coolteq.h Modulator

Design Guide

AN002077

1 Introduction

This application note gives guidelines for the physical design and performance optimization aspects of Envelope Tracking Power Amplifier pallet employing the Nujira Coolteq.h Modulator. It assumes that the reader is already familiar with general RF power amplifier design principles and the Coolteq.h Modulator datasheet. For aspects such as modulator control, reference envelope creation and integration with DPD please refer to the Coolteq.h Modulator User Guide [1].

2 Envelope Tracking –Background and Theory

The envelope tracking technique is based on continually varying the RF device drain (or collector) voltage as a function of the instantaneous RF device output power.

By suitably selecting the drain voltage for the instantaneous RF amplitude, the amplifier can be kept in compression for a large portion of the signal's dynamic range. This yields an envelope tracking (ET) efficiency locus synthesised from the individual efficiency curve peaks for each drain voltage as shown in **Figure 1**.

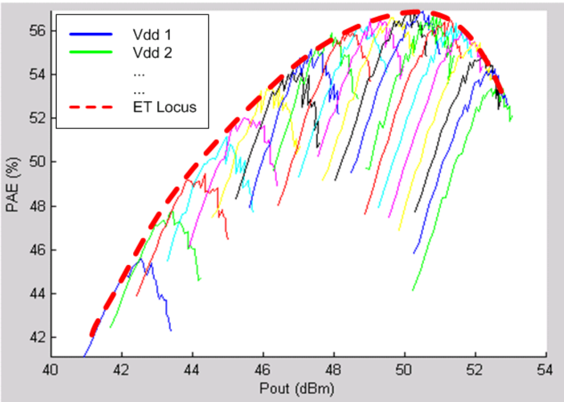


Figure 1. Fixed drain curves and resulting ET efficiency curve

Next let us consider how the mean efficiency of an envelope tracking amplifier can be calculated when the ET efficiency curve and the statistical properties of the signal are known.

For a signal with *prob(V_{RF})* amplitude probability density function the mean efficiency will be given by:

$$eff_{PAmean} = \frac{\int_{0}^{V_{RF\max}} Pdf(V_{RF})}{\int_{0}^{V_{RF\max}} \frac{Pdf(V_{RF})}{eff(V_{RF}, V_{dd})}} \qquad (1)$$

where,

$$Pdf(V_{RF}) = prob(V_{RF})P(V_{RF}) \qquad (2)$$

is the power density function, $P(V_{RF})$ and $eff(V_{RF})$ are the output power and associated efficiency as a function of RF amplitude (V_{RF}). It must be noted here that in the efficiency is a function of both RF amplitude and drain voltage V_{dd} as shown by equation (1), and that in an envelope tracking system V_{dd} is related to RF amplitude by a so called shaping function:

$$V_{dd} = f_{ET}(V_{RF}) \qquad (3)$$

Hence equation (1) can be re-written as a function of V_{RF} only:

$$eff_{PAmean} = \frac{\int_0^{V_{RF\max}} Pdf(V_{RF})}{\int_0^{V_{RF\max}} \frac{Pdf(V_{RF})}{eff(V_{RF}, f_{ET}(V_{RF}))}} \qquad (4)$$

Two key aspects of envelope tracking systems are apparent from equation (4):

- Efficiency is dependent upon the statistical properties of the signal, for example mean power and Peak to Average Power Ratio (PAPR)
- Efficiency is influenced by the function that maps the drain voltage from the instantaneous RF amplitude (shaping function)

Equation (4) is illustrated in **Figure 2** showing the efficiency curve of an ET power amplifier and a signal's power density function, $Pdf(V_{RF})$. The area below the $Pdf(V_{RF})$ curve equates to the mean RF power, i.e. the nominator of the right side of expression (4). The area below the $Pdf(V_{RF})/eff(V_{RF})$ curve (denominator of the expression) corresponds to the mean DC power consumed.

