5 Steps to Selecting the Right RF Power Amplifier

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You need an RF power amplifier. You have measured the power of your signal and it is not enough. You may even have decided on a power level in Watts that you think will meet your needs. Are you ready to shop for an amplifier of that wattage? With so many variations in price, size, and efficiency for amplifiers that are all rated at the same number of Watts many RF amplifier purchasers are unhappy with their selection. Some of the unfortunate results of amplifier selection by Watts include: unacceptable distortion or interference, insufficient gain, premature amplifier failure, and wasted money. Following these 5 steps will help you avoid these mistakes.

Step 1 - Know Your Signal
Step 2 – Do the Math
Step 3 - Window Shopping
Step 4 - Compare Apples to Apples
Step 5 – Shopping for Bells and Whistles

Step 1 – Know Your Signal

You need to know 2 things about your signal: what type of modulation is on the signal and the actual Peak power of your signal to be amplified. Knowing the modulation is the most important as it defines broad variations in amplifiers that will provide acceptable performance. Knowing the Peak power of your signal will allow you calculate your gain and/or power requirements, as shown in later steps.

Signal Modulation and Power- CW, SSB, FM, and PM are Easy

To avoid distortion, amplifiers need to be able to faithfully process your signal's peak power. No matter what the modulation type is, you need to know the Peak power. Fortunately, for many modulation types Average power is the same as Peak power: CW, SSB (single tone and voice), FM, and Phase Modulation all have Average equal to Peak power. The power in these RF carriers is relatively easy to measure with an Average power meter, a Spectrum Analyzer, or an RF Wattmeter. Many RF amplifiers are rated for CW power, so that spec will apply for SSB (single tone and voice), FM, and Phase Modulated signals as well. For SSB, since the carrier is suppressed, the significant power is all in the sideband carrier.

Watch Out for AM Modulation

AM Peak power depends on the percentage of modulation, but you may need to allow for 100% modulation, which creates signal peaks of 4x the un-modulated carrier, or +6dB. That means that you would need a 400W amp to faithfully AM modulate a 100W CW signal. If you have less power available, or "headroom",

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your amplifier will be operating in compression, which will distort the signal by “clipping” or cutting off the peaks of the waveform. Although some distortion may by tolerable for speech communication, since AM communications are subject to a variety of other impairments, you should specify your RF amplifier to produce the minimum AM distortion possible. AM voice communications usually use modulation depth in the range of 70-80%. Specifying performance at 90% modulation will provide a safe margin for most AM communications.

AM Peak Power (dBm) = CW Power (dBm) + 6db (100% modulation)
AM Peak Power (Watts) = CW Power (Watts) × 4 (100% modulation)

A 100W amplifier will begin to clip a 100W carrier as soon as any AM modulation is applied. Clipping is a form of distortion that causes more problems than just reducing signal “readability”. Clipping also causes increased harmonic products in the form of carriers of substantial power, which can cause interference far off-frequency.

AM average power is not the same as CW average power, as it varies with the modulation depth. The average power increases with modulation depth. For sine wave modulation, the relationship is as follows:

Modulation Index (M) = Modulation Depth / 100
AM Average Power Increase = $(1 + M^2 / 2)$
AM Average Power Increase in dB = $10 \log_{10} (1 + M^2 / 2)$

Example: For a 100 WCW signal with 70% Modulation:
AM Average Power Increase = $(1 + 0.70^2 / 2)$
AM Average Power Increase = $(1 + .245)$
AM Average Power Increase (ratio) = 1.245

AM Average Power Increase in dB = $10 \log_{10} (1 + M^2 / 2)$
(Continued from the example above)
AM Average Power Increase dB = $10 \log_{10} (1.245)$
AM Average Power Increase dB = 0.95

To calculate the Peak power required when you know your AM Modulation Depth or Index:

AM Peak Power (Watts) = $(M + 1)^2$ x CW Power

Example- For a 3WCW signal with 80% Modulation Depth:
Peak Power (W) = $(0.8 + 1)^2$ x 3 WCW
Peak Power (W) = $(1.8)^2$ x 3 WCW
Peak Power = 9.72 Watts

