Application Note
Multi-Tone: Testing, Theory and Practice

Multi-tone testing has many benefits. While the multi-tone methodology was initially implemented to increase the speed of immunity testing, it has been found that this method also improves equipment efficiency, offers greater flexibility to truly test the equipment (EUT) under real world threat conditions, and can be fully compliant to standards. Benefits can also include more efficient use of finite financial and human resources as well as faster time-to-market for new and enhanced products.

1.0 Introduction

1.1 What is multi tone?

Multi tone signals are composed of multiply single sine waves or tones with a unique amplitude, phase and frequency. In the spectrum domain, the multi tone or RF energy will be present at a unique frequency. In the time domain, the multiply signals or tones will be a composite signal in which each of the tones will add or cancel to make a composite signal.

1.2 Where are multi tones used, and who is using them?

One area in which multi-tones are used is modern audio measurements to test consumers & professional audio devices, broadband devise and internet audio. Multi tones can be used in an open-loop audio test where the analyzer does not have to sync up with the generator. This allows an audio signal to be tested over long a long distance, such as the internet or mobile phone. Standard multi tone signals have evenly-spaced tones with equal amplitude; this however does not represent real-world test conditions. Therefore custom multitoned sets need to be created.

Multi-tone tests are part of many test specifications used to test the frequency response of a device and measure intermodulation distortion. Two Tone and multi tone signals are used in the communications industry to test for nonlinear distortion for amplifiers, receivers, etc.

A vector signal generator, VSG is the primary hardware in a multi tone generator system; it can be used in almost every RF and communication application including the following below:

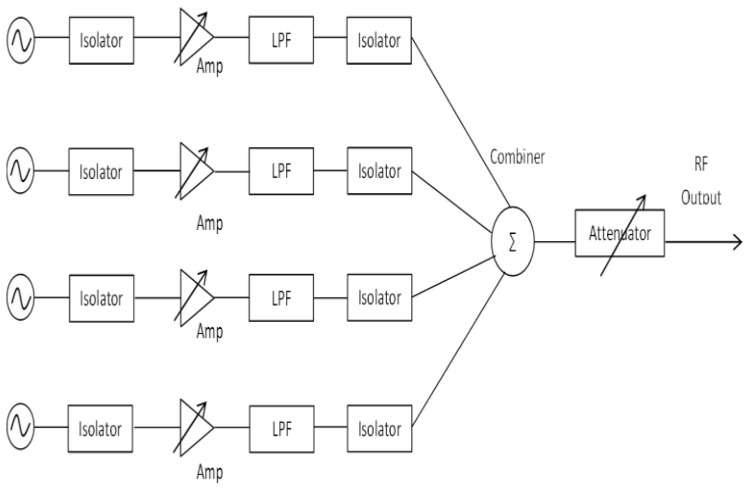
- Antenna resonant frequency measurement and testing
- Amplifier linearity
- Amplifier frequency response
- Selectivity measurement
- On-site effective sensitivity test
- Cable fault detection
- Filter tuning
- Antenna response to FM
- Frequency hopping

VSGs are ideal for complex user-defined, arbitrary waveform signal generator for multi tone generation. Multi tone testing is usually required in every terrestrial and satellite-communications (sitcom) application.

