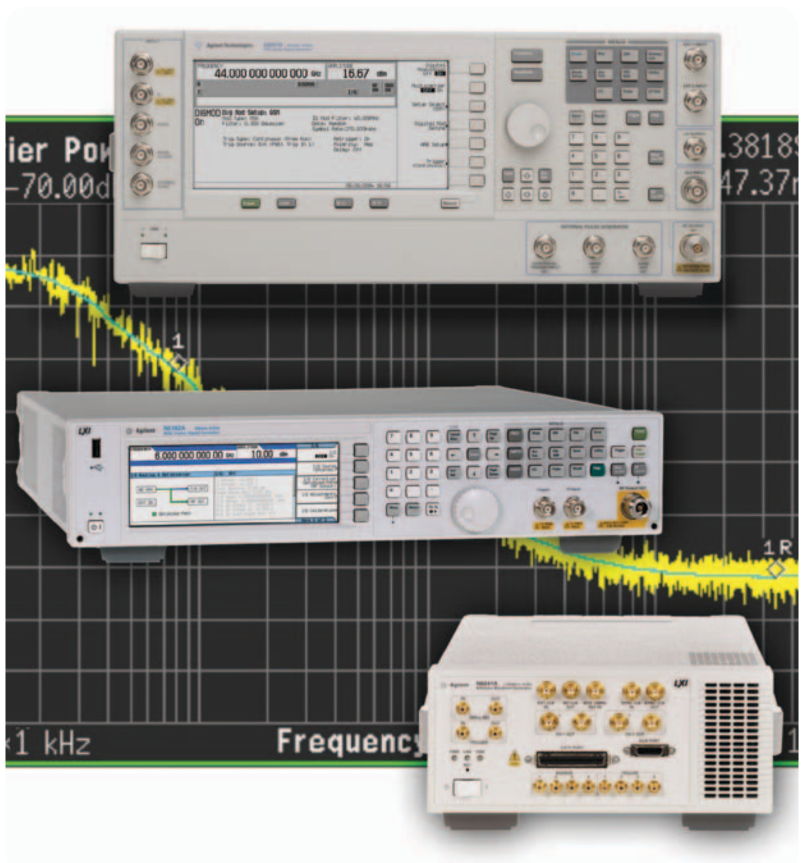
Signal Source Solutions for Coherent and Phase Stable Multi-Channel Systems

Application Note



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Introduction

Coherent multi-channel systems have unique properties that enable beam forming, direction finding and improved reception in a dispersive channel. As enabling technology matures and demands for these capabilities increase, the ability to efficiently test and exercise these systems is of growing importance.

When performing characterization, special signal simulation capabilities are required to accurately recreate the operational environment. Namely, signals must be created in a way that they will coherently combine to simulate their real-world behavior. This application note will discuss test signal requirements for the evaluation of multi channel RF systems, including example test configurations with varying degrees of coherence, example test requirements, and an examination of errors and uncertainty that limit coherence.

Definition and Explanation of Coherency

What are coherent and phase stable signals?

Two signals are said to be coherent if they have a constant relative phase at all instances in time. They are of interest because when present together they will combine either constructively (add) or destructively (subtract) from one another depending on their relative phase.

Having the same frequency does not qualify signals as being phase coherent, even if precisely frequency matched. This is because uncorrelated phase noise and phase drift between the signals will cause their relative phase relationship to vary over time. If these random phase variations are of any significance, the signals will not add or subtract.

It should be noted that coherency does not imply that the signals are free from phase impairments. To the contrary, two coherent signals may have even large amounts phase noise and phase drift as long as it is common between them and their phase varies in precisely the same manner. The difference between coherent signals and noncoherent signals is not black and white. Signals can be marginally coherent if the relative phase instabilities are small enough such that the signals still exhibit some constructive or destructive combining when present together. Coherence is then a statistical property between signals that can be calculated using the following formula:

$$\rho_{XY} = \frac{E\{(X-\mu_X)(Y-\mu_Y)\}}{\sigma_X \sigma_Y} = \frac{\sigma_{XY}}{\sigma_X \sigma_Y}$$

Where:
- ρ = coherence
- E = expected value operator
- μ = average value
- σ = std deviation
- σ_{XY} = covariance of signal X and signal Y
- X = signal X
- Y = signal Y

The result is a number between zero and one. Signals with a coherence of one are fully coherent and signals with a coherence of zero are completely noncoherent. For clarity, the term "phase stable" will be used in this application note to refer to signals and systems that are partially coherent to draw distinction from fully coherent signals.

In addition to having the ability to generate coherent and phase stable signals, it is often necessary to modify the phase relationship between signals. Systems with this capability will be described as coherent systems with phase control.

In summary, the following terms and definitions will be used for the purposes of this application note:

Phase-stable signals: Have coherence better than 0 but less than 1 over a given observation period

Phase-coherent signals: Have coherence nearing 1 over a given observation period

Phase control: The ability to modify the relative phase relation between each of multiple signals

Why Coherent Multi-Channel Systems?

Multi-channel systems use multiple antennas that are spatially separated to provide added capabilities. These include the means to combat multi-path and dispersive channel fading, direct energy using beam forming, improve data throughput using inverse channel property estimation techniques, or determine the direction of signal origination. Important to employing many of these capabilities is the ability to coherently establish and manage phase relationships between signals. Below is a closer look at some multi-channel technologies.

Multi-channel applications

Spatial diversity systems

Spatial diversity antennas provide a solution to the signal multi-path problem. A signal transmitted from an antenna radiates outward toward the receiver. Some of that signal will travel in a direct line-of-sight to a receiver antenna. Unfortunately, some of that signal may be reflected from nearby objects or atmospheric ducting and take a less direct path to the receiver antenna. Depending on the arrival phase of each electromagnetic wave from the direct or reflected rays, the electromagnetic waves may combine destructively or constructively. If the waves combine destructively, there will be no energy available at the main receiver to use for data detection (Figure 1a). However, if a second spatial diversity antenna is used, placed at the appropriate physical separation from the main antenna, it will enable the signals to combine constructively and much more energy will be available for data detection in its receiver. With proper antenna separation distances, the diversity antenna will have maximum signal power when the main antenna is at a signal null. Conversely, when the diversity antenna is at a spatial signal null, the main antenna will be at a signal maximum.

Diversity systems may vary in their approach. Some may simply select and switch to the antenna with the greatest signal power. However, switching may be difficult in highly mobile applications where multi-path effects change rapidly. Other systems take advantage of the additional energy and coherently combine or sum the signal energy coming from each antenna.