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Example- For a 100 WCW signal with 90% Modulation Depth:
Peak Power (W) = $(0.9 + 1)^2$ x 100 WCW
Peak Power (W) = $(1.9)^2$ x 100 WCW
Peak Power = 361 Watts

Multi-Tone and Complex Modulation Peak Power
If your signal is composed of multiple discrete CW, SSB, FM or PM carriers, you can essentially add the powers of all the carriers to arrive at a Peak power level. If the number of carriers is dynamic, or the signal is created by complex (phase and amplitude) modulation you will need to resort to other means of measurement. If you have a Peak Power Meter, and you are sure no other significant contributions to the signal power are present, it should provide a valid Peak measurement. Checking with a spectrum analyzer is always prudent to be sure of what a broadband power sensor is "seeing". Lacking a Peak power meter, a spectrum analyzer with a broadband statistical power measurement like CCDF, or a format-specific analyzer that can report Peak power, with an Average power measurement you can estimate a Peak power level based on your signal format Peak-to-Average ratio (PAR) or Crest Factor. For example, 64QAM has a PAR value of about 3.7dB. PAR actually uses the RMS value, not average, so add 1.5dB to the average power to get RMS power. For a 64QAM signal with 0 dBm average power:

0dBm average + 1.5dB ≅ 1.5dBm RMS
1.5dBm RMS + 3.7dB PAR ≅ 5.2dBm Peak

Modulation Format	Approx. PAR (dB) Without CFR	Approx. PAR (dB) With CFR
64QAM	3.7	N/A
8VSB	6.5-8.1	4-6
W-CDMA (DL)	10.6	2.2-6.5
WIMAX/OFDM/WLAN	12-13	6-7

These higher PAR levels translate to higher power being needed in an amplifier. That can be seen as inefficiency, as the heavy lifting is being done at lower power levels, or as a reasonable cost of increasing the density of the data. Crest Factor reduction (CFR) schemes that pre-clip the signal can reduce the PAR for some types of modulation, but even so, complex modulated signals will still degrade slowly over a wide power range as the signal peaks are increasingly clipped in the amplifier (see **fig. 1**). This causes progressively increasing digital errors and also pushes energy into adjacent channels, creating "noise". It is important to remember that PAR for complex-waveform signals can vary with the data payload sent, so try to test your

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system with a worst-case data set. Pseudo-noise (PN) data produced by a signal generator may not represent your worst-case signal.

So What if the Amplifier Runs out of Headroom?
Running an amplifier out of the linear range doesn't just mean you get less power out. It can create big problems:

1. **You can damage the amplifier.** Power amps typically specify a P_1 level to represent a safe power output level (see **Step 4** for a brief discussion about P_1). It is good practice to make sure your Peak signal levels stay under the P_1 level to avoid over-driving the amplifier. Some of the excess power that can not be translated into the output waveform can appear on the output transistors as heat. Typical destructive levels for these expensive devices are about P_6 or P_7, only 5-6 dB above P_1. Add attenuation to the amplifier input as necessary to keep under P_1 levels. Many AR Modular RF amplifier designs offer over-drive protection in the form of an Automatic Limiter Circuit (ALC) to prevent accidental over-drive levels. Amplifiers employing newer Gallium-Nitride (GaN) devices are more damage-resistant than the LDMOS devices that preceded them.
2. **You can ruin your signal.** As your signal peaks cannot be reproduced with the same gain as the lower level signals, they are distorted. This can mean the amplifier is useless at your desired power level, and must be used with lower gain or drive levels and less power out. In general, you must adjust the input level to reduce the output power, or get a bigger amp. Many AR Modular RF models offer wide-range gain controls that help with fixed power levels.
3. **You can make other problems.** The power that is missing from your distorted signal is appearing somewhere else- as interference out of your frequency channel or as harmonics way off-frequency. Complex-modulated signals can create interference in adjacent channels. Harmonics are especially a problem with broadband amplifiers that amplify the 2nd or 3rd harmonic of the lower frequencies covered. Since no input filters can be employed, a conservative design with lots of headroom is needed. Output filters can fix harmonics but can dissipate a lot of heat at high power, and need to be well designed mechanically to be able to transfer the heat to a sink.

