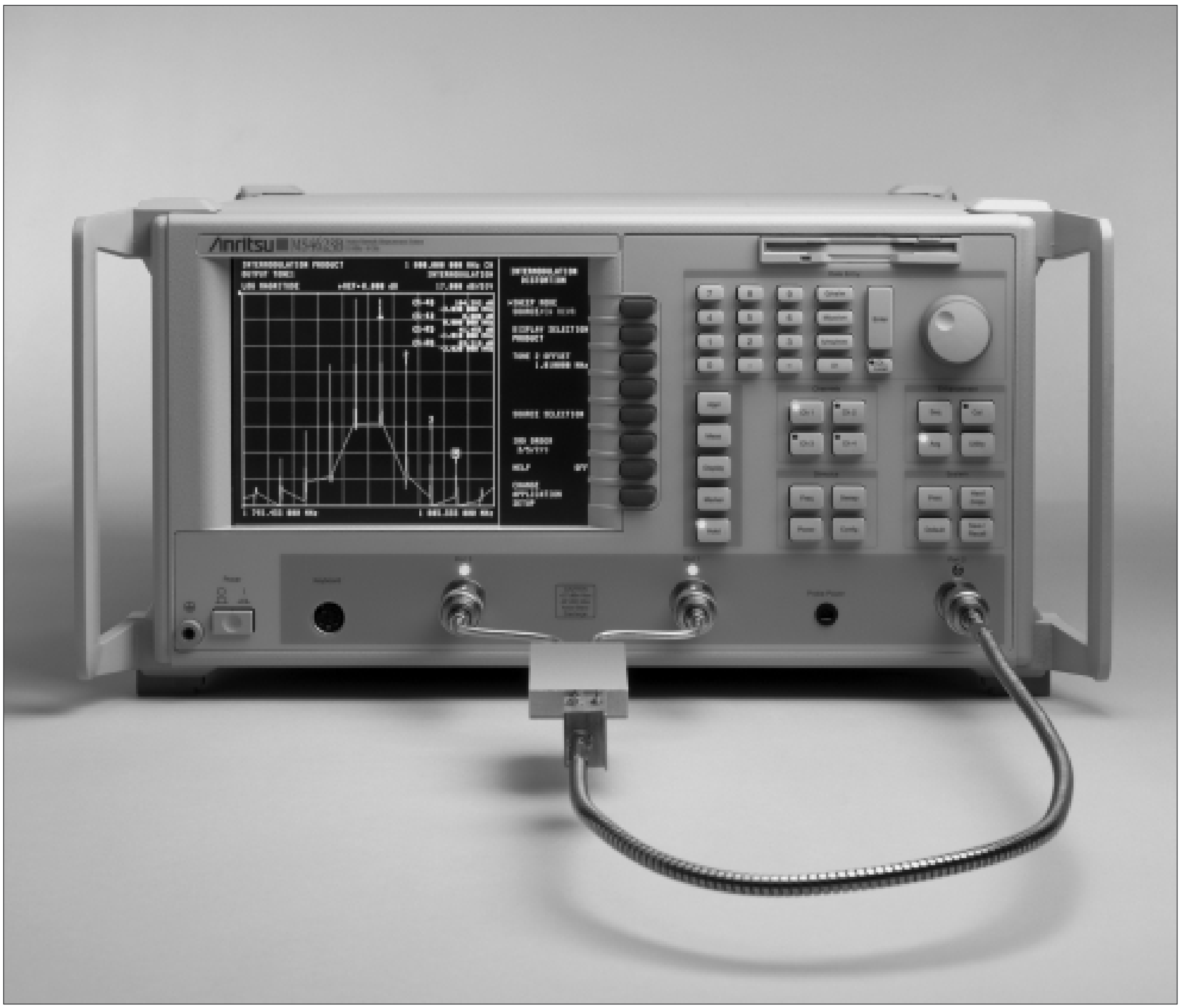
Intermodulation Distortion (IMD)

Scorpion® Option 13

Application Note



Fast, Flexible, and Accurate IMD Measurements Using a Vector Network Measurement System

Introduction

In this application note methods to successfully measure two-tone intermodulation distortion products using the IMD option on the MS462xx Vector Network Measurement System are reviewed. The application is designed to properly configure the receiver to perform CW or swept measurements of all necessary signals, set up the sources, coordinate necessary calibrations, and present the results in a useful form. Since the IMD application is quite flexible and there are a number of setup options, a careful analysis of the measurement needs will lead to a better measurement system.