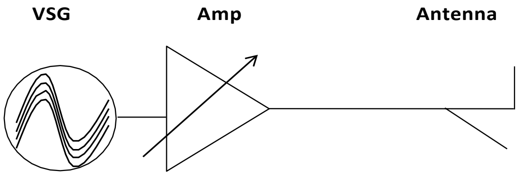
2.0 Multi-tone Practice

2.1 How do you generate multiple signals?

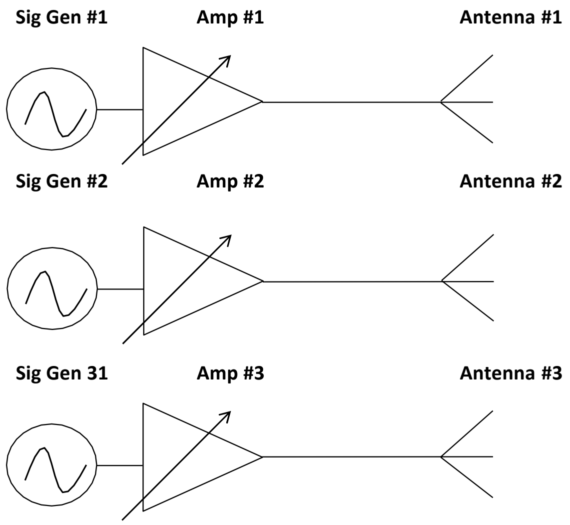
The traditional way to generate multiple signals is to use multiply independent CW generators that are added together using a combiner. Multiple isolators are used to insure the signal generators do not interfere with each other to minimize the intermodulation distortion between generators. Amplifiers after each signal generator are used to fine tune the amplitude for each tone without changing the signal generator level. This method is used to hold the signal generator intermodulation, IMD constant. Combiners should have low loss, and sufficient isolation to minimize distortion. A variable attenuator is used to change the level of the composite signal without adjusting each signal generator so the signal generator IMD can remain constant.



An alternate way to generate multiple signals is to replace each independent signal generators with one Vector signal generator (VSG). The VSG does not require multiple signal generators to create multi tone signals. It can generate fixed or random initial phase sets, deliver accurate repeatable multi tone signals and is easily configurable by setting each tone independently. VSG are useful for simulating a wide variety of digitally modulated signals, including cellular, wireless LAN, Bluetooth, GNSS, and military communications formats.



And a third, more cumbersome, way to generate multiple signals is to have multiple signal generators, multiply amplifiers, and multiple antennas. The signals would be combined in free space. Since there are separate amplifiers, the amplitude of the tone would vary and could be hard to control the phase with respect to each tone.



2.2 Comparison of VSG to analog signal generator.

2.2.1 Analog Signal Generator Overview

- Analog signals are generated as CW tones with some amplitude, center frequency and starting phase.
- The introduction of voltage controlled oscillators, VCOs, allow the user to dynamically vary the carrier frequency (FM) and phase (PM) over time.
- Issues that affect the quality of the generated waveform are stability and VCO phase noise as well as distortion and bandwidth limits on the modulation.

2.2.2 Digital Vector Signal Generators

- Output is a series of discrete voltage levels instead of a sine wave.
- The series of discrete voltages makes it possible to create a wide range of signals and gives the flexibility to modify signals.
- Any arbitrary signal within the bandwidth of the digital signal can be described mathematically, stored in digital memory and then played out.
- The range of the carrier and modulation frequencies of the arbitrary waveform generator is determined by the sample rate.
- The voltage resolution or effective bits determines the accuracy of each output voltage which the output waveform then translates into noise and distortion.

2.2.3 Disadvantages of using a Traditional Analog Signal Generator

- Test setup - This can be complicated and time consuming due to the amount of test equipment involved.
- Modification of signal parameters – Since multiple signal generators are used to produce each tone, adding or removing tones requires hardware modifications to the test setup in addition to software modifications to change the amplitude or frequency for each signal generator.
- Random phase sets – It is difficult to generate random phase sets because most CW generators do not have the capability to set the phase of individual tones.
- Cost of test -- Capital equipment cost is high because the more tones required directly impacts the number of signal generators required.

2.2.4 Advantages of using the Vector Signal Generator:

- Simple test set up and procedure – VSG requires only one generator and one user interface.
- Signal parameter control – easy to modify signal parameters such as amplitude, tone spacing and phase with digitally accurate fixed or random initial phase setting.
- Test setup repeatable- test waveforms can be easily stored and quickly recalled for playback ensuring the same test stimulus.
- Accurate and meaningful test results – multi tone signals with random phase sets that simulate real world operating conditions can be generated easily.
- Save time- spend less time setting up and more time making test measurements.
- Reduce cost- use only one signal generator to produce multiply tones that traditional setup require multiply analog signal generators and a combiner.

2.3 Vector signal generator concerns/issues.

- **Available Power** – a linear amplifier is required
- **Carrier feed-through** – a high level of carrier feed-through is not desirable because it results in intermodulation produced at one-half the tone spacing instead of the designated tone spacing intervals. The VSG uses the (in-phase/quadrature) I/Q modulator. Small amounts of carrier feed-through are present when an even number of tones are generated. With odd number of tones, there is always a tone at the carrier frequency. This carrier feed-through can be reduced by optimizing the I/Q gain offsets.
- **Images -** occur as a result of the I and Q signals being slightly out of quadrature at the input of the I/Q modulator. When non-symmetric tone patterns are generated, images can be reduced with slight adjustments to the quadrature skew setting in the I/Q Adjustment Menu.
- **Relative tone spacing -** is limited to the bandwidth of the internal baseband generator. The tone spacing, phase and amplitude be set on a tone to tone bases.