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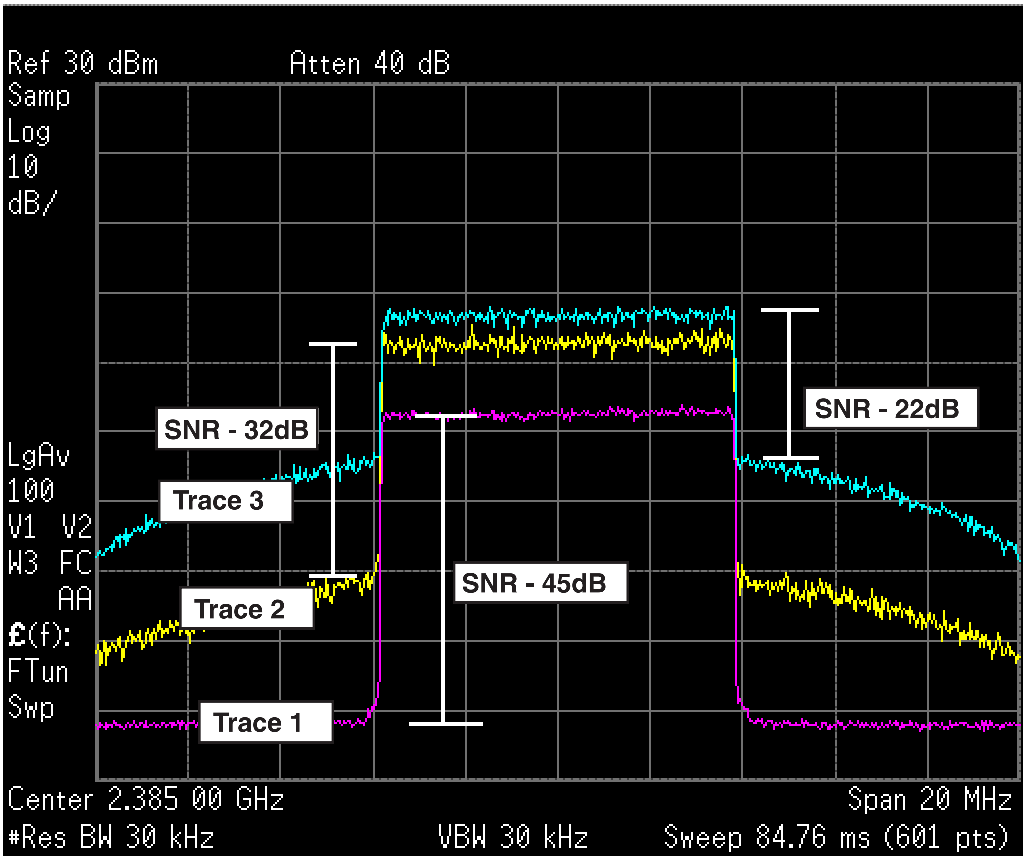

Fig. 1: OFDM signal spectrum showing increasing IMD as amplifier enters gain compression

Figure 1 shows an OFDM signal degrading in an amplifier as the Peak power approaches and crosses over the P1 compression point. Trace 1 is an uncompressed signal with better than a 45dB signal-to-noise ratio (SNR). Trace 2 shows the input signal 10dB higher than for Trace 1, with signal peaks just touching the P1 point. While the gain across the data channel has increased by 10dB, Intermodulation distortion has created "shoulders" of noise, reducing the SNR to 33dB. Increasing the drive by only 5dB in Trace 3 shows that the power in the adjacent channels has increased by 16dB, and SNR has been reduced to about 22dB. Your specific application will determine what level of SNR is required or can be tolerated.

Complex Modulation Needs More Headroom But How Much?

As shown, complex-modulation formats exhibit high Peak powers compared to their Average power. With Crest Factor reduction (CFR) schemes, digital and amplifier linearization techniques, and the variables of the signal payload, the effective PAR and range of acceptable non-linearity is wide. Most digital formats can suffer modest to moderate distortion and remain usable. For example, absent other distortion, WLAN modulation can still provide acceptable performance when Peak power is limited to an amplifier's P_1 power point (see **Step 4** for an explanation of P_1).