There are many ways to characterize the distortion properties of a device but two-tone intermodulation distortion (IMD, related terms referring to third order intercept point TOI and the term IP3 are also used) is one of the most common. The two-tone IMD measurement describes a fairly common communications scenario: if strong tones in neighboring channels are present, can they introduce spurious signal energy in a troublesome amount into an adjacent channel? This is a very real and legal issue for equipment makers and renders this measurement of significant importance. While the two-tone measurement is not perfectly realistic in that it assumes that the signals are CW (or narrowband modulated at best), it is a relatively straightforward measurement conceptually, is well defined, and is quite repeatable.

The general assumption for this measurement is that two tones are applied to a device under test (DUT) at frequencies of f_1 and f_2 ($|f_1–f_2|$ small). The difference in frequency between the two tones, termed the offset, is often between a few hundred kHz and a few MHz, although other values are possible. The non-linear characteristics of the DUT generates intermodulation products; among them are signals at $2f_1–f_2$ and $2f_2–f_1$, which will be very close to the original tones in frequency and represent potential adjacent channel spurious signals. The relationship of these various spectral components is illustrated in Figure 1. Since these are third order products, their amplitude dependence on input power will be about three times that of the fundamental (prior to saturation). Hence, if one plots P_{out} (fundamental) and P_{out} (third order product) as a function of P_{in}, the slopes of the curves will be approximately 1:1 and 3:1, respectively, at sufficiently low power where the system is linear. With these disparate slopes, the lines will eventually intersect and the point of intersection is termed the third order intercept point (TOI). The amplitude of P_{out} (third order) relative to P_{out} (fundamental) at a given input power level is termed the IMD level. These concepts are illustrated in Figure 2.

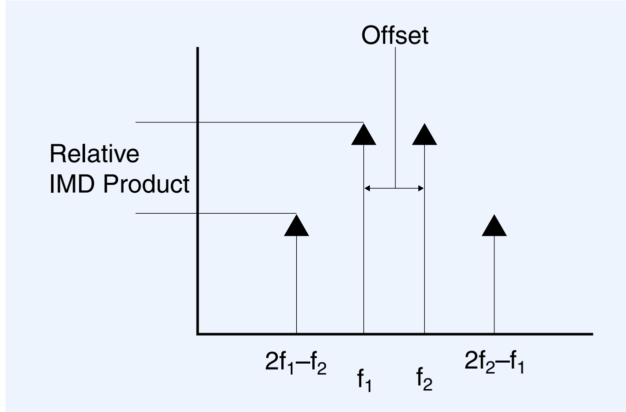


Figure 1. *The frequency relationships in a two-tone IMD measurement are illustrated in this diagram. Tones at f_1 and f_2 are applied to the DUT and third order products at $2f_1–f_2$ and $2f_2–f_1$ may be generated. The relative magnitude of these tones defines the intermodulation distortion.*

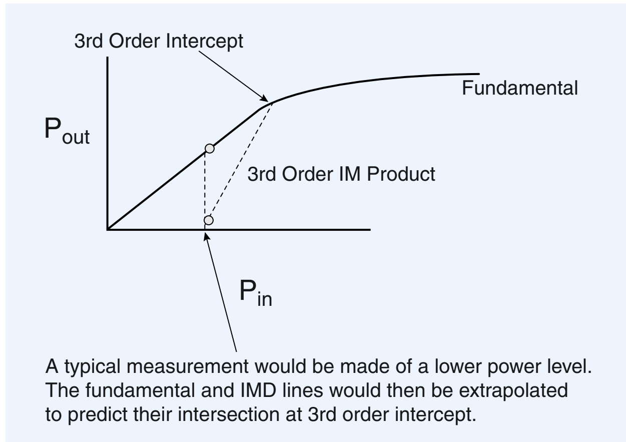


Figure 2. *An illustration of the power relationship between the fundamental tones and the third order products in a simple non-linear DUT is shown in this diagram. The Third Order Intercept is based on an extrapolation from measurements at low power and assumes ideal slopes for the output tone level dependencies.*

