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Measuring Multi-tone Intermodulation Distortion in Power Amplifiers

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presented by:

Marta Iglesias
Frank Palmer

Abstract:

Characterization of power amplifier distortion is critical to evaluate transmitter performance. The latest digital communications transmitter architectures reduce amplifier count and cost by employing Multi-Carrier Power Amplifiers (MCPA) that handle multiple channels with improved power-added efficiency, reducing the overall operating costs of the base station. Testing two-tone intermodulation distortion (IMD) or single-carrier adjacent channel power ratio (ACPR) is not enough to evaluate MCPAs. MCPAs can be characterized by multi-tone IMD measurements that simulate realistic signal stimulus conditions and provide repeatable results. However, while two-tone IMD is a simple, well understood, and generally easy to perform test, multi-tone IMD is more complex to generate and interpret. A stimulus signal with the appropriate phase relationships among the tones is necessary to simulate real life conditions and provide repeatable results. In addition, a high dynamic range measurement setup is required to minimize measurement uncertainty. This paper discusses these requirements and shows a few measurement examples.

Agenda

- Review of classic CW distortion measurements
- Adjacent Channel Power Ratio (ACPR)
- Noise Power Ratio (NPR)
- Multi-tone Intermodulation Distortion (M-IMD)
  - Theory:
    - Three-tone IMD
    - N-tone IMD
    - Time-domain profile of multi-tone stimulus
  - Signal generation approach: analog or digital?
  - Which time-domain profile shall I use?
  - How can I improve my measurement dynamic range?
- Summary

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Why test distortion?

- Distortion is caused by non-linear behavior of PA
- Distortion affects transmitter performance:
  - Phase and amplitude distortion creates bit errors
    - check for AM-AM and AM-PM
  - Intermodulation distortion causes spectral regrowth
    - check for third order IMD and ACPR
  - Harmonic distortion causes out-of-band emissions
    - check for harmonics

Transmitter power amplifiers play an important role in boosting signals and directly affect maximum range and antenna size. As signal levels increase, amplifiers start exhibiting the nonlinear characteristics all systems must tolerate to some degree. Non-linearities typically cause either phase and amplitude distortion that create bit errors or spectral re-growth that interferes with adjacent channels. Common metrics are AM-AM and AM-PM conversion for BER-limited radios and intermodulation distortion, third-order intercept point, and adjacent power ratios for spectral re-growth-limited radios.

Classic CW Distortion Measurements

- One- and Two-Tone Distortion Measurements
  - Harmonic Distortion
  - 2-tone Third-order Intermodulation
- AM-AM
- AM-PM

Classic CW Distortion Measurements

One- and two-tone distortion measurements

- **Non-linear devices can be modeled by Maclaurin series:**

$$V_o = K_0 + K_1 V_i + K_2 V_i^2 + K_3 V_i^3 + \ldots$$

- **This assumes:**
  - **Memoryless device**

Non-linear devices can be approximately modeled by Maclaurin series expansion. This assumes that the device under test can be considered memoryless. This assumption is generally not true for MCPA modules because they typically work close to saturation and use linearization schemes such as feedforward or pre-distortion techniques, which cause memory effects on the MCPA. However, the Maclaurin model can still be useful to understand how distortion behaves and how to model linearity in test equipment.

Classic CW Distortion Measurements

Harmonic Distortion

- **Single-tone input:**

$$V_i = V_1 \cos(\omega_1 t + \phi_1) \rightarrow V_i = V_1 \cos \omega_1 t$$

  - **1st order (fundamental)**

$$K_1 V_1 \cos \omega_1 t$$

  - **2nd order**

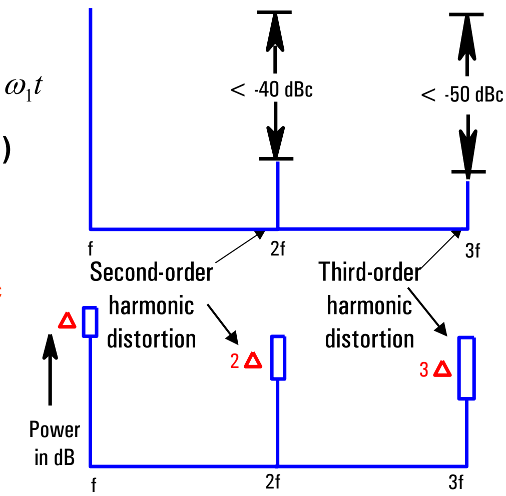
2nd harmonic

$$K_2 V_1^2 \left(\frac{1}{2} + \boxed{\frac{1}{2}\cos 2\omega_1 t}\right)$$

  - **3rd order**

3rd harmonic

$$K_3 V_1^3 \left(\frac{3}{4}\cos \omega_1 t + \boxed{\frac{1}{4}\cos 3\omega_1 t}\right)$$



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The most critical out-of-band distortion is typically the 2nd order and 3rd order distortion. If we develop the 2nd order and 3rd order terms in the Maclaurin series for a single tone input, we obtain distortion terms at the multiples of the fundamental frequency. These correspond to the 2nd order and 3rd order harmonics. Note that the level of the second harmonic is proportional to the square of the fundamental and that the level of the third harmonic is proportional to the cube of the fundamental. If the fundamental level changes by some number of dB, the level of 2nd and 3rd order harmonics change by two and three times that number of dB, respectively. For example, a 1 dB increase in the fundamental results in a 2 dB increase in the 2nd harmonic and a 3 dB increase in the 3rd harmonic.

However, harmonic distortion is typically specified *relative* to the fundamental level. This means that for the above example the *difference* between the 2nd harmonic and the fundamental will be 1 dB *less* than it was, and the *difference* between the 3rd harmonic and the fundamental will be 2 dB *less*.

Therefore, when specifying the relative or absolute level of the 2nd harmonic distortion, for example, it is imperative to also specify the level of the fundamental at which the distortion was measured. Once this is provided, the 2nd harmonic distortion can theoretically be predicted for any power level at the fundamental. However, this prediction only holds true for the more linear section of the power transfer function of the device, so it can only model distortion in devices under small signal excitation. [1]

Notice that the development of the 3rd order term in the Maclaurin equation also provides a distortion term at the fundamental frequency. This term may look larger than the 3rd order harmonic, but it is not significant relative to the fundamental. So, we are typically not worried about distortion at the fundamental frequency until the device gain or phase starts changing (see AM-AM and AM-PM later). Remember that specifications on out-of-channel and out-of-band distortion must be more strict to prevent this distortion to interfere with much smaller signals from the same or different systems.

Classic CW Distortion Measurements

Two-tone IMD

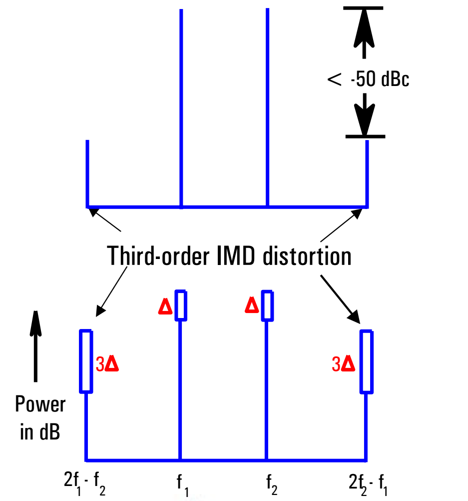
- **Two-tone input:**

$$V_i = V_1 \cos\omega_1 t + V_2 \cos\omega_2 t \Rightarrow$$
$$V_1(\cos\omega_1 t + \cos\omega_2 t)$$

- **3rd order**

$$K_3 V_1^3 \left(\frac{3}{4}\cos(2\omega_1 - \omega_2)t + \frac{3}{4}\cos(2\omega_2 - \omega_1)t + \frac{9}{4}\cos\omega_1 t + \frac{9}{4}\cos\omega_2 t + \ldots\right)$$

3rd order IMD



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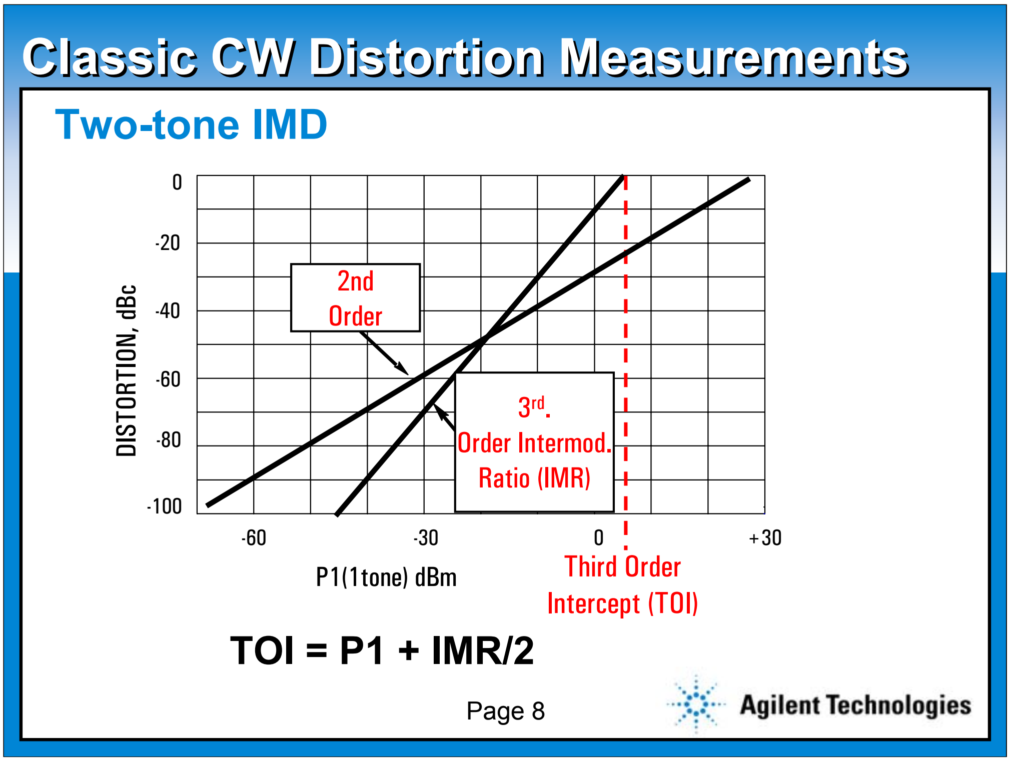
Intermodulation (IMD) is the formation of combination frequencies resulting from a nonlinear transfer characteristic when the input signal comprises several frequencies. The 3rd order intermodulation products are typically the most problematic, since their frequencies are relatively close to the fundamental frequencies.

The two-tone CW distortion measurement is the most common test used to characterized the 3rd order IMD in a device.

As with any 3rd order distortion, when the level of the fundamental increases by some number of dB, the level of the IMD will increase by three times that number in dB, but its level *relative* to the fundamental will *decrease* by *twice* that number in dB. Therefore, when specifying the relative or absolute level of 3rd order IMD, the level of the fundamental must also be specified. Once this is provided, the 3rd order IMD can also be theoretically predicted for any power level at the fundamental, assuming small signal excitation conditions.

Note that the two fundamental tones are shown equal in amplitude. This is the usual case but is not necessary.



There are many different terms used to specify 3rd order IMD. IM3 or Intermodulation Ratio (IMR) are two different names for the same thing. As explained earlier, the distortion *relative* to the fundamental tones is typically specified along with the level of the fundamental tones (assumed here to be equal). Hence the vertical axis of the graph is labeled dBc, dB *relative* to the fundamental.

For example, IMR=-70 dBc at –30 dBm (each tone; not their total power). From this point, knowing that the slope of the relative third order distortion to the fundamental is 2:1, the 3rd order distortion curve for a device can be drawn and the distortion can be predicted for other power levels. For example, at –20 dBm, the IMR=-50 dBc.

