# Comparison of Combining Schemes for 1-2kW Solid State Power Amplifiers in the 0.1 – 2 GHz Frequency Band

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## Abstract

RF simulations of two different methods of implementing power combining of eight, 1kW, 500 MHz solid state power amplifiers are presented. The first using eight circulator plus isolation loads feeding an 8-way impedance combiner. The second method utilizes an eight input Gysel type power combiner. The overall electrical performance, response to the loss of one or two amplifiers, and estimated costs of each method is also compared to illustrate the issues involved.

## Introduction

The steady progress of Solid State Power Amplifier technology has made the prospect of replacing high power tube transmitters more realizable in the 100 – 2000 MHz frequency bands. The method used to combine the outputs of those SSPA's has become more important since there is a push to achieve high efficiency and electrical performance while still protecting the output stages of the amplifiers. Ferrite circulators, feeding n-port impedance power splitter/combiners, are the tried and true method of protection from high power reflections. However, at these output levels, there are significant impacts to both the insertion loss and power dissipation of using circulators.

Using a corporate feed/combiner network of isolated 4-port devices is also an established method to combine these power levels. However, with the number SSPA's required to generate the 10-60kW final output range to compete with tube transmitters, this scheme becomes cumbersome and space inefficient. In addition, the isolation load power requirements get more demanding, and expensive, as the signal gets closer to the final output. The SSPA output power also makes the N-port Wilkinson type combiners not usable due to the roughly 100W power dissipation limit on the isolation resistors.

The N-port Gysel type combiner offers an attractive alternative for combining multiple high power inputs. The configuration can be implemented in a space saving configuration, often in a 19" rack mountable package, and uses isolation loads that are on the same order as the power output of the SSPA. By using two levels of Gysel combiners, a system can easily be created to combine 50 to 80 SSPA outputs. The electrical performance can also be optimized to be very wideband (1 octave or more) for those applications that require that feature with high power.

This paper compares two methods to specifically implement combining eight 1kW SSPA's at 500 MHz to illustrate some of the issues involved. The first uses eight, 1kW circulators (Type N coax inputs) feeding an 8-way, coax impedance power splitter/combiner with a 3-1/8 output. The second method demonstrates an 8 input Gysel combiner also with Type N inputs and a 3-1/8 coax output. RF simulations establish the overall electrical performance of each method and the response of the two systems to a few possible scenarios of one or two of the SSPA's going dead or operating at reduced power. A comparison of the final implemented monetary cost of each system is also presented.

## Circulator with 8-way Splitter Method

The analysis tool used to perform the RF simulations in this paper was Keysight's Genesys. The microwave circuit diagram is shown in Figure 1. You see from the diagram that the 8-way impedance power splitter is the star network of transmission lines (TL1-TL9) on the right side with the output being the 50 ohm port #10. The output quarter-wave section is a 30.4 ohm section in 3-1/8 coax. The eight 86.6 ohm quarter-wave sections feeding the output can be realized in any smaller sized coax that can handle the 1kW input power. This arrangement of quarter-wave transformers gives a reasonably broad-band splitter/combiner network by balancing the transition impedance ratio between any input and the output to the effective star point impedance. As a point of reference, if this network were viewed as and power splitter with port 10 as the input, then this port would have return loss of better than 20 dB from 465 to 535 MHz (14% BW).

The center 8 symbols are the circulators with the load ports shown just below them starting with port 2 thru 9. For analysis purposes, these are ideal circulators with no insertion loss and infinite isolation. The remainder of the circuit symbols on the left hand side are ideal attenuators and phase shifters which are fed, in parallel by the ideal amplifier from port 1 with the gain set to 9.03 dB (gain of 8). This arrangement allows one to simulate 8 SSPA's feeding each circulator with 1kW of power. The attenuator and phase shifter allows individual control of the SSPA's output to simulate the effective power distribution given certain conditions. For example, as shown in Figure 1, if Attn_1 is set to 40 dB, this simulates the power loss of one of the eight SSPA's. The simulation then shows where the remaining power of the seven SSPA's is distributed.