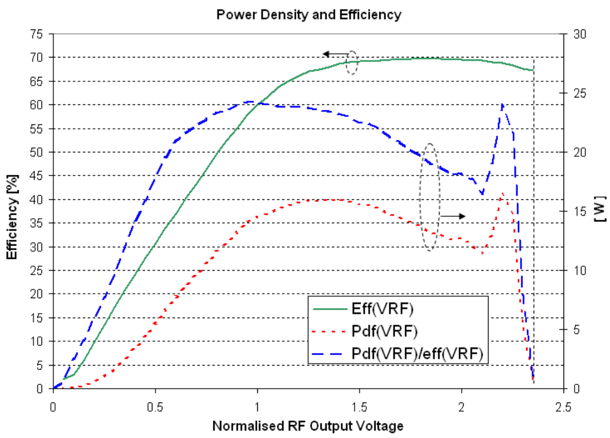


Figure 2. Efficiency locus and signal statistics

From equation (4) and **Figure 2** it is apparent that to obtain high overall mean efficiency the amplifier has to exhibit high efficiency for the majority of the $Pdf(V_{RF})$ region. In an ET system this is achieved by dynamically adjusting the drain voltage so that the amplifier is kept in compression for a large part of the power density curve.

A key consideration of designing a power amplifier is lifting the efficiency locus at low V_{dd} (i.e. low power) levels. The efficiency locus of the PA can be influenced primarily by the RF impedance match, which has to be optimised uniquely for ET by means of load-pull.

3 RF System Design

In the concept phase it is useful to get an indication on what the achievable efficiency will be for the final ET PA stage and also for the complete RF line-up. It should also be verified that the Modulator will be able to deliver the peak and average power required for the application.

For this purpose Nujira has developed a spreadsheet 'ET_PA_calculator.xls' that is an easy to use tool supplied with this document. A screenshot of the spreadsheet is shown in **Figure 3.** Figures for PA and Coolteq.h efficiencies and losses in the line-up can be entered and the results are calculated by the spreadsheet.

The PA device efficiency (both mean and at the peak power) for this calculation has to be estimated from pulse characterising the device for a range of drain voltages as described in **Section 5.** Please consult Nujira for an appropriate figure for Modulator efficiency for the given application.

