"Practical Intercept Measurements and Cascaded Intermod Equations"

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Circuit linearity has always been a major design issue. Design performance is typically limited by intermod performance at the top end of the dynamic range and by noise on the bottom end. Intermod and noise performance are at odds with one another and many times improving the performance of one means degradation of the other. This paper will describe the importance of intercept points in RF system specifications, current intercept calculation techniques compared with practical measurement techniques in the lab.

Intercept Points

The following figure illustrates 3rd order intermod and noise performance boundaries. As shown a higher intercept point yields larger dynamic range. Consequently, intercept points are commonly used as a performance characteristic of RF systems. In general the higher the intercept point the more tolerant the system is to interference.
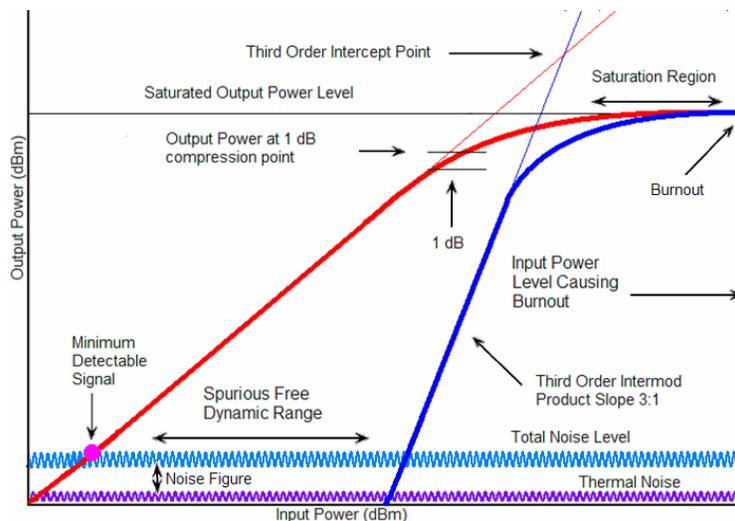

Figure 1 – Non-Linear Power In / Out Curves

In a cascade of RF behavioral models a diagram similar to that above can be derived to determine the overall system performance. The cascaded intercept point is generally referred to the input or output for convenience. Transmitters and amplifiers generally have their intercept points referred to the output and receivers have them referred to their input.

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Cascaded Intermod Equations

Using basic assumptions the intercept point for a cascade can be determined. Cascaded equations[1] come in two flavors, coherent and non-coherent. If the intermods throughout the cascade are assumed to be in phase then coherent addition should be used. This will yield a worst case intercept point. However, if the intermods are assumed to be out of phase then non-coherent addition can be used.

Cascaded Intercept (Coherent Addition)

$$1 / ITOI_{cascade} = 1 / ITOI_1 + 1 / (ITOI_2 / G_1) + \ldots + 1 / (ITOI_n / G_1G_2 \ldots G_{n-1})$$

Cascaded Intercept (Non-Coherent Addition)

$$1 / (ITOI_{cascade})^2 = 1 / (ITOI_1)^2 + 1 / (ITOI_2 / G_1)^2 + \ldots + 1 / (ITOI_n / G_1G_2 \ldots G_{n-1})^2$$

Where
  ITOI – Numeric Stage Input Third Order Intercept
  G – Number Stage Gain

The basic assumptions are:
  1. There is no concept of frequency
  2. All stages have been perfectly matched
  3. No consideration for filtered tones that generate the intermods
  4. Multiple paths are ignored (only valid for two port lineups)
  5. Gain is assumed to be independent of power level
  6. Intermods never travel backwards (reverse isolation is assumed to be infinite)

The calculation of cascaded intermods is generally in a spreadsheet. Note there is no relationship between these calculations and the physical measurements of the intercept points in the lab. There is no mention of frequencies and power levels of tones that are need to make measurements in the lab.