The switching or combining of signals may take place either at RF, IF or digital baseband. Performing these functions at digital baseband is attractive because DSP can be employed efficiently, typically by using a digital automatic delay equalizer (DADE) to seamlessly align the signals with large delays and constructively combine. This requires multiple RF and IF paths that are phase-stable relative to each other if not fully coherent.

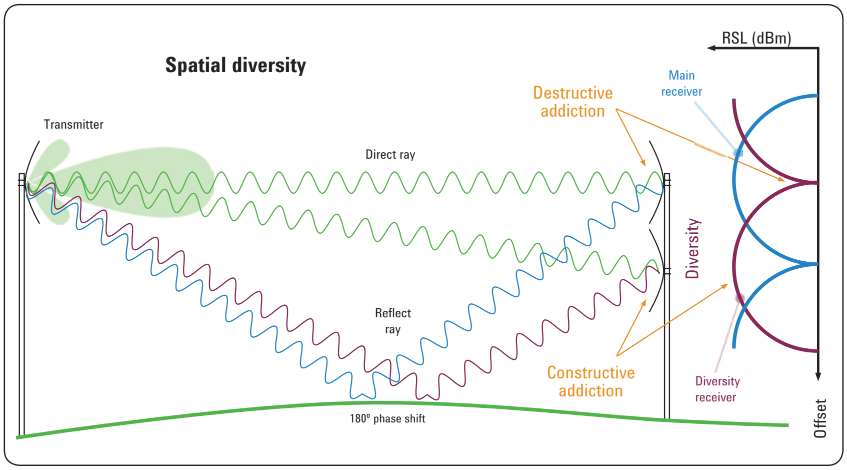


Figure 1a. The coherent nature of multi-path signals causes them to combine constructively or destructively. A spatial-diversity antenna ensures good reception in a multi-path environment by using spatially separated antennas.

MIMO systems

Multiple-input/multiple/output (MIMO) systems go a step further than spatial diversity systems. Rather than switch or combine signals from spatially diverse paths to combat the effects of multi-path, a MIMO system uses multi-path effects to its advantage. It does this through the use of space-time coding. Essentially, a MIMO system encodes data onto the transmit signals in such a way that the receiver is able to process and break multi-path channels into multiple spatial channels that can uniquely transmit data.[1] To do this, MIMO systems typically employ computationally rigorous inverse channel property estimation algorithms performed in DSP (Figure 1b), thus requiring systems with multiple phase-stable or phase-coherent transmit and receive RF and IF paths in both the transmitter and receiver. To avoid symbol interference from multipath, MIMO systems usually use long symbol duration modulations such as OFDM. Theoretically, a MIMO system may multiply its data bandwidth capacity by the number of transmit and receive antenna pairs used. Modern MIMO systems also offer some advantages in data security because they can take advantage of spatially diverse transmitter sources.

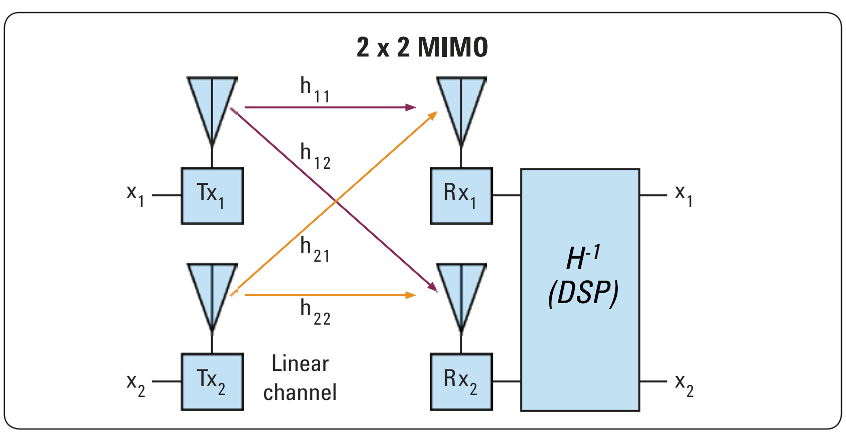


Figure 1b. MIMO systems use multiple antennas, space-time coding and channel-estimation algorithms to create multiple spatial data channels capable of uniquely transmitting data.

1. *Durgin, Gregory D., Space-Time Wireless Channels, pg 15, Pearson Education Inc., 2003*

Beam forming

Another important capability that comes with the use of multiple antenna apertures is the forming of a narrow antenna beam or flat-plate radiator. Coherently driven antennas with the appropriate phase delay between antenna elements can form signal beams (Figure 1c). Phased array antennas use delays created in the beam forming network (BFN) to produce a uniform wavefront traveling in a specific direction. The uniform wavefront allows a group of low directivity antennas to act like a highly directional antenna in aggregate for either transmit or receive applications.

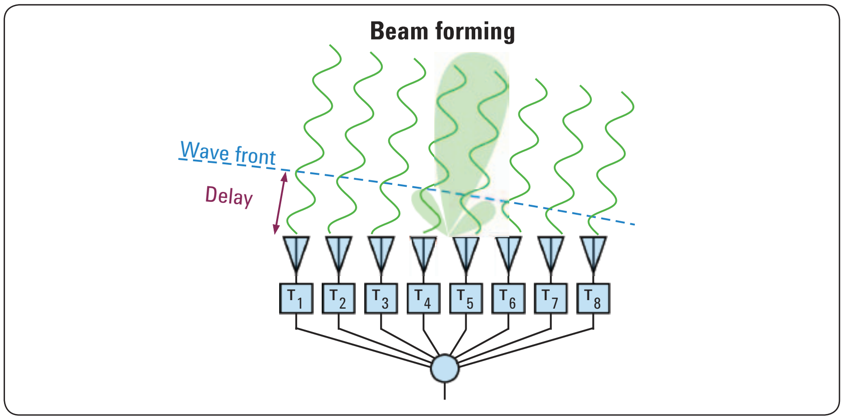


Figure 1c. A phased array of antennas forms a beam by adjusting the phase between coherent antennas such that the signals constructively combine in the desired direction and destructively combine in other directions.

A key advantage of using multiple antenna apertures instead of a single larger aperture that is mechanically adjustable, such as a big parabolic dish, is that phased arrays can have electronically adjustable delays, enabling the antenna beam to move from one point in space to another very rapidly—a key capability for radar applications.