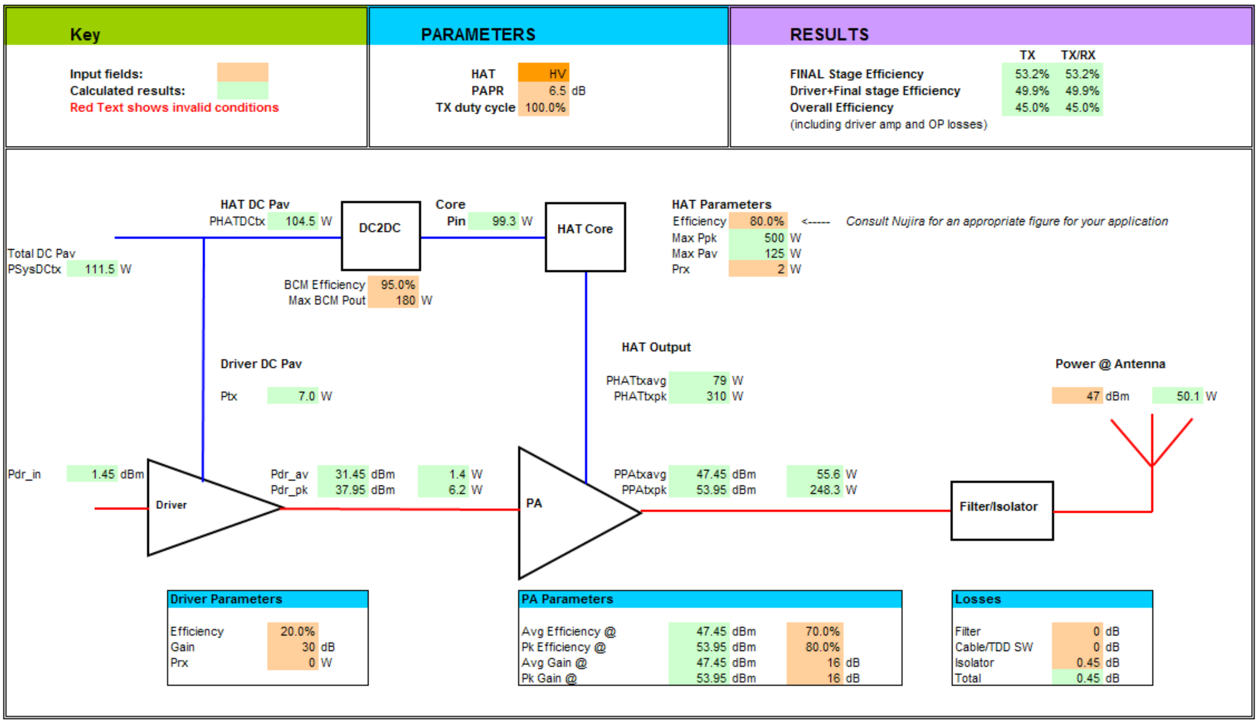


Figure 3. ET PA Calculator spreadsheet.

4 Design Process

Figure 4 shows the typical design and optimisation flow of an RF PA to be used in an envelope tracking system with Nujira's Coolteq.h Modulators.