Intercept Measurements in the Lab

Intercept measurements in the lab are broken down into two groups, in-band and out-of-band. In-band measurements are used when tones are not attenuated by filtering through the cascade. For example, intercept point for a power amplifier is generally done with 2 tones that exhibit the same power throughout the system. Out-of-band measurements are used when they are attenuated like filtering in an Intermediate Frequency (IF).

In-Band Intercept Measurements

  For in-band measurements two tones, f_1 and f_2 are created by two signal generators and combined before entering the Device Under Test (DUT). Care needs to be taken in the setup to ensure reverse intermods will not be generated in the signal generators before appearing at the DUT input. A typical setup is as shown below using two tones.

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[1] McClaning K., and T. Vito (2000). *Radio Receiver Design* Atlanta, GA: Noble, pp. 605-626
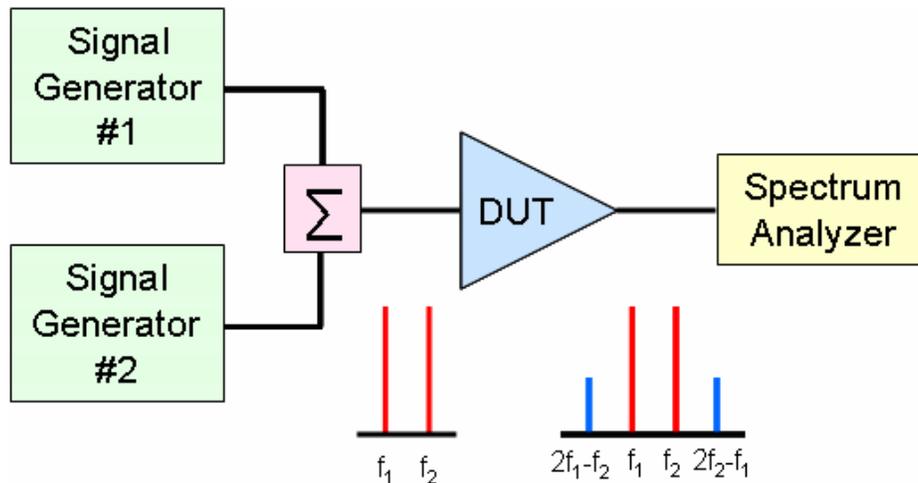
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Figure 2 - In-Band Intermod Measurement Setup

The intercept point is determined from the measured power level of the two tones and the power level of the intermods themselves on a spectrum analyzer as shown in the following figure.
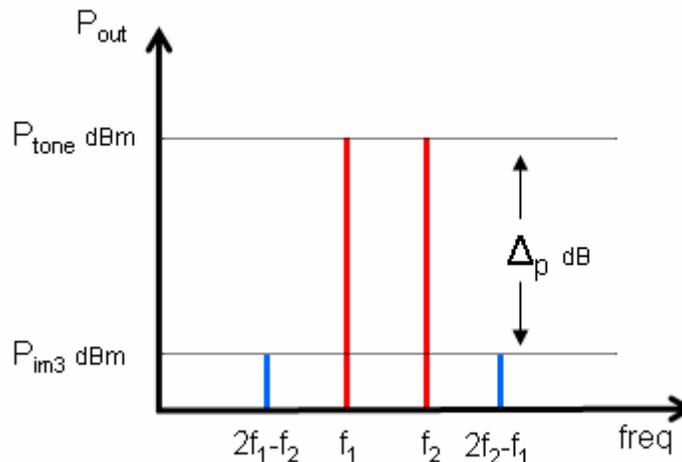