The electronically adjustable beam of a phased array antenna is controlled with a steering matrix—a set of weighting coefficients that control the delays in the BFN. Changing the delay or phase-shift weighting between antenna elements allows the beam to sweep through space rapidly or aim at a specific location. However, phase control of each element of the phased array requires strong coherency between each signal path.

Agilent N6841A RF Sensor with N6854A RF Geolocation Software

Geolocation provides an alternate method to locating signals that is different to traditional direction finding techniques. The Agilent N6854A geolocation software extends the capabilities of the N6841A RF sensors to include estimated position based on time difference of arrival (TDOA) techniques. For more information, please refer to *Agilent Application Note Techniques and Trends in Signal Monitoring, Frequency Management and Geolocation of Wireless Emitters*, publication number 5990-3861EN or **www.agilent.com/find/surveillance**.

In addition to radar, phased arrays are also used in spatial division multiple access (SDMA) systems. In these systems a beam is directed only at the desired receiver for communications (Figure 1d). Thus, all receivers may share the same frequency data link, but only the receiver at which the beam is directed can receive the signal. SDMA systems are of particular interest to those trying to create systems in which the probability of signal intercept is low.

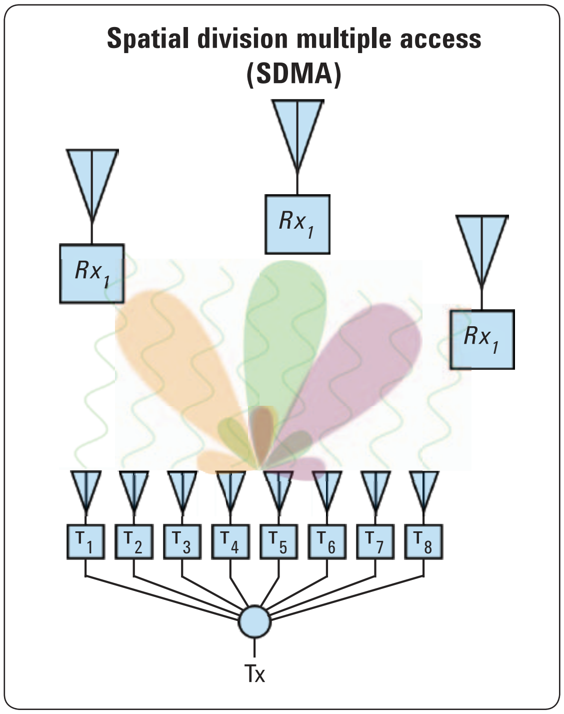


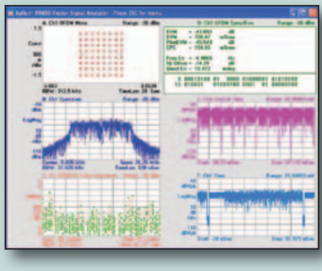
Figure 1d. An SDMA system uses beam forming to direct or receive energy only to or from a specific transmitter or receiver.

Direction finding

Multi-channel coherent systems are also useful in determining the location of a signal emitter. With multi-channel and coherent systems, it is possible to find the direction from which the signal is originating.

There are several methods for determining the location of a signal emitter using different types of direction finding (DF) radio equipment. The simplest method is to use a steerable narrow-beam antenna. This beam can be formed by using an electronically steered phased array antenna as discussed above. The angle of arrival (AoA) can then be determined by scanning the antenna and detecting the direction from which the greatest energy is received. Enhanced precision may be gained with these systems by adding the ability to make multiple measurements from different positions or from multiple antennas and triangulating.

Agilent 89601A Vector Signal Analysis Software



The Agilent 89601A vector signal analysis software is a flexible tool that includes analysis options for a wide range of common modulations. The VSA software is supported on a number of platforms including multi-channel oscilloscopes, multi-channel vector signal analyzers, and most Agilent spectrum analyzers. The software can make a variety of multi-channel measurements including built-in measurements for cross correlation, coherence and cross spectrum.

- High-resolution spectrum analysis
- Advanced general-purpose modulation analysis: AM/FM/PM, 2FSK to 1024QAM
- Extensive standards-based analysis coverage, including LTE (MIMO), WiMAX™ (MIMO), WLAN (MIMO), 3GPP, RFID, and UWB
- Compatible with more than 30 Agilent signal analyzers, scopes and logic analyzers

A phase interferometer is another approach to measuring AoA. Interferometers can provide very high angular resolution but require multi-channel receivers that have low phase noise and are fully coherent. The phase interferometer compares the phase shift observed between antennas created by the wave-front arriving from different directions (Figure 1e). This phase shift, ϕ, is related to the AoA of the signal. Because the phase shift becomes ambiguous after 360° it is often necessary to have additional antennas and coherent receivers to provide a complete 360° of directional coverage.

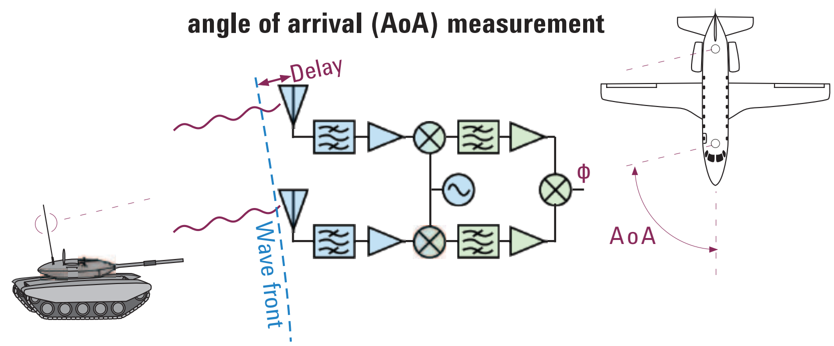
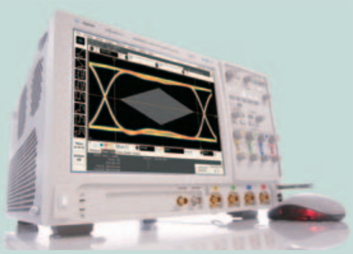


Figure 1e. A direction-finding system can determine the angle of arrival of a transmitted signal by measuring the phase delay at two spatially separated receivers.

Test challenges

The applications discussed above require multiple channels with static phase relationships between them. Because operation of these systems requires management or detection of the phase relationship between signals, testing their operation also requires at least phase-stable if not fully coherent test signals. In many cases, these signals must be coherent and must also have a specific or definable phase relationship and therefore require coherent test-signal generators with phase-control capability. This section will take a closer look at some specific test challenges and the reason that phase-stable or coherent test signals are required.