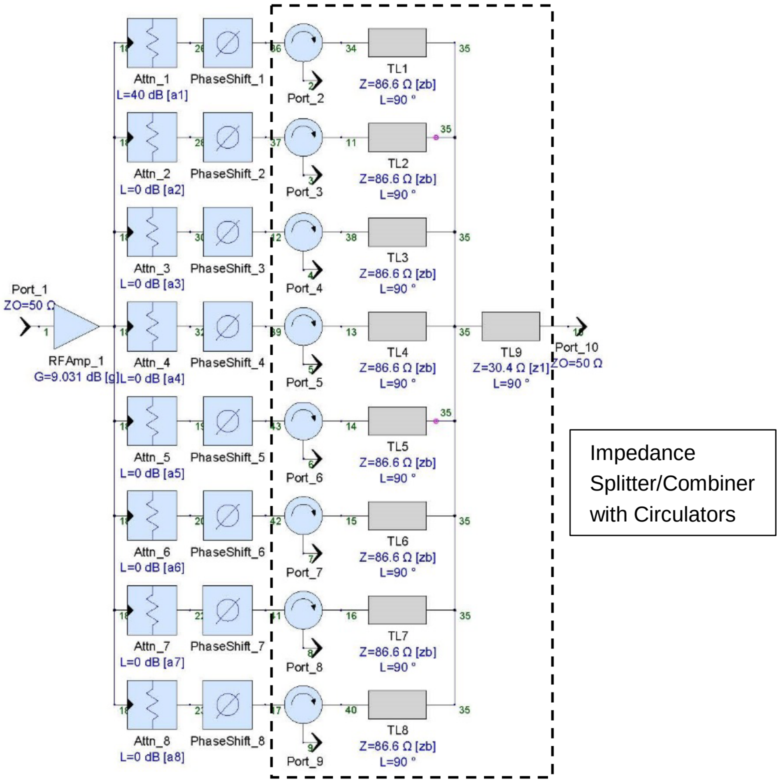

Figure 1. Schematic of 8-way Impedance Splitter/Combiner with circulators and feeding network

Many different scenarios can thus be anticipated with this arrangement simply by applying different attenuations and phase shift distributions. For example, tolerances with respect to amplitude and phase balance of the SSPA's could be determined with respect to output power efficiency, or how to size the loads placed on the outputs of the circulators given the expected operating conditions or worst case scenarios. These simulations would be invaluable for the transmitter manufacturer to determine the operating conditions for the system of SSPA’s.

For the sake of comparison in this paper, 6 scenarios were simulated to illustrate the response of the combining networks. Table I gives the power output (in kW) at ports 2 thru 10 for the following conditions:

1. Nominal: All SSPA’s in perfect amplitude and phase balance
2. 1 Amp 10$^{o}$: One amplifier (port 2) with phase error of 10 degrees
3. 1 Amp 20$^{o}$: One amplifier (port 2) with phase error of 20 degrees
4. 2 Amp 20$^{o}$: Two amplifiers (ports 2 & 3) with phase error of 20 degrees
5. 1 Amp Dn: One amplifier (port 2) completely off, no output
6. 2 Amp Dn: Two amplifiers (ports 2 & 3) completely off, no output

| Port | Nominal | 1 Amp 10$^{o}$ | 1 Amp 20$^{o}$ | 2 Amp 20$^{o}$ | 1 Amp Dn | 2 Amp Dn |
|---|---|---|---|---|---|---|
| #10 Main Output | 8.000 | 7.973 | 7.894 | 7.761 | 6.142 | 4.530 |
| #2 Refl. Power Thru Circulator | <.001 | .023 | .092 | .119 | .740 | .543 |
| #3 Refl. Power Thru Circulator | <.001 | <.001 | .002 | .119 | .017 | .543 |
| #4 Refl. Power Thru Circulator | <.001 | <.001 | .002 | <.001 | .017 | .064 |
| #5 Refl. Power Thru Circulator | <.001 | <.001 | .002 | <.001 | .017 | .064 |
| #6 Refl. Power Thru Circulator | <.001 | <.001 | .002 | <.001 | .017 | .064 |
| #7 Refl. Power Thru Circulator | <.001 | <.001 | .002 | <.001 | .017 | .064 |
| #8 Refl. Power Thru Circulator | <.001 | <.001 | .002 | <.001 | .017 | .064 |
| #9 Refl. Power Thru Circulator | <.001 | <.001 | .002 | <.001 | .017 | .064 |

Table I: Distribution of SSPA power (in kW) under various conditions for
Circulator Splitter/Combiner Network

