Paper 11 John Worsnop G4BAO

Modifying 1960MHz High power Solid state Amplifiers for 13cm

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1. Introduction

This paper describes my work done to convert a number of surplus 1960MHz high power solid state cellular base station amplifiers to the 13cms band.

After doing some work on my own PA design for 1296, converting some 900MHz amplifiers for 1296MHz, (2) and looking at the work done by Chris Bartram GW4DGU on similar Amplifiers, I decided to tackle 2.3GHz conversions.
This was quite timely, as cellular phone systems have expanded there has been much concern over the power consumption of base stations; indeed I read somewhere that the UK Vodafone network at one time required the equivalent of a small nuclear power station to provide for it alone. This electricity cost has been tackled by network operators investing much in PA design, and replacing many of the Power Amplifiers with more efficient deigns, leaving many surplus SSPAs available for conversion.

2. Available amplifiers and their configuration

Such amplifiers operating in the 1960MHz or 2100MHz band had an original specification in the order of 30 Watts per carrier, so a multi carrier CDMA amplifier typically had the potential for over 200Watts in CW or SSB mode. Amplifiers such as the ILAM, IPAM, PKLAM and P2PAM looked good targets, along with a number of others from the Andrew Corporation

There has been much previous work done on this topic, and the paper by R.L Frey WA2AAU (1) first brought to my attention the possibility that 1960MHz amplifiers could be "stretched" up to 13cms.

3. Overview of available configurations

1960MHz vs. 2120MHz amplifiers (hard vs. easy!)

Easy

As a general rule, I found that amplifiers designed for the 2120MHz band would work directly on 13cms without any RF modification beyond (in the difficult cases) a little retuning. It is simply a case of "fixing" the bias to the devices by either hacking it on permanently under the control of a PTT line, or in more difficult cases where the bias is under complex processor control via a DAC, ripping out the bias and control and replacing it with a simple regulator and individual potentiometer controls for each device.

Hard

Being an RF Engineer, this does not really "float my boat," so I looked at the more difficult problem of moving a basic RF design for 1960MHz up to 2.3GHz. Obviously the same comments about biasing apply in these cases.

Consequently this paper will focus on the 1960 – 2320MHz re-banding process, and leave the 2100MHz amplifiers as a simpler, DC circuitry and control problem for others.

So, we are left with the challenge of moving a design that in most cases uses FETS that are internally matched for the 1960MHz band to operate 400MHz above their design range, with no data at 2320MHz. By definition, this has to be a cut and try approach, as I do not have the equipment to characterise the devices at 2320MHz

More in hope than anticipation, I decided to have a go at fitting an 85 watt 1960MHz device to my 23cm PA board and see what I could get out on 13cm. This is described in detail on my website (3). Surprisingly, results were acceptable, and matched well with Frey's results on similar devices so I was encouraged.

Amplifier topologies

The cellular amplifiers usually come in two basic topologies:

1. Individual single-device "pallets" fitted to motherboards with stripline hybrid combiners
2. One big PCB with all devices and hybrids together.

Figure 1 Typical "Pallet" Amplifier from Andrew Corp (P2PAM)

Figure 2 Typical "all in one" amplifier

The above topologies subdivide in to:

1. Driver stages, plus two output devices with quadrature hybrid combining

2. Driver stages, plus three output devices with more complex combining (Figure 2)
3. Driver stages, plus four output devices with quadrature combining (Figure 1)
4. Driver stages, plus Doherty output configuration

Much detailed information on hybrids and amplifier combining can be found on the Anaren website (5) and the excellent Microwaves101 website (5). I have raided these sites heavily for information for this paper, and give them due acknowledgement.

Two output devices with quadrature hybrid combining

In this topology, each device is matched to 50 ohms and the drive power is split equally but the amplifiers are fed 90 degrees out of Phase and recombined at the output.

Figure 3 A 3 dB Hybrid as a splitter

The 3dB Hybrid produces a pair of equal signals with a 90 degree phase difference.

Figure 4 A 3dB Hybrid as a combiner

The 3dB Hybrid takes a pair of equal signals with a 90 degree phase difference (in quadrature) and combines them.