Agilent 90000 Series Four-Channel Oscilloscope with 89601A Vector Signal Analysis Software



- A high bandwidth, high frequency oscilloscope is a useful tool for analyzing RF signals in the time domain and frequency domain simultaneously with Agilent's 89601A VSA software. Further, the four coherent measurement channels make it a very useful tool for measurements of coherent signals in multi-channel systems.
- 13 GHz bandwidth
- 40 GSa/s on each of four analog channels
- Standard 10 Mpts memory per channel, upgradeable to industry-leading 1 Gpts

Agilent PNA Vector Network Analyzer with U3022A Multi-Port Test Set

The Agilent U3022AE10 multiport test set, combined with two-port PNA, PNA-L or PNA-X network analyzer and Option 551, offers full crossbar and calibrated measurements up to 12-port.

- Coupler based test set for highest accuracy and stability
- No external PC or software required
- Full 12-port calibration

Phase matching

The systems discussed above require defined phase relationships between channels. However, even small differences between cable lengths, amplifier devices and filters can create delays or phase shifts that destroy the desired phase relationships. In addition, phase often varies as a function of frequency and temperature. For example, group delay is common in components such as filters.

These delay effects can make it very difficult to achieve precision delay matching between channels of a multi-channel coherent system. Components must be tuned not only for the passband shape but also for the group-delay response relative to the other components in the system. To make this even more challenging, the group delay and amplitude matching must track over temperature. Even small delay differences at intermediate frequencies can appear as large phase errors relative to the RF signal (see Figure 2).

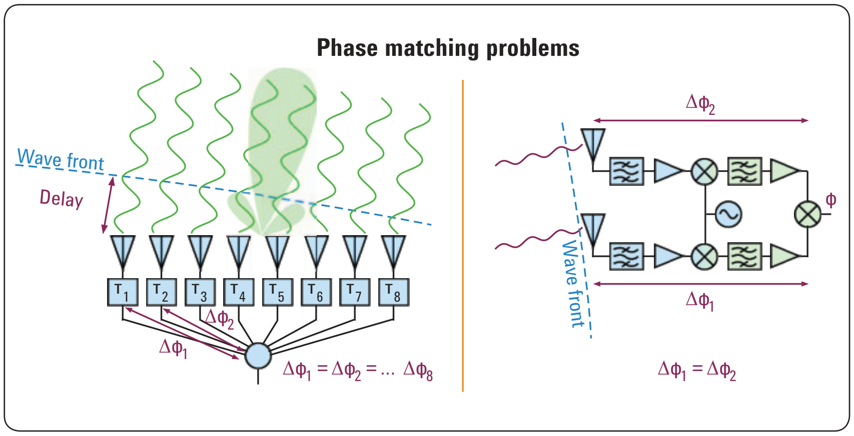


Figure 2. Coherent multi-channel systems often require phase matching between channels.

A multiport vector network analyzer (VNA) is likely the best solution for measuring delay or phase differences between components or between channels with the highest degree of accuracy. However, for scenarios that require a complex stimulus, a vector signal generator (VSG) may be the tool of choice. A single VSG and a signal splitter may be sufficient to stimulate multiple coherent signal ports. The phase difference in the responses can then be measured directly using a coherent multi-channel analyzer such as a high frequency oscilloscope or multichannel vector signal analyzer (VSA).

The advantage, however, of using multiple coherent sources with phase control is that they have the capability to readily change the phase relationship between the stimulus signals.

Agilent E8267D PSG Vector Signal Generator

Agilent's E8267D PSG vector signal generator is the industry's first integrated microwave VSG with I/Q modulation up to 44 GHz. It features an advanced wideband internal baseband generator capable of flexible arbitrary waveform playback or sophisticated real-time signal generation. The E8267D PSG also has a built-in wideband I/Q modulator that delivers up to 2 GHz RF modulation bandwidth and is a perfect complement to Agilent's N6030A standalone wideband AWG for I/Q waveform simulations up to 1 GHz RF bandwidth.

- Vector signal generation to 44 GHz and up to 2 GHz modulation BW
- +22 dBm @ 20 GHz and +18 dBm @ 40 GHz output power (typ)
- Supports coherent multi-channel configuration with options
- Compatible with Agilent Signal Studio waveform-creation software

Providing low-noise LOs

Another challenge with coherent systems is the complexity of generating a test local oscillator (LO). Frequently in the development process, one desires to use a test LO source to drive an upconverting or downconverting mixer. In a single-channel noncoherent system, there are many commercially available signal sources such as the Agilent PSG vector signal generator suitable for LO signal test purposes. Coherent multi-channel systems require at least two phase-coherent LOs to drive each channel. A simple power splitter and a high-output-power signal generator such as the PSG can easily accomplish this for a single-frequency-conversion multi-channel system.

However, for multiple-frequency-conversion systems it is necessary to maintain a phase-stable relationship between each conversion synthesizer along with low phase noise. Lower-frequency LOs must have a fixed mathematical frequency relationship to the higher-frequency LOs and test-signal generators must be phase-stable to each other from a common reference source. A single master reference is essential.

This may seem easy, but in practice locking two general purpose signal sources together to obtain higher-frequency phase-stable LOs can be difficult. Though most signal sources offer the familiar 10 MHz reference input to facilitate phase-stable LO generation, for many modern systems the results range from poor to unusable. Since most test-signal generators offer very small step size, the 10 MHz signal is frequently divided to lower clock rates before being multiplied to higher frequencies. This typically results in large multiplication factors to get to microwave frequencies in the gigahertz range. The result is the phase noise increases by the familiar 20 Log(N) ratio (where N is the multiplication factor). The larger the multiplication factors the higher the phase noise. The higher the phase noise of the phase-stable LOs, the lower the coherency factor possible between the channels. This effect can badly limit the performance capability of multi-channel coherent systems that rely on coherent cancellation of noise at the system detectors. This problem is worsened by drift or Allen variance problems created by the comparatively long update period from a comparatively low-frequency reference (possibly divided to an even lower frequency internally).

Phase-stable or low-phase-noise LO requirements greatly complicate frequency synthesizers. What' more, most commercially available signal generators that have external references often fall short of providing the necessary phase stability for test LOs at different frequencies in multi-channel systems. As will be shown below, signal analyzers such as the PSG have special options to improve phase stability between multiple sources.