Figure 3 - In-Band DUT Output Spectrum

From this information the output third order intercept is determined as follows:

$$OTOI_{dBm} = P_{tone\ out,\ dBm} + \Delta_p / 2$$

The input third order intercept is:

$$ITOI_{dBm} = OTOI_{dBm} - Gain_{DUT}$$

Out-of-Band Intercept Measurements

Out-of-band measurements are more complicated since the tones have been attenuated at the IF output. This is illustrated in the following two figures.
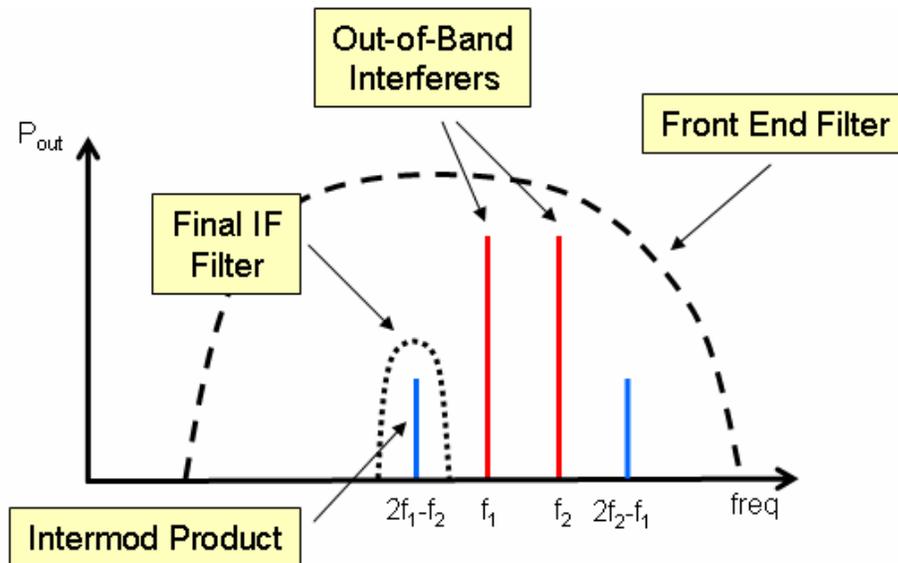
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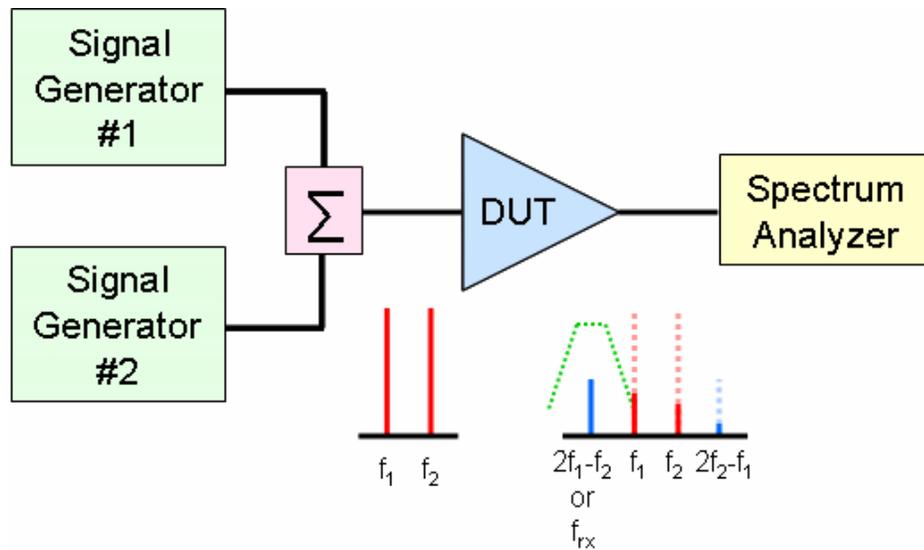*Figure 4 - Third-Order Distortion Inside the Receiver Input Filter*

Figure 5 - Out-of-Band Intermod Measurement Setup (Won't Work)