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OFDM modulation with a PAR of 12 may allow a Peak power de-rating of as much as 6 dB from Peak. De-rating the input power to allow the amp to meet the Peak power requirements is commonly referred to as "back off" and is expressed in dB. Even de-rating by 6dB leaves the Peak power still 6dB over average, and that must allowed for by either backing off the CW P_1 point by 6dB or by adding 6dB of headroom to the output power rating of the amp. Your specific application must determine the effective PAR value you apply to the average power of your signal when calculating the Peak power, but Peak power will always be significantly more than average power. Using an effective PAR, or "back off" of 6-7dB should provide a useful working number.

Pulse Modulation
Measuring pulse Peak power can be done easily with a Peak power meter regardless of pulse width. You can also calculate Peak power by dividing Average Power by the duty cycle of the pulse modulation.

Duty Cycle (dB) = 10 $\log_{10}$**(duty cycle ratio)**

Example: For a pulsed RF train with an Average power of 0dBm and a duty cycle of 15%:

0dBm + 10 $\log_{10}(0.15)$ = 8.24dBm Peak

Try to use representative pulse trains or a worst-case scenario to obtain Peak values that will allow enough headroom for your pulse peaks.

Step 2 – Do the Math – Do You Need Gain or Power Numbers?

Your application determines either the signal level you want your amplifier to produce (in Watts or dBm) or the amount of gain you require. If you require a specific signal level, the difference between that power level and the peak power of your signal is the minimum degree of amplification, or gain, you require. If you have a specific gain requirement then your signal peak power added to the gain will provide the minimum power out necessary for the amplifier to produce.

Power Out (dBm) – Peak Power In (dBm) = Gain (dB) Required

For example, you may know the Peak Envelope Power (PEP) required to provide a specific Effective Radiated Power (ERP) at an antenna. In that case, for a signal with a Peak power of +10dBm and a desired PEP of 50 Watts:

dBm = 10 $\log_{10}$**(milliwatts)**

10 $\log_{10}$(50,000 mW) = +47 dBm
+47dBm PEP - 10dBm Peak = +37dB Gain @ 50W Peak Output (+10 dBm Input)

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Many RF amplifiers with have different power input specifications, but 0 dBm is fairly common. In the example above, to avoid over-driving the amplifier, it may be necessary to add 10 dB attenuation to the RF amplifier input to reduce the input power to 0 dBm. In that case the example looks like this:

+47dBm PEP - 10dBm Peak + 10 dB Attenuation = +47dB Gain (0 dBm Input)

If you know the Gain required but not the Wattage necessary to provide it, add the Peak power to the gain, and convert the sum to Watts:

Peak power (dBm) + Gain (dB) = Peak power out (dBm)

Power (Watts) = antilog$_{10}$(dBm/10)

For example, you have a Peak signal power of +3dBm and require a Gain of 40dB to obtain a final peak power level of +43dBm to drive a larger power amplifier. Remember to add 3dB to the Gain to compensate for the 3 dB attenuator to bring the input level to 0dBm:

0dBm Peak + 40dB Gain + 3dB Attenuation = +43dBm = 20 Watts Peak

If your signal level is below 0dBm, you can search for amplifiers with higher gain that will produce the desired power level in **Step 3**. To determine the maximum Input Power level for an amplifier, subtract Gain from the CW P_1 power out:

Peak power out dB – Gain dB = Peak Input level

For example, to find the Peak input level for a 20W amp with 48dB gain:

20W = +43dBm
+43dBm – 48dB = -5dBm

Step 3 – Window Shopping- Select by Type, Frequency, and Power

This step is where you can begin to pre-select amplifiers that might meet your requirements. Here is where CW and Pulse amps will diverge. The other big break point for selection is whether you are shopping for a "module", or a system. A module is usually a smaller unit that comes with or without a heat sink, and usually without any controls or indicators, designed to be integrated into an assembly. A full system is self-contained, complete with chassis, cooling, AC-DC power supplies, front-panel and remote controls and indicators.

As amplifiers are usually designed over more frequency ranges than power levels, it can save time to first

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screen a vendor's lists by Power Out, then by frequency, then by Gain.

