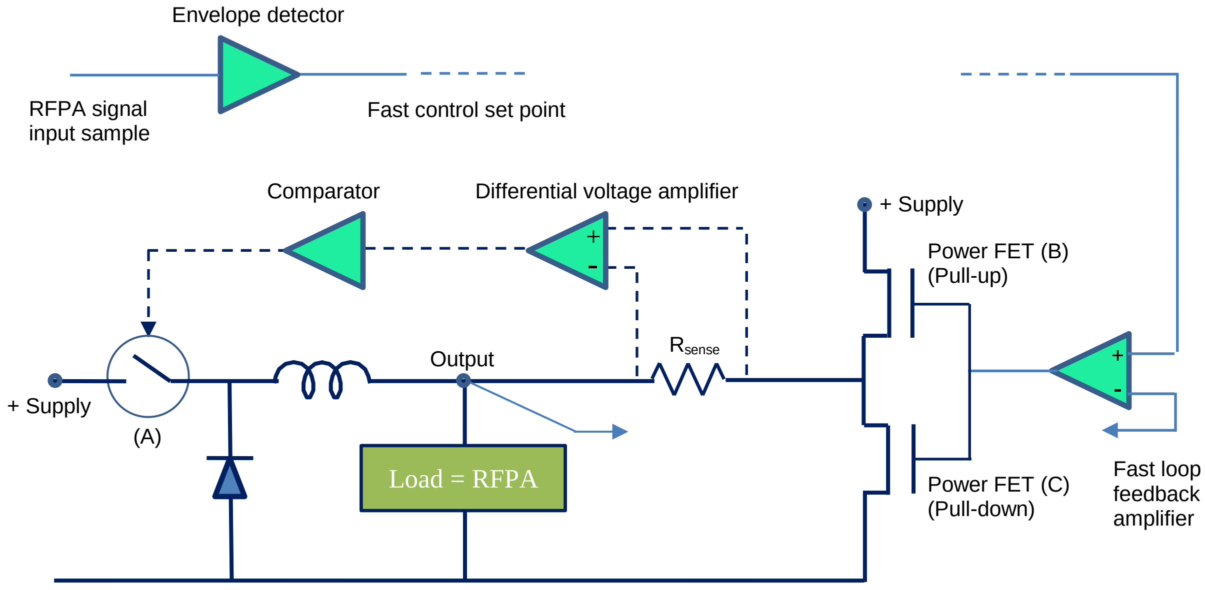


*Figure 2 Complete drain bias modulator (simplified)*

available DC supply voltage and the minimum required to maintain the RFPA in correct operation. A non-linear function can alternatively be used to provide some measure of linearisation while maintaining high mean efficiency. The ideal efficiency of the switched converter is reduced by the minimum DC power that must be supplied to the Class A/B amplifier to provide its output in the highest part of envelope spectrum.

The converter switching control can no longer be performed using the output voltage. Instead a current sensing circuit using a small resistor measures current flowing from the Class A/B amplifier, in the sense shown in Fig 2. The converter switch is turned on when the measured current exceeds set threshold, as determined by a comparator with appropriate hysteresis. The action of the switching is therefore to minimise power supplied by the 'fast' amplifier.

## 3 Design Case Study

A basic design choice is whether to configure any or all of the three power transistors in the modulator to operate as common source (emitter) or as common drain (collector) amplifiers (i.e. voltage followers). On the basis of speed and low output impedance, the design described here used MOSFET enhancement mode power transistors, in source follower configuration, in all three positions. The main control loop uses a voltage feedback operational amplifier giving a closed loop gain of 11. This and the offset are adjusted so that the detector output will swing the RFPA rail voltage between 8 V at envelope nulls and 26V at signal peaks. The supply rail voltage to the modulator is 28 V and the maximum modulator output is limited to about 2 V less in the voltage follower configuration. The follower configuration introduces some circuit complexities and reduces the achievable output swing somewhat. Rail decoupling capacitance in the main RF amplifier must be minimised; however low frequency supply line oscillation is prevented by the feedback action of the modulator. The prototype modulator used transistors with > 60V voltage rating and peak current ratings of 15 A, 35 A and 15 A in positions A, B, C in Fig. 2.

The assumption that the RFPA load behaves as a memoryless resistor proves to be approximately justified if a delay line is included in the input path to the RFPA to allow for the greater response time of the modulator. In this experiment a cable delay line of 20 ns was used, but compact ceramic lines are also available.

## 4 Intrinsic Efficiency

It is instructive when evaluating the system to have a measure of the "intrinsic" efficiency of the envelope modulated amplifier, meaning the mean RF output power as a fraction of the average power supplied to its supply, without including losses in the envelope modulator. This quantity requires a more complex measurement since both current and voltage at the RFPA supply terminal are varying at the modulation rate and are not perfectly correlated. Here the current measurement was performed using a circuit similar to that used to sense the current in

Fig. 2. The current and voltage waveforms were recorded using a digital oscilloscope and their averaged product was computed offline.