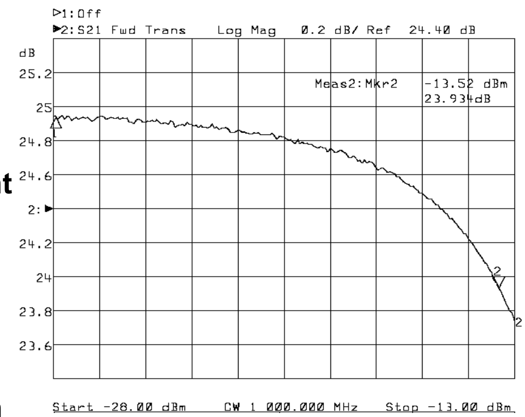
The Third Order Intercept (TOI) is the theoretical power level for the fundamental at which the 3rd order IMR is 0. In reality, the 3rd order distortion curve cannot be predicted for large signal levels, at which the power transfer function is no longer linear. However, the TOI is used as a single figure of merit from which the IMR can be calculated (or vice versa) given a power level for the fundamental.

The 2nd order harmonic curve can also be calculated by knowing the 2nd order harmonic distortion at a certain power level at the fundamental, and by knowing that the slope is 1:1.

Classic CW Distortion Measurements

AM-AM (Gain Compression)

- Effects:
  - Decrease of modulation quality
  - Increase of adjacent channel distortion
- Characterized by 1-dB compression point
- Correlate CCDF to gain vs. input power to determine PA operating point



Gain vs. input power

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Gain compression or AM-AM conversion occurs when the amplifier's power source cannot supply the necessary current, resulting in clipping of the output signal. At this point the non-linearities of the device cause both a decrease of the modulation quality and an increase of the distortion in the adjacent channel. For this reason, gain compression can usually be detected by both analyzing the adjacent channel distortion performance with measurements such as the adjacent channel power ratio (ACPR) or by analyzing the modulation quality of the signal with measurements such as error vector magnitude (EVM) or code domain power (CDP).

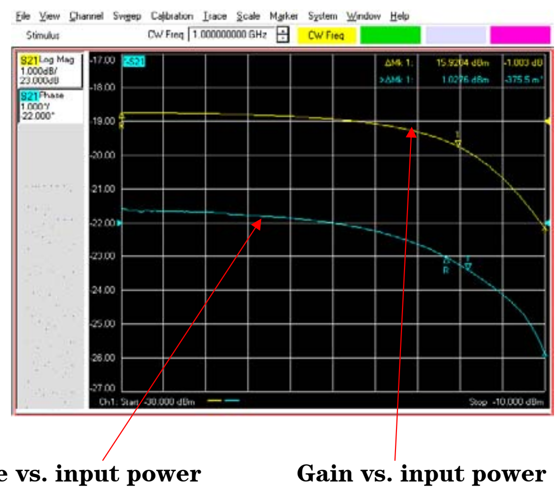
The parameter that is used to specify the gain compression performance of a device is its 1dB compression point. This is the point at which the output signal is compressed by 1dB from the ideal input/output transfer function. The gain compression curve of the device has traditionally been characterized by the Gain-to-Signal amplitude curve for a CW signal with a network analyzer.

However, unlike CW signals, a multi-carrier signal typically has high peak-to-average power ratio statistics. CCDF (Complementary Cumulative Distribution Function) analysis of the signal is essential to determine the correct average power at the amplifier input for optimum amplifier performance, i.e. the best compromise between output level and compression. One way to achieve this is by correlating the CCDF signal to the amplifier gain versus input power plot. [2]

Classic CW Distortion Measurements

AM-PM

- **Effects:**
  - **Decrease of modulation quality**
- **Measure:**
  - **Phase vs. input power**
  - **Phase vs. frequency at a spot power delta**



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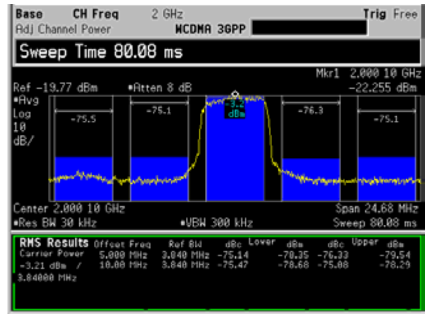
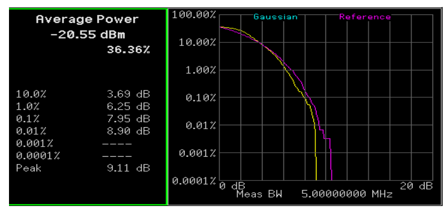
In addition to compression (AM-AM conversion) the non-linearities in power amplifiers also cause phase distortion for high levels of signal amplitude. This effect is known as AM-PM conversion.
The phenomena that gives rise to AM-PM again begins with the power source limitation creating a clipping of the waveform. This causes a shift of the zero-crossing of the sine wave, which in turn causes a phase shift of the output signal. As signal power increases, AM-PM typically occurs before AM-AM.
The non-linearities of the device at this point will cause both a decrease in modulation quality and an increase of adjacent channel distortion, although the latter will not be as obvious as in the case of AM-AM.
AM-PM has traditionally been characterized on CW signals using Network Analyzers. There are two types of AM-PM CW measurements: spot and swept. The classical diagram of AM-PM versus power level is a spot frequency versus swept power measurement, as shown in the slide.
Another approach is to use a swept frequency measurement on a spot power delta. This measurement is best suited for broadband devices that operate over a range of frequencies. [1]

Adjacent Channel Power Ratio

Single-carrier ACPR

- Used in cellular digital communications systems
- Stimulus signal is digitally modulated
- Measures distortion in adjacent and alternate channels relative to signal in main channel
- CCDF of signal affects ACPR





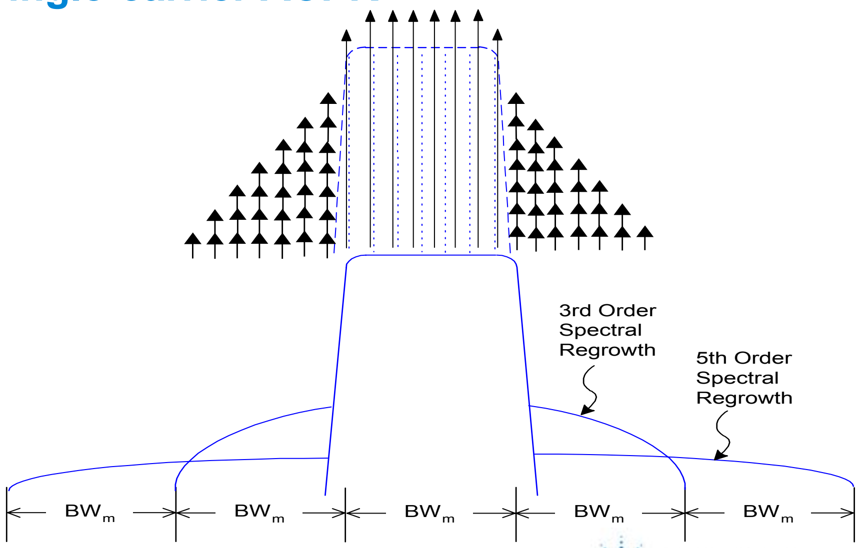
Until now we have talked about distortion measurements that are typically performed using CW signals as the stimulus. However, in digital communications systems, signals are digitally modulated. In order to characterize the distortion of a device or system, a digitally modulated stimulus is better because it yields results closer to real-life performance.

In digital communications, Adjacent Channel Power Ratio (ACPR) is analogous to 2-tone IMD. A digitally modulated signal with the appropriate signal format is used as the stimulus. ACPR is the ratio between the power in the adjacent (or alternate) channel and the main channel.

In some digital modulation systems, the power statistics of the signal can vary depending on the signal’s configuration. For example, in CDMA systems, the peak-to-average power ratio statistics of the signal varies depending on the number of code channels, the code channel number assignments, etc [2]. The power statistics of a signal can be characterized by the Complementary Cumulative Distribution Function curve. The power statistics or CCDF of the signal affects the ACPR measurement result. This means that the parameters of the stimulus signal need to be well defined and specified to get consistent/repeatable results across manufacturers and represent real-life signals.

Adjacent Channel Power Ratio

Single-carrier ACPR



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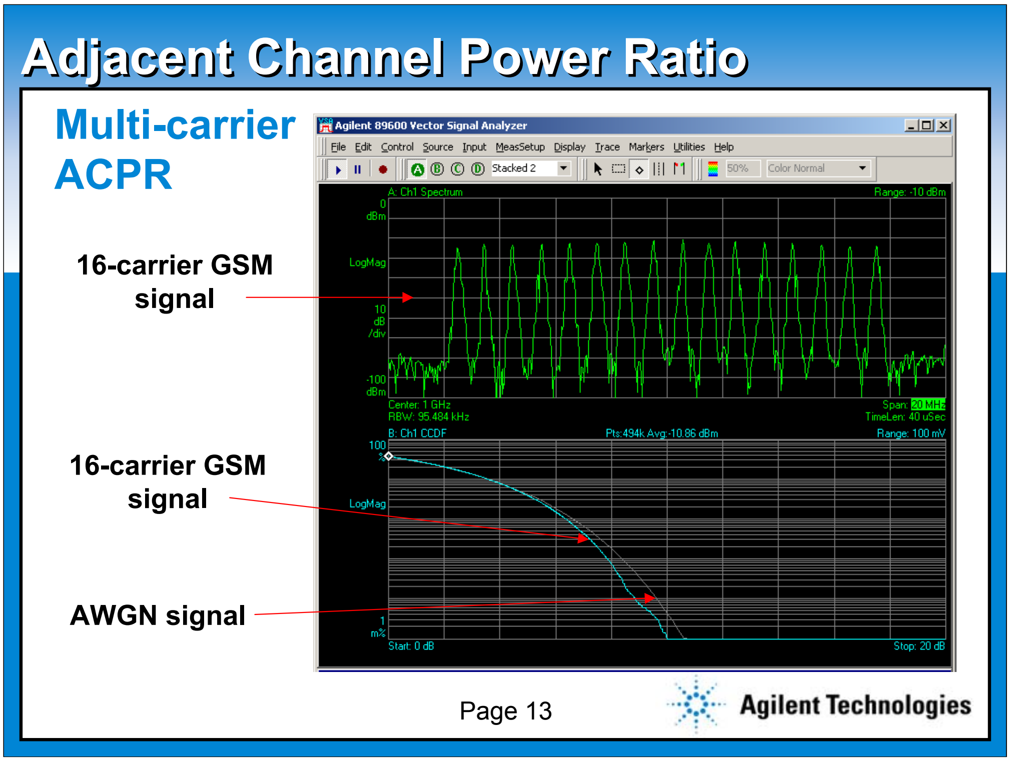
Intuitively, the digitally modulated signal can be modeled as a number of closely spaced CW signals. A number of distortion products results from this approximation. Each distortion product is the result of the 3rd order interaction between two of these CW signals. All the distortion products at a single frequency add as vectors.

As it will be shown later, considering only the distortion products caused by 2-tone combinations of the CW signals does not necessarily lead to a complete representation of the modulated signal distortion. However, this simplified model can be useful to understand the distortion phenomenon and make approximations.

When plotted on the log-amplitude scale, it is apparent that 3rd order spectral regrowth (another term for distortion) spreads out one modulation bandwidth away from the edge of the main channel. Fifth order spectral regrowth extends two modulation bandwidths away from the edge of the main channel.

Third order spectral regrowth is predominant in the adjacent channels and 5th order is only significant in the first alternate channels.



The latest digital communications transmitter architectures reduce amplifier count and cost by employing Multi-Carrier Power Amplifiers (MCPA) that handle multiple channels with improved power-added efficiency.

Multi-carrier signals have more demanding CCDFs than single-carrier signals. Therefore, more linearity is required from the MCPA. For example, the spectrum measurement above shows the spectrum and CCDF of a GSM signal with 16 carriers with random phases and random data. While the peak-to-average power ratio of a GSM signal would be close to zero, the CCDF of the 16-carrier GSM signal approaches a 10 dB peak-to-average power ratio for a 0.001% probability.

Since ACPR is influenced on the peak-to-average power ratio of the signal, single-carrier ACPR does not provide a realistic measure of the real performance of MCPAs. Multi-carrier signals are needed to assess ACPR on multi-carrier devices.