Generally, the IP3/TOI measurement is done at a single power level and straight lines constructed (since the slopes are assumed and the one data point will then establish the equation of a line). The intersection of these extrapolation lines determines the IP3/TOI value. The intercept point generated by this measurement has its limitations; foremost among which is that the intermodulation product does not always follow the 3:1 slope ratio. Thus the simple analysis will lead to an erroneous intercept point. Also, the details of the intermodulation power may be of interest in itself.

An initial thought may be to do a measurement set at a few different power levels and attempt to do a more accurate extrapolation of the intercept point based on this data. This would seem inadvisable for several reasons:

- From experiments and manufacturer data, a few added points will not help accuracy very much and, if properly positioned, could produce an even worse result than that obtained with the single point.
- Definition problems arise if the tones are of unequal amplitude. For the second power level, would the instrument raise both tones equally? Raise only one? In the single point scenario, the instrument has the luxury of assuming the default P_{in} scale definition: the tones are assumed to rise by the same amount at each succeeding step along the P_{in} axis

For these and other reasons, the two most common measurements are the raw IMD product (usually expressed relative to one of the main tones) and the IP3 extrapolation discussed above. The MS462xx Vector Network Measurement System is set up to measure these two quantities directly.

The Measurement Flow

The measurement process is illustrated in the flow chart of Figure 3. The first two steps, designing the setup and analyzing potential uncertainties are the most important since there are many potential choices.

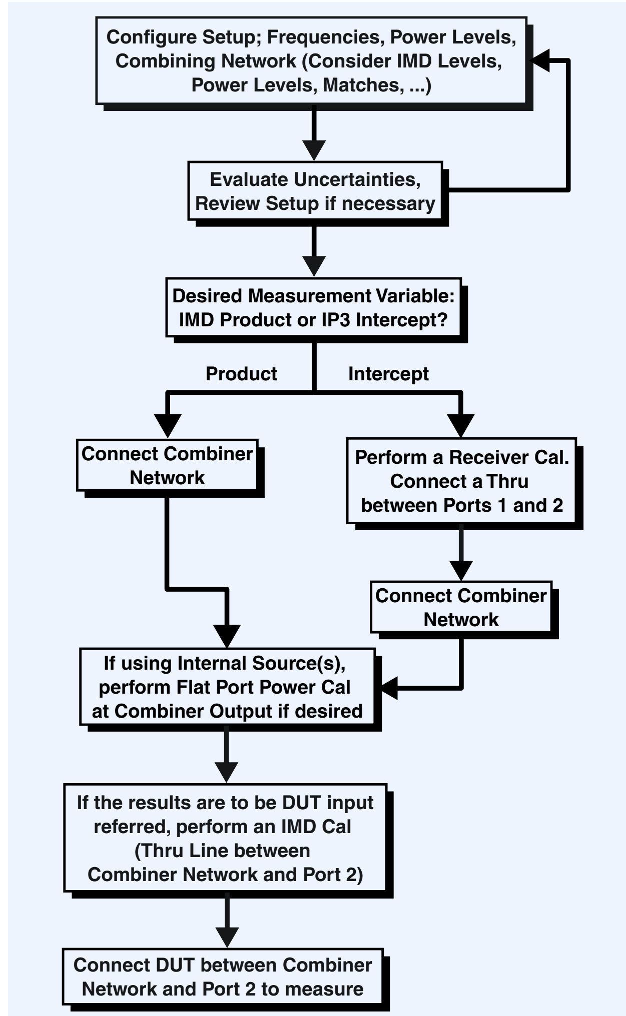


Figure 3. *A flow chart describing the IMD measurement process in the MS4623X. Generally less effort is required for strict product measurements since absolute power knowledge is not required.*