3.0 Multi Tone Theory

The multi tone test system contains one vector signal generator that generators the multiply signals or tones. A larger RF power amplifier may also be required so the multi tone signals are not distorted. In addition, either a vector signal analyzer or spectrum analyzer should be used to measure the energy in the spectrum domain because traditional power meters measure the entire spectrum wideband, including the harmonics and intermodulation products.

3.1 Generating multi tone signals

Many signal generators also offer various types of modulation, including analog and composite (digital) modulation. Classic analog-modulation types include amplitude-modulation (AM), frequency-modulation (FM), phase-modulation (ΦM), and pulse-modulation signals. Modulation is important because it's the information-carrying part of the signal.

The following below are a list of common test signals:

1. Sine Wave – most common signal for testing
2. Square Wave – superposition of many sine waves at odd harmonics of the fundamental frequency. The amplitude of each harmonic is inversely proportional to its frequency.
3. Triangle and saw tooth - have harmonic components that are multiples of the fundamental frequency
4. Impulse – contains all frequencies that can be represented for a given sampling rate and number of samples.

Chirp signals are sine waves swept from a start frequency to a stop frequency. They generate discrete frequencies within the start and stop frequency band

3.1.1 Modulation Parameters to Control

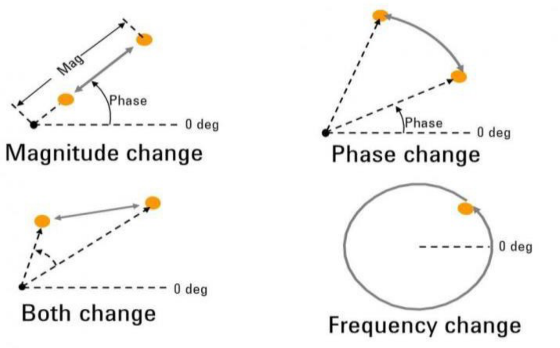
To better understand analog modulation, consider the basic equation of a sine wave: $V(t) = A(t) \times \cos(2\pi f_C t + \Phi(t))$

Amplitude Frequency Phase

In this equation, three parameters can be varied: amplitude, frequency and phase. Varying the sine wave's amplitude achieves amplitude and pulse modulations. Varying the sine wave's frequency or phase generates FM and ΦM, respectively.

Composite modulation, also known as vector or digital modulation, occurs when two or more modulation types are used to create a composite modulated signal. For example, AM and ΦM can be combined to create various magnitude and phase values. Varying the signal's phase in conjunction with the AM control in the automatic-loop-control, ALC, circuit can produce a digitally modulated signal.

I/Q diagrams are particularly useful because they mirror the way an I/Q modulator creates most digital communications signals. Independent dc voltages (I and Q components) provided to the input of an I/Q modulator correlate to a composite signal with a specific amplitude and phase at the modulator output. All types of modulation can be represented on a polar plane using vector (phasor) notation, although magnitude and phase values aren't typically used when describing the vectors in digital modulation, see examples below. Instead, the polar plane is mapped to a rectangular format (with a horizontal and vertical axis) called the I-Q plane, where I stands for in- phase and Q denotes quadrature.


Vector Signal Changes or Modifications

A magnitude change with no rotation represents amplitude modulation (AM), and a vector that rotates along an arc (the length of which indicates the maximum phase deviation) represents phase modulation (ΦM). Simultaneous AM and ΦM are indicated by a vector whose length and phase change with time. FM results in a vector that rotates clockwise or counterclockwise.

Quickly transmitting large amounts of binary bits at high rates in composite signals requires large information bandwidths. The faster the data rate, the wider the bandwidth. Available bandwidth can be used more efficiently by grouping blocks of digital data (1s, 0s) into symbols, although this increases signal complexity. The number of bits per symbol will vary depending on the specific format. Transmitting digital data via multi-bit symbols requires less bandwidth. For example, for two bits/symbol, the symbol rate is one-half the bit rate, and for four bits/symbol, the symbol rate is one-quarter the bit rate.