Adjacent Channel Power Ratio

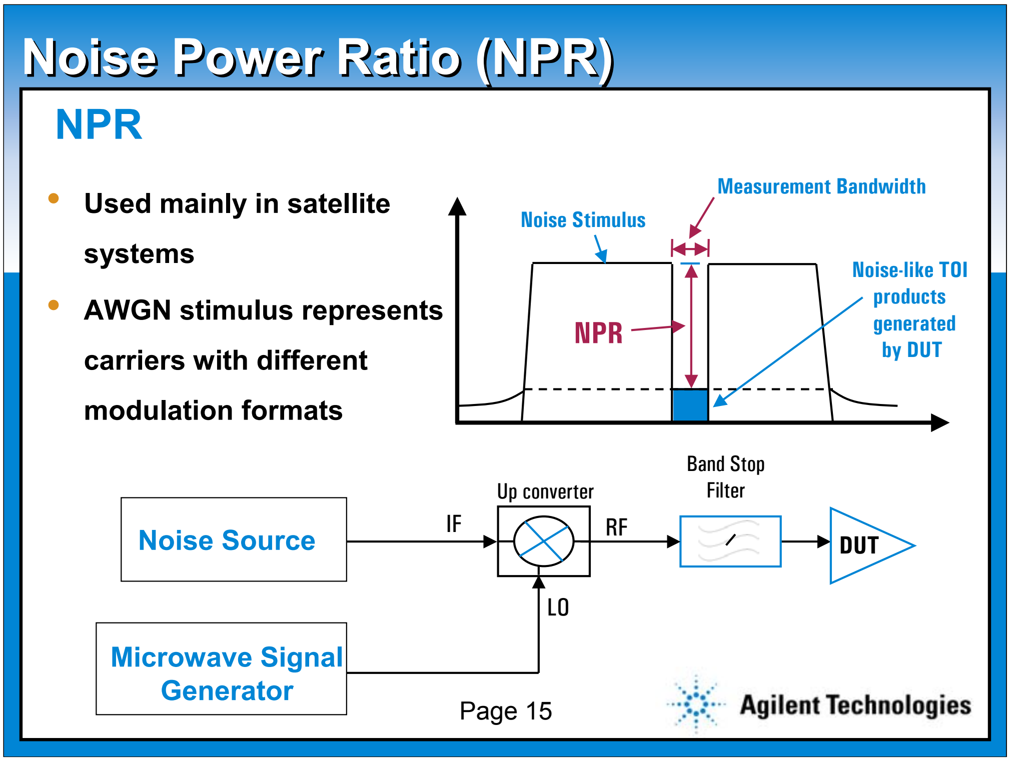
Multi-carrier ACPR

- CHALLENGES
  - High dynamic range from source and signal analyzer
    - Typically need multiple sources with isolators/combiner & band stop filters
      - ➢ TIME & COST↑↑
- ALTERNATIVE:
  - Use multi-tone IMD measurements in addition to ACPR

The main challenge associated with multi-carrier ACPR is the high dynamic range required to get accurate results.

High peak-to-average power ratios from multi-carrier signals demand high linearity from the PAs in order to achieve reasonably low distortion. The distortion from the instrumentation needs to be around 15-20 dB lower than that of the PAs, in order to provide accurate measurements. From the signal stimulus side, multiple sources (one for each carrier), isolators, and a combiner are typically required just to provide the multi-carrier signal. Band stop (or notch) filters might be needed to improve the required dynamic range. With this technique one faces calibration and switching issues as well as the need to procure different filters for each frequency range. This whole setup demands both time and money to configure it properly.

As will be shown later, a good alternative is to use multi-tone IMD measurements in addition to ACPR measurements.



Noise Power Ratio (NPR) measurements are used particularly in microwave satellite systems, where different modulation formats might be present. As the number of carriers increases, the CCDF of the signal approaches that of Additive White Gaussian Noise (AWGN). The NPR method uses AWGN to simulate the loading of multiple signals in the device.

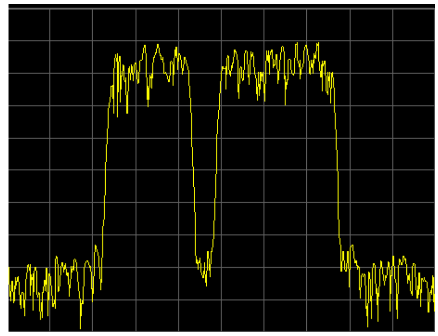
NPR evaluates in-band IMD. Since the amplifier's linear output components mask the in-band distortion, a notch (or band stop) filter is required to remove a slice of input signal spectrum.

Today NPR signals are created using a number of instruments, devices, and accessories. First AWGN is created at baseband. Next, the noise signal is up-converted using a generic microwave source and an external mixer. Then, the notch is created in the measurement bandwidth by inserting a band stop filter. Finally, NPR is measured by comparing the power of the spectral components in the passband without the notch to the power of the spectral components in the notch.

Noise Power Ratio

NPR

- CHALLENGES:
  - Need signal generator + AWGN source + band stop filter
    - ➢ TIME & COST↑↑
  - AWGN is constant only if measured in a long period
    - ➢ REPEATABILITY↓↓
- ALTERNATIVE:
  - Use multi-tone IMD measurements with a large tone density instead of traditional NPR



So, the traditional NPR setup includes several devices: microwave generator, AWGN source, and band stop filter. This has an effect on both the setup time and the cost.

But the main issue with this traditional setup is however repeatability. Noise parameters are random in nature. The measured value of the power fluctuates in time. The longer the period over which it is averaged, the more repeatable the measured values will be.

An alternative to avoid long measurement times or low repeatability is to use multi-tone IMD measurements with a large tone density, instead of traditional NPR. In the following sections we will see how a large number of tones can form synthetic noise.

Multi-tone Intermodulation Distortion

- Theory:
  - Three-tone IMD
  - N-tone IMD
  - Time-domain profile of multi-tone stimulus
- Signal generation approach: analog or digital?
- Which time-domain profile shall I use?
- How can I improve my measurement dynamic range?

Multi-tone Intermodulation Distortion

Theory - Three-tone IMD

- **Three-tone input:**

$$V_i = V_1\cos\omega_1 t + V_2\cos\omega_2 t + V_3\cos\omega_3 t \Rightarrow$$

$$V_1(\cos\omega_1 t + \cos\omega_2 t + \cos\omega_3 t)$$

  - **3rd order**

1-tone terms

2-tone terms

3-tone terms

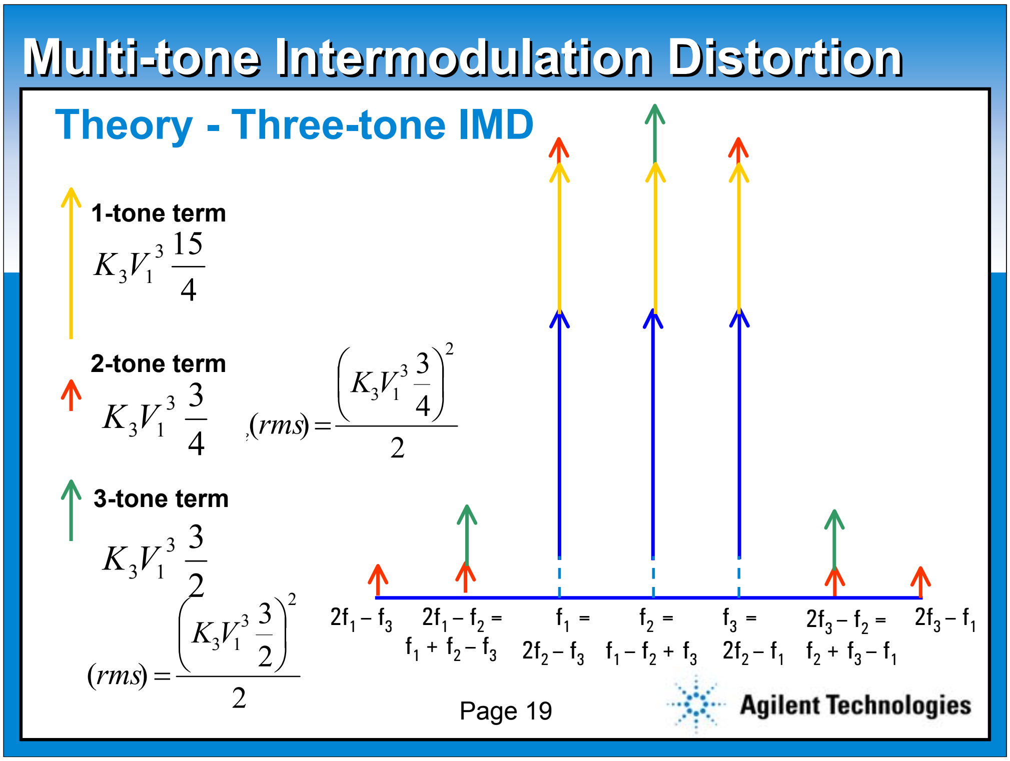
$$K_3V_1^3\Big(\frac{15}{4}\cos\omega_1 t + \frac{15}{4}\cos\omega_2 t + \frac{15}{4}\cos\omega_3 t +$$

$$\frac{3}{4}\cos(2\omega_1-\omega_2)t + \frac{3}{4}\cos(2\omega_2-\omega_1)t + \frac{3}{4}\cos(2\omega_1-\omega_3)t +$$

$$\frac{3}{4}\cos(2\omega_3-\omega_1)t + \frac{3}{4}\cos(2\omega_3-\omega_2)t + \frac{3}{4}\cos(2\omega_2-\omega_3)t +$$

$$\frac{3}{2}\cos(\omega_1+\omega_2-\omega_3)t + \frac{3}{2}\cos(\omega_1-\omega_2+\omega_3)t + \frac{3}{2}\cos(\omega_2+\omega_3-\omega_1)t + \ldots\Big)$$

In order to understand the nonlinear behavior of devices for a multi-tone stimulus, we will first look at the simple three-tone case.
The mathematical analysis of third order intermodulation for the case of a three-tone input, provides three kinds of terms that will fall in the area of interest:
-1-tone terms that fall at the fundamental frequencies: these were essentially the same distortion products that were obtained for the 1-tone input or 2-tone input third order analysis, and are typically disregarded since it is considered that their influence will be small relative to the power of the fundamental tones
-2-tone terms: these represent the distortion products caused by the combination of two of the tones. For a 3-tone input, there can be only 3 combinations of 2-tones (1-2, 2-3, 1-3). Each one of these combinations will cause two intermodulation products. Therefore, there are a total of six 2-tone terms.
-3-tone terms: these represent the distortion products caused by the combination of three of the tones. For a 3-tone input, there is only one possible combination (1-2-3). Each 3-tone combination causes three 3-tone terms. So, in this case there is a total of three 3-tone terms.



The graphical representation of the main tones (in blue) and the distortion terms is provided in the slide. The voltage value for each kind of term is also provided. It can be seen that the 3-tone term is twice the amplitude of the 2-tone term. The average power (RMS of voltage) for each kind of term is also provided. Since only the relationship among the tones is important, the power is calculated for an output resistance of 1 ohm. Any other value could have been chosen instead, since that would not change the relative power among terms.

Even if the 1-tone, 2-tone, and 3-tone terms are represented as vectors that appear to be in-phase with each other, this assumption is not necessarily true. So, what would be the distortion at a single frequency after combining all the distortion terms at that frequency?

Multi-tone Intermodulation Distortion

Theory - Three-tone IMD

- Several terms at a frequency add as vectors
- Total IMD power at a frequency depends on relative phase of fundamental tones:
  - Worst case: same phase for all tones.

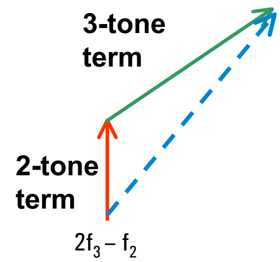
Voltage addition

$$IMD(rms) = \frac{\left(K_3 V_1^3 \frac{3}{4}\right)^2 3^2}{2}$$

  - For random independent phases with uniform distribution.