- ***Which sources to use?*** If the MS462xx was purchased with the optional second source, all that the user must provide is a combining network (see below). In cases where extremely low phase noise is important, or for a number of other reasons, external synthesizers can be used. In all cases, the sources will be controlled by the MS462xx for more convenient measurements. If external sources are used, evaluate their pulling sensitivity prior to designing the combiner network. Use the source submenu within IMD to set these up: Source 1 is always internal, Sources 3 and 4 are always external and source 2 will be internal (port 3 access) if the optional second source is installed.
- ***CW or Swept measurement?*** Under the application menu, one can select the CW receiver mode for a display similar to that seen on a spectrum analyzer (tones fixed, all four tones visible as spectral entities). The markers can be positioned for direct IMD readings. This is a quick and familiar measurement but limited. The swept measurement allows the tones to be swept over any band and, at each frequency point, all four tones are measured to perform the required computations.
- ***What power levels and frequencies are to be used?*** These are generally set by the DUT and the test requirements. The power levels needed may affect the combiner network since the maximum internal source power may be as low as 5 dBm and the combiner network will usually contribute loss. Amplifiers may be required. The offset frequency (tone spacing) may not be set by the test requirements. When choosing an offset, select one as large as practical for the application (1 MHz is common) and avoid the image offset frequencies discussed in the appendix. Because of source phase noise, available dynamic range for the IMD measurement will start to decrease as the offset drops below about 200 kHz.
- ***Is the DUT a mixer?*** If so, set up the DUT LO using the source menus and select the DUT type as mixer at application control. Be aware the mixer spurs and mixer match may be an issue and filters or pads may be helpful.
- ***What combining network should be used?*** This is a complicated question dependent on DUT, measurement, and source details. A very complete combining network is shown in Figure 4.

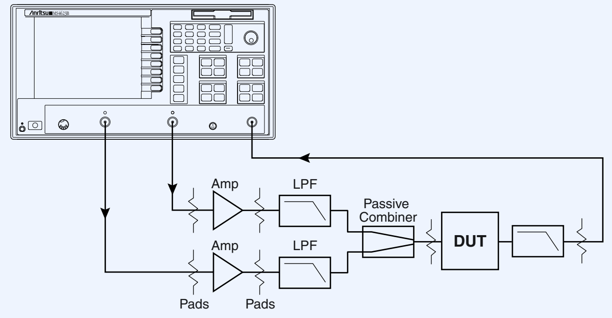


***Figure 4**. An example of a reasonably elaborate combining network. The added isolation (from the amplifiers) and signal filtering provided by this assembly may be needed for measuring extremely small intermodulation products.*

This level of complexity may be required if very low IMD levels are being measured (of order –70 or –80 dBc), if the sources can be easily pulled (external), if the source spur levels are very high, if the DUT is very sensitive to match, or for other reasons. In some cases, this structure can be simplified to that shown in Figure 5.

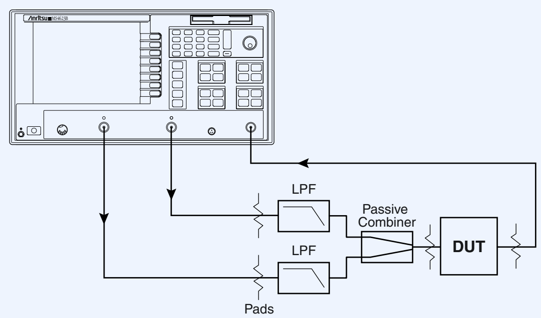


***Figure 5.** A simpler combining network. The lower levels of isolation provided by this network may be acceptable for measuring larger intermodulation products. Additional amplifiers may be needed if the DUT drive level must be higher than the system can provide (+5 to +10 dBm/tone prior to the network losses).*

It is recommended that filters always be used to reduce source harmonics to well below the expected IMD levels (can cause additional mix products in the DUT) and that a true combiner (resistive, Wilkinson, etc.) instead of a tee connection be used. The pads, which may be small, provide some additional isolation and impedance buffering. The pad before the receiver is still optional and is mainly there to ensure that receiver compression is not an issue. This approach is most likely to be valid if the expected IMD products are larger than –60 dBc.