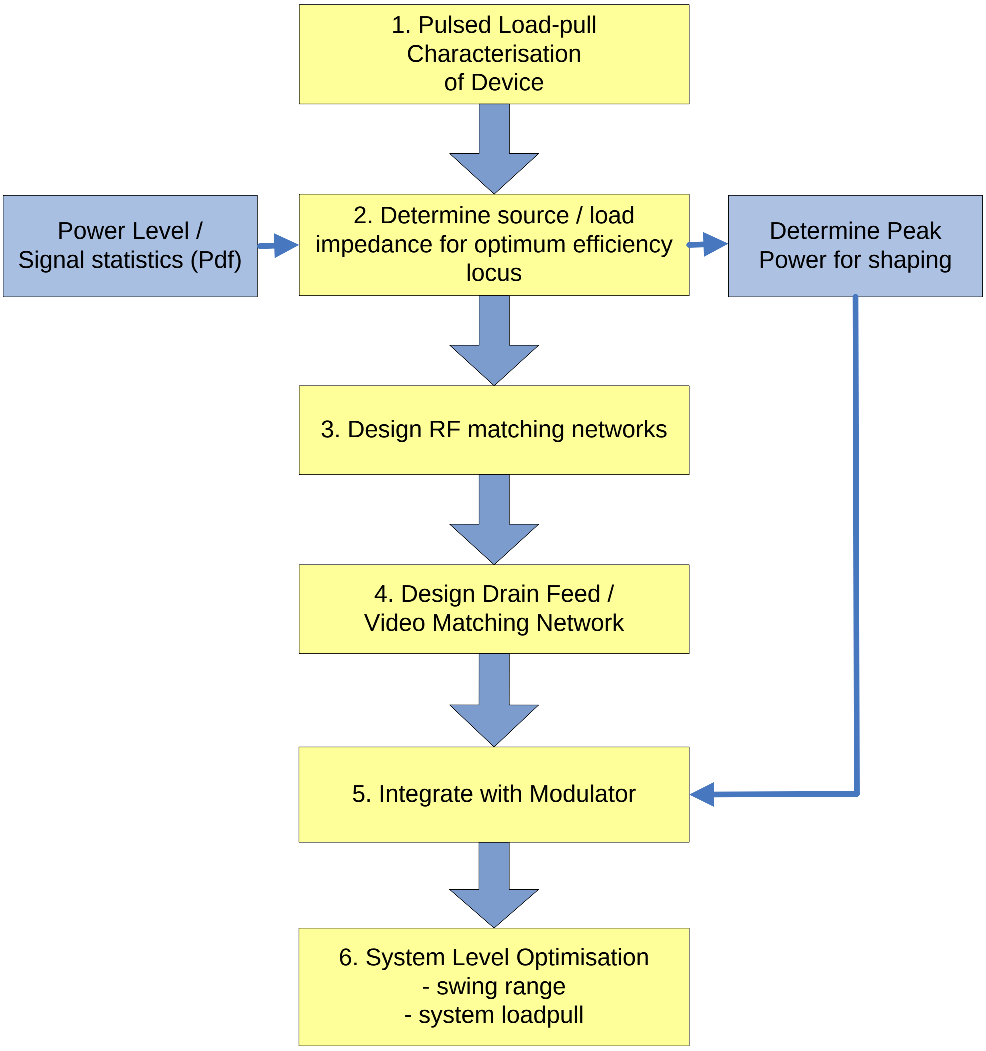


Figure 4. ET PA Design Flow

As outlined in **Section 2**, the design of the power amplifier consists of finding and implementing the optimum matching circuit for the PA device to maximize the mean efficiency of the ET amplifier for a signal with a given power density function (Steps 1-2-3 in **Figure 4**).

In addition the interconnection between the PA device drain and Modulator output pins has to be carefully designed to give a flat frequency response and low impedance within the operating bandwidth of the Modulator which is typically 3 times the modulation bandwidth (Step 4).

Finally, optimisation can be performed at system level with the integrated PA-Modulator prototype (Step 4).

These design phases are described in more detail in the following sections.

5 Device Characterisation

In order to find the optimum RF device output load impedance match for a given PA device, it is necessary to collect data at a number of impedance points for efficiency as a function of both drain voltage and output power. It is then possible to calculate the mean efficiency for each of these impedance points for a given signal using equation (4).

This process is typically done by using load-pull tuners within a pulsed measurement system.

An example of the measurement data collected for a specific load impedance match point by pulse characterisation measurement can be represented by a 3-dimensional surface as shown in **Figure 5**.

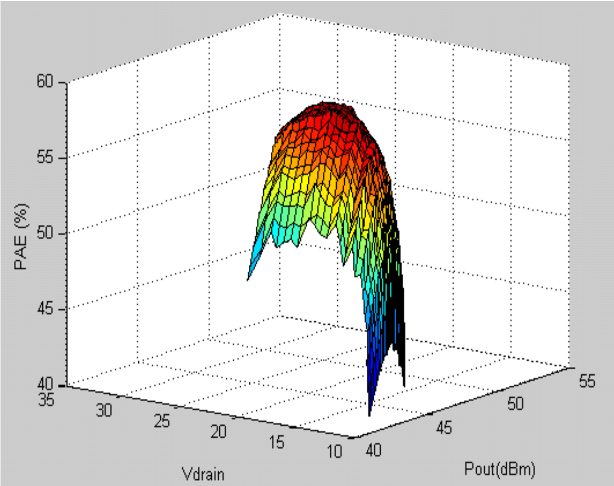


Figure 5. Efficiency versus P_{out} and V_{dd}.

From this data the optimum relationship between V_{dd} and P_{out} can be obtained that gives the best overall efficiency (see **Figure 6**). By fitting a curve on the optimum efficiency points, the shaping function ($V_{dd}=f_{ET}(V_{RF})$) can be determined for the valid drain modulation voltage range, shown by the red line in **Figure 6**. Note that it cannot extend beyond the Modulator's output voltage range, which is 10-28V in this example.