Power addition

$$IMD(rms) = \frac{\left(K_3 V_1^3 \frac{3}{4}\right)^2 5}{2}$$



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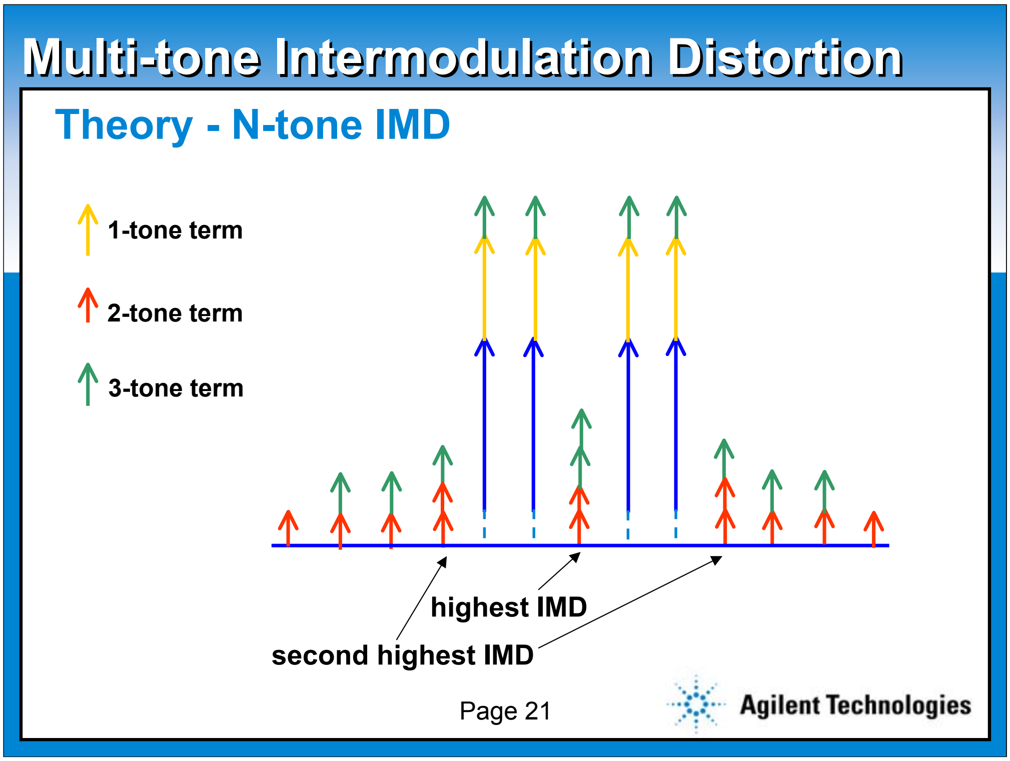
The different 1-tone, 2-tone, and 3-tone terms at a single frequency add as vectors to form the total distortion at that frequency. Therefore, the total distortion depends on the relative phases among the distortion terms, which in turn depends on the relative phases among the fundamental tones.

The worst case scenario, from a distortion point of view, occurs if all the fundamental tones are periodically in phase. The result is that the distortion components at each offset frequency are in phase, and the total voltage at each frequency is simply the sum of the voltages of the individual components. The power at each frequency is therefore based on a straight sum of the voltages. For example, if only 2-tone and 3-tone components are present, the power is 9 times (9.5 dB greater than) that of the 2-tone component alone.

The worst case is not common. Typically the phases are independent and random with a uniform distribution. In this case, the distortion power at each frequency is the sum of the power contributed by each term. For the above example, the total power would be 5 times (7 dB greater than) that of the 2-tone component alone.

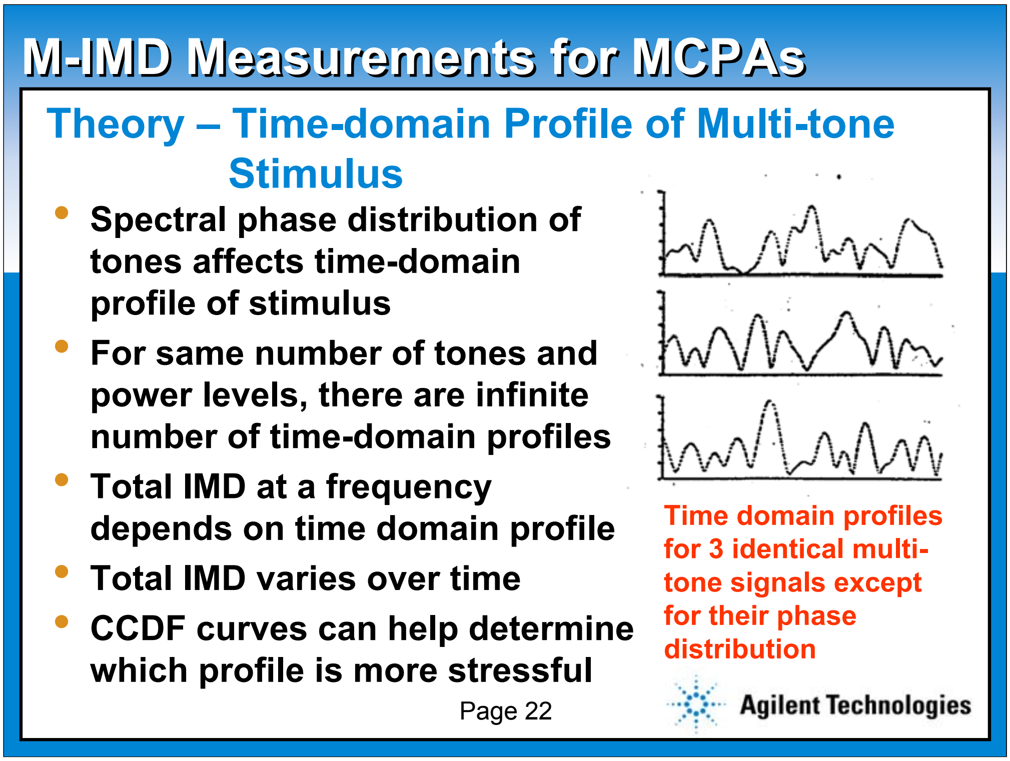


Now, let's consider the more general N-tone case. A graphic representation for a 4-tone input with a notched tone at the center will help illustrate the main tendencies:

-3rd order IMD for N tones always consists of 2-tone-combination and 3-tone-combination terms or products (1-tone-term distortion only appears at the fundamental frequencies)

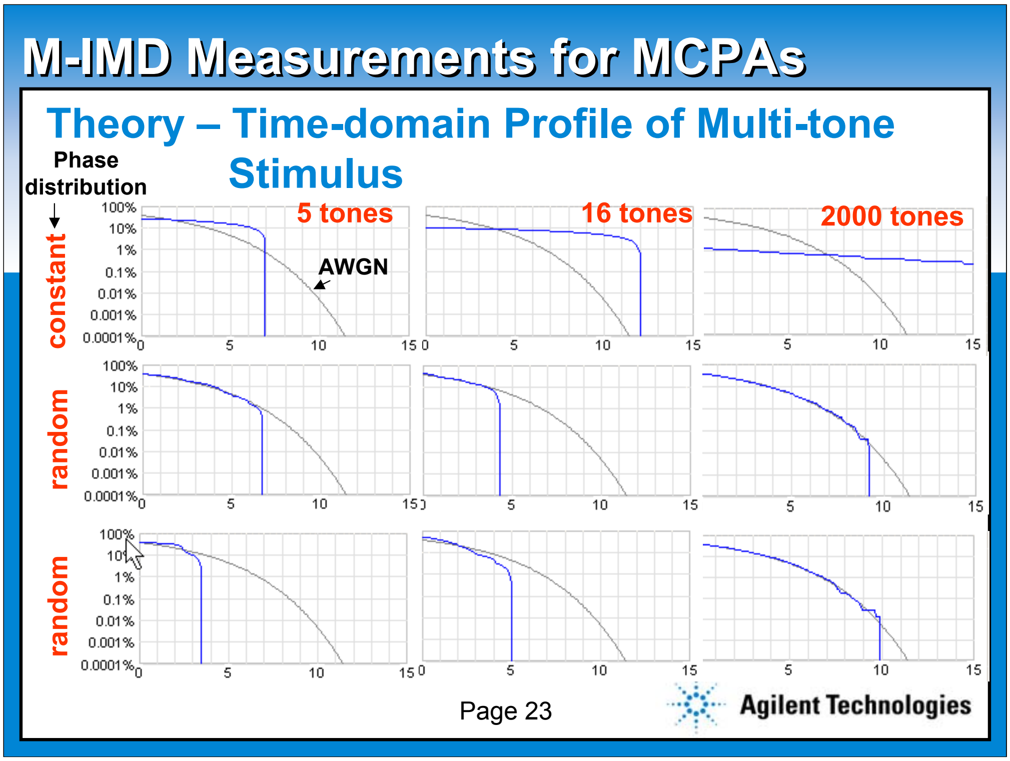
-for N tones evenly spaced in frequency by d, the worst IMD frequencies are typically –d from the lowest frequency and +d from the highest frequency of the tones.

-for N tones evenly spaced in frequency with a gap in the center (center tone off), the worst IMD typically occurs at the center



As mentioned before, the total IMD at a certain frequency will depend on the phase relationship among tones. The total IMD will also vary over time. To understand what is happening to the IMD, consider the stimulus in the time domain. For identical power levels and spectral power distributions, the stimulus can take on an infinite number of different shapes. The spectral phase distribution affects the time-domain profile of the stimulus by determining how the tones add up at each instant.

This slide shows three stimuli that are identical except for their phase distributions. The best way to characterize each stimulus signal and compare it with others is by using the CCDF. The CCDF tells us which profile is more stressful (which profile will cause higher distortion).



The higher the number of tones, the larger the range of variation of peak-to-average power ratio statistics caused by the phase distribution among the tones. For example, 16-tone signals can have CCDFs that have a larger variation (from the most to the least stressful) than 5-tone signals.

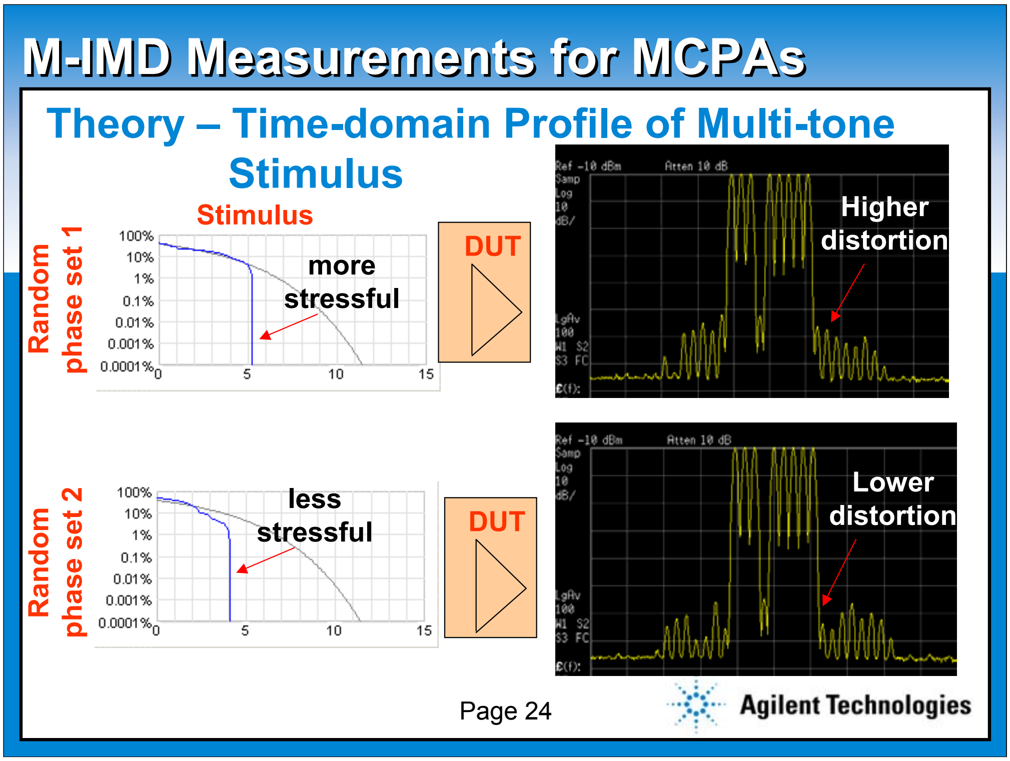
A constant phase distribution (i.e. all tones are periodically in phase) is always the worst case, and causes the most stressful CCDF.

A parabolic phase distribution (not shown in the slide) would typically produce the least stressful time-domain profile or CCDF, for a given number of channels, although this is not always the case.