IQ or vector modulation, which is commonly used in modern digital communications and radar systems due to the large modulation bandwidths and the ease in creating composite modulated signals, has a number of important characteristics. These include symbol rate (the number of symbols/second), modulation bandwidth (the maximum effective bandwidth of the IQ modulator), frequency response/flatness, IQ quadrature skew (a measure of how orthogonal the

I. and Q. planes are to each other), and IQ gain balance (a measure of how closely the I. channel and Q. channel are in gain).

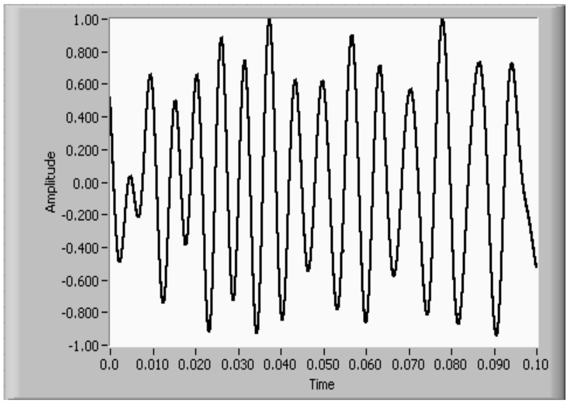
When the IQ characteristics aren't ideal, magnitude and phase errors will occur that may cause transmission of incorrect digital information. Digital errors are referred to as bit errors, often expressed as a bit-error rate.

3.2 Amplitude of Multi-tone

The composite amplitude of multi tone signal can be measured by the crest factor which is defined as the ratio of the peak magnitude to the RMS value of the signals. Relative phases of each tone with respect to each other determine the multi tone signal's crest factor. A multi tone signal with a large crest factor contains less energy than one with a smaller crest factor. If you have a higher crest factor then individual signal sine tones have lower signal-to-noise ratios. Proper selection of phase is critical to generate a useful multi tone signal. The maximum number of tones needs to be considered to avoid amplitude clipping of the signal. You can use different combinations of phase relationship and amplitude to get a lower crest factor.

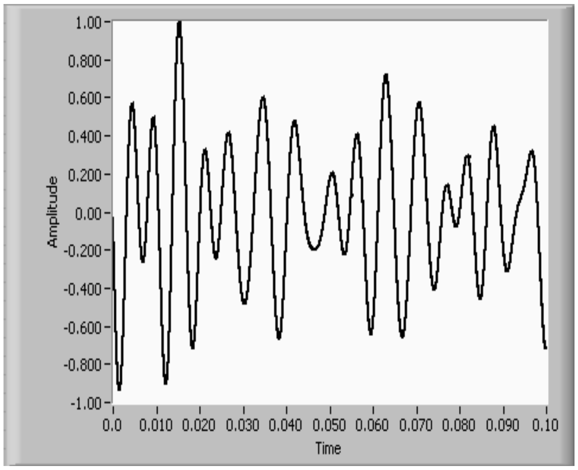
3.2.1 Phase Generation of Multi-Tone

The phase of the multi tone signal is another parameter that can be controlled and can affect the composite signal crest factor. To create multitoned signal with low crest factor you can vary the phase difference linearity from 0 to 360 degrees between adjacent single tones like chirp signals. It is recommended that you vary the tone phases randomly to reduce the crest factor. Varying the phases generates multi tone signals with very low crest factors. Multi tones are very sensitive to phase distortion. In addition, the signal path may induce non-linear phase distortion. Multi-Tone might display some repetitive time domain characteristics in the multi tone signal.



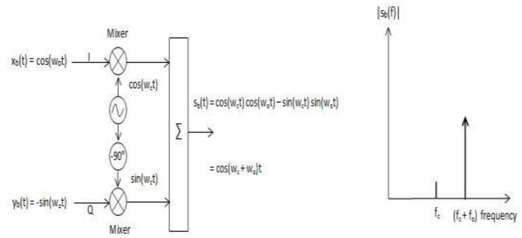
The signal in the previous illustration resembles a chirp signal in that its frequency appears to decrease from left to right. This apparent decrease in frequency from left to right is characteristic of multi tone signals generated by linearly varying the phase difference between adjacent frequency tones. You might want a signal that is more noise-like than the signal in the previous illustration.