One of the first observations to note is that phase imbalances of less than 10$^{o}$ do not cause much degradation in the output power in terms of percent power loss. The 10$^{o}$ phase imbalance of one SSPA causes less than 0.3% power reduction at the output. The majority of miss-directed power comes back at the SSPA that is out of balance which is shunted by the circulator to its associated load (note that this will be a common phenomena of these combining networks). Even a 20$^{o}$ imbalance of one or two SSPAs cause a power reduction of 1.3% and 2.9%, respectively. More simulations could be run to determine an RMS phase error that is required to achieve a certain efficiency goal, and thus, the requirements of the “drive” phase compensation network on the input of the SSPAs.

The impact of having a SSPA lose power all together is much more dramatic, however. Note, the power from the seven remaining amplifiers will not all go towards the output. In fact, only 87.7% of the remaining 7kW will be seen at the output. The remainder is lost in the circulator loads, and most of that power is directed towards the SSPA that is down. Thus, if the intention is to still operate the system with one SSPA lost, then the designer must size the loads on the circulator to handle at least 75% of the SSPA output. The situation is even worse when two SSPAs are down: 75.5% of the 6kW power to the output, the rest to the circulator loads.

Of course, the situation is different, if instead of an SSPA being total lost, one or two amplifiers run at reduced power. This situation was not presented but can be inferred from the data. For example, if one amplifier is running at 750W compared to the 1kW for the other seven, then 87.7% of that difference (250W) would go to the circulator load for that SSPA in the form of reflected power (i.e. 0.877*250W=219W). Thus, the total output would then be 7531W, or a 2.8% reduction of the total available power.

With any of the above scenarios, the combiner system would still allow the SSPA system to operate at predictable reduced power with the circulators protecting all individual SSPAs from high power reflections. Note, this continued operation necessitates being able to dissipate the additional heat generated from the loads.

One must also take note, that even with all the SSPAs operating at identical power and perfect phase balance there is still the practical insertion loss of the circulators which for these power levels are of the order of 0.2 to 0.5 dB which corresponds to 5 to 10% power lost which is the major drawback of this scheme of combining.

## 8 Input Gysel Combiner

The Gysel circuit diagram is shown in Figure 2. The star network on the output side is essentially the same as an impedance splitter/combiner. The important difference is the additional star network to the left comprised of transmission lines TL3, TL7-13 and a set of intermediate quarter-wave lines, TL2, TL6, TL14-19. It is this additional network of transmission lines that makes the input to the Gysel combiner matched independent of the condition of the other inputs. Much like how a 4-port passive device can have all ports matched, while a 3-port cannot. The extra Gysel combiner ports are shown as port #11 thru #18. These ports are terminated in isolation loads that will absorb any imbalance power distribution. The input ports to the Gysel combiner are located between output star network (i.e. between TL1 and TL2) and the additional network. The circulators shown in this schematic are there only for the purposes to direct any reflected power to ports #2 - #9. They are not part of the Gysel combiner. They are there only for the purpose of providing a simultaneous excitation for the combiner inputs for the simulation. Thus, the exact same excitation scenarios are performed to compare the operation of the Gysel network to the previous circulator impedance splitter/combiner network.