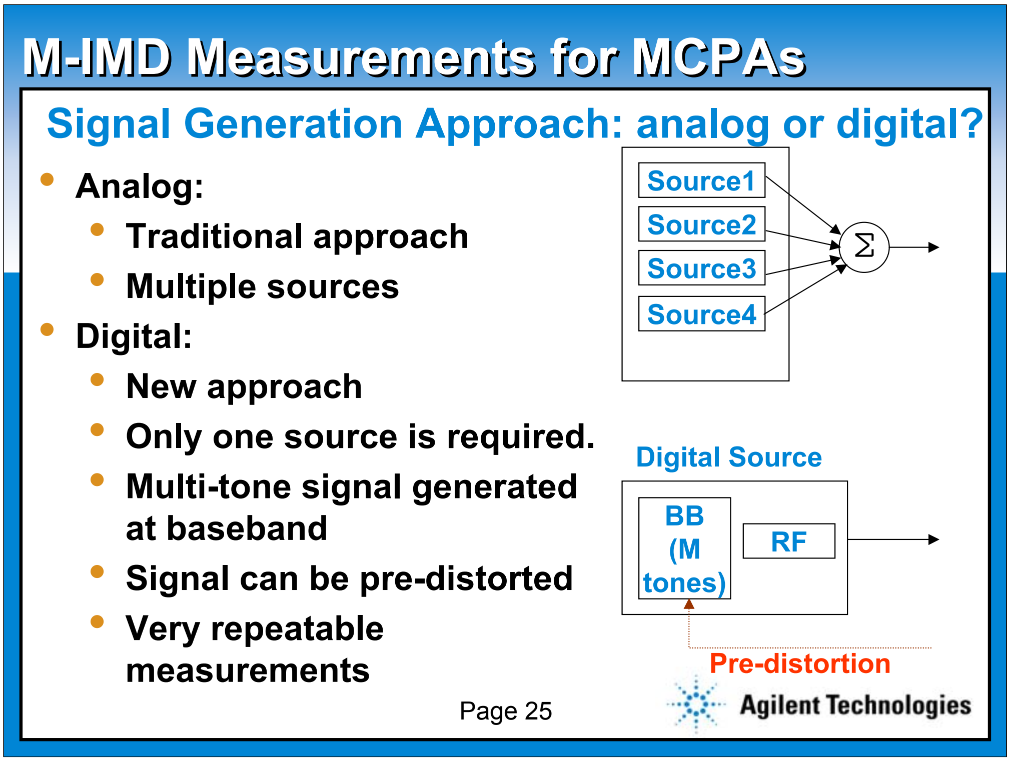
For a fixed number of tones, there will be an infinite number of random phase distributions (initial phase for each tone chosen randomly) or phase sets. The CCDF for a signal with a fixed number of tones and a random phase set will be different from the same signal with a different random phase set. The CCDFs for these two signals will also be different, and can very several dB. The CCDF variation of random phase sets can go from the most stressful (represented by the constant distribution) CCDF to the least stressful CCDF (that is typically represented by the parabolic distribution). However, given the infinite number of random sets possible, the possibility of choosing a random set where all the phases are the same is very small.

A large number of tones (more than 1000) with random phase distribution produce a CCDF that approximates the CCDF of the AWGN. For this large number of tones, different random phase sets will typically show very little variation in their CCDFs. The probability of large variation of the CCDF among random distributions decreases as the number of tones increases.

A CCDF that approximates the CCDF of AWGN can also be obtained with a fewer number of tones, if the random distribution is chosen carefully.



The CCDF graphs above correspond to 8-tone signals with a notch in the center and the same amplitude for all the tones. The two signals have different sets of random phases, which produce different CCDFs. The spectrum of the signal shows that there is a correlation between the CCDF of the stimulus and the degree of distortion that it causes. The signal with a more stressful CCDF causes higher distortion.



From the practical test perspective, there are two approaches to generate multi-tone signals.

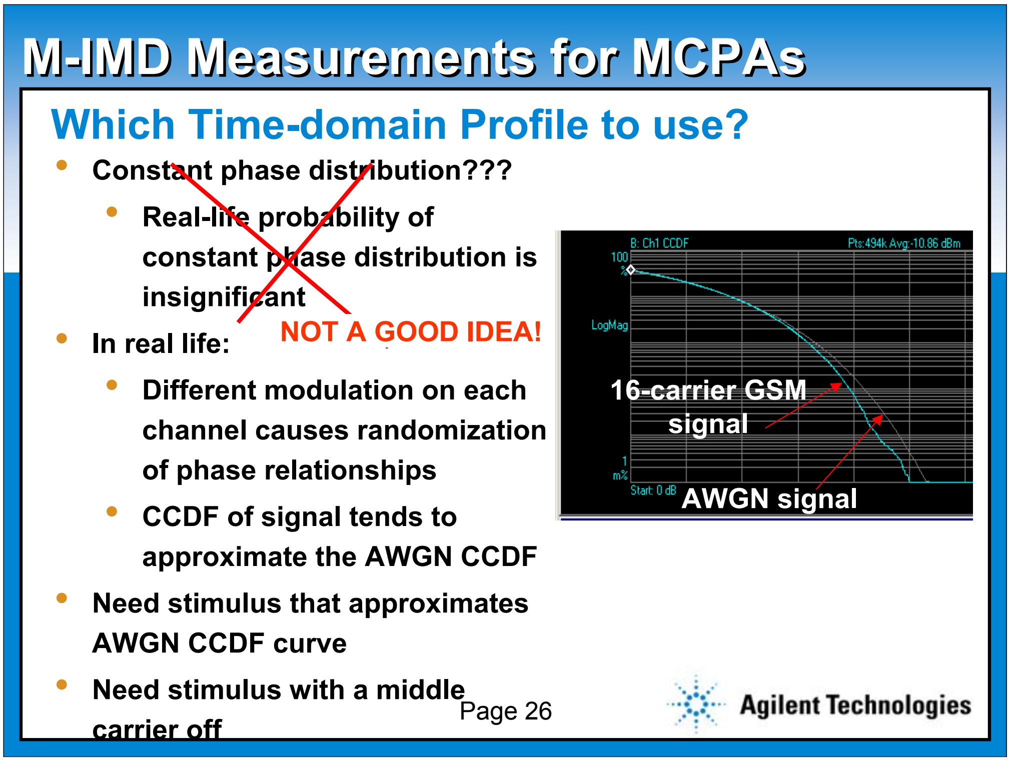
The analog approach has traditionally been used. In this approach multiple sources (one for each tone) are used. The sources can be independent or be part of a single system that controls all of them.

The digital approach is new and takes advantage of digital techniques to generate multiple tones from a single source. One of the advantages of this approach is that pre-distortion can be used to improve the dynamic range of the source. The other major advantage is that it provides very repeatable measurements.

The following pages provide a more detailed analysis of how these different approaches deal with two main issues of multi-tone IMD analysis:

-what stimulus to use?

-how to obtain the best dynamic range?

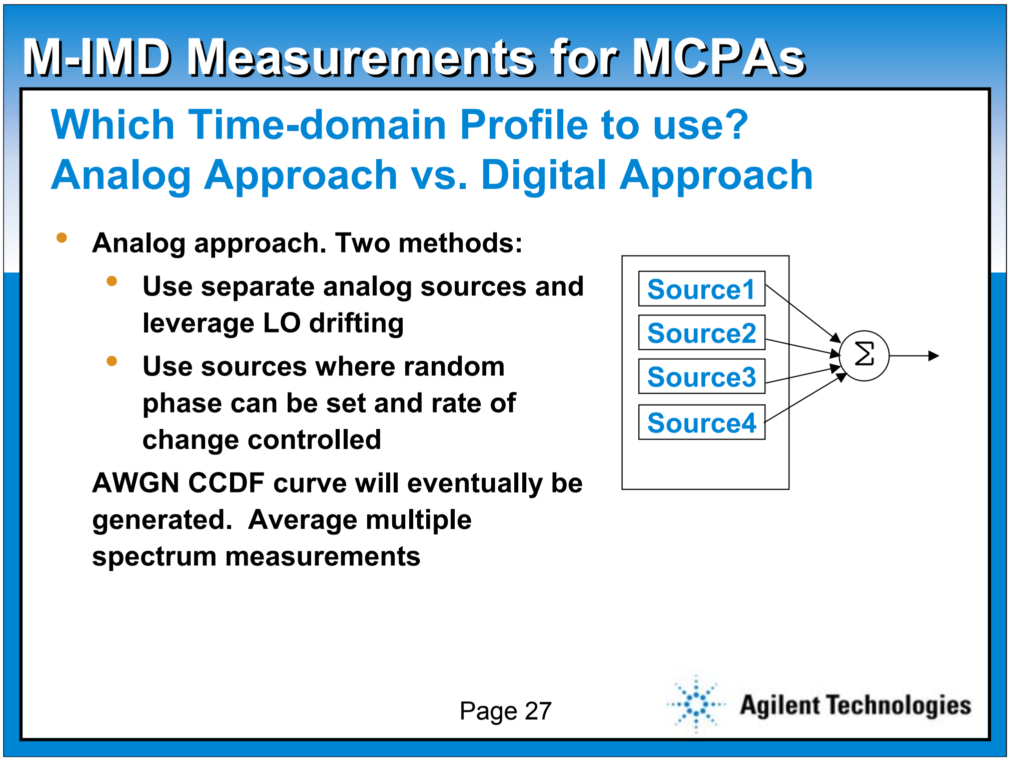


The constant phase distribution (i.e. all tones are periodically in phase) would provide the worst case scenario. While this stimulus would give us very high confidence that the amplifier would meet specifications, it would lead us to overdesigning of the power amplifier, since a constant phase distribution is not representative of typical operating conditions.

In real life, the different modulation schemes on each channel cause randomization of the phase relationships among channels. When all the carriers are combined the result is a signal whose CCDF will be very close to the CCDF of AWGN. Therefore, an appropriate stimulus would be a signal with a CCDF that approaches the CCDF of the multi-carrier signal or the CCDF of AWGN.

The stimulus signal should also occupy the bandwidth of the combined carriers. Ideally, one of the carriers in the middle should be off, since it has been shown that carriers in the middle will receive the worst IMD from the adjacent channels.

This reminds us of the NPR case, in which AWGN is used as a stimulus that is representative of different carriers with different modulation formats, and there is a notch in part of the signal where the distortion is measured. This notch represents a carrier.



Therefore, an appropriate stimulus would be a signal with a CCDF that approaches the CCDF of the multi-carrier signal. The method depends on the generation approach.

For analog sources, there are two possible methods:

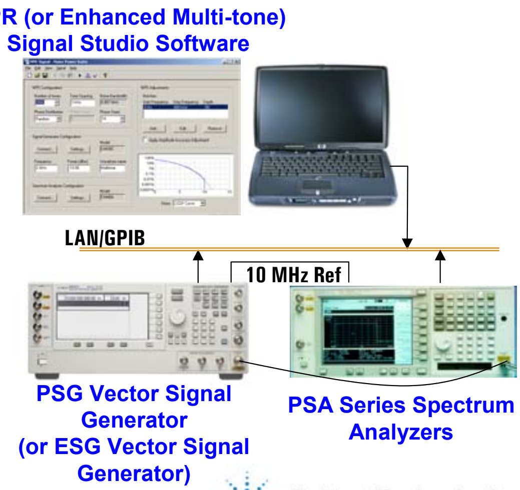
-use separate analog sources and leverage LO drifting of the different sources to create the phase randomization necessary to create an AWGN distribution. This approach is essentially correct, but it would mean long measurement times as the carriers slowly drift and build the CCDF curve.

-use analog sources within a system where the phase can be set to random and the rate of change phase of each tone can be controlled in order to produce the randomization necessary to obtain an AWGN distribution. This would provide shorter generation times, but would still not provide a very repeatable signal. Multiple measurements would still need to be averaged in order to provide repeatable results.

M-IMD Measurements for MCPAs

Which Time-domain Profile to use?
Analog Approach vs. Digital Approach

- Digital approach:
  - Use 1000’s of tones at high spectral density to approximate AWGN CCDF
  - Use notch with 100’s of tones that represents one of the channels
  - Measure and average all distortion products within the notch



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Here is a representative configuration for the digital approach.

