# Two-tone IMD measurement techniques

*Seven rules to ensure the best characterization of non-linear RF components*

**By Keith Barkley**

Two-tone testing for intermodulation distortion (IMD) has a long and venerable history. Since the dawn of RF engineering, it has been used to characterize the non-linearity of RF components, both active and passive.

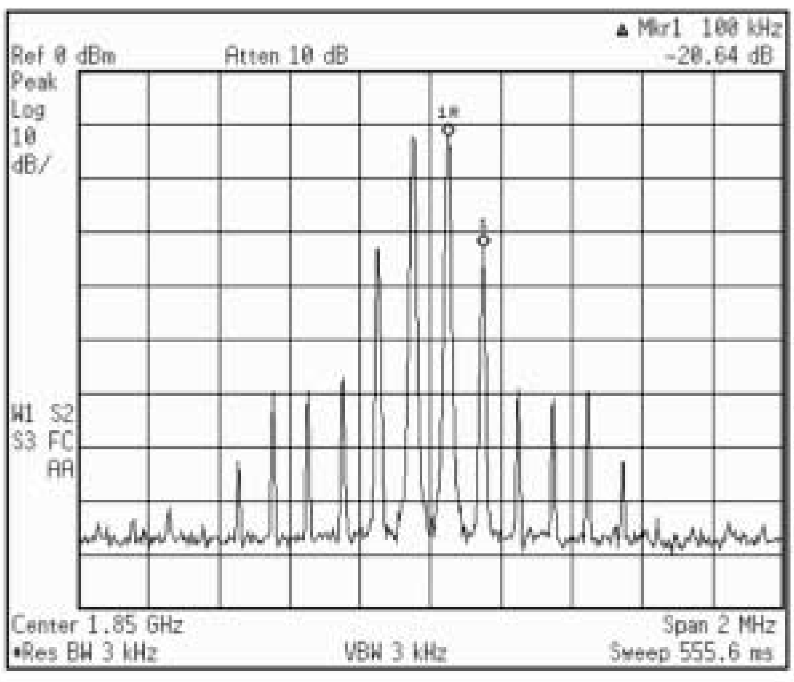


**Figure 1. An example of a device with poor IMD response.**

Measurement methods, pitfalls and tidbits of information have been gathered over the years by myriad sources, here and elsewhere. A few simple rules can help in setting up a test system that can accurately measure two-tone IMD for RF power transistors. For this discussion, $f_1$ and $f_2$ will denote the two signals' input into the device and $\Delta f$ will be the frequency separation between them.

## Where it comes from

While the causes and intricacies of the generation of IMD are beyond the scope of this discussion[1], intermodulation distortion is a result of a non-linear transfer function. Everything, with the possible exception of a signal in free space, generates IMD. *Rule #0: Everything generates IMD.*

A device that adds IMD to its output signal will have unwanted frequency components generated at specific frequencies. The third-order products will occur at a frequency of $(2 \bullet f_1 - f_2)$ and $(2 \bullet f_2 - f_1)$, showing up as extra frequency components $\Delta f$ above and below the two input frequencies. Fifth-order IMD will show up as extra frequency components above and below the third-order distortion, exactly $\Delta$f apart. The other odd-order IMD products follow suit. The sample spectrum, as seen on a spectrum analyzer, of a device exhibiting poor IMD characteristics is shown in Figure 1.

Some may consider it an oversight that most literature touches only on the odd-order IMD products, leading one to believe that second-order distortion products have gone the way of TV channel 1 in the United States. In fact, second-order products are generated, they just tend to be out-of-band for most RF applications. The second-order products fall at the sum and difference of the two tones, or at $(f_2 - f_1)$ and $(f_2 + f_1)$.

Designers of multi-octave amplifiers must pay attention to second-order effects, as well. The easiest way to lessen second-order distortion is to use a push-pull amplifier. The second-order products generally cancel, greatly reducing them.

GSM, CDMA, PCN, 8VSB, $\pi$/4DPQSK, NAMPS, 64QAM and EDGE are just part of the alphabet soup that is proposed or current digital modulation schemes. How does old-fashioned two-tone testing fit into all of these standards? The jury is still out. It is highly desired to find some correlation between the performance of a component under two-tone test conditions and its behavior subjected to these complicated digital signals[2].