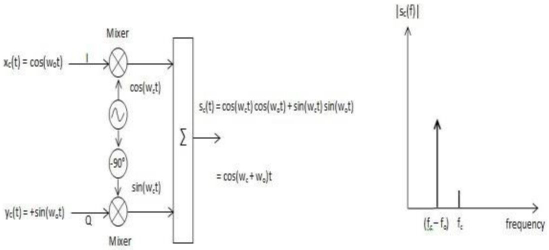
Varying the tone phases randomly results in a multi tone signal whose amplitudes are nearly Gaussian in distribution as the number of tones increases. In addition to being more noise-like, the signal is much less sensitive to phase distortion. The following illustration shows a signal created by varying the tone phases randomly.



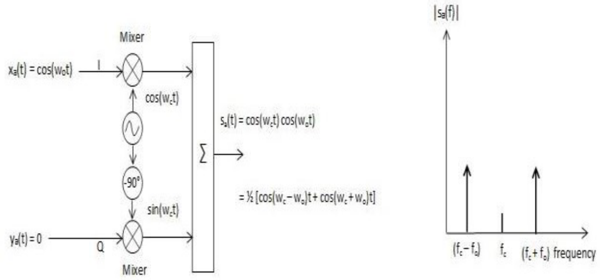
3.2.2 Generating Multi Tone Signals with I/Q Modulator

To create a single discrete tone, the modulating waveforms are fed both to the (I) and (Q) inputs. There is full control of the individual discrete tones parameters including amplitude, phase and frequency. Depending on the sign, the modulated waveform on the (Q) input the tone will appear above or below the carrier frequency. To generate multi tones, additional frequency components are added to the modulating waveform on both the (I) and (Q) input centered about the carrier frequency.





To generate double sideband suppressed carrier amplitude modulation (DSBSC-AM) signals, the modulating waveform is fed to the in-phase (I) and zero is fed to the quadrature (Q). The figure below demonstrates how the output creates two tones symmetrically around the carrier.



3.3 Intermodulation and harmonics distortion

Intermodulation (IMD) and harmonic distortion are types of nonlinear distortion. Intermodulation distortion is the result of unwanted intermodulation between multiple frequency tones that comprise a multi tone signal. Harmonics are integer tones of the fundamental input signals generated when a signal passes through a nonlinear device.

The output signal tones of a device can be calculated from the input signal tone using a transfer function which provides a mathematical relationship between the output and input tones. Every transfer function can be described by a polynomial called the Taylor-series. Since the Taylor-series is infinite, the number of harmonics in the output, in theory, is infinite. Within the signal amplitude higher order harmonics amplitude decreases exponentially and thus can practically be ignored for multi tone applications. When decreasing the input signal, the amplitude of the harmonic signal decreases exponentially by a factor of A^n.

Figure 1 shows what happens when two tones are inputted into a non-linear device. The intermodulation between each frequency tone will form additional signals at frequencies that are not just at harmonic frequencies, but also at the sum and difference frequencies of the original frequencies as well as at multiples of those sum and difference frequencies. Figure 2 shows the mathematical equations of a two-tone intermod product.

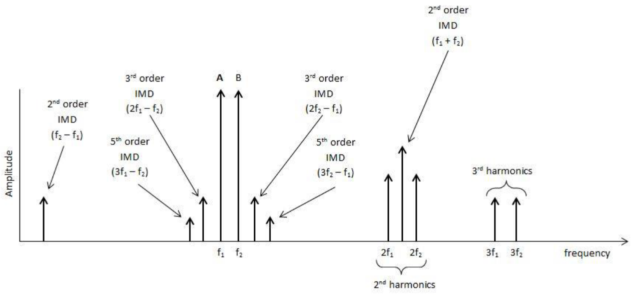


Figure 1: Graphical representation of Intermodulation

Vo is the transfer function to determine the output signal based on the input signals

$$V_o = a_1 v_i + a_2 v_i^2 + a_3 v_i^3 + \ldots.$$

The following equation is used to calculate two tone input.