Without knowing what the un-attenuated tone power level is the intercept point cannot be determined as shown in the following diagram.
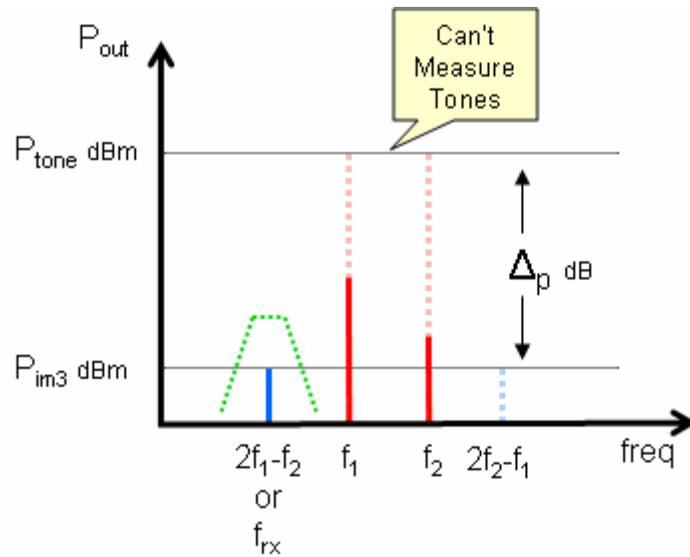
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Figure 6 - Out-of-Band DUT Output Spectrum (Won't Work)

To remedy this additional steps are needed to determine an out-of-band intercept point.

To solve this problem a virtual tone can be determined which, is the power of the tone at the DUT input plus the in-channel cascaded gain. Once the virtual tone power and the in-channel gain are determined then both input and output intercept points can be found.
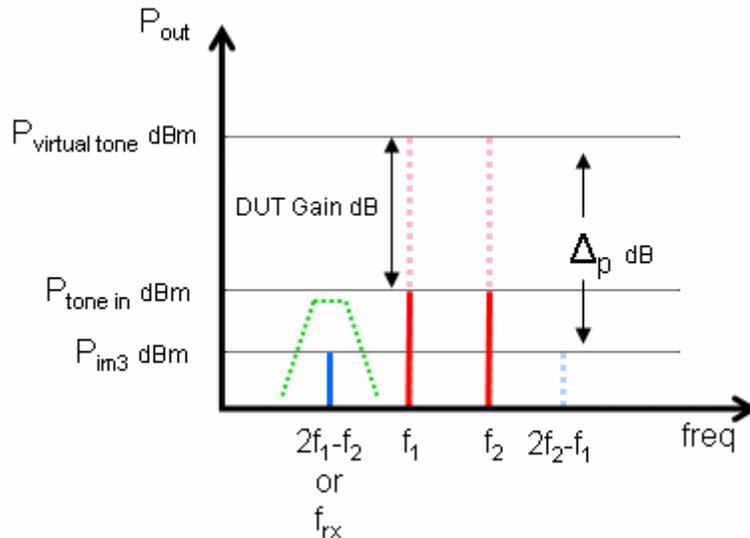

Figure 7 - Out-of-Band DUT Output Spectrum (Virtual Tone)