## How to set up an IMD test station

A generic two-tone IMD station is shown in Figure 2. It consists of two parallel paths with two signal generators, two amplifiers and four circulators summed in a two-way combiner routed through an (optional) adjustable attenuator and then fed into the device under test (DUT). A spectrum analyzer is used to perform the actual measurement.

Unless one is cost-conscious, it is best to use a synthesizer as opposed to an RF sweeper. While using two sweepers is possible, at small $\Delta f$ the frequency will need continuous readjustment to keep the tone spacing relatively constant. At a tone spacing of less than 50 kHz, it is not worth the trouble, especially in production testing.

The adjustable attenuator is used to keep the lev-

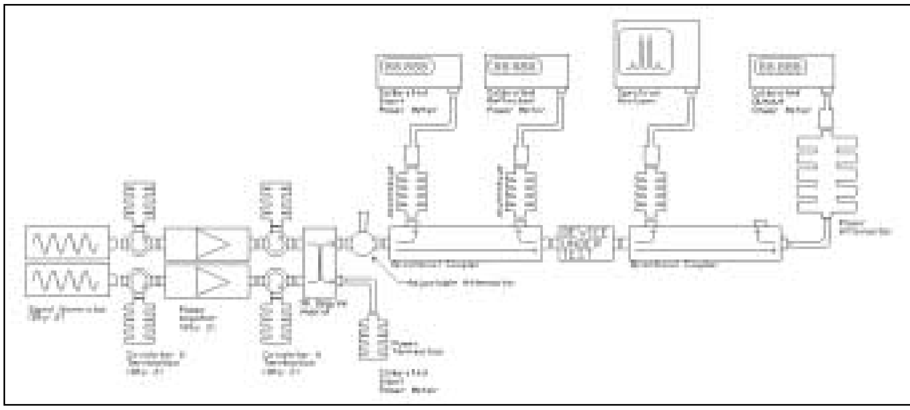
Figure 2. Typical IMD measurement system.

els of the RF driver amplifiers constant, while allowing for an adjustable RF power level at the DUT. This will keep the source IMD (SIMD) from changing as the power is adjusted, and it will allow the adjustment of both tone levels simultaneously. The only disadvantage is that the attenuator must be able to handle the average power and, if it is a non-linear device, generates IMD of its own (Rule #0).

It is important to measure the residual, or SIMD of the test station to ensure that it will not interfere with the measurement. At the same time, also look for spurious responses coming from the system that may contribute to SIMD from unlikely or unnoticed sources. Synthesizers use frequency references at nice round frequencies that may or may not coincide with the required $\Delta f$. To measure the SIMD, simply remove the DUT and connect the two-tone source to your load and measure the IMD of the source over all required power levels and frequencies. (The formulas for calculating SIMD are given at the end of the article.)

## Fine tuning

It appears that locking the synthesizers and spectrum analyzer together with a common frequency reference would be a good thing to do, and in general, probably is, especially at narrow tone spacing. If the spacing is above 10 kHz, there is probably no benefit, and it may exacerbate any problems due to spurious responses from the synthesizer. One other benefit of locking them together is that one may be able to use the test station to achieve a single frequency power of twice the individual amplifier power. The synthesizers can be set to exactly the same frequency, and the phase of one of them can be adjusted to maximize the available power.

The other reason to look closely at the output of the two-tone generator is to identify any spurious responses that may confuse things if seen while testing a component.

## Reverse IMD test and check

A slight modification of the two-tone measurement system is a test of reverse IMD, that is, the IMD of a component when the second tone is injected into the output port of the DUT. This test simulates a situation common in communications equipment where an interfering signal from a co-located transmitter is conducted back through the system and into the amplifier. The equipment to perform this test is shown in Figure 3.

A directional coupler is used to inject the signal back into the DUT. The circulator is needed to prevent the signal source from generating IMD products of its own and from interfering with the measurement.

Correlation of the test system must be done without the DUT in place. A power meter (with attenuation, if necessary) is connected at the output port of the DUT looking toward the load. The signal is applied to the directional coupler. Typically, this involves injecting the signal into what is usually thought of as the port that couples out the signal from the main line going toward the load. Most directional couplers have internal terminations that cannot handle much power (check the data sheet carefully. The signal source is adjusted so that the level at the output port of the DUT is set at the specified level. Because directional couplers are symmetrical, the power level of the reverse tone at the signal generator will be attenuated by the coupling factor, so it may need to be 20 to 30 dB higher than the power required at the DUT.