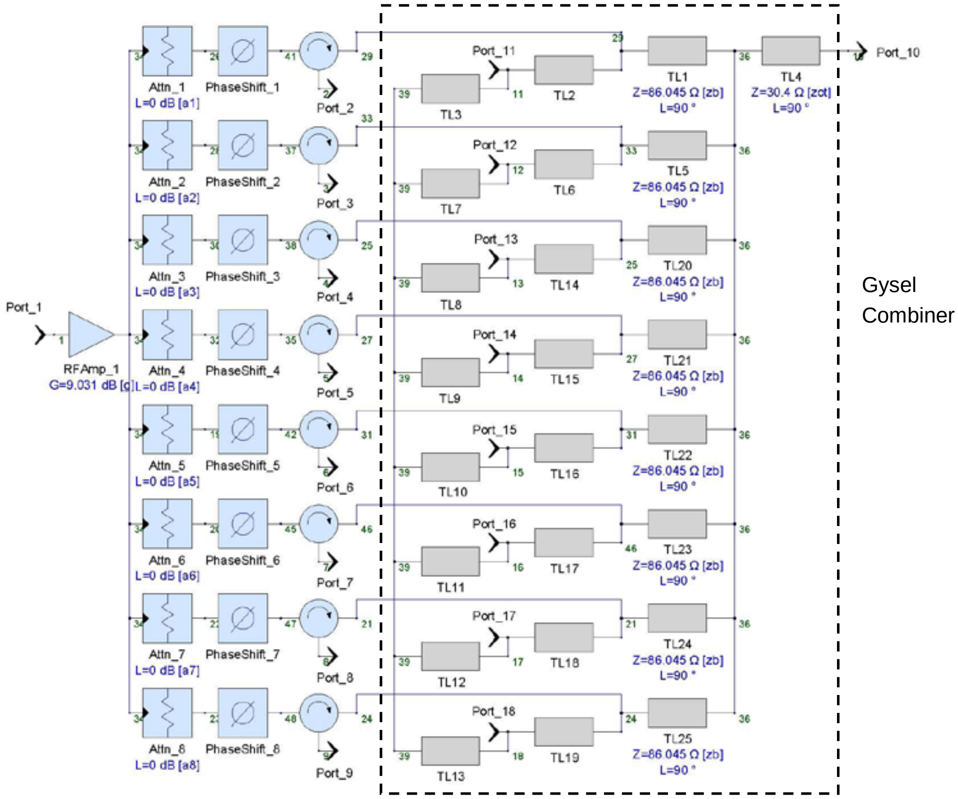

Figure 2. Schematic of 8-way Gysel combiner and feeding network, circulators

It is clear from Table II, that the matched input condition of the Gysel network is well demonstrated. The simulation produced no appreciable power being reflected back towards the SSPAs for any condition. This illustrates a major advantage of the Gysel combiner in that it requires no circulators to protect the SSPAs, eliminating both the insertion loss and monetary cost of these devices. If one examines the power directed towards the isolation load ports, we find that these levels are very comparable to the reflected power towards the circulators in the previous combiner.

| Port | Nominal | 1 Amp 10° | 1 Amp 20° | 2 Amp 20° | 1 Amp Dn | 2 Amp Dn |
|---|---|---|---|---|---|---|
| #10 Main Output | 8.000 | 7.972 | 7.889 | 7.816 | 6.138 | 4.530 |
| #2 Refl. Power Thru Circulator | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 |
| #3 Refl. Power Thru Circulator | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 |
| #4 Refl. Power Thru Circulator | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 |
| #5 Refl. Power Thru Circulator | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 |
| #6 Refl. Power Thru Circulator | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 |
| #7 Refl. Power Thru Circulator | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 |
| #8 Refl. Power Thru Circulator | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 |
| #9 Refl. Power Thru Circulator | <.001 | <.001 | <.001 | <.001 | <.001 | <.001 |
| #11 Isolation Load for Input 2 | <.001 | .024 | .091 | .070 | .750 | .551 |
| #12 Isolation Load for Input 3 | <.001 | <.001 | .002 | .070 | .017 | .551 |
| #13 Isolation Load for Input 4 | <.001 | <.001 | .002 | .007 | .017 | .061 |
| #14 Isolation Load for Input 5 | <.001 | <.001 | .002 | .007 | .017 | .061 |
| #15 Isolation Load for Input 6 | <.001 | <.001 | .002 | .007 | .017 | .061 |
| #16 Isolation Load for Input 7 | <.001 | <.001 | .002 | .007 | .017 | .061 |
| #17 Isolation Load for Input 8 | <.001 | <.001 | .002 | .007 | .017 | .061 |
| #18 Isolation Load for Input 9 | <.001 | <.001 | .002 | .007 | .018 | .061 |

Table II: Distribution of SSPA power (in kW) under various conditions for
Gysel Combiner Network

This is not an unexpected result in that the output star network is the same and the previous combiner. Thus, the features, operating characteristics, and conditions for operation for system of SSPAs are all comparable to that of the previous combining scheme with one major difference. The Gysel combining scheme is inherently much more electrically efficient because of the lack of circulators. In fact, the Gysel can be almost 100% efficient in power combination with an insertion loss of less than 0.03-05 dB (0.7 – 1.2% power loss) in the UHF frequency band.