In both the minimal and maximal combining scenarios, and anything in between, the frequency range selected may need to be revisited since the filters will reduce the available span to usually less than an octave (obviously not too important if in CW RCVR mode). If it is known that the given source impurities are particularly small or irrelevant, this condition can be relaxed somewhat.

Before accepting a setup, the user should consider a number of possible sources of uncertainty.

- ***DUT Compression*** If the DUT is already compressing, the extrapolated intercept point will be inaccurate (see Figure 2).
- ***Receiver Compression and IMD*** The receiver IP3 is typically about +35 dBm (excitation near 0 dBm) and can limit the measurement in some cases. Also the receiver enters compression above about +10 dBm port power. If the DUT output levels are high, use an output pad.
- ***Dynamic Range and Noise Levels*** While receiver IMD may limit the upper end of dynamic range, the source or receiver noise levels will usually limit the low end. If the internal sources are used, source phase noise will start to become important for offsets below a few hundred kHz (results will vary for external sources). A typical noise floor (0 dBm main tone levels) will be about –75 dBc or lower for higher offsets, degrading to about –70 dBc for a 200 kHz offset (internal sources). If an inadequate combining network is used, in isolation terms, these levels will rise due to pulling. Use a sufficiently small IF bandwidth to minimize noise effects.
- ***Input Signal Effects*** If the signal entering the DUT is already corrupt with harmonics, IMD products, or spurs, the results could be distorted. Filters are suggested for harmonic (and some spur) suppression. To keep self-IMD products low, ensure that there is sufficient combiner network isolation to prevent source pulling (frequency and amplitude pull) and that any amplifiers in the combining network are sufficiently linear.
- ***Spurs from DUT*** Particularly if the DUT is a mixer, spurs into the receiver may present a problem. Use adequate filtering.
- ***Frequency Accuracy*** If using external sources, ensure that the MS462X is linked to the same 10 MHz reference. Even a few PPM difference in references can affect readings when using small IF bandwidths.
- ***Images*** Because of the receiver structure of the MS462xx, there are certain offset frequencies that will cause a main tone to land in the image response of the receiver while measuring the IMD product. The issue is detailed in the appendix but the most troublesome offsets are 78.125, 125, 156.25 and 250 kHz. Avoiding these frequencies by even 5 kHz can usually remove any difficulty.
- ***Impedances*** Ensure that any filters used see their desired impedance levels and that the DUT is not presented with an impedance that may lead to altered behavior.

The remaining steps in the measurement flow center around performing calibrations and selecting measurement types. The available calibrations can be described as characterizing the receiver behavior, flattening the source behavior with frequency, or characterizing the path between the source and the receiver ports.

Measurement Variables and Receiver Cals

These selections are usually dictated by the test requirements but there are some important effects. If just the IMD product is required, this is a relative power measurement (product relative to main tone). As a result, the receiver calibration may be skipped. This receiver calibration, required for intercept measurements, establishes an absolute power calibration at the receiver port and is available under the power menu and under the IMD cal menu. This very general calibration uses a simple thru line between port 1 and port 2 and uses the internal ALC accuracy to determine the frequency response of the receiver.

Flat Port Power Calibrations

Because the input power to the DUT is often a critical test parameter and the combining network often has a frequency dependent insertion loss, it may be desired to flatten the power at the output of the combining network. This calibration, available if using internal sources, uses a routine under the power menus and a power meter to adjust the ALC systems as a function of frequency to produce a set level. This calibration may be done for any number of frequency points and at any accessible power level. It must be performed separately for source 1 and source 2 although the power meter connection does not have to change. This step is less relevant if in CW RCVR mode.