$$V_i = A\cos(\theta_1) + B\cos(\theta_2)$$

where $\theta_1 = \omega_1 t + \phi_1$ and $\theta_2 = \omega_2 t + \phi_2$

The next equation is used to calculate the 2nd harmonic of two tone input based on the addition theorem for the cosine function.

$$\begin{aligned} v_i^2 = {} & (A^2/2)(1 + \cos(2\theta_1)) + AB(\cos(\theta_1 - \theta_2) \\ & + \cos(\theta_1 + \theta_2)) + (B^2/2)(1 + \cos(2\theta_2)) \end{aligned}$$

And the following equation is used to calculate the 3rd harmonic of two tone input.

$$\begin{aligned} v_i^3 = {} & (((3A^3)/4) + ((3AB^2)/2)))\cos\theta_1 \\ & + (((3B^3)/4) + ((3A^2B/2)))\cos\theta_2 \\ & + ((3A^2B)/4)(\cos(2\theta_1 - \theta_2) \\ & + \cos(2\theta_1 + \theta_2)) + ((3AB^2)/4)(\cos(2\theta_2 - \\ & + \cos(2\theta_2 + \theta_1)) + ((A^3/4)\cos(3\theta_1)) \qquad \theta_1) \\ & + ((B^3/4)\cos(3\theta_2)) \end{aligned}$$

Figure 2: Mathematical representation of Intermodulation products

Care must be taken to ensure that these unwanted signals do not significantly affect the quality of the immunity test. These intermodulations can be minimized through the use of digital signal generation techniques (VSG) and properly sized amplifiers.

3.4 Power requirement of Multi-Tone testing

The level of input power of each tone of a multi tone signal should be set by taking into account the number of tones and desired level of distortion that can be tolerated. The power required to generate multi-tone signals can be defined in both peak and average terms. The average power is defined as a sum of the power of each tone. The peak power is the maximum instantaneous power of the combination of all the tones. Maximum peak power happens in the moment of time when all the voltage vectors from each of the tones are aligned. The power for average or peak is defined below. Note that this assumes that all the tones are equal in power.

$$P_{MSAVG} = (P_{SSx} + P_{SSx+} P_{SSx}) \ * N \quad \text{(watts)}$$

or

$$= (P_{SSx} + P_{SSx+} \ P_{SSx}) * \text{Log}\,(N) \quad \text{(dBm)}$$

$$P_{MSPK} = (P_{SSx} + P_{SSx+} \ P_{SSx}) * N^2 \quad \text{(watts)}$$

or

$$= (P_{SSx} + P_{SSx+} P_{SSx})* 20 \ \text{Log}\,(N) \ \text{(dBm)}$$

Where: PMSAVG = Average power of multi- tone signals
PMSPK = Peak power of multi-tone signals
PSSx = Power of single tone signal
N = Number of tone signals

In order to reduce all distortion, the peak power can be used to calculate the number of signals that can be generated by a given amplifier. However, since the individual signals differ in frequency, their relative phase is always changing. The peak power level is only reached when all of the tone signals vectors are aligned, the more tones that are generated, the shorter the occurrence of the instantaneous peak power.

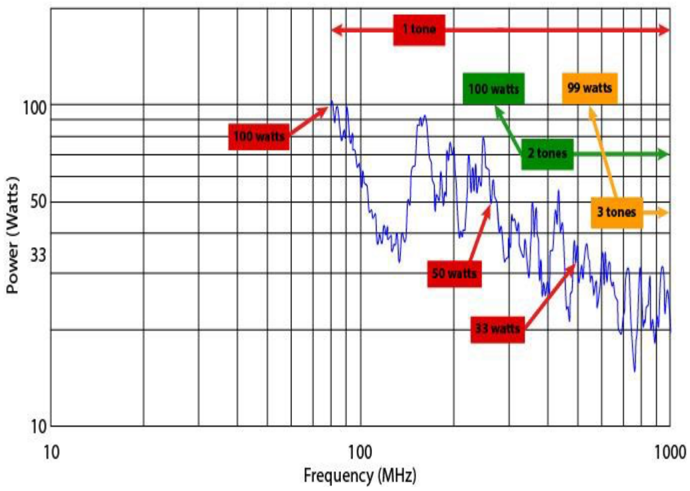
When the peak power can't be reached intermodulation distortion occurs. This distortion can be minimized by only using amplifiers within their linear operating limits (P_{1dB}). Ways to remedy this situation are to either increase the size of the amplifier or reduce the power of the tones.