## 5 Results

The drain supply modulator can be used to supply any RF amplifier within its power capability. The prototype was used to drive a single stage Class A/B power amplifier designed to operate from 450 to 520 MHz using two LDMOS transistors in balanced configuration, with a total peak power capability of 70 W. Tests were made with a COFDM format signal using a modest target modulation bandwidth of 2.5 MHz. Operating with a constant supply voltage of 27. 6V, at 8 W mean output power (  dB back-off) the RFPA showed an *overall* DC-RF efficiency (28V supply to RF output) of 37.1 % and an adjacent channel leakage ratio (ACLR) of 31.5 dB. With modulation enabled at the same mean power output, the overall efficiency was increased to 46.7 % with an ACLR of 29.0 dB.

## 6 Efficiency Analysis

The modulator circuitry shown in Fig. 2 can be grouped into sections such as the envelope detector, fast loop amplifier, current sensor and comparator, which have only a signal processing function and present a roughly constant power demand, and those containing the three power transistors and their drivers. The latter have losses which increase with the power rating of the amplifier being modulated, as well as with the modulation bandwidth. All these losses are removed when the test amplifier is measured without modulation. Gate bias supplies incur a small additional loss which is always present; overall efficiencies quoted include this, and, when tracking is applied, all modulator losses.

Measured with no load and no modulation, the modulator (and bias circuits) consumed 2.1 W from the 28 V supply. The intrinsic efficiency of the fully modulated RFPA, as defined and measured above, was estimated as 57 %. With this information, the observed efficiency factors can be broken down approximately as in Table 1. The last column is an inferred quantity.

Table 1 shows clearly how the modulator losses inevitably reduce the very considerable gains in intrinsic efficiency. It is estimated that the same envelope tracking modulator could drive an RFPA of 50 W mean power capability, and it is interesting to project the above analysis to estimate the expected overall efficiency. For a given RFPA architecture and technology, and modulation format, the intrinsic efficiency can be assumed to be roughly constant. The improvement factor for intrinsic efficiency with envelope tracking is mainly a function of the modulation, and can also be taken as constant. Finally the modulator power stages can be assumed to work at approximately constant efficiency. With these crude assumptions it is easy to project the overall efficiency to other output power levels, as shown in Fig. 3. In advance of further prototyping and more detailed analysis, the curve gives a rough prediction of the achievable overall efficiency when the same envelope tracking modulator is used to drive amplifiers of different power capability. This figure shows, as expected, that the power output must significantly exceed the processing overheads to make the use of envelope tracking worthwhile.

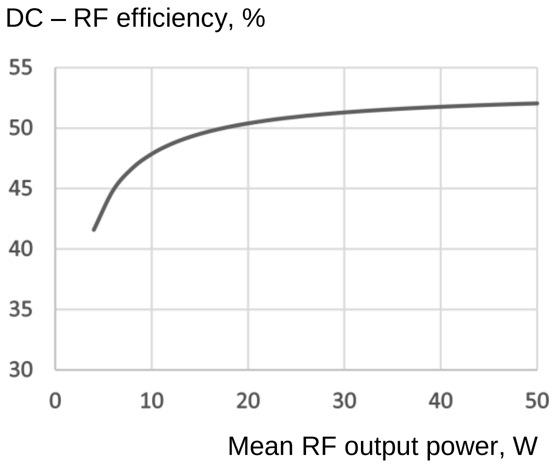


*Figure 3 Predicted efficiency versus mean RF output power*

## 7 Conclusion

This experience with an in-house constructed envelope modulator confirmed that useful improvements in DC-RF efficiency can be obtained using the envelope tracking technique. The analysis shows that it is worth minimising the signal processing power overheads. Apart from its high power core, the trial design was rather complex (containing 15 small-footprint integrated circuits) and it was concluded that some effort should be made to simplify it. The design based on source followers does increase complexity and degrades the efficiency significantly. In future work it is intended to trial an alternative design based on common source power stages, and to include some linearisation in the transfer function at the output side of the envelope detector .

| | Mean Output Power | Overall Efficiency | Modulator Signal Processing Loss | Intrinsic Efficiency | Modulator Power Stage losses |
|---|---|---|---|---|---|
| Without ET | 8 W | 37.1 % | 0 | 38.6 % | 0 |
| With ET | 8 W | 46.7 % | 2.1 W | 57.0 % | 1.0 W |

***Table 1 Measured efficiency and analysis***

**References**


[1] S. C. Cripps, RF Power Amplifiers for Wireless Communications, 2nd ed, Artech House, 2006.

[2] M. H. Rashid, Power Electronics: Circuits, Devices, and Applications, 4th ed, Pearson, 2013.