Once the signal level is calibrated, the DUT can be replaced and set into operation. The reverse tone can be applied and the level of the IMD can be checked as stated in the specification. For example, the specification may call out for a 10 dBm reverse tone, and all resulting IMD products need to be –80 dBc or better, compared to the main tone at 40 dBm.

## Fast forward

There are three secrets to setting up a successful two-tone station: isolation, isolation and more isolation.

*Rule #1: Get as much isolation as possible.*

It may seem that too many circulators are in the test system, but a single circulator has only about 20 dB of isolation. It may be necessary to cascade two to double the isolation between stages.

In fact, some signal coupling may not come through the RF cables at all, but through radiation or even conduction through the AC power line. If big problems exist with excessive IMD in a test system, try moving the equipment around. Take the generators out of the 19-inch rack and pile them around the bench with some separation between them. Plug the two halves of the system into separate AC circuits. At the signal levels involved with –80 dBc IMDs, it does not take much signal to cause a problem.

*Rule #2: Check your test system.*

It does seem that a lot of added expense exists in using two amplifiers instead of one larger Class-A amplifier. It will take a large amplifier to generate acceptably small levels of source IMD at the DUT. A good rule of thumb is to assume that the driver amplifier will have –30 dBc of third-order IMD at its rated power level. (With the test tones set at one-fourth

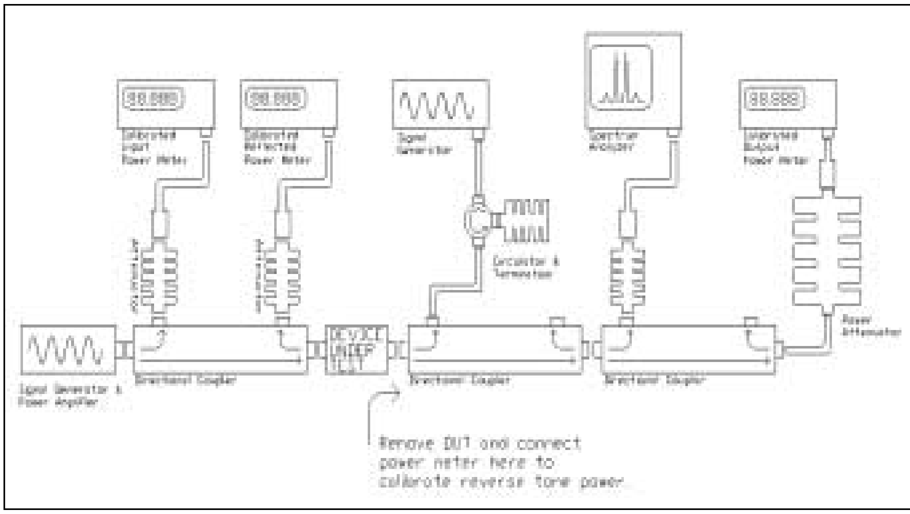

Figure 3. A reverse IMD measurement system.

the rated power per tone.) 2 dB of third-order IMD improvement will be seen for every 1 dB the power is reduced. For example, if a 100 W Class-A driver amplifier is used at 10 W (2.5 W per tone), one can expect a source IMD improvement of 20 dB, or –50 dBc of third-order source IMD.

## Pitfalls of IMD testing

When specifying and making two-tone IMD measurements, one must be precise about the terminology used to state the amplitudes of the tones involved. There are three ways to specify the power of the tones:

• Per-tone—The absolute power of the individual tone. This is most accurately and easily seen on a spectrum analyzer. If a data sheet says that the part is tested at 1 W per tone, it means to apply the two signals such that each signal has an amplitude of 1 W. It may be referred to the input or the output of the device, though output is most convenient for measurement if there is only one spectrum analyzer.

• Average—The average value of the two tones. This is most accurately and easily measured with a true-RMS power meter. The value is simply the sum of the two powers of each tone. So, if there is 1 W per tone, the average is 2 W.

• Peak—Otherwise known as peak envelope power (PEP), it is the maximum instantaneous power of the combination of the two signals. A two-tone signal looks similar to an AM modulated tone. The envelope of the RF signal varies as a sinusoidal with a frequency of $\Delta f$. When the voltages of $f_1$ and $f_2$ are out of phase, they cancel and the envelope is at a null. When the two voltages are in-phase, they add, and the voltage at the instantaneous peak is twice that of either tone. Because power is equal to the square of the voltage divided by the resistance, when the voltage increases by a factor of two, the power increases by a factor of $2^2$, or four. Therefore, the PEP is four times the per-tone power and twice the average. In this example, the per-tone power is 1 W per tone, the average power is 2 W and the PEP is 4 W.