Remember, Cheap Specs will Shrink in the Wash- Shop for a Size Larger
At this early stage of the process it is essential to make your initial selection based on a wider range of advertised powers and frequencies than you think you need. Print out the data sheets for any potential candidates for further scrutiny in **Step 4**. As you zoom into the specs you will find that the band edges may not perform as well as you might wish, or the power specs quoted are overly optimistic. You might need to get an amplifier with wider coverage to improve flatness across your frequency band, or pick a slightly more powerful amplifier than the rating specified to get a reasonable margin of gain or power. You may also find that another spec will invalidate otherwise attractive features, like poor Harmonic specs from an amplifier being pushed a little too hard.

Step 4 – Comparing Apples to Apples

Here is where you need to look closely at the specs. Depending on the amplifiers you have selected so far, you need to make an educated choice which amps will actually provide the gain and power for your application. The important thing to accomplish at this step is to make sure you are comparing "apples to apples" or in this case Usable Watts to Usable Watts.

Signal Linearity and Usable Watts
All amplifiers will compress at some level. So this discussion will short-cut past the relative virtues of amplifier Classes of Operation so frequently seen in amplifier literature. Either an amplifier is Class A or it is not. If it is, the amplifier may be relied on to provide superior performance in terms of fidelity, low distortion, and immunity to VSWR over the entire linear power range.

AR Modular RF can provide Class A RF power amplifiers that exhibit the highest signal linearity for the most demanding applications, like the **KAW2180**, a 100W minimum dual-band Class A amplifier that operates from 0.01-1000 MHz. All other types of RF amplifier (usually Class AB) will provide some more distortion in exchange for efficiency, and may require some spec-diving to figure out how many linear watts you will really get.

RF power amplifier ratings can be expressed in many kinds of Watts: Average, P_1, CW, Peak, ALC Watts, even Peak-to-Peak (P-P). You job here is to "normalize" all the results to a common and meaningful value, like P_1 Watts, so a direct comparison can be made.

P_1 Power vs. Saturated Power
All amplifiers exhibit gain compression at higher operating levels, meaning the gain (not the level) decreases as input power rises. The output level at which the power has deviated from true linearity by 1dB is typically specified as the P_1 point. Even Class A amplifiers have a P_1 point. The P_1 power level is the most useful reference to output power as it can be measured directly and accurately and indicates the practical power limit that may be safely and conservatively employed. Beyond the P_1 point, as input power increases,

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compression also increases until the departure from linear gain is -3dB, or one-half the power out that occurs at lower powers. This is known as the Saturation level or P_3. This not generally regarded as a usable or safe power level. The P_1 level is typically about 2dB below the P_3 saturated power level.

Saturated Power P_3 – 2dB = Usable Power P_1

For example, for an amp specified at 100W out P_3 saturated power, the actual "usable" power, or P_1 level, is found:

100W P_3 – 2dB = +50dBm P_3 – 2dB = +48dBm P_1 = $\text{antilog}_{10}(4.8)$ = 63 Watts P_1

Modulation usually requires some type of linearization to be effective when using power levels above P_1. Your job here is to look through all the specs of amplifiers that have "made the cut" so far, and make sure that for any amp specified in Watts, or anything other than P_1 watts, you find the P_1 level specification. If you don't, you may discover that the rated power is the saturation level. AR Modular RF typically specifies a minimum power level below P_1 as the rated power out. See if any amp specifications provide you with a margin, and when you look at P_1 power levels, include that margin in your comparison.

Gain- Too Much of a Good Thing?

Make sure you are checking the gain of the amplifiers that can provide the power out you want, and referencing it to your signal level. The designed input power level may be too far from your signal level. You don't want to have add a preamplifier or use excessive attenuation, but it is not unusual have to add a small amount of attenuation on the input. Pick an amplifier that provides enough margin that you can add a pad on the input in case you find it is necessary later to reduce the power out of the amplifier. Variable Gain is a useful feature for setting system levels.

Converting CW to AM Modulation Specs

As stated before, AM Peak power is 4x CW power or +6dB. Use the P_1 level for CW watts to calculate AM power. Divide CW-rated power by 4 (or subtract 6dB) to estimate available AM Power. If the specs say something like "100W CW, AM, FM, PM, SSB", it does not mean you may modulate a 100W carrier with 100% AM. You should be able to modulate 25W with 100% AM. With an under-powered amp, your only alternative available to produce low-distortion AM is to reduce the RF "drive" to the amp until the un-modulated carrier is 25% of the linear output (-6 dB), drastically reducing the output power. This is an especially poor outcome if the original power spec was for saturated power, as the result is decreased by another 37%.