Input Referrals and the IMD Calibration

If the desired result (product or intercept) is to be referred to the DUT input, the tone level entering the DUT must be known so that the DUT gain can be computed. The IMD calibration performs this task and requires only a simple thru line connection between port 2 and the output of the combining network. The main tone levels to be input to the DUT are stored as a function of frequency for later gain computation. Obviously if the power levels or frequencies are changed, this cal will have to be repeated. This step can be omitted if the measurements are to be output-referred or if CW RCVR mode is to be used.

The Measurements

At last, the DUT can be connected between the output of the combining network and port 2 and the desired variable measured. Aside from selecting the input/output referral and the intercept vs. product, the user must also select the distortion relative to Tone 1 or Tone 2. If the tone amplitudes are equal, these results will often not be too different but may be for certain DUTs. When distortion relative to Tone 1 is selected, the upper IMD sideband is measured (and lower sideband for measurements relative to Tone 2). Some example measurements are shown below.

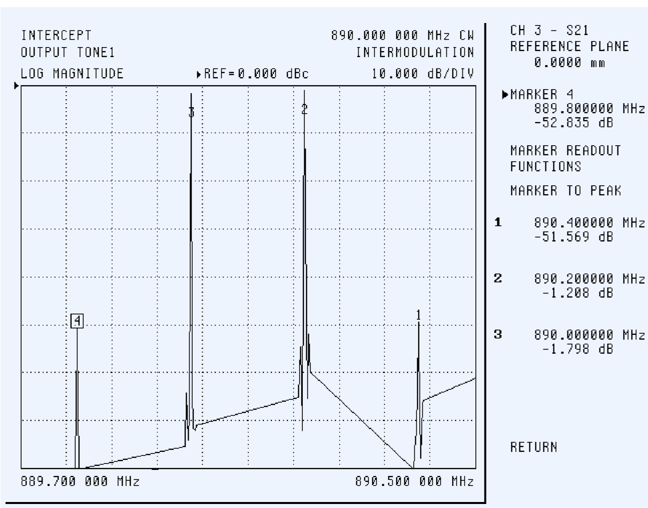


Figure 6. *A CW RCVR mode example measurement for a test DUT. The tones in this case are fixed at 890 MHz and 890.2 MHz while the receiver sweeps a small swath of frequencies around the two IMD products and around the main tones.*

The plot in Figure 6 is an example of the spectrum-analyzer-like display of CW RCVR mode. The amplifier DUT in this case was measured with a tone offset of 200 kHz and an output tone amplitude of about 0 dBm. The tones were placed at 890 and 890.2 MHz for this example and the markers show an IMD product on the order of –50 dBc. This product amplitude is high enough that a very simple combining network could be used.

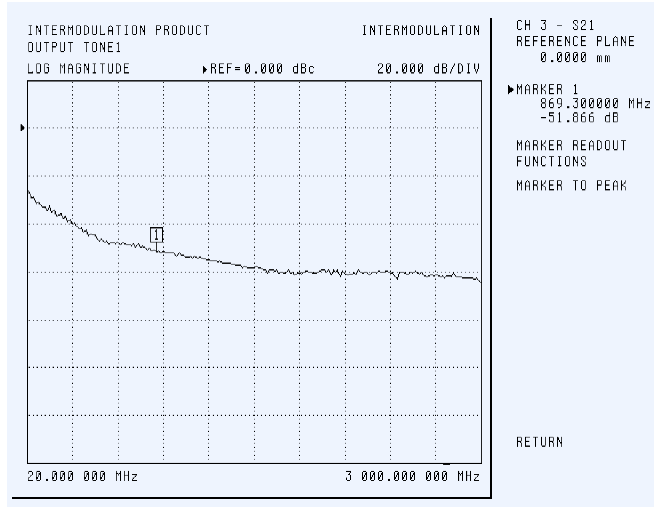


Figure 7. *An example illustrating an amplifier is IMD product as a function of frequency is shown in this plot. Tone 1 is swept from 20 MHz to 3 GHz with tone 2 always being 200 kHz higher (in this case), the system receiver measures both tone and the two IMD products at each sweep point (201 in this case). The product relative to tone 1 output amplitude reaches a minimum of about –65 dBc at higher frequencies.*

The plot in Figure 7 is a swept version of the measurement of a DUT similar to that used in Figure 6. The offset is again 200 kHz but now the tones are swept from 20 MHz to 3 GHz. This measurement methodology is much faster than any spectrum analyzer equivalent when multiple frequencies must be measured. In this plot, the amplitude of the IMD product relative to the tone 1 output amplitude is displayed. Note that in ALL SWEPT IMD measurements, the frequency displayed along the bottom axis of the graph is that of TONE 1.