The common industry practice uses an average reading power meter and calculates the PEP as twice the average power reading. This is not technically correct because the PEP is always less than twice the average power in the presence of harmonic and intermodulation distortion. However, at the typical IMD specification levels, around –30 dBc, the error is negligible. If a peak reading power meter is used to measure the PEP directly, that fact should be noted with the results so that measurements can be compared with another system that uses average reading meters.

It is sometimes easy to get confused, so I suggest the next rule: *Rule #3: Stick to one method of power measurement.*

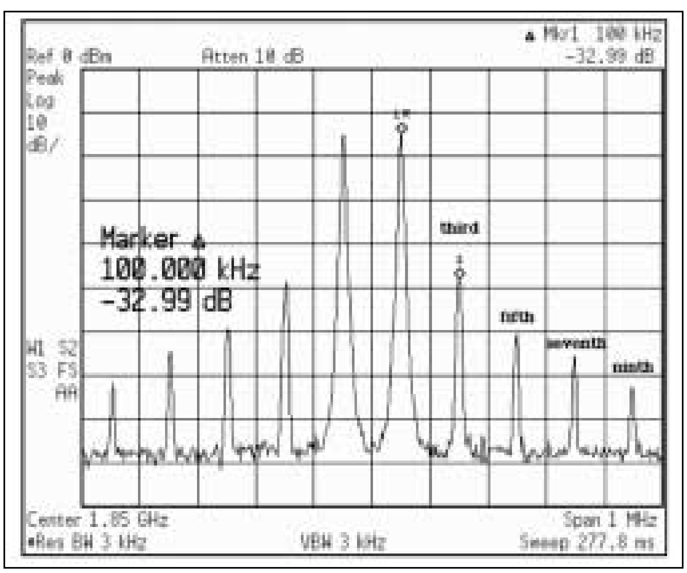

Figure 4. Example IMD measurement.

## Clearing the throat

Now that the terms are more clearly defined, conventions can be specified more clearly. Depending on the manufacturer, company data sheets may specify either the per-tone or the PEP of the signal. It may be referred to as the input or the output. However, the IMD in dBc is always referred to as the output, and the reference level of the carrier (the “c” in dBc) is the per-tone level. In other words, the IMD is measured from the highest of the two input tones to the highest of the IMD product being measured (third, fifth...).

The reason to belabor these points is that one must read manufacturers’ data sheets carefully. It is easy to manipulate the numbers to make one manufacturer’s device seem better than its competitor’s.

One manufacturer of power RF semiconductors uses the PEP as the reference for the carrier level, giving it a 6 dB boost in third-order IMD performance over the industry. Unfortunately, there may be no way to tell by looking at a data sheet where the carrier reference is set because the data sheet usually just says “dBc.”

Figure 4 shows a real-world example. This spectrum analyzer is attached to a coupler at the output of the DUT. This particular device is operated at its data sheet conditions of 26 V, and an ICQ of 25 mA. The output power is set at the specified 2 W PEP. To make a measurement, both tones are turned on and the adjustable attenuator is set to achieve 1 W on the true RMS reading power meter, for the 2 W PEP. In this case, because the PEP is set through the power meter, the spectrum analyzer is being used as a relative measuring device only. Therefore, it is not necessary to calibrate the spectrum analyzer to the absolute power level.