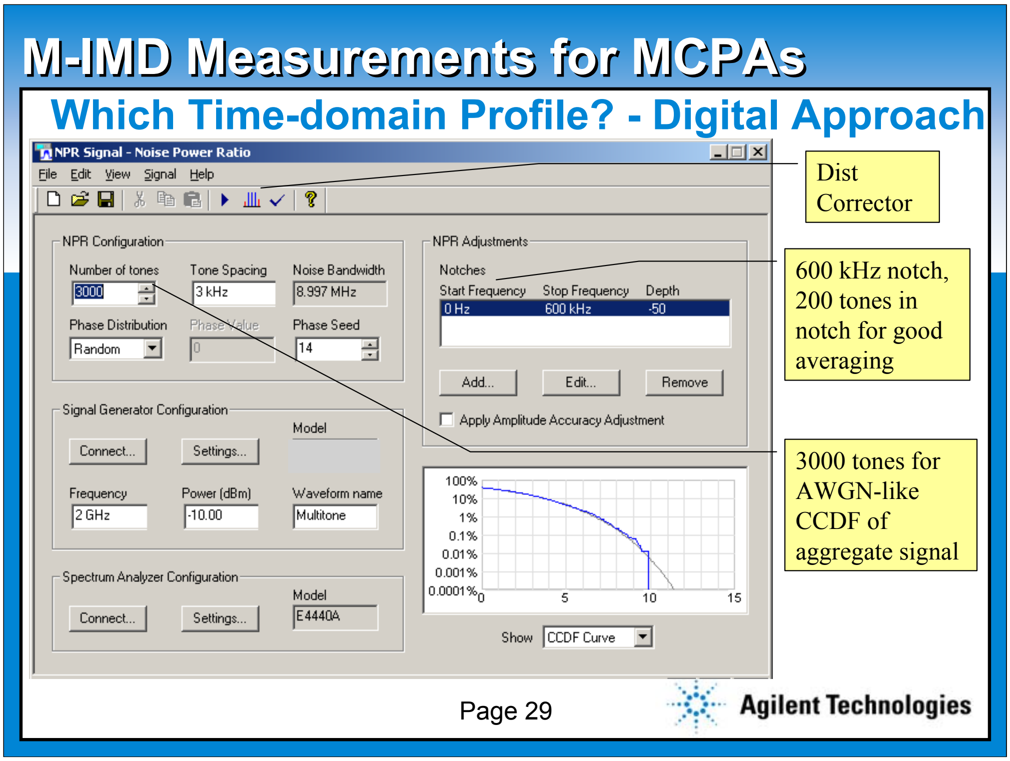
It uses the following technique:

-Use 1000’s of tones with random phase distribution at high spectral density to approximate AWGN CCDF or the CCDF of the multi-carrier signal of interest. This is basically equivalent to a synthetic noise source. The user can also try different random phase sets and choose the phase set that provides the CCDF of interest (typically close to the CCDF of the multi-carrier signal or of AWGN).

-Select a notch with hundreds of tones that represent one of the channels.

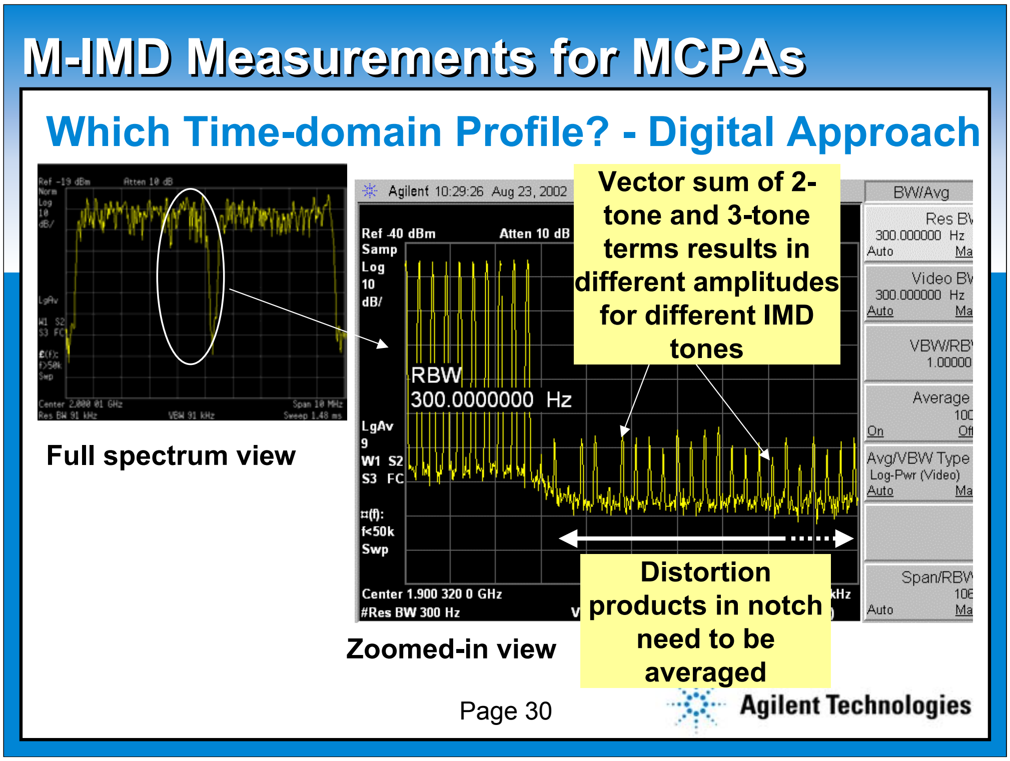
-Make the measurement by integrating the distortion in the frequency band of interest, and average over several measurements to obtain better repeatability, if necessary.

Since the stimulus signal is generated digitally, and it has a certain period, the measurement is much more repeatable than in the previous cases.

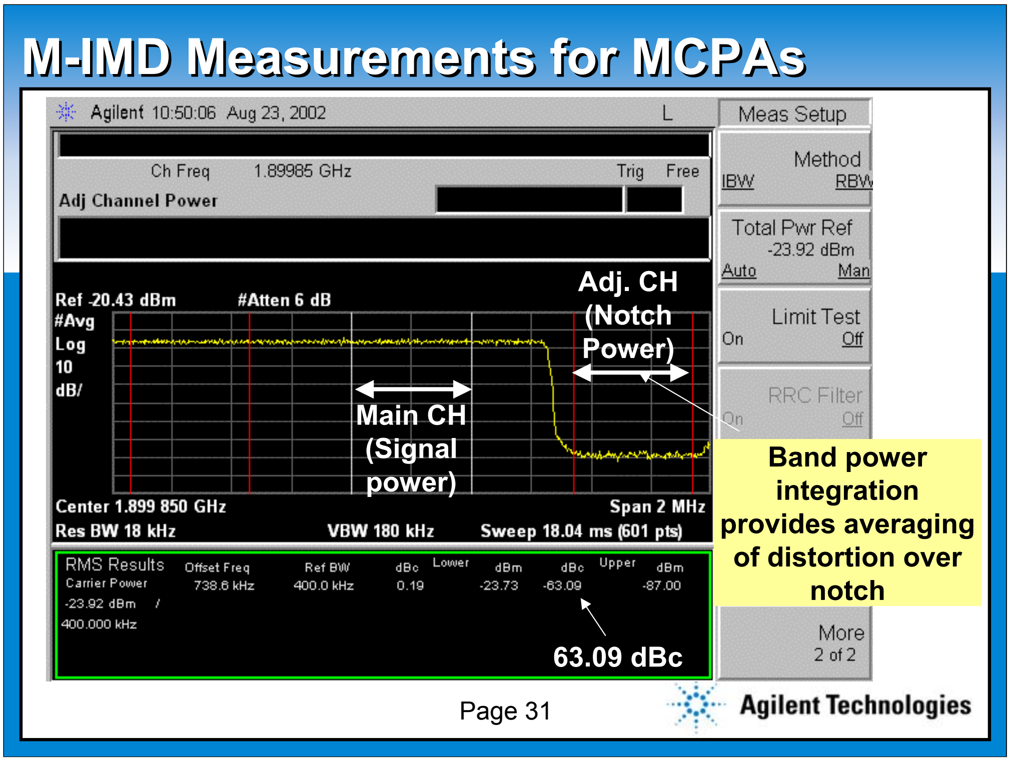


This is an example of the stimulus configuration using the digital approach to test a GSM multi-carrier power amplifier for 15 carriers (14 carriers with one carrier off in the center) with a 600 kHz separation between each. 3000 tones are generated with a tone spacing of 3 kHz over a total frequency range of 9 MHz. Each carrier is represented by 200 tones (600 kHz). The notch is created over 600 kHz, so it covers 200 tones. The notch also represents one of the carriers. The distortion in the notch needs to be integrated, which is basically equivalent to averaging the distortion in the 200 tones, which will reduce the measurement variance.

A distortion corrector is available in the same tool. This can be used to improve the dynamic range of the stimulus signal, as will be shown later.



As we discussed earlier, the IMD at a single frequency consists of the vector sum of all the 3rd order two-tone and three-tone terms at that frequency. Because of the large number of tones used at the same amplitude, we can assume that, for each IMD tone in the notch, there will be the same number of 3rd order two-tone and three-tone terms, and at the same amplitude, than for any other IMD tone in the notch. However, since the phases of the fundamental tones are random, the 3rd order terms will add as vectors in a different way for each IMD tone. Thus, their amplitudes will vary, as shown in the slide. Placing many tones in the notch allows all possible phases to be seen and integrated over frequency in the ACPR function.



Integrating the distortion power over the band of interest basically provides the averaging of all the distortion tones in the notch. The integration can be performed using an ACPR measurement. The main channel corresponds to one of the channels that are on (represented by 200 tones. The upper adjacent channel corresponds to the notched carrier (also 200 tones).

Trace averaging can also be applied to further improve repeatability.

M-IMD Measurements for MCPAs

Which Time-domain Profile to use?
Analog Approach vs. Digital Approach

Approach ↓		meas. time	repeatability	# tones available	cost
Analog	Separate sources	very long	very low	< 8	very high
	System w/phase control	long	low	8 to 32	high
Digital		short	very high	< 4000	low