The linearity and harmonic checks of immunity standards can be used to determine the number of signals that can be generated by a given amplifier with acceptable distortion.

For immunity testing, the required power to generate a disturbance tone signal varies as a function of frequency. See Figure 4. Note that due to antenna gain, required power falls off rapidly with frequency. Here multi-tone testing can take advantage of the full power of the amplifier and reduce overall test time.

In this specific case, a 250 watt amplifier provides a 2x speedup at the lower frequencies with a much greater reduction in test time at the higher frequencies. In many cases, test labs have the power to produce high RF fields but historically have not fully utilized that power because they are running single tone tests which require lower power levels. With multi-tone testing, test labs can make better use of their unused amplifier power while reducing test times. The justification for adding higher power amplifiers to the test lab has become a little easier because the high power amp will allow for testing at higher field levels, as well as result in a reduction in test time and more efficient use of resources when utilizing multi-tone technology.

IEC 61000-4-3 Vertical 10V/m @ 3 meters Resultant From UFA



4.0 EMC Testing with Multi Tone

4.1 Overview

The concept of Multi-tone testing is simple. Rather than testing a single frequency during dwell period, multiple frequencies are tested at the same time.

While simple in concept, the actual hardware implementation has always been a hurdle. Simultaneously controlling multiple signal sources and properly combining their output signals in a repeatable fashion has been beyond the scope of traditional, analog test instrumentation. The solution is the combined use of two devices: a Vector Signal Generator (VSG), which can digitally produce multiple tones and complex modulations, and a frequency selective power measurement device, such as a Vector Signal Analyzer (VSA). Using this digital instrumentation under software control, the multiple tones necessary can be generated, measured, and controlled.

4.2 Level Settings

The multi-tone method can be applied to any standard that uses a substitution method of level setting.

For radiated immunity testing, isotropic field probes are used to set the level; these probes are not frequency selective and cannot parse out or measure multiple tones. Therefore, the level setting time cannot be improved using a multi tone process. The level setting procedure must be done using traditional single tones. In order to use multiple signals, a secondary level setting procedure will need to be performed using frequency selective power measurement equipment such as a vector signal analyzer, VSA. This secondary procedure will use the power required by frequency to assure a test level of a single tone to determine how many signals can be combined into a test set without saturating the amplifier and introducing too much distortion.

Linearity and harmonic content measurements are also required as part of the level setting process. These measurements should be performed on all signals within a test set, adding each new signal until the aggregate of the set fails one or both linearity or harmonic checks. The result is the maximum number of signals that can be used together as a set. The time spent on this additional level setting procedure is offset by time-savings achieved by the VSG in leveling to the desired field strength.

4.3 Testing

Once a determination of how many tones can be used and in what groups or sets, testing can proceed at record speed. For each dwell time, a set of tones is presented to the equipment under test (EUT). If there is no EUT fault, the test continues. If a fault occurs, the user has the option to immediately investigate with a single tone to verify if the failure also exists when only a single test frequency is used, or continue with the multi-tone test noting where failures occurred. In the second case, after test completion, the failed frequency ranges would be rescanned with a single tone to see if the fault is unique to multi-tone testing or remains even when testing with a single frequency. Additional investigation and threshholding can also be performed at this time. If the EUT demonstrates sensitivity to multi-tones but not with a single tone, the EUT may be considered compliant with the test standard. The only downside is that at these particular frequencies, one cannot reduce the test time. Nevertheless since large sections of frequency ranges can be scanned and tested quickly, the overall test time is still reduced dramatically. The graphical representation in Figure 3 captures this testing concept visually. Note that the test proceeds quickly from the lowest frequency up to a point when a fault is encountered. At this point multi-tone testing is suspended and the test reverts to single tone conventional testing. In this hypothetical scenario, it is seen that the EUT passes the single tone testing and multi-tone testing is resumed without further failures throughout the remaining frequency range.