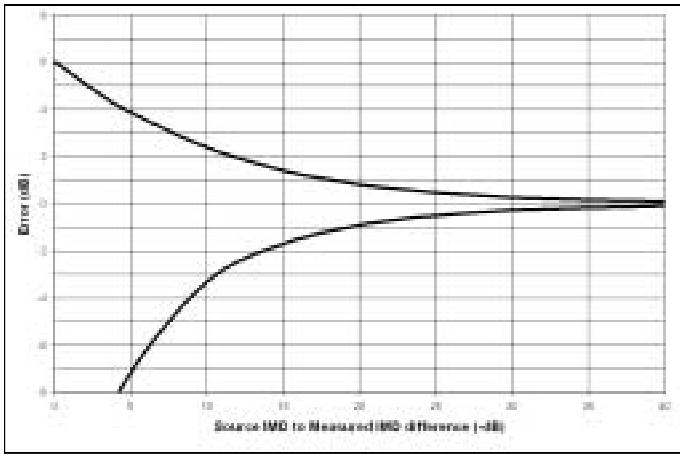

**Figure 5. Maximum and minimum error vs. SIMD/measured IMD difference.**

The levels of the tones are checked on the spectrum analyzer to make sure they are within 0.2 dB of each other. If they are not, the levels of the signal generators must be adjusted to bring them within 0.2 dB. (Note: Observe the behavior of the delta marker function on the spectrum analyzer. On some analyzers, when the delta reference is set, it stays at an absolute power level no matter what the signal is doing “underneath.” More friendly analyzers will have the delta reference follow the level of the signal. If an analyzer is of the first type, make sure to adjust the level of the tone where the delta marker is located, not the tone where the delta reference is set.)

When the tones are set to equal amplitudes, the IMD products are measured by comparing the level of the highest of the two tones to the highest of the desired IMD product. Some spectrum analyzers have a feature that automatically shows the absolute or relative level of all the peaks on the display. With this function, measuring the levels of all the IMD products can be accomplished with just a glance at the analyzer.

Measurements at other PEP levels can be easily accomplished by adjusting the power to a new level with the adjustable attenuator, and making the measurement. (Note: If the tone spacing is wide, 1 MHz or greater, then the amplitude flatness over frequency may change, requiring that the levels of the tones be correlated at each frequency to maintain the proper relationship.) In this example, the third-order IMD products are at –33dBc, the fifths are at –47 dBc and the sevenths are at –53 dBc.

## Understand the components

A power meter may provide an inaccurate reading of average power in two situations. The first is when something other than a true RMS power meter is used. Thermocouples, thermistors and diode detectors operated in the square-law region are true RMS readings and give an accurate indication of the actual average power. Power meters that use diodes in the non-square-law region must be watched closely to get accurate results. In fact, it could be suggested that one only use true RMS power meters for two-tone IMD measurements.

The second way to get misleading average power readings is if the signal does not look like a two-tone signal. Any frequency components besides the two tones (including IMD products) add to the average power. Luckily, the problem is linear and well-behaved. If the third-order distortion is –30 dBc, then the error is 0.1 %. If the thirds, fifths and sevenths are all –15 dBc, the average power meter reading is about 10% higher than the level of the two main tones.

Harmonics must also be watched. The power in harmonics will add linearly to the measurement and cause error. A peak-type diode power sensor is extremely sensitive to harmonics. When using one of these meters, a harmonic filter is almost always required for power devices that generate significant harmonic powers.

Any IMD generated in the test system is going to be at the exact frequency of IMD generated by the DUT. This means that the IMD measured at the output of the DUT will be the result of the vector sum of the SIMD and the DUT IMD. This leads to more error than you might expect. It is not a simple linear addition of the two powers, but an addition of the voltages, much like the PEP discussion. *Rule #4: Power meters can lie.*

## Doing the math

Here are the formulas for calculating the worst-case error due to SIMD:

The maximum positive error (the voltages are in phase) is:

$$(err+) = 20\log\left(1 + 10^{\frac{SIMD-MIMD}{20}}\right)$$

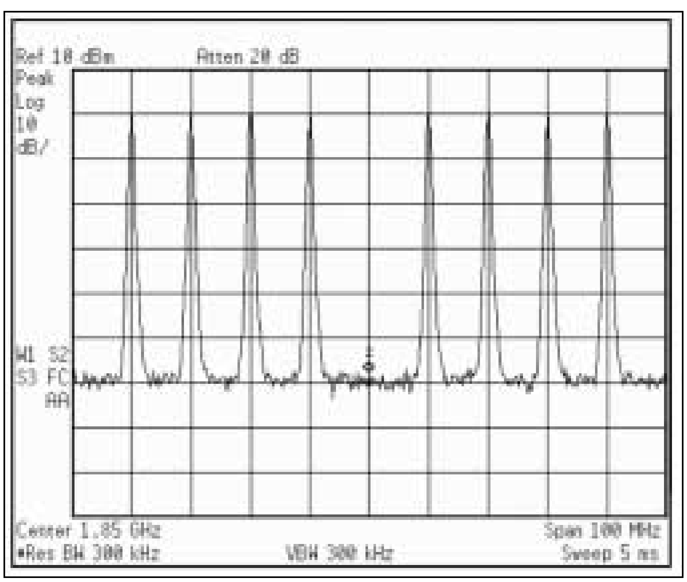

**Figure 6. Multi-tone test signal.**

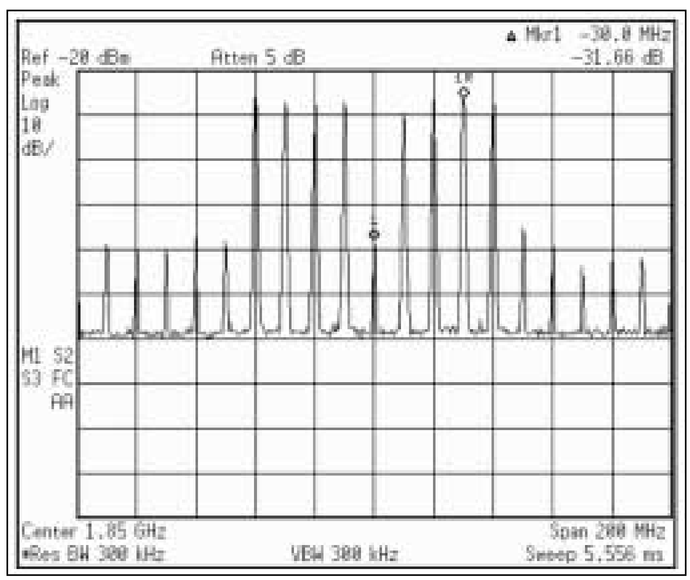

**Figure 7. Device response to multi-tone test signal.**

| Number of tones | average power (W) | PEP (W) | Peak to average ratio |
|---|---|---|---|
| 2 | 2 | 4 | 2 |
| 3 | 3 | 9 | 3 |
| 4 | 4 | 16 | 4 |
| 5 | 5 | 25 | 5 |
| 6 | 6 | 36 | 6 |
| 7 | 7 | 49 | 7 |
| 8 | 8 | 64 | 8 |

**Table 1: Comparison of peak and average power for various numbers of tones.**

The maximum negative error (the voltages are out of phase) is:

$$(err-) = 20\log\left(1 - 10^{\frac{SIMD-MIMD}{20}}\right)$$

Where SIMD is the absolute value of the IMD at the input of the DUT, and MIMD is the IMD measured at the output of the DUT.

For example, what is the possible error if a –30 dBc third-order IMD is measured at the output of the device and the residual SIMD was –40 dBc? The difference between the measurement and the source is –10 dB. Plugging the numbers in the formula yields:

$$(err+) = 20\log\left(1 + 10^{\frac{-40-(30)}{20}}\right)$$

$$= 20\log\left(1 + 10^{-0.50}\right) \approx 2.4$$

and

$$(err-) = 20\log\left(1 - 10^{\frac{-40-(30)}{20}}\right)$$

$$= 20\log\left(1 - 10^{-0.50}\right) \approx -3.3$$

The somewhat surprising results are that if the SIMD is 10 dB below the IMD measured at the DUT, the error is between +2.4 and –3.3 dB. A plot of the maximum and minimum error vs. the IMD difference is shown in Figure 5. The true IMD of the DUT lies somewhere between the two curves, depending on the magnitude and phase of the SIMD and IMD generated by the DUT. This leads to the suggestion that the source should have IMDs at least 30 dB below where it is desired to take accurate measurements. *Rule #5: Keep Source IMD to a minimum*.

## The importance of the SA

The spectrum analyzer (SA) is the heart of the IMD measurement system. Generally, setting the controls on the spectrum analyzer for measuring IMD is simple[3]. The eye can be a good judge. Be sure that the power going into the mixer is less than the power that the manufacturer uses in the IMD specification of the analyzer.

For example, if the specifications of the analyzer say that third-order intermodulation distortion is less than –80 dBc at –20 dBm input to the mixer, make sure that the per-tone power is –23 dBm, or lower, to prevent the analyzer from influencing the measurement. If an analyzer has a minimum distortion/minimum noise switch, use the minimum distortion setting.

Span, sweep speed, resolution and video bandwidths can be set to get a readable trace at whatever conditions yield the best dynamic range and show all the required IMD products on the screen. If necessary, the span can be lowered to show only a single component and the center frequency adjusted to the proper frequency. This is usually the best way to programmatically read the IMD. (Here is a situation where having the reference frequencies linked to a master clock can really help.)

Make sure that the level of the lowest IMD product to measure is above the noise floor. A signal only 3 dB higher than the noise level is still accurately measured[4]. With a slow enough scan and averaging, almost any IMD component can be resolved from the noise.