Figure 5 The 2 device configuration

Combining two devices with 3 dB hybrids produces twice the power output of the single device, (less losses) and has the advantage that if the match of the devices is not quite perfect the amplifier as a whole preserves a good match at the expense of power dissipation in the 50 ohm terminations

Three output devices with more complex combining

Three output devices can be combined by using 5 dB hybrids that produce signals at 1/3 and 2/3 of the input power, and in quadrature. (See Figure 6).

Figure 6 A 5 dB hybrid coupler

The 2/3 signal can then be further split using a 3dB hybrid, leaving 3 signals at 1/3 input power with a 90 degree phase difference between each.

The three signals can then be combined after amplification at the output to produce 3x the power of a single device. (See Figure 7)

Figure 7 The 3 device configuration

Four output devices with quadrature combining

Figure 8 The 4 device configuration

Four devices can be combined with six 3 dB hybrids as shown in Figure 8

Doherty output configuration

The Doherty amplifier has improved efficiency over the topologies described earlier. They use a Doherty combiner, shown in Figure 9 below.

Figure 9 Doherty Amplifier

The Doherty amplifier uses two amplifiers; one is called the "carrier" amplifier while the second is called the "peaking" amplifier. Carrier amp is biased in Class AB while the peaking amplifier is biased in Class C which only conducts at half of the cycle. The Doherty amplifier works by splitting the input signal using a 3 dB hybrid as previously described. At the output, the two signals are out of phase by 90 degrees, but a quarter wave line is added to the peaking amplifier, to bring the signals back into phase. The two signals in parallel create a $Z_0/2$ impedance. This is stepped up to Z_0 by a quarter wave transformer. In a 50 ohm system the transformer line would be 35 ohms.

4. Devices to be found in the 1960MHz amplifiers

Recognising devices

Most of the work I have done has involved boards using Freescale, (formerly Motorola) devices. The part numbers are easy to recognise. For instance an MRFxx19130 is a 130Watt 1900MHz part, and a MRFxx21150 is a 150 Watt 2100MHz part. You will also see devices starting SRFxx and PRFxx which are usually special or pre production versions of the same device.

Internal Matching

Most high power S band devices use internal matching to improve efficiency and make matching easier. The can be used slightly beyond their design range by external matching but often you end up with lower efficiency and high Q narrow band amplifier design.

I take the view that for amateur and especially EME use this should not be a big issue as we tend to operate over a very small bandwidth and can easily provide bigger power supplies and good cooling systems to compensate. Such extra costs easily compensate for the extreme cost of commercial PAs specifically designed for amateur band use.

5. Which amplifiers should I attempt to modify?

One of the problems associated with changing 1960MHz designs is that while it is relatively easy to re-match the devices, the hybrid couplers used have a bandwidth limit, and as a rule many 1900MHz hybrids have a poor power and phase split at 2320MHz. Consequently, the phase and power split at 2320 MHz is just not good enough and the impedances presented to the devices are unknown and hard to characterise at this frequency.

The advantage of a design where each device is on its own separate pallet is that you can remove the pallet, and work on it separately and re match it at 2320 MHz, then carefully characterise the hybrids and either use them or replace them with ones that do work well at 2320MHz.

When you have a PA where all the devices and hybrids are on the same PCB, you end up with a problem with "too many variables," (i.e drive power and phase, presented source and load impedances, input and output matching) and it becomes almost impossible to re match the whole amplifier in one go.

Faced with this problem, you either simply avoid amplifiers that have a single PCB or take the approach of Frey, (1) and separate out each device in turn and try to re match it. It can then either be used as a lower power PA on its own, or multiple devices combined externally with in-band combiners.

6. Running up the Amplifiers

Checking out the unmodified amplifier

Before any modification is attempted, the amplifier should be run up as it comes, on its operating frequency. This will determine whether the amplifier control circuitry needs modifying. In most cases, the amplifier will default to a standby mode where the device gates are biased off. Checking the gate voltages of the PA stages will quickly determine this. If the voltages are above 3V, the devices are on and you will see a large supply current, 2.4 volts or less, the devices are off and the main supply will be a few hundred mA.

Initial analysis

It is often very informative to analyse the existing design by measuring all the matching capacitor values, and measuring the microstrip lines with a vernier calliper and working out their impedances and lengths, the amplifier circuit can then be modelled using the excellent (and freeware) "QUCS" (Quite Universal Circuit Simulator) (6) to get a handle on the original design.