In the lab measuring the in-channel cascaded gain and intermod power is a two step process. First, the in-channel gain is measured using a single signal generator as shown below.
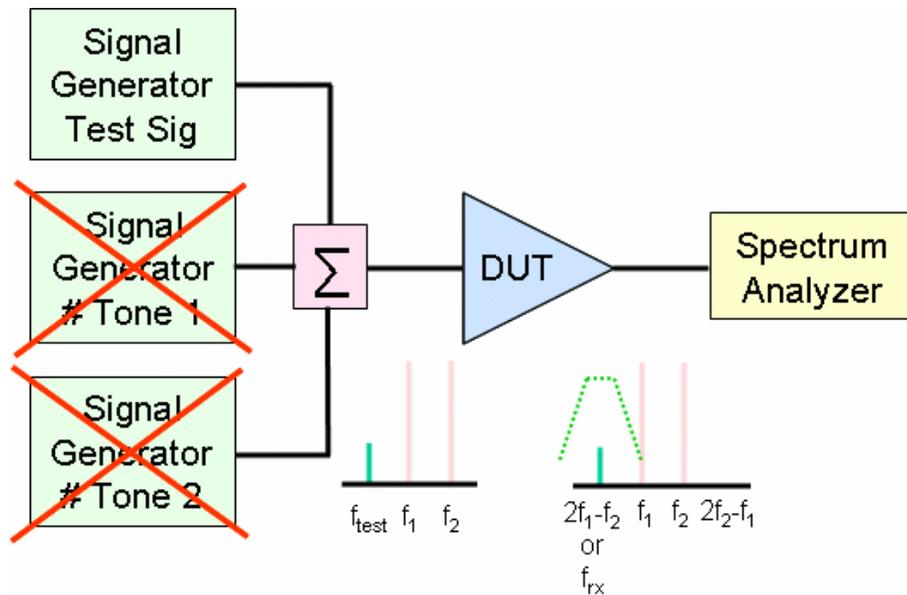
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Figure 8 - Out-of-Band Intermod Measurement Setup - Step #1

Next, the in-channel signal generator is disabled and the two tone generators are enabled and the in-channel intermod power is measured as shown below.
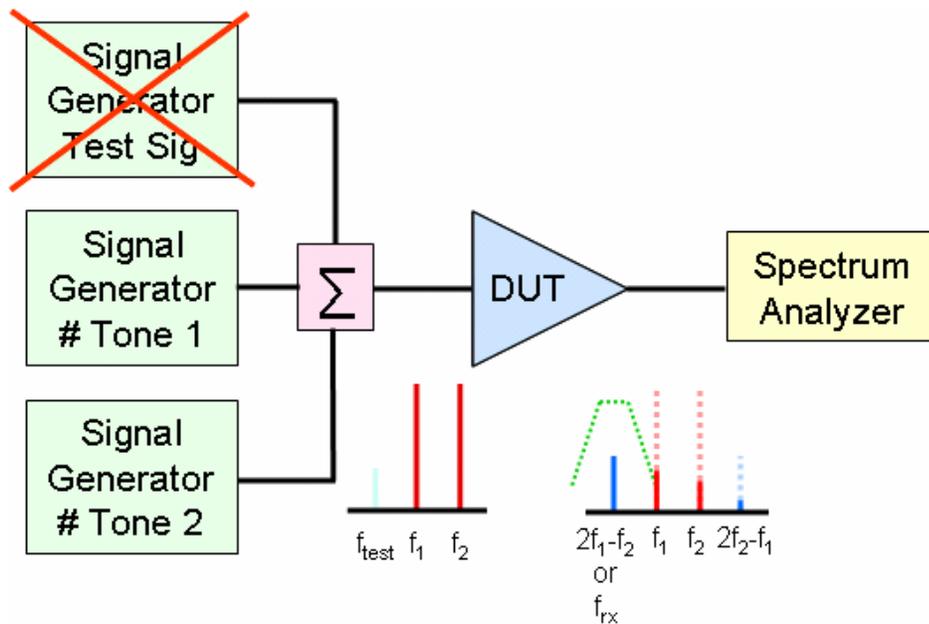
Figure 9 - Out-of-Band Intermod Measurement Setup - Step #2

Be aware that it is very difficult in practice to measure intermod power levels near the noise floor of the receiver. One common technique is to measure the S/N ratio at the receiver output given a known on-channel signal generator input power level. When the on-channel signal generator is disabled and two tones are injected into the receiver the power level of the two tones can be adjusted until the S/N ratio decreases by 3 dB. At this point we know that the power level of the intermod is equivalent to the power level of the on-channel signal generator.