Nonlinear effects in coherent multi-channel system

Another challenge for the coherent system designer is the unusual behavior of coherent signals to nonlinear effects. To illustrate, imagine placing a single sinusoidal frequency into an amplifier and saturating the amplifier with that signal. The amplitude of that signal would stop further amplification at the saturation power level of the device.

Now imagine placing a coherent frequency comb signal into the same amplifier. The output of the comb wouldn't simply be clipped off. Instead, harmonic energy that is coherently related to the lower frequency tones would combine constructively and destructively. The comb pickets become seemingly random in their amplitude (Figure 3).

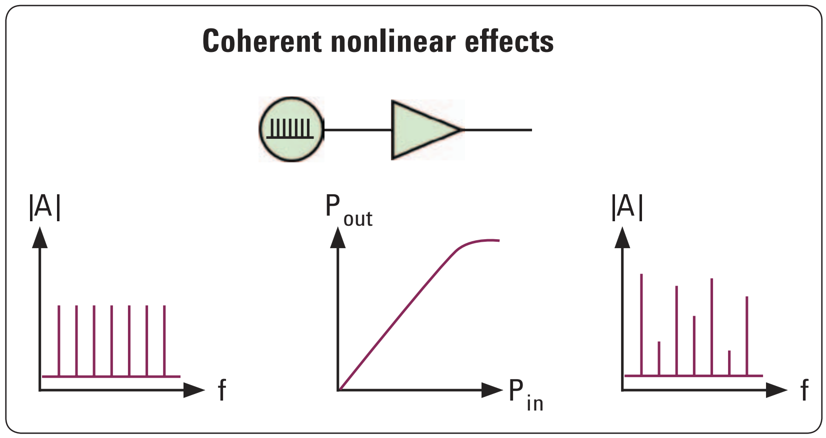


Figure 3. Nonlinear products can combine in unpredictable ways in coherent systems.

Because signals in coherent systems can result in coherently related distortion products, nonlinear effects have the potential to produce a variety of confusing results that are difficult to diagnose. Tests with noncoherent signal conditions may be inadequate at predicting the nonlinear behavior when coherent signals are present. This is particularly true if cross-channel nonlinear effects are present.

Comprehensive nonlinear analysis of coherent systems therefore demands some means of testing under coherently related conditions.

Simulation

Finally, a significant challenge for the multi-channel and coherent system designer is providing test stimulus to ensure the system is functioning properly. It may be possible to field test; however, using the actual platforms and emitters the system is designed to operate with is often cost-prohibitive or not easily available. For instance, flying several airplanes for days or weeks of testing, each at a cost of a few thousand dollars per hour, can quickly exceed the cost of even elaborate test setups. Providing the types of stimuli necessary to emulate real-world operating conditions requires signal generators that can produce phase-stable and coherently related stimuli. In addition, to simulate real-world conditions it may be necessary to control and adjust the phase relationship between signals to mimic an approaching wavefront to multiple antenna ports.

Fortunately, as we will see in the next sections, Agilent offers a variety of solutions that can meet these demanding requirements.

Issues with common multi-source approaches

There are some common issues to be aware of with popular approaches that attempt to make signal sources phase coherent. These issues greatly limit the utility of most signal sources for coherent multi-channel applications.

Locking 10 MHz references

As alluded to earlier, the simplest way to achieve a degree of phase stability between instruments is to lock the 10 MHz references of multiple signal sources. However, though this solution provides frequency coherency, the phase coherency (or phase stability as defined previously) will be limited. We can understand this by looking closely at the signal source block diagram in Figure 4.

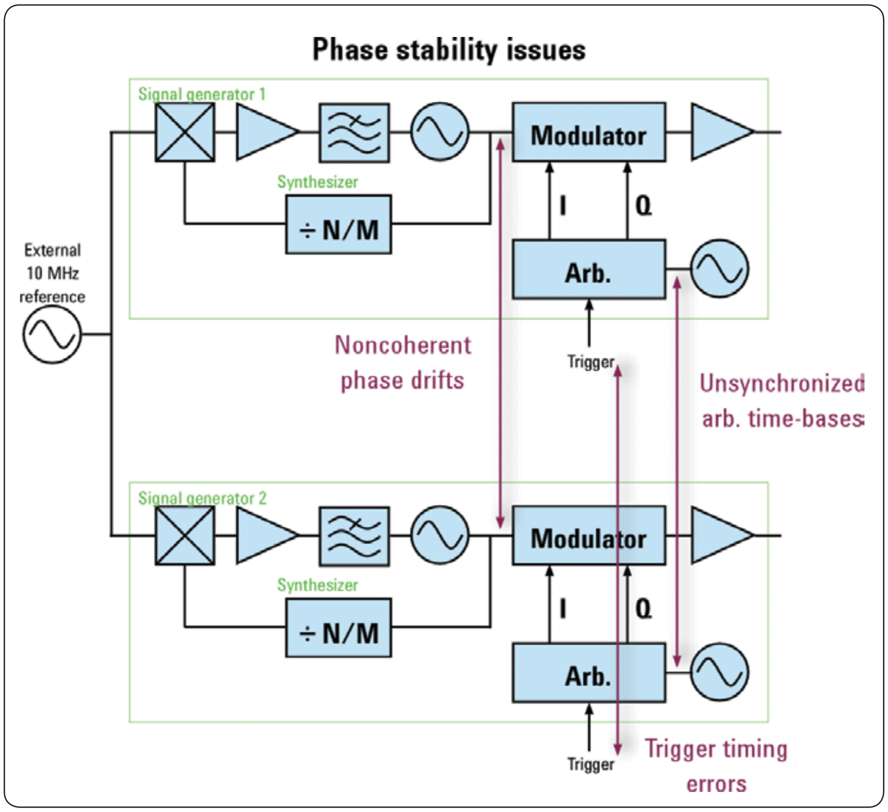


Figure 4. Locking the 10 MHz references of multiple sources provides only limited phase stability between instruments.

First, although the signal generator's synthesizers are tracking against the same time base, they have separate internal oscillators, each with its own phase noise, and they have separate hardware phase-locked loops that will have drift error signals independent of each other. Of course, more or less of this error will track out within the constraints of the loop bandwidth and tracking ability of the of the generator's synthesizer (Figures 5 and 6). Typically, at frequencies well within the loop bandwidth, the gain of the open-loop response is high, so tracking is good. However, it is not perfect and may not completely track out higher-order effects (Figure 5). Moreover, the achievable residual phase errors tend to degrade substantially around the tracking loop bandwidth and allow noncoherent phase variations (Figure 6). These phase variations multiply as the 10 MHz reference is converted to higher frequencies and therefore can result in significant errors.