To determine the PCB material, simply locate what is obviously a 50 ohm line, (such as one right at the input or output to a combiner) measure its width and the PCB thickness then using QUCS you can quickly reverse engineer that to a value of the permittivity of the PCB material.

You can then play with the matching networks and analyse the results before "cutting copper" to guide you to a quicker solution.

Biasing the Amplifiers

Vdd Drain supply

Many of these amplifiers run off -48 or +24 volts and have internal 24/48 to 28 Volt switched mode PSU modules to provide the drain supplies to the devices.

These PSU modules are not large enough to run the PAs at full CW power and usually need to be bypassed or disconnected and a separate 28V supply provided

Vgg Gate supply

In the rare case of the gate supply defaulting to "ON" then it is a case of finding a way to turn it on and off under control of a PTT supply. Often this is not a trivial task without a circuit diagram for the unit.

Often, removing the switch mode PSU means losing the supplies somewhere else and hence the bias on the amplifier. It is beyond the scope of this paper to provide details of control circuitry for particular amplifiers.

The simplest solution in most cases is to first disconnect the amplifier gate bias supplies and replace them with a simple regulated supply such as that shown in Figure 10, and, and in the process throw away any control board that is separate from the RF PCB.

Figure 10 Bias supply for driver plus 4 output devices

Tuning procedure

The following procedure can now be carried out with a single amplifier pallet, or for each of the stages isolated as described previously.

Test equipment required

- Signal generator covering 1900 – 2400 MHz.
- Driver amplifier capable of up to 5 watts over 1900 - 2400MHz
- RF power meter + attenuators allowing power measurement from a few mW to 250 Watts.
- Thruline RF power meter 5W or low power meter and dual directional; coupler
- 28 Volt 30A PSU
- 48 Volt 15A PSU
- 30 Amp (preferably "clamp" type) DC Ammeter.
- Digital multimeter

Test setup

Figure 11 Test setup

Figure 12 Test setup

With the amplifier terminated, and no drive, apply the bias supplies, and slowly increase the gate voltage on each device in turn to give the required Drain current as specified by the manufacturer for Class AB operation (usually in the order of 5 to 10% of the final PA current at full power.

Test at operational frequency

Without the matching stub in circuit, apply drive at the original frequency and check and note the output power, total drain current, and gain for future comparison to the modified amplifier.

Initial input matching using an external 2 - stub tuner

Input and output matching are interactive, so my approach to re matching these amplifiers relies on reducing the number of variables before starting to modify the PCB.
By initially using a 2 stub tuner to match the input of the whole amplifier, that is, device plus 1900MHz matching network this just leaves you to work on the output matching circuit for best output and efficiency.

Output matching seems quite uncritical between 1960 and 2320MHz, and usually the output can be matched by adding small tabs or low value (a few pF) capacitors to ground after the output "fat line" Often in older designs like the Andrew Pallets, there is already a trimmer in this position and it can be adjusted to match the output.

The aim in this output matching is to tune for maximum output power at the best efficiency (lowest drain current for a given power). Once this has been achieved, you can then remove the input stub tuner, knowing the output is close to matched and work on the input matching.

A note on the use of trimmers for matching

At S band, component losses become extremely important, and in the case of power amplifier output tuning, the RF currents flowing in matching and coupling capacitors can be high. Do a "back of a fag packet" calculation on the output coupling capacitor for a 200Watt amplifier in to a 50 ohm resistive load. Pout $=I^2R$, and you will see that the current in the capacitor is 2 Amps, so losses become very important. Circulating currents in lower impedance matching networks can be even higher, and I have seen poorly chosen components reach "skin removal temperature" due to losses. I try and use decent ATC100 and 700 or similar capacitors designed for the frequency where possible, and only use my small collection of very expensive and very high quality microwave trimmers when I need to get a rough idea what value is needed. I use a trimmer in circuit to "tweak" then measure its value with my G4HUP component bridge (8). Usually this is close enough to allow you to then replace it with a fixed capacitor with a careful use of 0.5 and 1pF capacitors or fine tuning.

The "fat line and capacitor" input network

If you look at many published designs for amateur 13cm PAs, the input matching is simple and consists of a series, low impedance, (5 -10 ohms) microstrip in the order of 0.2 to 0.25 wavelengths long, from the gate, followed by a series or shunt capacitor, often a trimmer, to allow fine tuning of the match. If you plot some typical device impedances on a Smith Chart, you will see why. (Figure 13)

They lie mainly to the far left (low impedance) side of the chart close to the horizontal axis. A series line of the correct impedance will then match the device to 50 ohms at the chart centre, and the series capacitor allows final "trimming" for best match.