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Intercept Measurement Summary

The process of measuring the intercept point is very different than using cascaded equations. When determining the intercept point in the lab the user must physically create both tones at the frequencies of interest. The spacing between the tones needs to be such that the third order intermods will appear at the desired locations. The power level of the input tones needs to be sufficiently low to keep the DUT in linear operation but large enough to be seen in the dynamic range of the spectrum analyzer. When measuring the intermod and tone power levels the user must select the appropriate frequencies on the spectrum analyzer to place the markers. Out-of-band intermod measurements require an additional step to measure the in-channel cascaded gain. This is a very different process than using cascaded intermod equations that remain ignorant of frequencies, impedances, directions, and power levels.

Intercept Points Other Than 3rd Order

Thus far only 3rd order intercept points have been addressed. However, for a two tone source the general intercept equation is:

$$IP_n = (P_{tone} - P_{intermod,\, n}) / (n - 1) + P_{tone}$$

Where:

IP$_n$ is the nth order intercept point
n is the intercept order
P$_{intermod,\, n}$ is the power level of the nth order intermod (created by the two tones)
All power levels are measured in dBm

This equation only applies for intermods created with two tones. Intermods created with more than two tones have slightly different amplitudes and don't fit the above relationship directly. However, the measurement technique in the lab follows the same process except the frequency of the intermod will changed based on the order of the intermod. For instance, even order products are generally located at twice the frequency of the two tones or closed to DC.

Cascaded Intermod Equations and SPECTRASYS

SPECTRASYS doesn't use cascaded intermod equations and is not restricted to their limitations. Measuring intercept points in SPECTRASYS is akin to making measurements in the lab. SPECTRASYS needs to know both the frequency of the intermod and the frequency of one of the tones. These values are specified on a path. The path frequency is the frequency of the intermod being measured and the 'Tone (Interferer) Frequency' is the frequency of the tone used to determine the intercept point. Unlike a marker on a spectrum analyzer SPECTRASYS has the ability to measure the power of a spectrum across a channel. Care must be given to ensure the channel bandwidth is wide enough to cover the bandwidth of the intermod yet narrow enough to exclude the power level of any tones used to create the intermods.

Because SPECTRASYS has the ability to differentiate between signals and intermods the two step out-of-band process can be done in a single step as shown in the following figure. The out-of-band configuration is the general case and will also work for in-band intercept measurements.
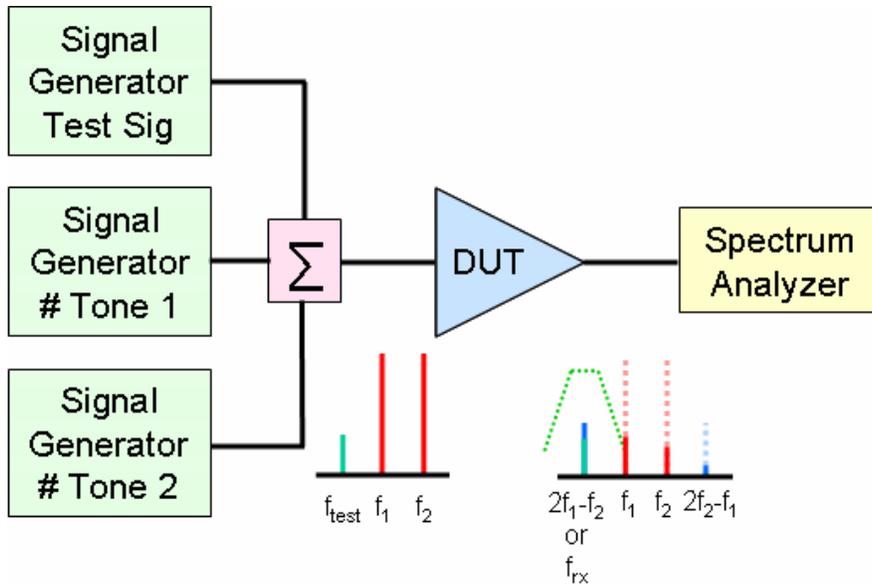
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Figure 10 - SPECTRASYS Out-of-Band Intermod Setup

The user can view measurements showing frequencies and power levels of the tones and intermods being used in intercept calculations.