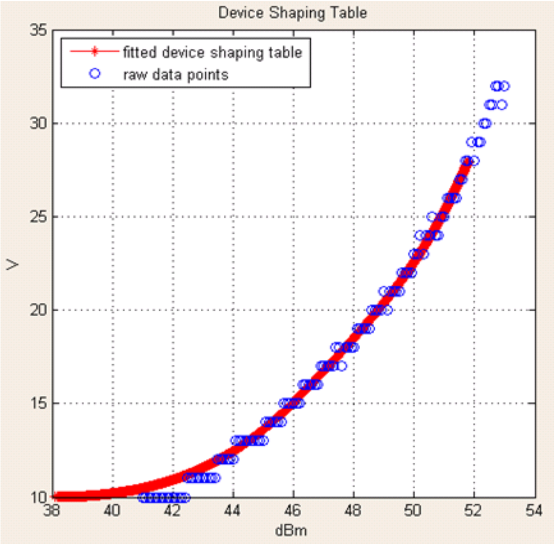
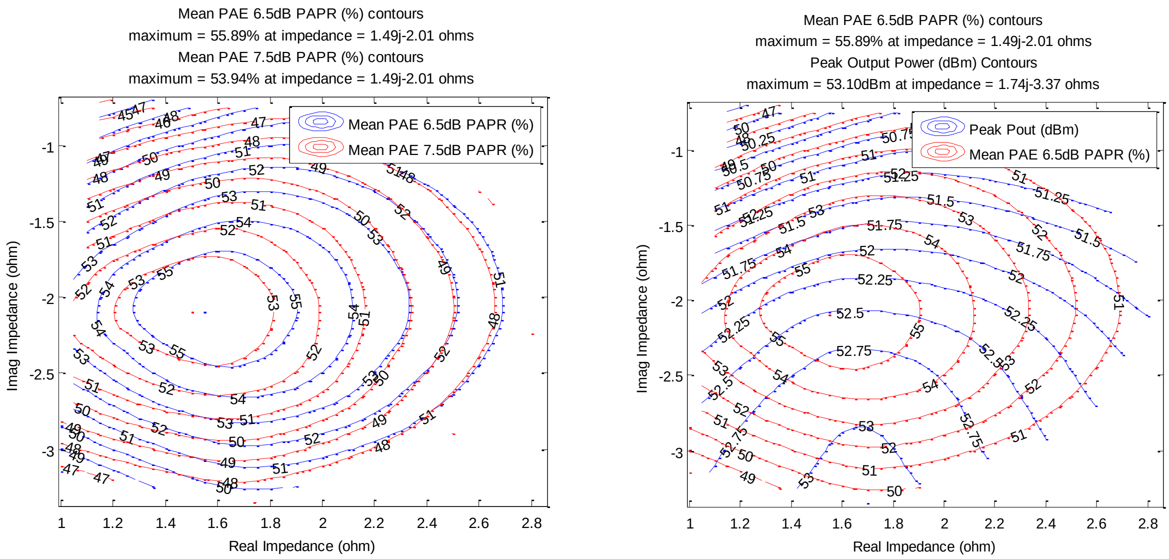


Figure 6. Corresponding optimum V_{dd} vs P_{out} points from measurement data (blue circles) and Fitted and shaped V_{dd} vs P_{out} function (red line).

Once the shaping function is known the mean efficiency can be obtained using equation (4).

By repeating this measurement and calculation process for a set of load impedance points, contour plots of the mean ET PA device efficiency can be drawn on the impedance plane, as shown by **Figure 7a**.



(a) (b)

Figure 7. ET Mean Efficiency and Peak Power versus Load Impedance

Figure 7a further illustrates the fact that ET efficiency is influenced by the assumed power density function of the signal to be amplified, as the contour plots are different for 6.5dB and 7.5dB PAPR signals.

Besides the mean efficiency, the saturation power and gain have to be taken into account and a trade-off has to be found between efficiency and these other constraints.

Figure 7b shows an example of overlaid contour plots of mean efficiency and peak power. Typically the highest efficiency point that can still deliver the required peak power for the application is selected.

Nujira can assist its customers with device characterisation and optimum impedance selection using its automated load-pull system and analysis software.

6 Implementation

In addition to the power amplifier device the following components have to be accommodated on the PA pallet to form an envelope tracking amplifier:

1. Nujira Modulator. For information including dimensions and pinout refer to the datasheet [2].
2. Bias inductor. A Coilcraft SER2013-472 (4.7μH) is recommended for this part. For information on this part including dimensions please refer to the Coilcraft product datasheet [3].
3. Drain Feed and Video matching stub, components.
4. Power supply filtering capacitors for the Modulator input supply.

The coolteq.h Modulator provides extremely low output impedance and produces high frequency and high dynamic range swings, such that low frequency decoupling is not necessary and should not be applied to the output of the Modulator.

6.1 Drain Feed and Video Matching Network

The interface between the Modulator and the PA device is a critical part of the envelope tracking amplifier that has a strong influence on overall system performance.

To achieve optimum spectral performance and efficiency from an envelope tracking system the voltage at the drain of the PA device has to follow accurately the reference envelope input into the Modulator. Therefore the drain feed network from the output of the Modulator to the drain of the PA device needs to exhibit a flat frequency response within the operating bandwidth of up to 50MHz. Note that the bandwidth of the envelope is typically 2.5 times that of the modulation bandwidth.