Be careful when adjusting the reference level to get a lower noise. This may lower the internal attenuation level and overload the mixer. It is better to narrow down the span, reduce the filter bandwidths and zero in on the desired IMD product. Verify that the delta marker function does what you expect in these circumstances.

Also, be sure to set the spectrum analyzer so the mixer is not being overloaded on one hand and not lost in the noise on the other. For typical two-tone measurements on power devices, these conditions are met easily.

Because almost every spectrum analyzer is different, and there are often neat features (as discussed above) hidden inside, another rule can be stated: *Rule #6: Get to know your spectrum analyzer.*

## Accuracy and expectations

It can be difficult to be truly accurate because of all the variables involved. However, several of the errors can be named, and most can be accounted for with careful attention to detail.

- Power level — For every 0.1 dB of error in measuring the device's PEP, the third-order IMD will be off by 0.2 dB.
- Frequency response — (This is more of a problem for wide $\Delta f$.) The frequency response of the measurement system, especially any directional couplers, should be factored in. With narrow tone spacing, (up to 100 kHz) this can usually be ignored.
- The log response of the spectrum analyzer — After the signal is detected, the video signal is sent to an amplifier that has a logarithmic response vs. signal amplitude. The output of this log-amp is then displayed on the screen. The log-amp error of a typical HP 71200A spectrum analyzer from the early 1980s is specified at 0.5 dB from 0 to 90 dB at IF bandwidths between 30 and 100 kHz. Newer analyzers digitize the detected video output (or even the IF) and use DSP to perform the log functions. A Rohde and Schwarz FSEB has both digital and analog specifications. The analog specification at resolution bandwidths of greater than 1 kHz is less than 0.3 dB over a range of 0 to 50 dB and less than 0.5 dB from 50 to 70 dB. In digital mode, the error is less than 0.3 dB over a 0 to 100 dB range at resolution bandwidths less than or equal to 1 kHz. So the error due to the logarithmic transformation can be estimated to be from 0.3 to 0.5 dB.

## The end analysis

Putting all these errors together, a rule of thumb is (when comparing two systems) do not trust differences of IMD measurements less than 1 dB. In absolute terms, a test system can be accurate to 0.75 to 1 dB. Two IMD measurements can be compared, if they are taken on the same system, at the same conditions, to within 0.5 dB.

*Rule # 7: The termination on the combiner must be able to handle half the average power input to the combiner.*

Say that the system is set up, as in Figure 2, with two 10 W amplifiers to boost the level of the signal generators. Connect the system to a power attenuator and power meter and prepare to verify the IMD levels of the system as this note suggests. Turn on all equipment, set signal generators to drive amplifiers to 10 W each, crank the adjustable attenuator to the minimum attenuation and look on the power meter expecting to see 20 W average, instead getting about 5 W average.

### When it doesn't add up

What happened? All the components are taken to the network analyzer and about 2 dB of loss can be accounted for. Where is the other 4 dB going? About 1 dB is because of the fact that a circulator can have higher loss in power conditions than at small signal. (This loss is variable and may never come up.)

By far, the largest loss, 3 dB, is dissipated in the isolation port of the combiner. (If using a Wilkinson two-way combiner, a "hidden" resistor is inside the unit that is dissipating the extra power. Check the data sheet to make sure that Rule #7 is being followed.) Most combiners are only "lossless" when the two input signals are at the same frequency and a particular phase relationship. All that extra power is being dumped into the 3.5 mm termination that was borrowed "only for a second" from the network analyzer calibration kit.

There are expensive combiners that are lossless with differing frequencies, but they are narrowband, difficult to find, and expensive.

### Measuring third-order intercept

A common measurement for Class A amplifiers is third-order intercept (TOI). In a well-behaved non-linear amplifier, the third order IMD will increase at a 3:1 ratio. This means that for every 1 dB the output is increased, the IMD (in dBc) will increase by 2 dB. If the curves are drawn for the output power and the third-order IMD power (not the ratio in dBc), the intersection of the two lines is the TOI. (In practice, one can never measure where they intersect because the amplifier will usually saturate long before the TOI point. The lines are extrapolated from the linear region.) It is easy to calculate the TOI. If one knows the IMD at a particular tone power, the TOI is ($P_{tone}$ + IMD/2) where $P_{tone}$ is in dBm and IMD is in –dBc. TOI must be calculated in a region where the measured distortion of the device is linearly well-behaved and the errors from the measurement system are at a minimum. In practice, it is a good idea to calculate TOI at IMD levels around –40 dBc.