CW P_1 Watts ÷ 4 = AM Peak Watts

For P_1 in dB:

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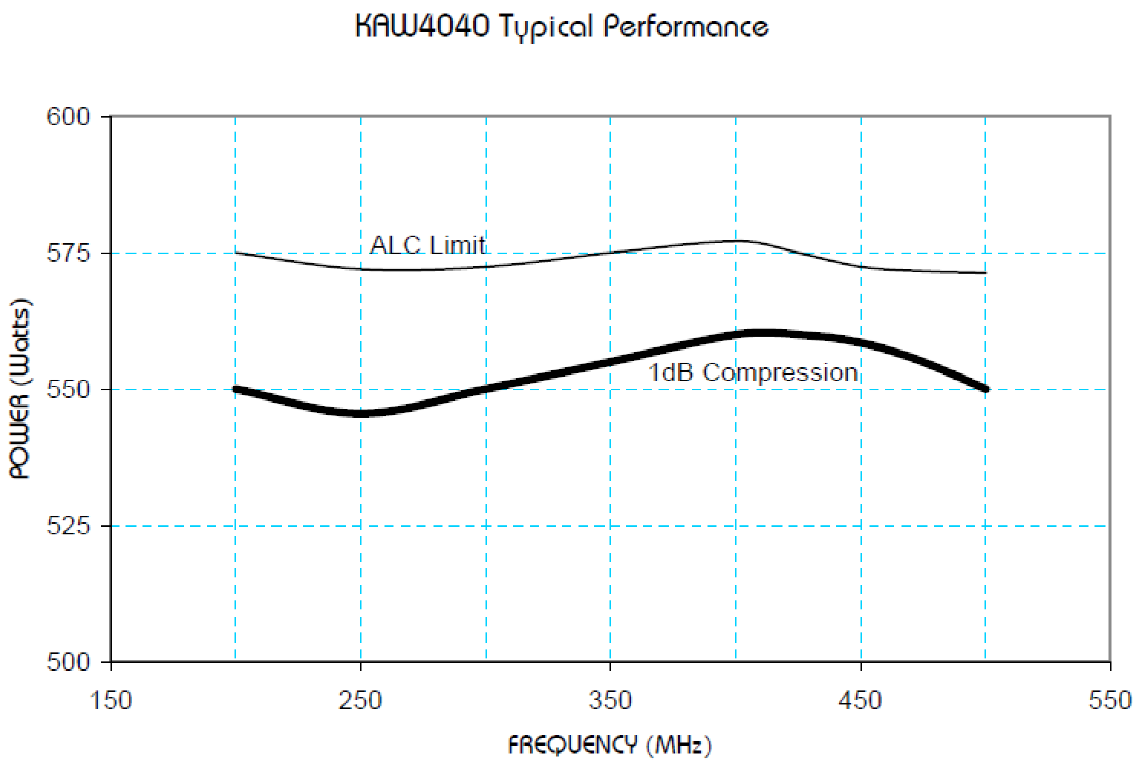
CW P_1 dB – 6dB = AM Peak Watts

Flatness and ALC Power Levels

Most RF amplifiers specify Flatness. In general, the wider the frequency coverage, the looser the Flatness spec becomes. Flatness is a good indication of the relative quality of broadband design quality. Flatter amps are easier to use as the gain is more predictable.

Automatic Level Control (ALC) is a feature mainly used for CW modulation. RF power amplifiers with ALC will usually specify an ALC Power level in addition to P_1 Watts. The main function of ALC is to provide overdrive protection to the device at the output of the amplifier. For CW signals the ALC level defines the maximum RF level available from the amplifier, regardless of drive level. ALC can help protect the amplifier from over-drive, and can also provide improved Flatness, especially for CW signals.
An adjustable ALC can allow you to vary the ALC level below the P_1 point. ALC is a "friendly" limiter, creating much lower distortion than P_1. The ALC function will need to be slowed or disabled for non-CW modulated signals, or serious distortion will result. Amplifiers with ALC Fast/Slow selection can enable some limited ALC functionality for non-CW signals, but it will be less responsive. For amplifiers with variable Gain, reducing the gain below the ALC Limit will also reduce Flatness as the gain lowers.