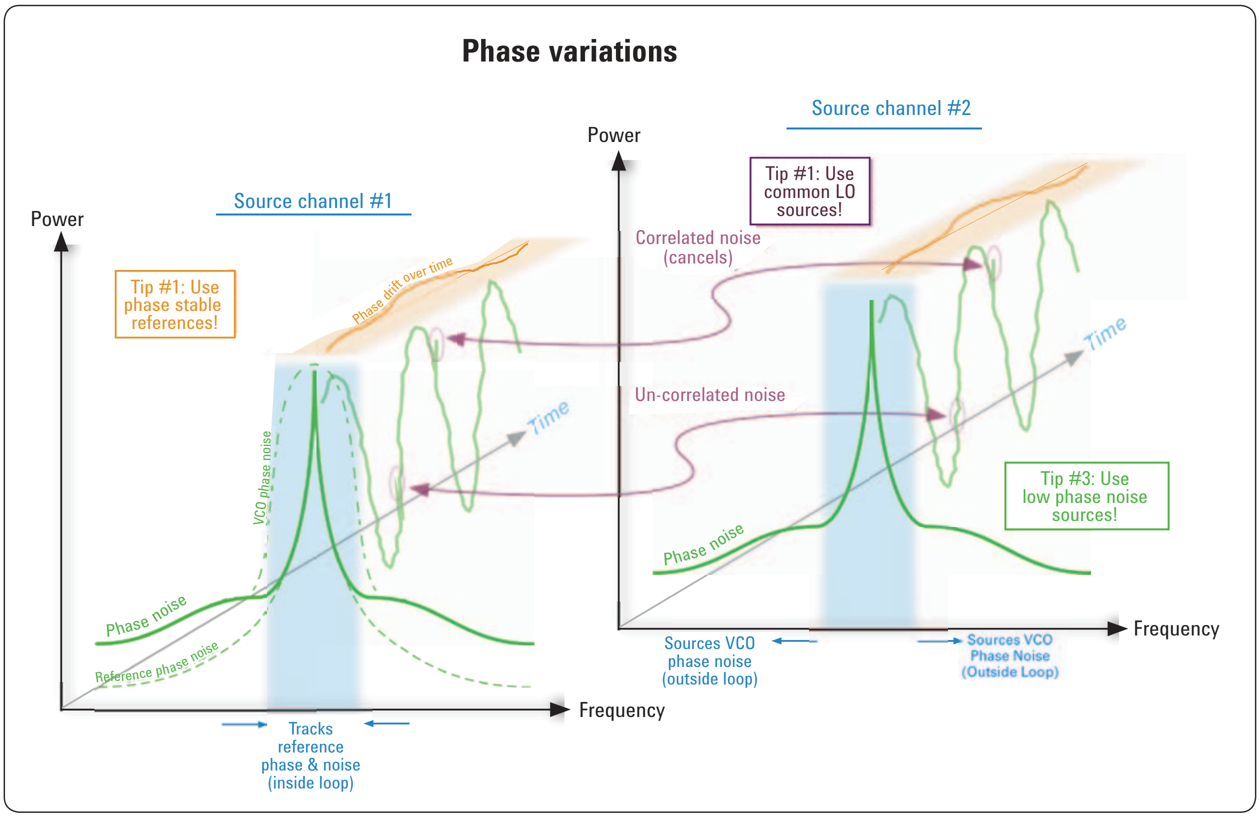


Figure 5. Phase variations between reference-locked signal sources track within the limits of loop bandwidth of their PLLs. Performance is improved by using high quality stable references and instruments with low phase noise, or by locking higher-frequency references or LOs.

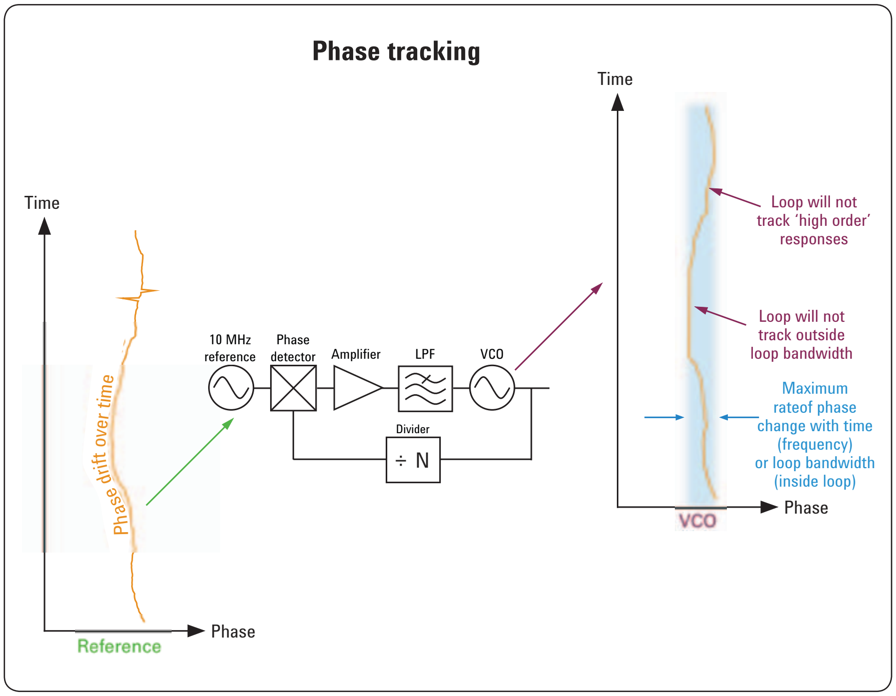


Figure 6. Phase tracking of signal source PLLs is generally good but not perfect and may not be able to track higher-order phase variations.

The uncorrelated noise component of the signal source's synthesizers will contribute additional errors. Inside the loop bandwidth the phase noise is dominated by the reference; however, outside the loop bandwidth the phase noise is determined by the synthesizer's oscillator (Figure 5). This uncorrelated phase noise will contribute to the phase error between the reference-locked signal sources.