Typically the maximum acceptable inductance of the feed-line is 5 nH. Any resistance in the feed-line will cause losses, hence it is also important to keep this to below approx. 30 mOhms.

The feed network has to provide as low as possible impedance at the device drain at video frequencies to minimize memory effects, while the impedance should be high in the RF band of interest.

At high RF frequencies (greater than 500MHz) a lambda/4 microstrip feed-line can normally satisfy these requirements. However, at lower RF frequencies as the carrier frequency approaches the envelope bandwidth (2.5x modulation BW) it may be necessary to use a feed-line that is shorter than lambda/4. In these cases it will be necessary to take into account the RF impedance of the feed-line at the drain when designing the output matching circuit.

Minimising the inductance and resistance between the Modulator output tab and the PA device is of critical importance.

6.2 Layout Design

Based on the considerations in **Section 6.1**, an example for the schematic diagram and layout for a power amplifier with Modulator is shown in **Figure 8**. As with conventional RF amplifiers it is strongly recommended that a low loss substrate material is used.

The drain feed line connecting the Modulator to the PA device is only marginally longer than $\lambda/4$ which is the absolute maximum length that is acceptable for most applications. Note also that the drain feed track should be made as wide as practically possible to reduce its inductance.

Components C1 and C2 are RF decoupling capacitors.

For flexibility of video matching another $\lambda/4$ stub is used at the opposite side of the drain tab. R1, R2, C1 and C2 are additional tuning components that are used to achieve a maximally flat video frequency response. These components are used to 'de-Q' the resonant circuit formed by the inductance of the feed-line and the drain capacitance of the PA device. The exact values of these have to be optimised during the video match tuning process.

The Modulator's input power supply decoupling requirement depends on the source and the length of cable / track used. Usually 2 X 330μF electrolytic, plus 4.7μF ceramic capacitors on both Va and Vs inputs provide a low enough ESR.

A photograph of an overall assembly of the envelope tracking amplifier described here with the Modulator is shown in **Figure 9** in the Appendix.

6.3 Thermo-mechanical Interface

The Modulator requires good thermal conductivity for its base-plate to an appropriate heat-sink; therefore it has to be mounted directly onto the PA heat sinking pallet.

To ensure that good thermal continuity is achieved between the modulator and the heat-sink the mounting screws must be tightened to a torque of 0.8Nm.