RF Pulse Amplifiers – A Different World

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Pulse amplifiers are a separate breed of RF amplifier. Pulse amplifiers are rated in Peak Watts and are commonly run at saturated power levels, where compression makes no difference to the modulation fidelity. Pulse-specific amp designs come in two types depending on the pulse modulation method. The first, Pulse Gated amplifiers can have a CW signal applied to the input and an external gating signal is applied to the amp to produce the pulsed output. Alternatively, a pulse train is applied to the amp input and the gating is used to quiet the amp between pulses. The non-Gating type has design features specifically for preserving the shape of pulsed signals with fast rise-times. A CW rated amp can also pass pulses, but the highest pulse fidelity is obtained by design features not usually contained in a CW amp. If your main requirement is for pulse performance, select from pulse amps with the correct Peak power rating.

Harmonic Distortion – Trouble is Just an Octave Away
Having worked your way down to a short list of amps that will meet your P_1, gain and frequency requirements, you need to pick an amplifier with low Harmonic levels, as compared to other like designs. Harmonics are a relative indicator of amplifier design quality and stress. Harmonic distortion is measured in dBc, or the power level as compared to the output carrier power. Harmonic specs vary widely, from relatively high levels in the low teens, like -13 dBc, to much lower levels like -60 dBc or less. The higher power range of numbers is usually associated with broader-band amplifiers that can not employ a filter at the harmonic frequency as it is in the gain passband. Out of the gain passband, filters can knock Harmonics down, but a filter following a high power amplifier can get really hot, depending on the energy absorbed, and that heat can lead to a short filter life. For narrower amps with a bandwidth less than an octave wide, a better scheme is to reduce them with a conservative design and then a cooler-running filter, if needed. Make sure when comparing Harmonics specs you understand any big differences as they can be the result of completely different types of amplifiers. If you require the absolute minimum of Harmonic distortion, use a Class A amplifier.

Wide-Band or Band-Switched – Automatic or Manual Transmission?
Finally, make sure how your wide-band operating frequencies are provided, either by “band-switching” or by a true, single broad-band design. Some frequencies just can not be effectively amplified by the same design if they are too far apart. If you can switch from one band to another (by switching from one amplifier to another) you may be able to get improved Gain, Flatness and Harmonic distortion performance for less cost.

Step 5 – Shop for Features – The “Bells and Whistles”

When you have worked your way this far you should have a short list of the available amplifiers in the power and frequency range that have a good chance of meeting your needs. Within this selection you can shop for the accessory functions that will make your amplifier more usable, like blanking, remote controls, variable Gain control, VSWR tolerance, efficiency or power consumption, size, other kinds of protection, interfaces, and finally cost.

Some intangible factors can make a big difference to your long-term happiness with your final selection. Chief among these is robustness of design, which appears as a gain or power margin above the rated power,

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which will equate to longer life with fewer problems. Other factors include the vendor's willingness to adapt a design for your specific needs, a long-term commitment to service by the vendor, and responsive customer support.

About Impedance Mismatch Tolerance

You may feel some important factors have been left out of this selection process, like load impedance variability. The truth is no one knows what happens with random VSWR. Almost anything is possible, even gain. The main thing is you want to avoid damaging the amplifier. Remember, reflected power has done its work, and whether it is an antenna or another amplifier, the important thing is to present the signal accurately to the load at as close to the right level as you can, and survive whatever returns. AR Modular RF is known for RF power amplifiers that can withstand nearly infinite mismatch conditions, like the **KAW4040**, a 200-500 MHz amplifier rated for 500W CW (minimum), with P_1 well above the 500W level, and full VSWR protection.

At this point, you may find no amplifier is a perfect fit for you. AR Modular RF would like to speak with you about your requirements. We routinely produce quality custom amplifier modules and systems and can modify our existing designs to meet your needs.

AR Modular RF fabricates all our amplifiers in Bothell, Washington, where the company has attained the reputation for making and supporting the finest RF Power amplifiers for over 3 decades.

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