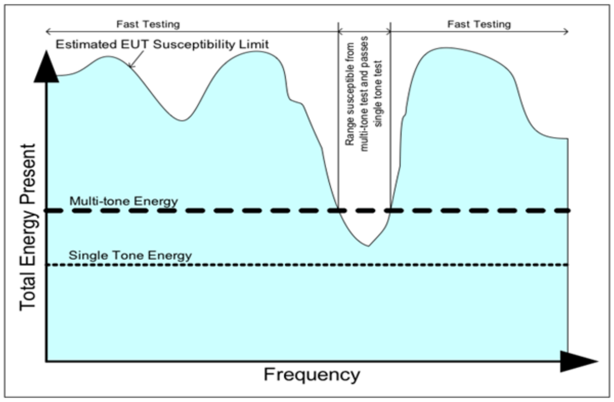


Figure 3: Simulated multi-tone test

4.4 Compliance

The ability to test and demonstrate compliance, while significantly reducing test time, is possible using the multi-tone method. To meet the EMC standard, each and every tone during the test:

- will be at the correct amplitude to produce the needed field
- will be at the required frequency
- will be at the required frequency % step, or in this case % spacing
- will carry the required modulation
- will dwell at the required dwell time for each frequency/tone

5.0 Advantages of Multi Tone testing

5.1 Reduced Test Time

Immunity testing can be very time consuming to perform. Often, tests take many hours, which constrains the throughput of a laboratory and limits the testing capacity for many facilities.

Historically, methods used to reduce the test time have focused on reducing the transition times (the time between the measurements of frequency steps) which unfortunately, represent only a fraction of total test time.

Multi-tone testing is a method designed to dramatically reduce test time by better using the required dwell time of the test. It is a process that adds multiple test frequencies (tones) to each test period (dwell time). By testing multiple frequencies simultaneously, the test efficiency is increased by a factor approximately equal to the number of tones used.

For example, if four tones were used, the test would be completed in about one quarter of the normal time or four times faster. See Figure 4.

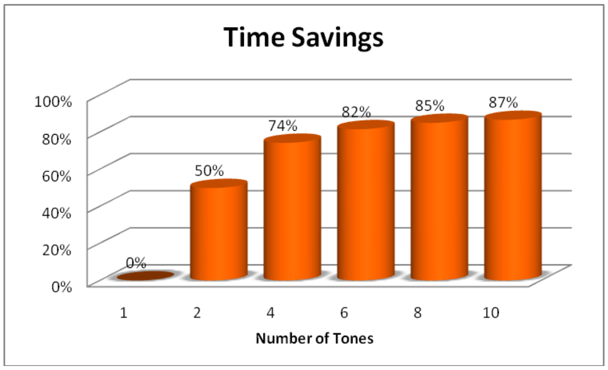


Figure 4: Percent time savings

5.2 Simulation of Real World Threats

Another benefit of using this technology is its ability to simulate real world threats which are multi-tone in nature. Real world applications expose EUTs to more than one tone at a time. Conventional one tone testing would never uncover susceptibility to these "actual" threats. Some equipment manufacturers have already experienced multi-tone induced EMC failures and have been using multi-tone testing to identify and correct product vulnerabilities. These real world threats may not only be multi-tone in nature; there may be multiple concurrent and interactive threats present. An example would be EUT used in close proximity to a fully populated, multi-use radio tower.

The medical standard 60601-1-2 has listed many known threats and requires testing at elevated levels and new modulations in these suspect bands. It also infers that product manufacturers should limit their liability by actively testing for any foreseeable threats. More standards more complex tests will likely follow.

6.0 Future enhancements of multi tone system

EMC testing is standards driven. As more standards are released that require more complex testing, demand for more efficient test methods will follow. This will drive the increased necessity for the use of digital signal generation and measurement techniques. The digital equipment is becoming more readily available and less frequency limited. This will allow this type of testing to see greater use in all application testing from consumer products such as handheld and household devices to more complex assemblies associated with automotive, aerospace and military industries

7.0 Summary of Multi-Tone system

The digital hardware (VSG, VSA) used to implement the multi-tone method is limited only by its usable frequency range and instantaneous bandwidth. This same hardware could also be used to generate complex modulations schemes as well as noise for broadband testing.

The multi-tone methodology can be adapted to other immunity test standards resulting in similar time-savings and improved efficiencies.

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