The following tables show a mapping of SPECTRASYS measurements to the intermod test setup and results.

Table 1 - SPECTRASYS Intercept Setup Measurements

Measurement	Description	Intermod Setup
CF	Channel Frequency	Intermod Frequency
TIMCP	Total Intermod Channel Power	Intermod Channel Power for each Order up to the Maximum Order
TIMCPn	Total Intermod Channel Power for Order n Only	Intermod Channel Power for the given Order n
ICF	Interferer (Tone) Channel Frequency	Tone Frequency used for Intercept Calculations
ICP	Interferer (Tone) Channel Power	Power Level of the Tone (Used for In-Band Measurements)
VTCP	Virtual Tone Channel Power	Power Level of the Virtual Tone based on the Desired Channel Power of the Test Signal. (Used for Out-of-Band Measurements)

Table 2 - SPECTRASYS Intercept Measurements

	Measurement	Description	Intermod Results
In-Band (Uses ICP)	IIP	Input Intercept Point	Input Intercept Point for each Order up to the Maximum Order
	IIPn	Input Intercept Point for Order n Only	Input Intercept Point for the given Order n
	OIP	Output Intercept Point	Output Intercept Point for each Order up to the Maximum Order
	OIPn	Output Intercept Point for Order n Only	Output Intercept Point for the given Order n

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Out-of-Band (Uses VTCP)	RX_IIP	Input Intercept Point	Input Intercept Point for each Order up to the Maximum Order
	RX_IIPn	Input Intercept Point for Order n Only	Input Intercept Point for the given Order n
	RX_OIP	Output Intercept Point	Output Intercept Point for each Order up to the Maximum Order
	RX_OIPn	Output Intercept Point for Order n Only	Output Intercept Point for the given Order n

NOTE: In-Band and Out-of-Band intercept measurements will yield the same results if the tones are attenuated.
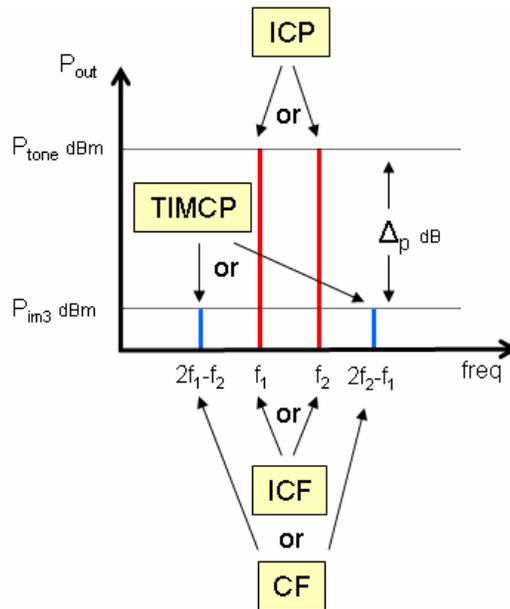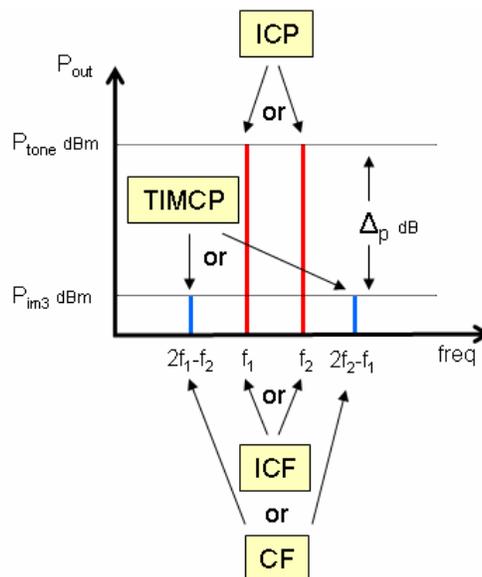

Figure 11 - In-Band SPECTRASYS Measurements

Figure 12 - Out-of-Band SPECTRASYS Measurements

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From the intermod power level and the measured tone power level intercept points for all orders up to and including the maximum order are calculated. However, only one of them will be valid since the intermod frequency will be different for each order.