That being said, it never makes sense to measure the TOI of a class AB amplifier. Most Class AB amplifiers have narrow areas where distortion is well-behaved and the IMD is often not even monotonic.

### Multitone testers and notched noise

While it is not commonly specified, another option for linearity testing is multitone testing where more than two tones are used. Because the PEP (instantaneous peak) increases as the square of the number of carriers, signals can be generated with high peak-to-average ratios rapidly. Table 1 shows how quickly the peak power of a number of 1W tones increases (this table should give one an appreciation for the linearity requirements of a CATV line amplifier, which has to handle 70–80 channels). Multitone testing is an effective test of an amplifier's linearity, especially for multichannel amplifiers.

Generators are on the market that use separate oscillators to generate the multitone signal. These oscillators can be phase-locked to provide random phase relationships, or adjusted to provide worst-case phase or best-case phase relationships. (While it is beyond the scope of this note, as the number of tones increases, the amount of time spent at the PEP level decreases. The time spent near the peak is a function of the phase of the individual tones. By adjusting the phase of the tones, the time spent at the PEP of the signal can be changed to near zero, which changes the peak value of the signal without changing the average power level.)

## How to use a multitone generator

With more tones, the peak level increases greatly while the average increases slowly. A multitone generator can output eight tones at about 2 mW per tone[5]. With eight tones, the PEP is 128 mW, which may be sufficient for testing medium-power RF transistors or high-gain devices like modules. If more power-per-tone is needed, the high peak-to-average value of the signal almost requires one to use separate amplifiers for each tone and then sum them in an eight-way combiner. The spectrum at the output of the eight-tone generator is shown in Figure 6. And after amplification by a power transistor, the signal is shown in Figure 7.

In practice, the eight tones are evenly spaced, possibly with a missing one as shown in the figures. When measuring the DUT, the distortion products at the missing tones, either in band or outside the band, are measured and compared to the level of the main tones. The device used as a source for this discussion has a multitone performance of –23 dBc.

Next-generation signal generators are now available and use an arbitrary waveform generator with an IQ modulator to produce almost any modulation on the carrier signal. It is possible to create an IQ waveform that will generate a multitone signal. This approach works fine with the following caveats:

- Generating the proper IQ signal — Software is available to generate the proper IQ signals (Rohde and Schwarz supplies software that specifically does this), but a new IQ signal must be loaded for every variation in tone spacing, tone phase or tone amplitude. No aspect of the signal can be adjusted, except level of all tones and center frequency, "on-the-fly."
- The generator is limited to a PEP level that is equal to the maximum that the generator can deliver, usually less than 100 mW — because the individual tones are not available for amplification, either the level from the generator or a "monster amp" must be used to get the tones to the level desired with little source IMD.

One other linearity test is to generate a band-limited noise signal and use a notch filter to remove a portion of the noise.

When passed through the DUT, the IMD products "pile up" in the notch and the distortion is read as the ratio of the level at the top of the noise to the noise in the notch. This represents a severe test of amplifier linearity and probably is the technique that represents the real world the best. This is the easiest to extend to higher powers because the noise is generated and amplified to the desired level. A high-power notch filter is used to remove the noise from the measurement band. Any distortion products added by the driver amplifier are removed by the notch filter.

A spectrum analyzer with an RMS detector makes measuring the noise level easier. Remember that the interest is in simply comparing two noise levels, not measuring absolute noise. It is probably not necessary to use the noise marker to measure noise-per-root-Hz, or make any elaborate corrections usually required for noise measurements with spectrum analyzers.

The IQ signal generators mentioned above can also generate these notched-band-limited noise signals. However, the PEP limitation also applies to these signals[6]. **RF**

## Summing up — remember the Rules:

*#0: Everything generates IMD. Corollary to #0: Everything generates IMD in unexpected ways.*

*#1: Get as much isolation as possible.*

*#2: Check the test system.*

*#3: Stick to one method of power measurement.*

*#4: Power meters can lie.*

*#5: Keep source IMD to a minimum.*

*#6: Get to know your spectrum analyzer.*

*#7: The termination on the combiner must be able to handle half the average power input to the combiner.*

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[6] Rohde and Schwarz, "*Application Manual — Software WinIQSIM for Calculating IQ Signals for Modulation Generator AMIQ,*" 1007.9245.42-01.


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