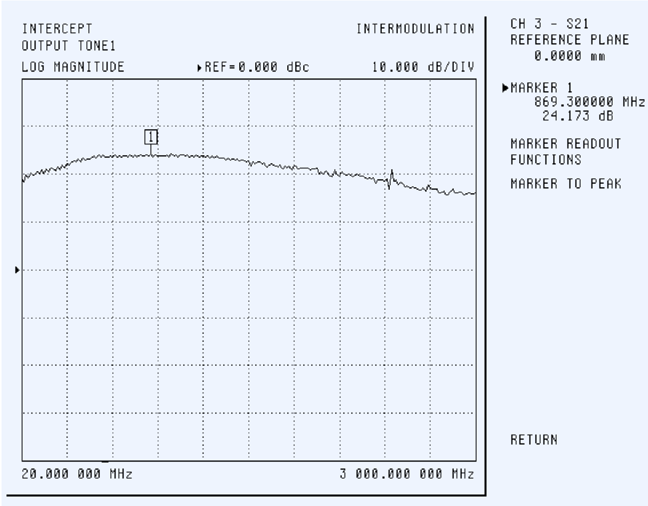


Figure 8. *A swept third-order-intercept plot illustrating the absolute power measurement required by many DUT manufacturers and customers. The common extrapolation algorithm is discussed in the text. As in Figure 7, the tones are swept and the receiver performs four measurements at each point.*

The plot in Figure 8 is a swept third order intercept plot based on a DUT similar to that used in the other examples. As in Figure 7, the tones are swept, but this time the intercept is computed using the algorithm discussed earlier. Since a receiver cal was performed for this measurement, the vertical scale reference is actually in dBm. At the marker frequency, the output referred IP3 of this DUT is about +24 dBm.

Conclusions

This application note has described the IMD measurement as implemented in the MS462xx Vector Network Measurement System including a number of choices that the user must make. These include setup details (source type, frequencies, swept or CW, power levels, combining network, etc.), the measurement desired (IMD product or intercept), the references (measure relative to which tone, relative to input or output), and the calibrations that can be performed. Since a great deal of flexibility is afforded, the careful consideration of these issues should allow the user to make measurements fitting many manufacturing and customer demands.

Appendix: Offset Frequency Selection

The MS462xx is a Vector Network Measurement System designed to make a wide variety of measurements necessary of RF components and subsystem manufacturers and as such, its receiver architecture is a bit different from that used in the typical IMD measurement: the spectrum analyzer. The MS462xx is much more flexible and much faster (particularly in swept measurement) than a spectrum analyzer but does have a few image responses that may affect an IMD measurement but not the other system measurements. Because multiple tones are obviously present during an IMD measurement, it is important that one of the main tones not land on an image response while the system is measuring a much smaller IMD product. For this reason, certain offset frequencies are to be avoided. The main offenders include 125 kHz, 78.125 kHz, 156.25 kHz, and 250 kHz. Certain mix products of these frequencies may occasionally present a problem if the IMD products to be observed are very small.

A simple test is possible to determine if a desired offset frequency is a problem. Assemble the combining network and set the system up for the required IMD product measurement. Connect a thru line from the combining network to port 2 and observe the product. If this level is sufficiently below the measurement needs, then the desired offset is certainly acceptable. If the organic IMD level is higher than acceptable, try changing the offset frequency by about 5 kHz. If the level drops substantially, then the original offset may present an image problem. If the IMD level does not improve substantially, it is likely not an image problem and the deficiency may lie in the combining network or other setup details (refer back to the text).

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