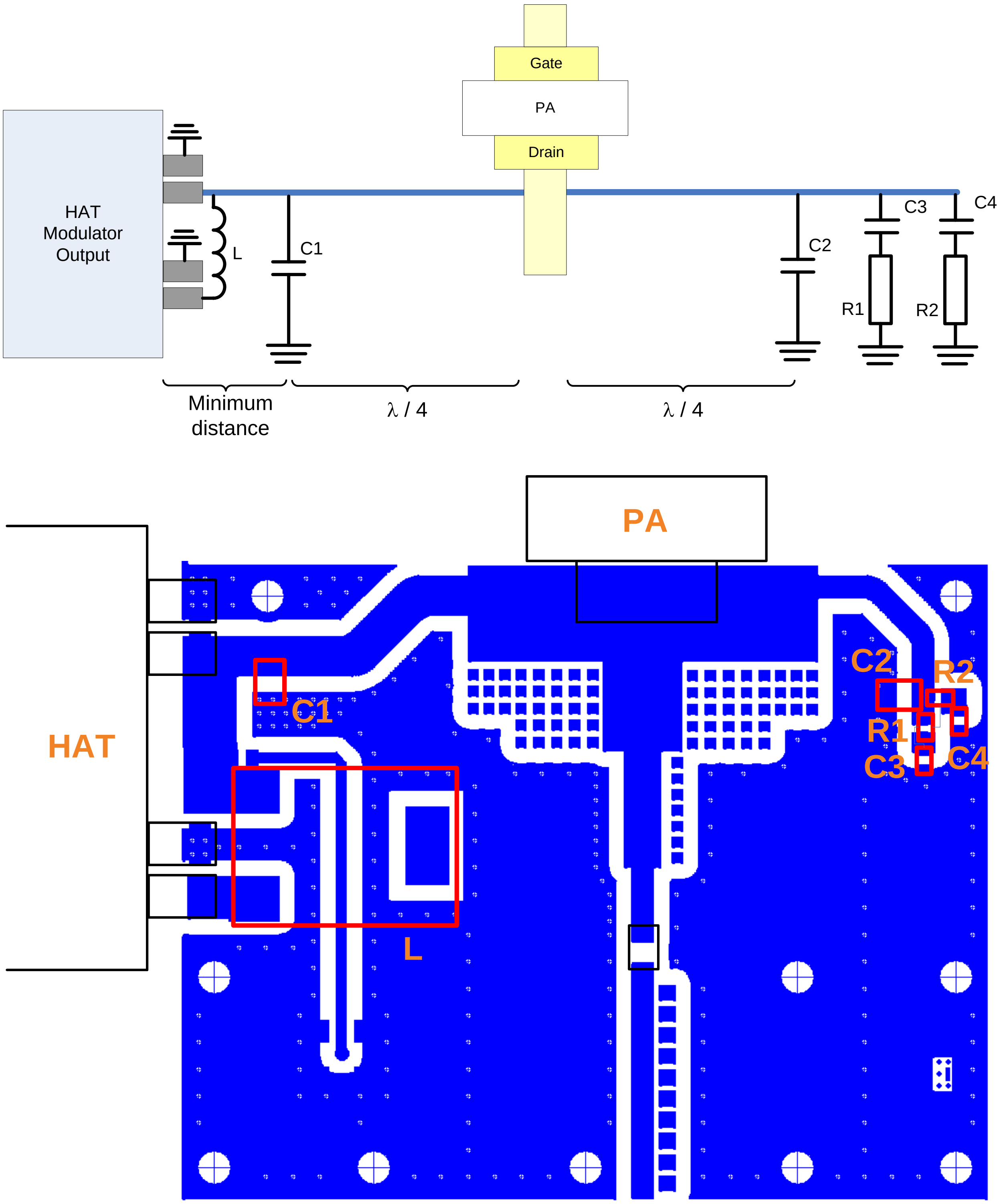


Figure 8. Example schematic diagram and layout of the output section of an ET amplifier.

7 System Level Optimisation

When initial PA prototypes with the Modulators are available, further improvement in efficiency may be achieved by performing system level optimisation.

This could consist of two steps:

1. Swing range optimisation
2. System level loadpull

During both of these tests the PA-Modulator is driven by the baseband system with the waveform that the amplifier is intended to be used for, for example WCDMA, LTE, etc. System performance is then tested for different swing ranges and RF load impedances.

Changing the swing range may bring an efficiency improvement as the efficiency of the Modulator is not a fixed value, but rather a complex function of delivered average power, signal power density and swing range. Typically the efficiency of the PA device increases as the drain modulation range is increased. The Modulator efficiency however can reduce somewhat for larger swing ranges. Therefore, the swing range that provides the best overall PA-Modulator efficiency should be found experimentally by testing with various swing range settings.

Regarding how to implement this test and how to set-up the Modulator for different swing ranges, please consult Nujira.

Performing system level loadpull is another optimisation step that may improve performance. During this test the terminating impedance for the amplifier is varied around the nominal 50Ω termination by employing a loadpull tuner.

In theory if the processes of pulse characterisation and the realisation of the output matching network were error free, the optimum performance would be obtained when the amplifier is terminated with 50Ω. However, typically, for the first amplifier prototype the best overall performance is obtained when the loadpull tuner is set to an impedance different to 50Ω. If this is the case, a second iteration of layout design should be introduced where the output matching network is altered so that the optimum impedance is presented to the PA device when the amplifier output is terminated by 50Ω.