In-Band Intercept Simulation

1. Create a two tone source and connect it to the DUT.
2. Create a path and set its frequency to the intermod frequency.
3. Set the 'Tone (Interferer) Frequency' of the path to the tones that will be used to calculate the intercept point.
4. Set the Channel Bandwidth to a value wider than the intermod but narrow enough to exclude any power from the tone.
5. Add the IIPn or OIPn measurement to a graph or table when n is the intercept order.

Out-of-Band Intercept Simulation

1. Create a three tone source and connect it to the DUT.
2. Set the frequency of the third test signal to the frequency of the intermod.
3. Create a path and set its frequency to the intermod frequency.
4. Set the 'Tone (Interferer) Frequency' of the path to the tones that will be used to calculate the intercept point.
5. Set the Channel Bandwidth to a value wider than the intermod but narrow enough to exclude any power from the tone.
6. Add the RX_IIPn or RX_OIPn measurement to a graph or table when n is the intercept order.

Troubleshooting Intermod Simulation

Here are a couple of key points to remember when troubleshooting intermod measurement problems. Using a table is generally much better at troubleshooting than level diagrams.

1. Look at the **'Channel Frequency** (CF)' measurement in a table. This must be the frequency of the intermods of interest.
2. Make sure there are intermods in the channel by looking at the **'Total Intermod Channel Power** (TIMCP)'** measurement.
3. If there are no intermods in the channel look at the spectrum and verify that an intermod of the order of interest has been created at the **'Channel Frequency'** of the path.
4. If there are no intermods at the channel frequency make sure **'Calculate Intermods'** has been enabled.
5. If there are still no intermods make sure the nonlinear models have their nonlinear parameters set correctly.
6. If the **'Total Intermod Channel Power'** doesn't seem to be too low verify that the **'Channel Measurement Bandwidth'** is wide enough to include the intermod order of interest.
7. If the **'Total Intermod Channel Power'** still doesn't seem to be correct then verify that the **'Channel Power** (CP)'** measurement is showing the approximate expected power. The **'Channel Measurement Bandwidth'** may be set so wide that other interferer frequencies fall within the channel and the **'Channel Power'** measurement will be very high.
8. If the **'Total Intermod Channel Power'** seems to be too high the intermods may be traveling backwards from a subsequent stage. The reverse isolation of this stage can be increased to verify this effect.
9. If the **'Intercept Point'** measurements (IIP, OIP, RX_IIP, or RX_OIP) measurements don't seem to be correct then first verify that the **'Interferer (Tone) Channel Frequency** (ICF)'** is set to the interfering frequency.

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10. If the **'Interferer Channel Frequency'** is set correctly then look at the **'Interferer Channel Power** (ICP)'** measurement for in-band intermod measurements or **'Virtual Tone Channel Power** (VTCP)'** measurement for out-of-band intermod measurements to verify and expected level of interferer channel power.
11. If the **'Output Intercept Point'** looks correct but the **'Input Intercept Point'** doesn't then verify that the **'Interferer Cascaded Gain** (ICGAIN)'** measurement is correct for the in-band intermod measurement case or the **'Cascaded Gain** (CGAIN)'** measurement is correct for the out-of-band intermod measurement case.

Author Information

Rulon VanDyke is the lead engineer in RF architecture simulation at Agilent Technologies. He received both a Bachelor of Science degree and Master of Science degree in electrical engineering from Brigham Young University in 1990. For 10 years, he designed first-, second-, and third-generation digital cellular transceivers and base stations for AT&T Bell Labs and Lucent Technologies. He may be reached via E-mail: Rulon_vandyke@agilent.com

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