Physically, there are several ways to implement the Gysel combiner, but at UHF frequencies, a relatively compact design can be implemented in a standard 19” rack mountable configuration. An example is shown in Figure 3 for the 500 MHz, 8-way version simulated in this paper.

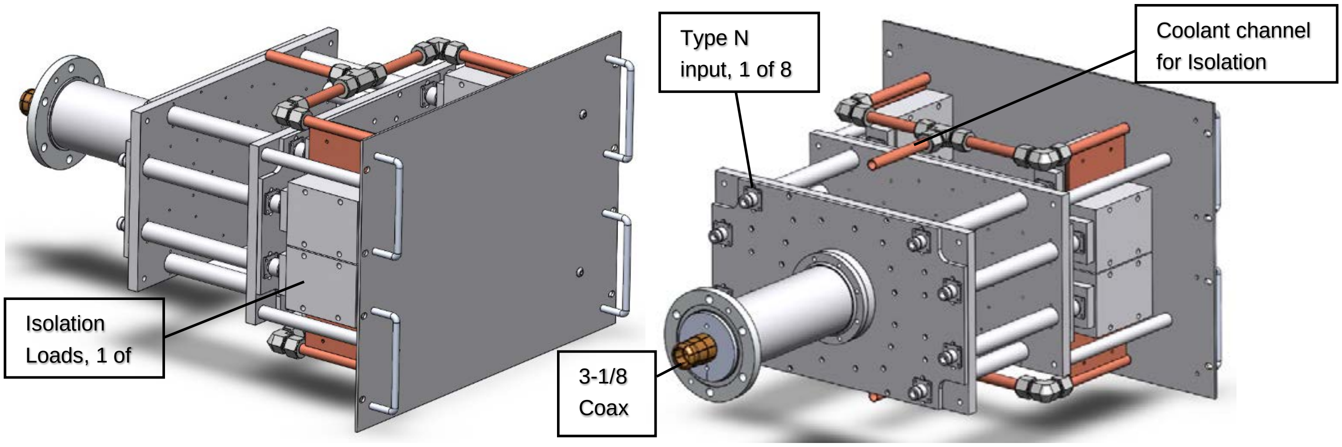

Figure 3. 8-way Gysel combiner in Rack mount configuration. 8 Type N inputs, standard 3-1/8 coax output.

**Monetary Cost of Implementing Each Method**

The estimated cost of each of the methods is intended to show only a general relative value based on what major components are present for the purpose of system design. The assumptions used will be to size the loads on the circulators and attached to the Gysel to be 75% of the individual SSPA output power to operate in a “one amp down” condition. Also, each combiner will be rack mounted and have cooling plates to absorb the heat from the loads. Tables III and IV show the major components and their associated estimated cost for each method.

| Component Description | Unit Cost ($) | Qty | Ext. Cost ($) |
|---|---|---|---|
| Circulator, Type N Ports, 500 MHz, 1kW Ave. Power | 1500 | 8 | 12000 |
| 8-way Splitter/Combiner, Radial Head, Type N in, 3-1/8 out | 3200 | 1 | 3200 |
| RF Load, Type N, 750W CW water cooled | 850 | 8 | 6800 |
| Combiner rack mount & load cooling plates | 650 | 1 | 650 |
| **Total** | | | **22650** |

Table III: Estimated Cost of Circulator 8-way Splitter Method

| Component Description | Unit Cost ($) | Qty | Ext. Cost ($) |
|---|---|---|---|
| 8-way Gysel, Type N in, 3-1/8 out, rack mount with cooling plates, no internal loads | 6500 | 1 | 6500 |
| RF Load, Type N, 750W CW water cooled | 850 | 8 | 6800 |
| **Total** | | | **13300** |

Table IV: Estimated Cost of 8-way Gysel Method

As shown, there is a significant cost reduction to using the Gysel combiner simply from the fact that no circulators are needed. Note also that even if system requirements size the loads to be smaller, and less expensive, the difference is cost remains the same.

## Conclusions

The paper outlined the basic operating principles and performance of two methods of combining eight 1kW solid state amplifiers. Clearly each method is viable and the overall electrical performance is similar with respect to bandwidth and power handling. The exception is in the efficiency of the system due to the insertion loss of the circulators that are not required for the Gysel combiner. In addition, the lack of circulators for the Gysel design makes it significantly less costly to implement for these power levels in the UHF frequency band.