8 Appendix

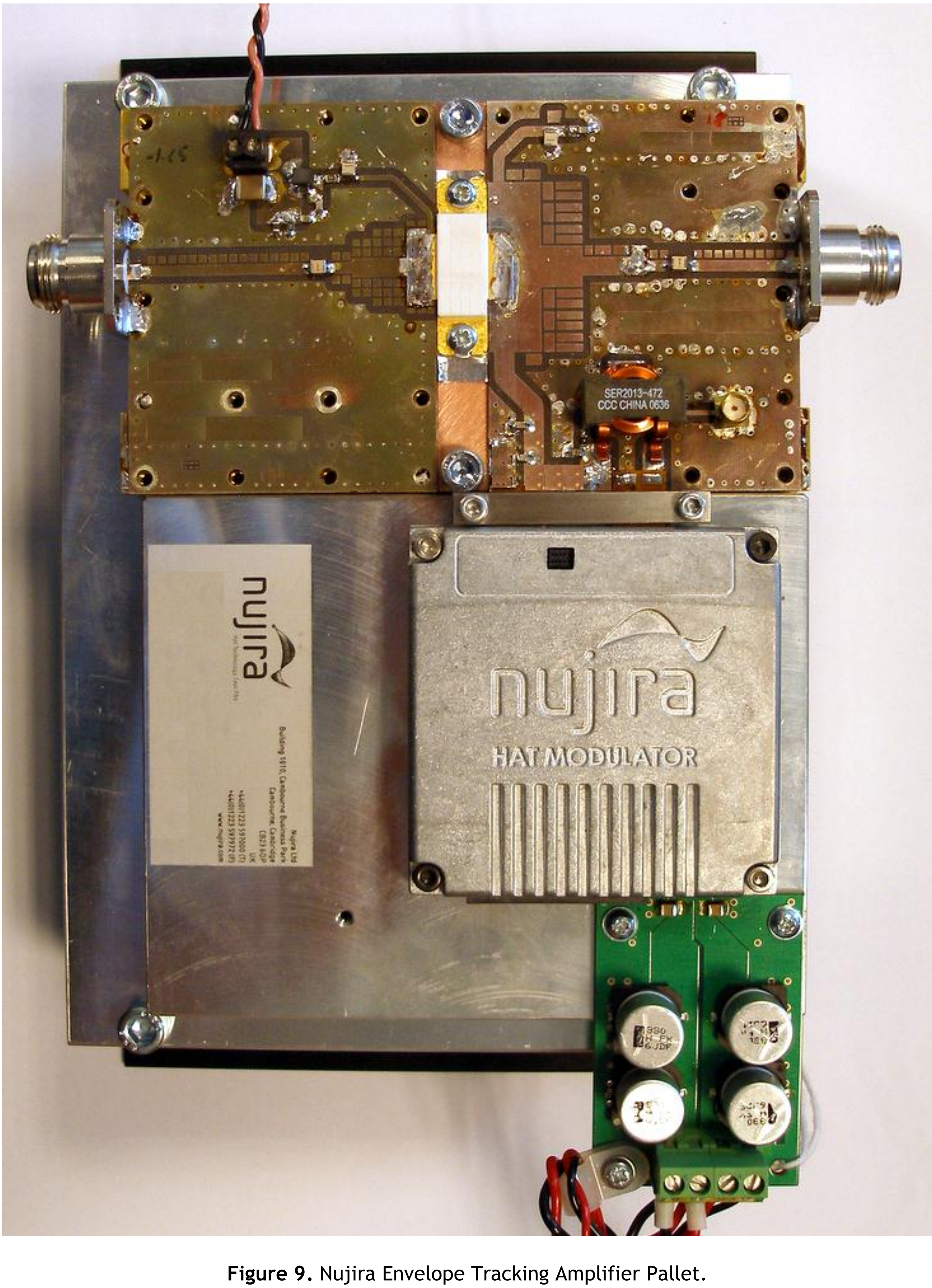


Figure 9. Nujira Envelope Tracking Amplifier Pallet.

9 References

[1] AN002098 coolteq.h Modulator User Guide, Nujira Ltd.

[2] PD002443 NCT-H3009 / PD002412 NCT-H4010 Datasheets, Nujira Ltd.

[3] Coilcraft Series SER2000 SMT Power Inductor Datasheet – Document 349-1, Coilcraft

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