Figure 13 Two impedances matched with "fat lines" of 5 and 10 ohms plus series C

In the example in Figure 13 quite a large change in device impedance just requires a line width change and a slightly different series capacitance to re match.

Adjustment procedure

I have noted in many of the 1960MHz amplifiers, you can re match the input to 2320MHz by widening the existing "fat line," followed by a series or shunt trimmer before the 50 ohm line to the input connector.

You need to interactively adjust the width and length of the extended fat line until you can get a dip on the input vswr with the trimmer at 2320MHz. This will usually coincide with maximum power output.

In the case of the Andrew Corporation Pallets used in the "P2PAM" amplifiers, (Figure 14) the original input shunt trimmer can be "recycled" to use as a shunt tuning element.
Due to the internal device matching, the tuning is often quite sharp, and the efficiency and gain are lower, but typically I've had over 100Watts out and 12 - 13dB gain over the 2320MHz band from a 130Watt 1960MHz device.

Figure 14 Andrew 130Watt Pallet before (L) and after (R) retuning

On some pallets there is not room to widen or lengthen the lines due to close proximity of ground plane. My simple solution to this is just to stick Kapton (PTFE) tape over the ground plane and stick the copper foil over that. See Figure 15

Figure 15 Use of Kapton tape underneath the tabs where space is limited.

There is no reason why this retuning approach cannot be taken with amplifiers that have all the circuitry on 1 PCB, it is just more difficult mechanically and electrically to isolate the stages and make connections to each one independently. The PKLAM which contains a PA by JRC is a good example, and is shown in Figure 16.

Figure 16 PKLAM amplifier with JRC PA board

The driver and output stages of this amplifier are a good general example of the approach for tackling this type of layout. A bias input is easily traced, and each stage has an individual potentiometer to adjust it, so bias can be applied to the whole board from a single connection.

The output stages of this JRC board use a pair of "Gemini" devices, (single package, two FET chips) each half fed 180 degrees out of phase (push pull). The power is split with miniature Soshin 180 degree hybrids, and each Gemini pair is fed in quadrature from what appear to be ferrite isolator 90 degree hybrids. The Isolator hybrids are designed for 1960MHz and may not work well enough at 2320 so each Gemini stage should be matched to 50 ohms first with the hybrids removed, and if necessary, some other way must be implemented to combine the Gemini devices.

Drive and pre driver stages are conventional single ended stages, and can be separated out and matched using the techniques described earlier. It is crucially important that each device stage of the whole amplifier is correctly matched and tuned before attempting to combine them, otherwise results will be poor. Frequency dependent components such as isolators and filters need to be measured for loss at 2320 and either replaced or bypassed. For Amateur use a good output low pass or band pass filter is all that is needed if these networks are removed.

7. Combiners and isolators – pitfalls

All these amplifiers are fitted with isolators on their output and miniature stripline hybrids to do the combining. These components are frequency sensitive.

Isolators

A 1960MHz isolator operating at 2320MHz will lose directivity causing forward power to be dissipated in its reverse power load, and a consequent increase in overall loss.

A typical specification for the 1920MHz isolator used in the Andrew P2PAM is shown in Appendix 1. I have run this isolator at close to 100Watts for short periods at 2320MHz, but have not tested it above this.

At the 300Watt level this can be a very risky problem indeed, and often it is just simpler to bypass the output isolator and fit an external one that is for the correct band. Alternatively if you ensure other VSWR protection, do not fit one at all! Added to the fact that many of these isolators are not rated above 100Watts the second option is often the best, especially if you plan to run full duty cycle JT modes.

Combiners

It is a slightly different story with combiners, as some seem to be rated up to 250 Watts and at least 2.2GHz but you will need to check the Anaren/Xinger website (5) before you decide whether you can risk using them. Obviously the power rating is less of an issue for the input combiners, but the accuracy of the amplitude and phase split is.

The bottom line is that if they are used significantly "out of band" the combining will be poor, power will be reduced, and in extremis the combiners will be destroyed with the risk of taking the output devices out due to subsequent mismatching.