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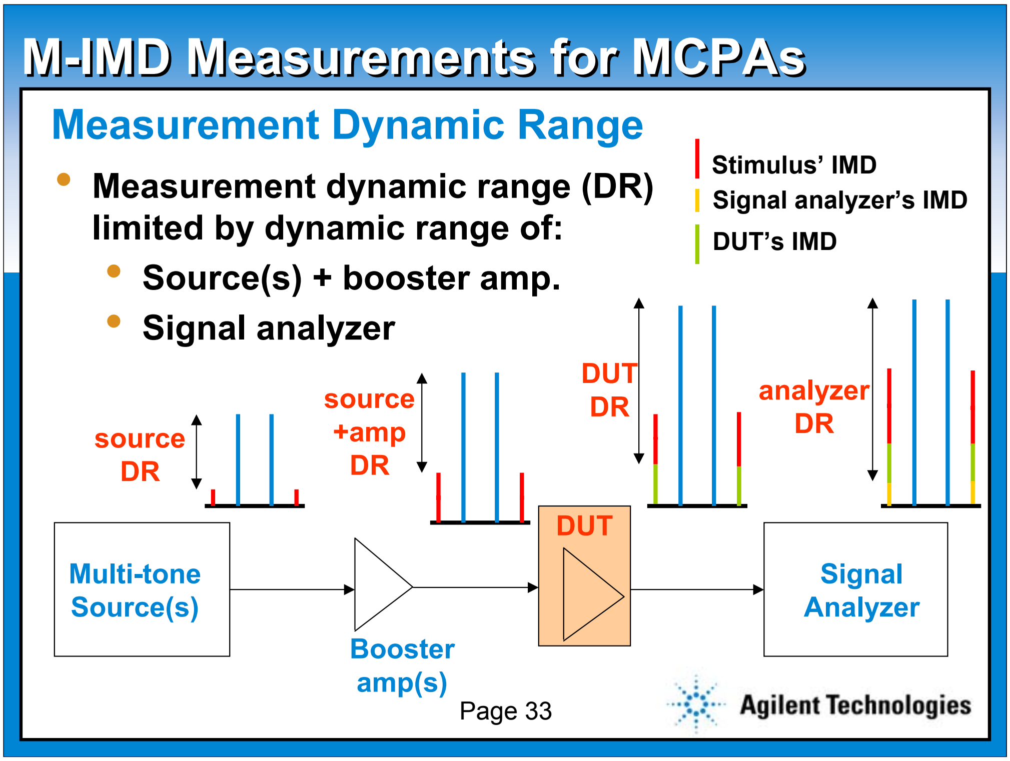
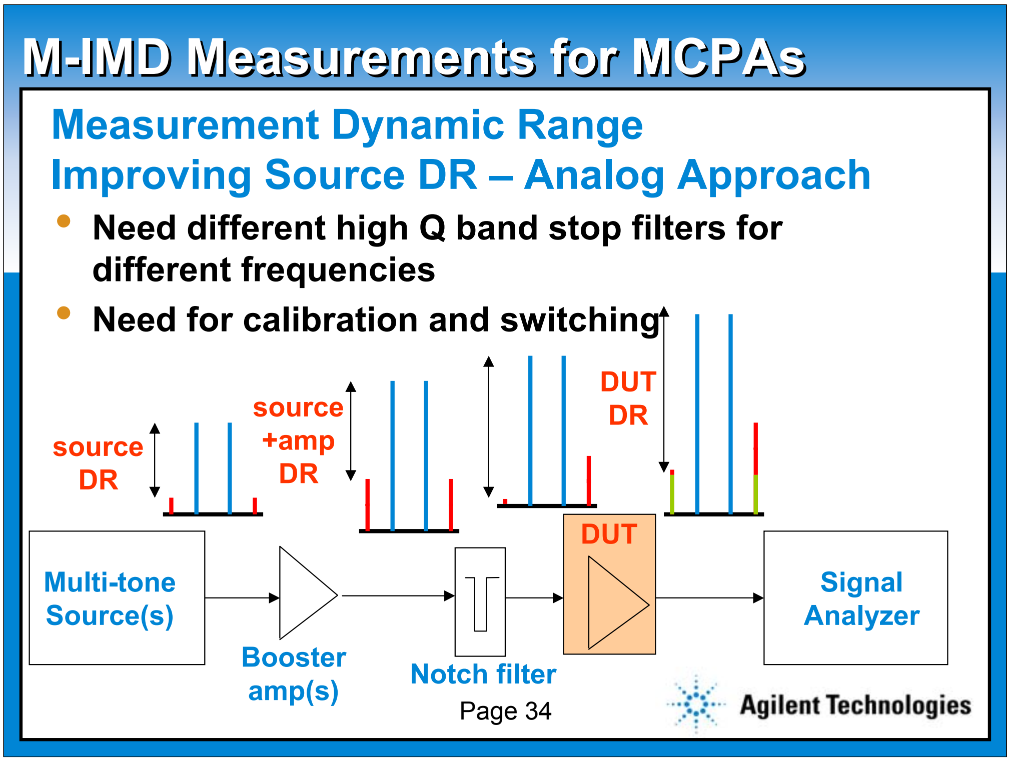
The table provides a comparison of the three methods suggested to obtain the right time-domain profile. As can be seen the digital method provides the most advantages in terms of measurement time or repeatability and cost.



The second challenge in multi-tone distortion tests is how to make the measurement with enough dynamic range to avoid measurement uncertainty from the instrumentation distortion. The measurement dynamic range is limited by both the source (and booster amplifier if used) and the signal analyzer. The slide shows how the different devices will contribute to the measurement dynamic range.

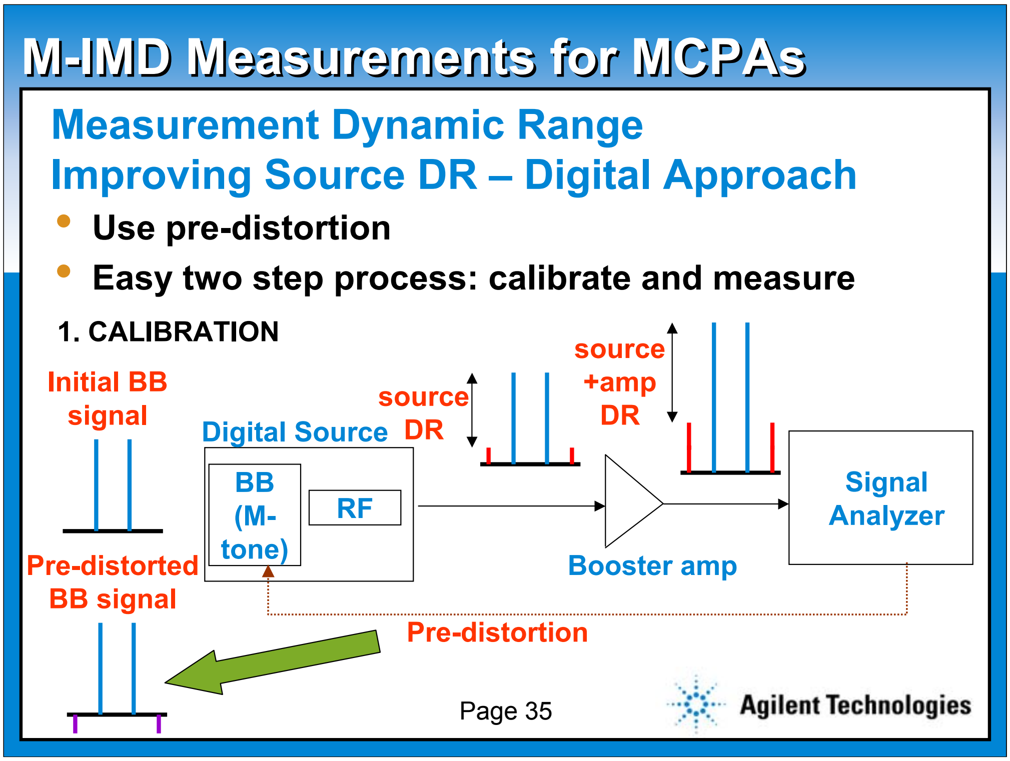
Notice that, although for the purpose of illustration the distortion from each device has been placed linearly on top of the distortion of the following device, the distortion from the different devices will not necessarily add in-phase.

Next we will see how the source dynamic range can be improved, for the analog and the digital generation approach.



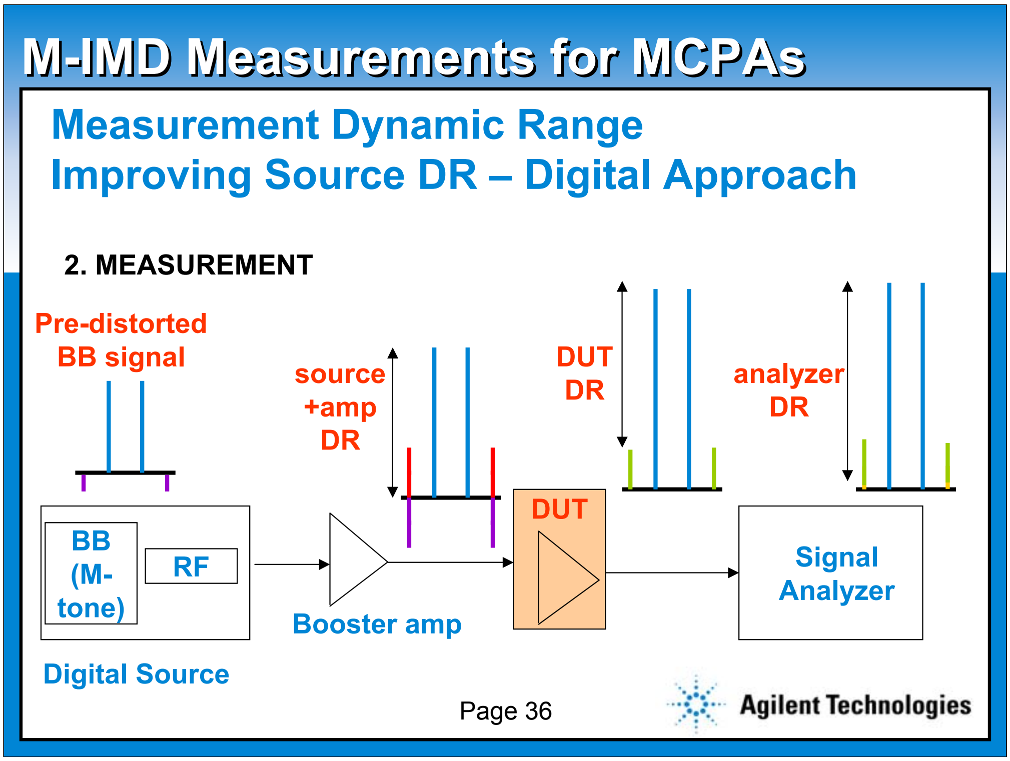
The analog source approach typically uses the “narrow band” technique that uses a passive notched filter to cancel part of the signal. This allows an operator to reduce the noise coming from the signal source (by canceling distortion on one side of the source).

With this technique one faces calibration and switching issues as well as the need to procure different filters for each frequency range.



The digital approach allows signal pre-distortion. Therefore, the dynamic range can be improved by measuring and compensating for the IMD generated by the source and the booster amplifier. The measurement will be performed in two stages. First, the initial baseband signal does not have any distortion, and the distortion from the source (generated by the RF section) and booster amplifier will be measured. The attenuation in the signal analyzer is set so that its distortion does not contribute to the distortion from the source and booster amplifier that it is measuring. The distortion measured by the signal analyzer will be used to pre-distort the stimulus signal. The baseband pre-distorted signal will then consist of the initial wanted tones and 180-degree out-of-phase distortion products intended to cancel the source and booster amplifier distortion. The calibration cycle needs to be repeated until the required dynamic range (level of distortion relative to the level of the fundamental) is reached at the output of the booster amplifier (or at the output of the source, if no booster amplifier is used).

Although not shown in the slide, pre-distortion is also used to correct for the power levels of each fundamental tone, which enhances the measurement repeatability.



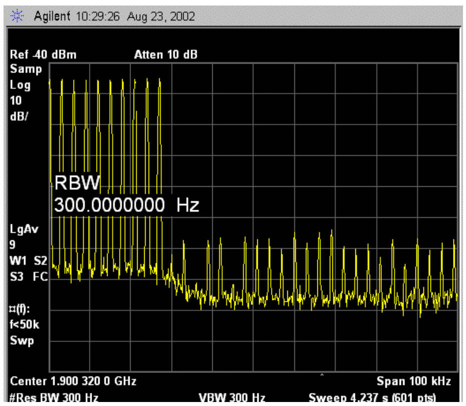
As shown above, the 180-degree out-of-phase distortion products at the output of the source and booster amplifier subtract from the distortion generated by the source and booster amplifier. Therefore, the resulting stimulus signal has the required dynamic range at the output of the booster amplifier.

The graphic in the slide also assumes that the attenuation in the spectrum analyzer is set to minimize distortion generated within the analyzer.