To illustrate, the level of phase stability of two reference-locked sources can be observed by measuring the close-in drift over time (Allan variances) and integrating the phase noise. For example, Figure 7 shows phase-drift measurement results for two Agilent MXG signal generators with locked 10 MHz references, measured with a two-channel high frequency oscilloscope. Over a one-hour period more than 20 degrees of drift is observed compared to less than 200 mdeg for a correctly generated coherent solution.

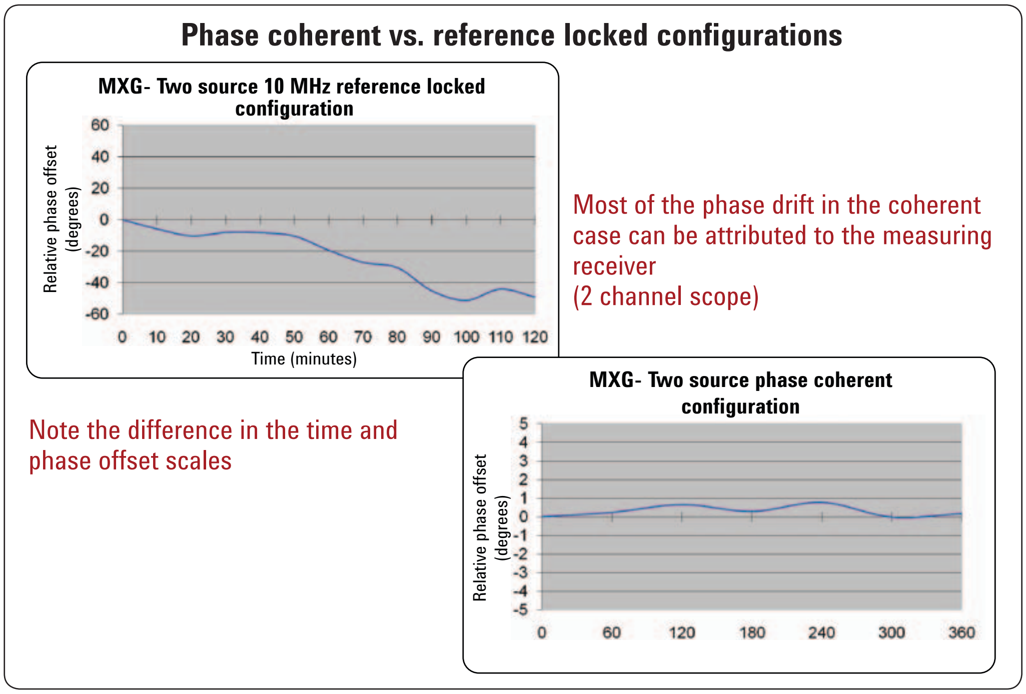


Figure 7. Measured phase drift of two 10 MHz-locked MXG signal generators compared to two coherently-locked MXGs (sharing a common LO).

The amount of phase error due to the noncoherent phase noise is determined by integrating the phase noise of the synthesizer with integration limits set equal to the bandwidth of the applicable signals used in the system. Figure 8 shows an example of a phase-noise measurement taken with the Agilent PSA spectrum analyzer. Built-in integration-bandwidth markers facilitate the measurement and can report the total phase error in degrees.

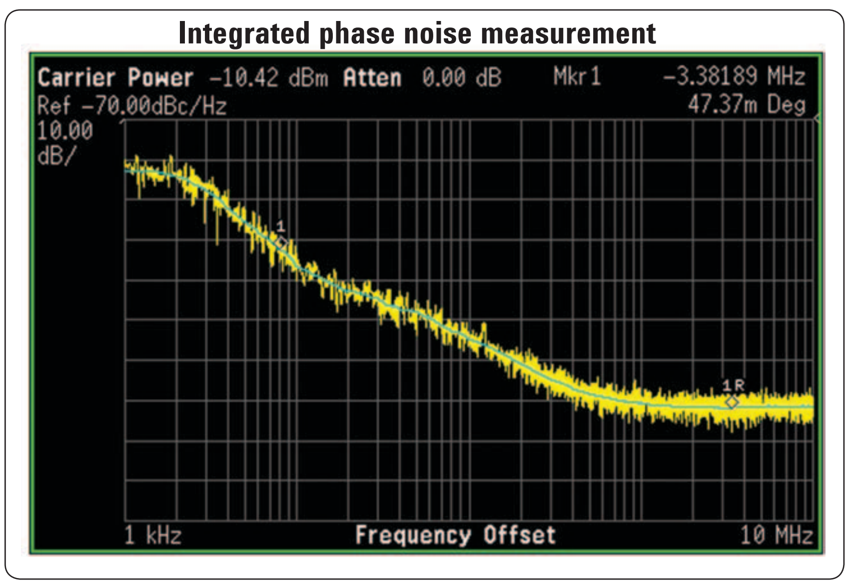


Figure 8. The total phase error due to phase noise between signal sources can be determined by integrating the uncorrelated phase noise with integration limits set equal to the bandwidth of the applicable signals used in the system.

Triggering the baseband AWG

A common approach to aligning the baseband generators (BBG) of multiple VSGs is to use a common trigger to start the waveform playback (Figure 4). However, if the two AWG sample clocks are not aligned, an error as large as the time spacing between samples may occur even when triggered simultaneously. This is because the starting sample will latch at the first rising edge of the sample clock after the trigger. For example, an AWG with a sample clock of 50 MHz would have 20 ns (1/50 MHz) between samples and therefore an alignment error could result in up to 20 ns of error between signal waveforms from the two AWGs when not synchronized correctly.

Further complications arise from the AWG's use of oversampling. If, for instance, an AWG with 50 MHz sampling clock is oversampling by a factor of four, the oversample clock rate is 200 MHz. Every 50 MHz sample is interpolated onto four oversampled points. It is therefore necessary to synchronize the oversampling such that there is consistency between instruments in how each sample is interpolated. To overcome these instrumentation problems, the following sections will outline configuration options available from Agilent. These special instrument features are designed to maximize phase stability, minimize phase noise, and properly align BBGs to avoid common limitations encountered in coherent signal generation.

Approaches to coherency problems

Available solutions can be grouped into two categories: phase-stable solutions (or solutions with coherence greater than zero but less than 1 as defined previously), and phase-coherent solutions. In general, phase-stable solutions involve features and options that minimize the phase drift and phase-noise errors. Phase-coherent solutions make it possible to share a common LO so that phase instabilities become common between multiple signal generators.