Checking the temperature of the coupler relative to the rest of the PCB with a laser thermometer or thermocouple…(or in extremis, a wet finger, **AFTER REMOVING ANY RF DRIVE**!!!)…… is a good way of checking how the combiners are coping with the overload. But be careful, they can get to a temperature that will burn skin if over run, so you have been warned!

The 100 Watt Combiners can fail in spectacular fashion with a puff of black smoke if they are run at 250 Watts output for any significant time.

Appendix 2 contains the specifications and applications notes for some combiners in common use in amplifiers of this kind.

8. Thermal considerations

I have already noted that one of the consequences of re banding these internally matched devices is a drop on DC to RF conversion efficiency. You can easily end up with an overall efficiency of less than 40%, so for a 270 Watt output, your DC input will be approaching 700 Watts meaning that 430 Watts will have to be dissipated as heat.
The heat sinking on these amplifiers are usually much underrated, firstly because in normal use the RF power will be closer to 100Watts, and they are designed for Forced air cooling in large racks. I usually fit two 5 inch muffin fans to the heatsink, (Figure 17) and run them continuously with the excellent fan controller board kit provided by Paul Wade W1GHZ (7)

Figure 17 Cooling fans on a P2PAM amplifier

9. Some examples and results achieved

I have re banded a number of amplifiers. Some I worked on just the driver and PA and some I have utilised the pre driver stages as well.

Andrew P2PAM pallets

This version of the P2PAM output pallet uses a single MRF5S9100 device, and the modification involves increasing the length of the input line and adding a 1pF capacitor and low value trimmer to ground. Due to the restricted space on the PCB the added "tab" goes over the ground plane, and is insulated from it with some kapton tape. See Figure 18 below

Figure 18 MRF5S19100 pallet from Andrew P2PAM

Some 70 Watts at 2320MHz was achieved from this 100Watt 1960MHz device at just under 50% efficiency. See Figure 19

Figure 19 Single MRF5S19100 pallet results

JRC PKLAM board

As of writing this paper I am still working on modifications to the JRC PKLAM board described earlier.

IPAM 2.1GHz Amplifier

Much work has been done on converting the control electronics of these amplifiers, notably by Doug G4DZU, and his unpublished paper is reproduced in Appendix 2. No RF modifications are required to use them on 2320MHz and they produce in excess of 250 Watts.

A small 100 Watt 2.1GHz Doherty Amplifier

This Doherty amplifier (Figure 20) of unknown manufacture was found to produce 100Watts for 5mW in without any RF modifications apart from linking out a driver stage bandpass filter. (Figure 21).

Figure 20 The Doherty Amplifier module

The Amplifier is a single large PCB with two low power MMIC drivers followed by a 5 Watt capable module driving the Doherty pair

Figure 21 the Doherty PCB

It uses two 130Watt NXP devices, and has the advantage of having fixed bias controls (probably for test purposes) already on the PCB that just need linking in to circuit by moving zero ohm resistors. (Figure 22)

Figure 22 changing to fixed bias

The bias can be switched on and off under PTT control by grounding pin 5 of IC501 removing the 9 Volt supply (Figure 23)

Figure 23 Bias on/off control point

I set the gate bias on the Class AB stage at 2.2 volts, and the Class C stage at 0.8 volts. The driver chip has 3 stages, and the bias on the last two of these was set at 3.09 and 2.81Volts. In this condition, the whole amplifier drew 1.7 Amps from the 28 Volt supply without drive power. At +7dBm (5mW) drive to the input, 100Watts RF out was achieved at around 9 Amps from the 28Volt supply.

It may be possible to get more output from these amplifiers by "tabbing" them, but I have not carried out this procedure.

10. Final comments and observations

Performing re-banding and other RF modifications to existing S band hardware is not something to be tackled by the feint hearted or those without some basic RF knowledge and test equipment as described in section 6.

While modern LDMOS devices are quite robust, it is VERY easy to destroy RF power devices ether by getting the bias levels wrong, over driving, or mismatching them. I have a numerous dead amplifiers that attest to this! Replacement QRO device are not cheap and it is often very difficult to physically remove and replace the "blown" device from the board and pallet assembly.

Fortunately much surplus equipment that has not been worked on or has "ready to wear" published modifications often come at little or no cost to people prepared to do a bit of trailblazing and do the work for others to copy.

11. References

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