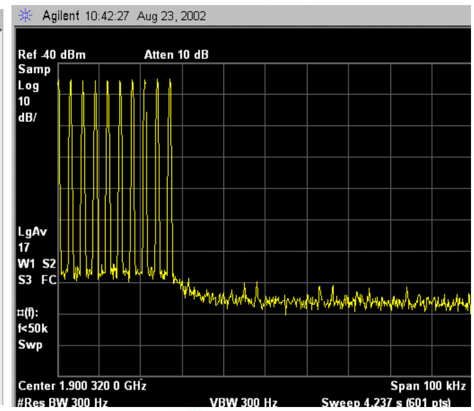
M-IMD Measurements for MCPAs

Measurement Dynamic Range
Improving Source DR – Digital Approach

Signal before calibration



Signal after calibration



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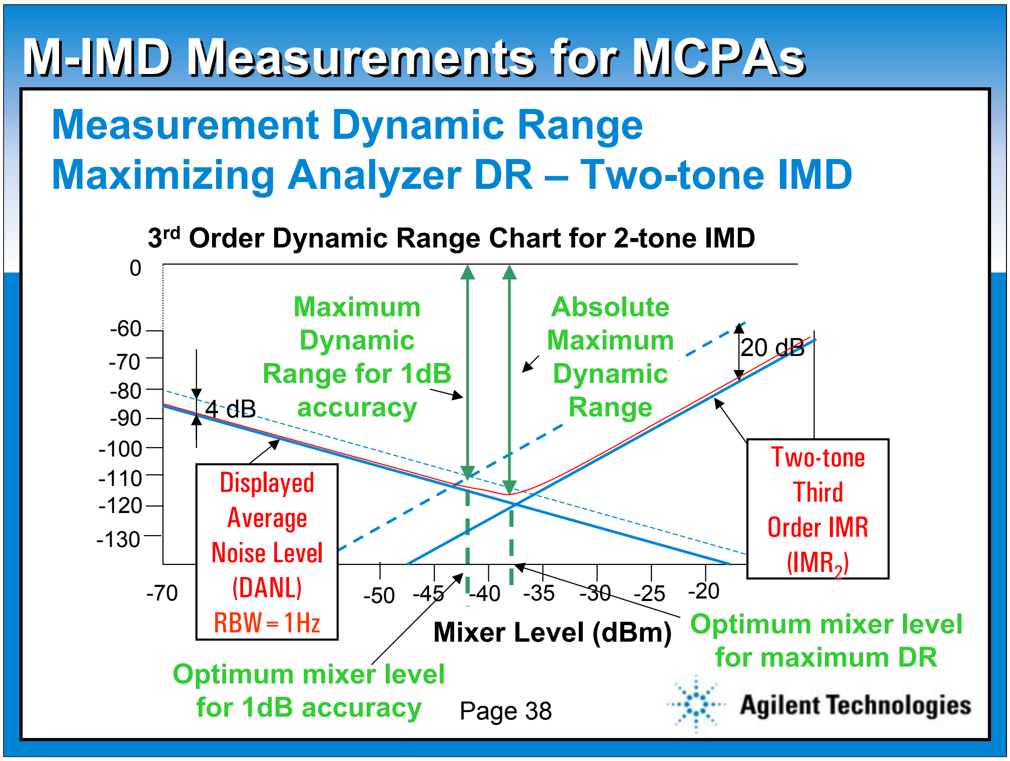
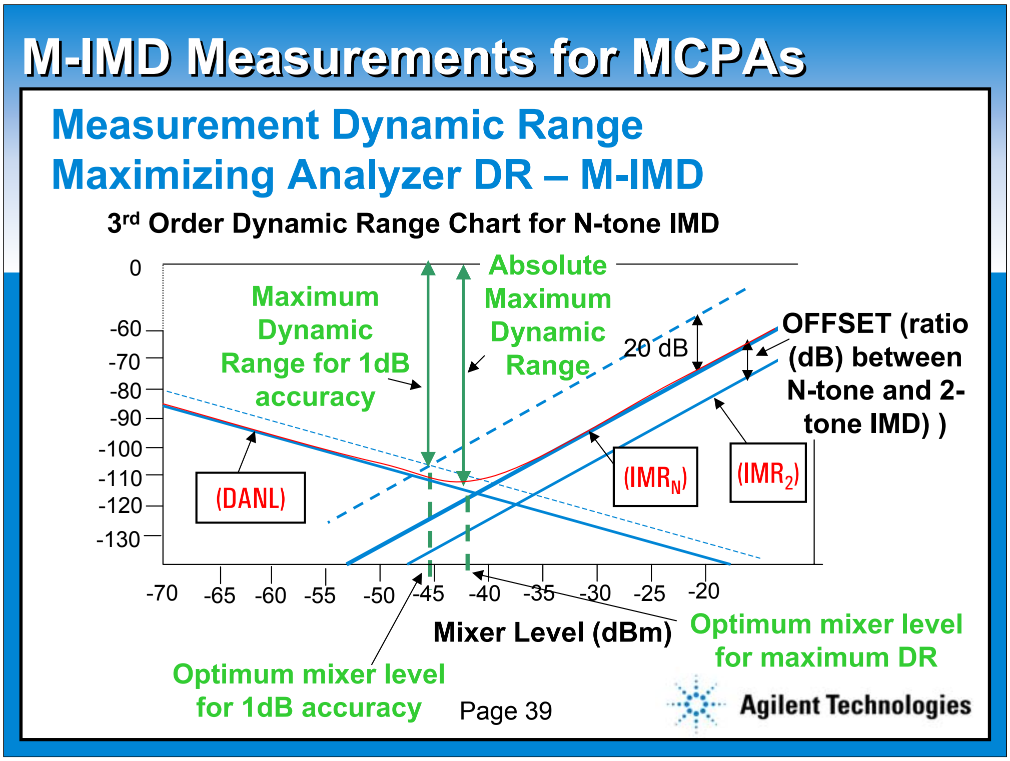
This slide shows the improvement in the stimulus signal used earlier (3000 tones, 200 tones in notch). The spectrum shows part of the notch before and after calibration.



From the spectrum analysis point of view, the best dynamic range will be obtained by choosing the optimum mixer level for the measurement.

The simplest case to analyze is the two-tone case. The slide shows a spectrum analyzer's dynamic range chart example for two-tone IMD. The absolute maximum dynamic range occurs when the IMR is nearly equal to the DANL. However, that might not be the best mixer level to use. The analyzer's IMD will be coherent to the DUT's IMD and the DANL will be incoherent. The coherent distortion has a larger effect on measurement uncertainty than incoherent distortion [3]. In order to have 1 dB of uncertainty (0.9 dB of error from the SA's generated IMD and 0.44 dB of error from the SA's DANL, being the rms of these values 1 dB), the analyzer's IMD needs to be at least 20 dB below the DUT's IMD, while the DANL needs to be only about 4 dB below the DUT's IMD. In order to calculate the maximum useable dynamic range for a 1 dB accuracy, and the optimum mixer level for 1 dB accuracy, the IMR and DANL lines need to be offset by 20 dB and 4 dB respectively, as shown in the slide (dotted lines). The coherence versus incoherence phenomenon moves the optimum mixer level to the left (lower mixer level) and effectively reduces the available dynamic range. In order to minimize the reduction of dynamic range, a good operating point is to have an error budget where 90% of the error is allocated to the coherent distortion (SA's IMD) and the remainder of the error budget is allocated to the incoherent distortion (SA's DANL), as in the example provided.

The contribution from the analyzer's phase noise to dynamic range (not shown in the chart above) might also be of concern if the measurement is made at frequency offsets close to the main tones.



The analyzer's dynamic range chart for a M-IMD measurement can be built from the two-tone measurement dynamic range chart. An offset needs to be added to the two-tone IMR line (IMR_2), in order to obtain the IMR line for N tones (IMR_N). The offset is the ratio between the N-tone IMD power at the frequency of interest and the 2-tone IMD power. For example, for the 3-tone case and assuming independent and random phases with uniform distribution, the power level of the IMD at the frequencies immediately above and below the main tones, is 5 times (7 dB) greater than the 2-tone case. Therefore, an offset of 7 dB should be added to the 2-tone IMR line, in order to obtain the 3-tone IMR line for the IMD at the frequency immediately above or below the frequencies of the main tones.

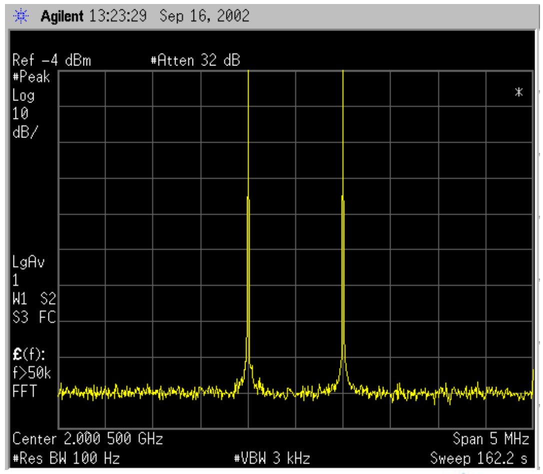
The phase relationship among the tones will affect the peak-to-average power ratio and therefore also affect the offset level. In general, the higher the peak-to-average power ratio, the higher the IMD, and therefore the higher the offset for the IMR line.

If the frequency of interest is not a discrete frequency offset, but it has a certain bandwidth, the offset will be a function not only of the frequency offset but also of the bandwidth over which the distortion power needs to be integrated. Notice that this offset could also be negative (the IMR line could be below the 2-tone IMR line) if the IMD integration bandwidth falls out of the area with the highest distortion.

When integrating across a bandwidth, the DANL line will increase by about 2.5 dB plus 10 times the log of the ratio of the bandwidth of integration to the noise bandwidth in which DANL is measured. [4]

M-IMD Measurements for MCPAs

Measurement Dynamic Range
Two-tone Measurement Example



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The slide shows a measurement example for a two-tone signal, using the digital approach with calibration, and the optimum mixer level in the analyzer.

Summary

- Distortion Measurements have typically been performed using CW signals
- MCPA testing requires more realistic signal stimulus that represents several modulated carriers
- Accurate MCPA distortion measurements require the use of an appropriate time domain signal profile
- Digital multi-tone generation approach provides repeatability and cost advantages over analog generation approaches
- Digital generation approach uses pre-distortion to improve dynamic range, which can minimize cost and setup time

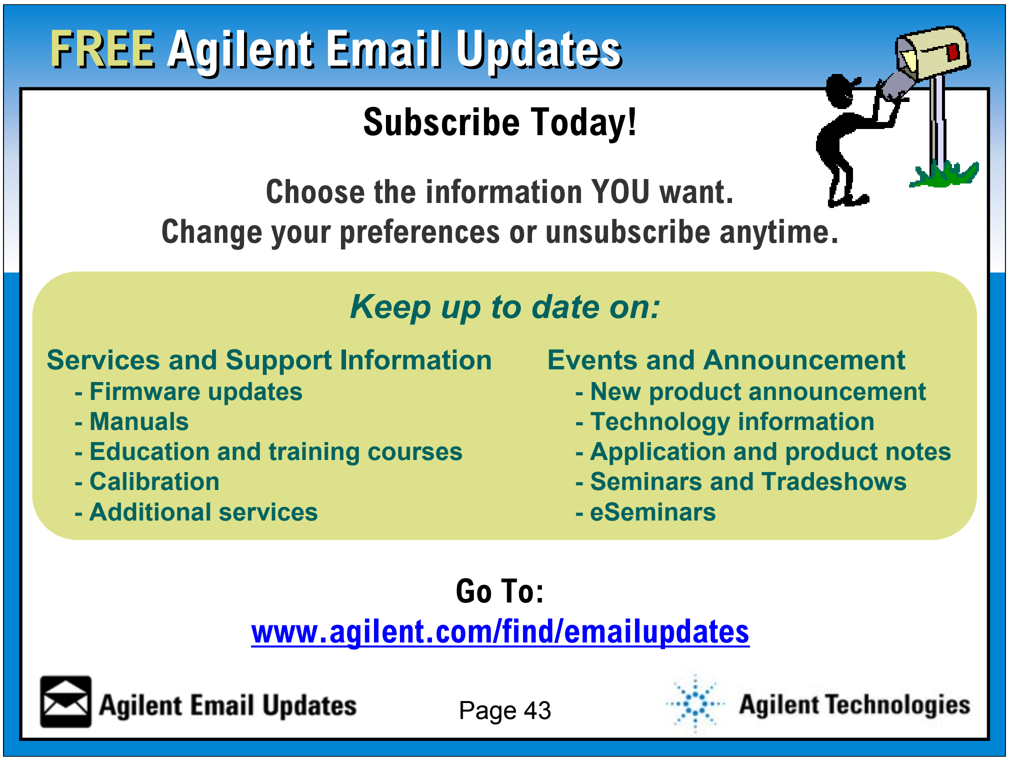
Bibliography

[1] Kent K. Johnson, Agilent Technologies, "**Lowering Cost and Improving Interoperability by Predicting Residual BER: Theory, Measurements, and Applications** ", literature number 5988-6082EN

[2] "**Characterizing Digitally Modulated Signals with CCDF curves**", Agilent Technologies Application Note, literature number 5968-6875E

[3] "**Spectrum Analysis Basics**", Agilent Technologies Application Note 150, literature number 5952-0292

[4] "**Optimizing Dynamic Range for Distortion Measurements**", Agilent PSA series Product Note, literature number 5980-3079EN



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