Phase-stable solutions

The phase stability of reference-locked instruments is dependent on the performance of the instrument used. In general, the phase stability between high end instruments will be better than that of mid- or lower-performance instruments due to superior phase noise, lower residual FM and better drift specifications. Instrument selection is therefore a critical decision in achieving the best performance. That said, within a class of instruments there may be performance-enhancement options or features that can be selected to improve the phase stability. For instance, instruments often provide options to improve phase-noise performance, or improve the reference stability or enable the use of a higher-quality external reference.

Phase-coherent solutions

Another approach to minimizing the sources of coherency error introduced by imperfect synthesizers and PLLs is to use a phase-coherent solution that effectively eliminates the relative phase errors by configuring the instruments to use a common LO (Figure 9). The synthesizer still has drift and phase noise, but because the drift and phase noise are common to both signals, the relative phase instabilities are essentially removed. The LO signals are then multiplied up separately to the desired frequency and used to drive separate in-phase and quadrature-phase (I/Q) modulators. The phase instabilities contributed by the multipliers and I/Q modulators are generally negligible. Having separate BBGs and separate I/Q modulators driven with a coherent LO provides a very flexible solution. This is because, in addition to being able to create multiple coherent complex waveforms, the BBG can modify the phase of each signal. However, the BBGs must be synchronized.

In Figure 9, the LO of the top signal generator is taken out, split and input as the LO for both instruments. Alternatively, a separate synthesizer can be used as a common LO for all instruments. This block diagram also shows how the BBGs can be synchronized by connecting a common trigger used to start both AWGs simultaneously. The BBGs also share a common external clock to ensure alignment of the waveform samples.

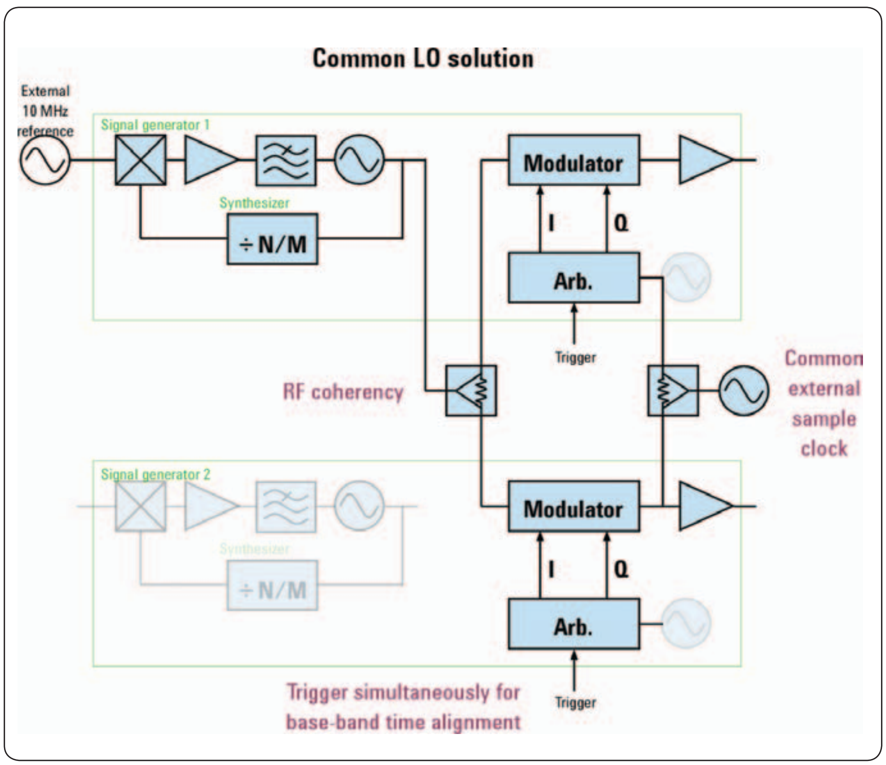


Figure 9. Sharing a common LO between signal generators effectively eliminates the relative phase errors between signals and provides full phase coherency. The LO may be provided by using an external source or by distributing the "master LO" of one instrument with other instruments.

Available Solutions from Agilent

In this section we will take at look at specific solutions available from Agilent that address the special needs of coherent multi-channel test.

MXG and PSG with locked 10 MHz reference

Although phase coherence is not achieved with a simple 10 MHz reference-locked configuration, there are options, features, and best practices available to improve the stability of the phase between instruments. There are also some advantages to a reference-locked system. In addition to simplicity, the system will retain the flexibility to tune multiple sources to different frequencies. Test systems that are locked at higher frequencies can lose this flexibility.

One of the first items to consider is the instrument's performance. The residual phase noise and phase drift of the generator's synthesizer will have a direct effect on the phase stability between reference-locked instruments.

The PSG signal generator offers an Option UNX, "ultra-low phase noise," that improves both phase noise and phase drift and is strongly recommended for improving phase stability in a reference-locked configuration. Option UNX provides the best phase-noise performance in a commercially available microwave signal generator.

Another consideration is the performance of the frequency reference. Like most signal generators, the MXG and PSG can use either an internal or external reference. Using the highest quality reference available as the master reference will improve the relative phase stability in two ways: first, a high quality reference will have less drift; second, the close-in phase noise for offsets less than 1 kHz is dominated by the reference and therefore an improvement in the reference phase noise directly improves the close-in phase noise and stability (within the loop bandwidth of the loops that follow).

Typically, 10 MHz is used as the reference. However, the Agilent MXG has an available Option 1ER that enables it to accept a reference from 1 MHz to 50 MHz, allowing for a wider potential selection of available external references. This is particularly helpful for locking to signals internal to products other than test and measurement equipment, which are usually equipped with a non-10 MHz reference port.

With Option UNX, the PSG also provides an additional reference oscillator bandwidth setting that can be used to optimize the phase noise at different offsets. This setting includes the ability to make the adjustment for both internal and external references.[1] The reference bandwidth defaults to 125 Hz for the internal reference and 650 Hz for an external reference. Increasing the reference bandwidth (or loop bandwidth) causes the phase-noise performance to be more dependent on the reference and narrowing causes more dependence on the synthesizer hardware. Performance can therefore be optimized depending on your confidence in the stability and phase noise of the reference versus the synthesizer hardware for various frequency offsets from the carrier. For the multi-channel scenario it is usually desirable to increase the loop bandwidth to the widest setting because this increases the dependence of phase stability performance on the reference, which is common to all signal generators (Figure 10). Another advantage to widening the reference loop bandwidth is an increase in overall loop gain, providing better close-in tracking of the reference, further improving short-term phase stability.

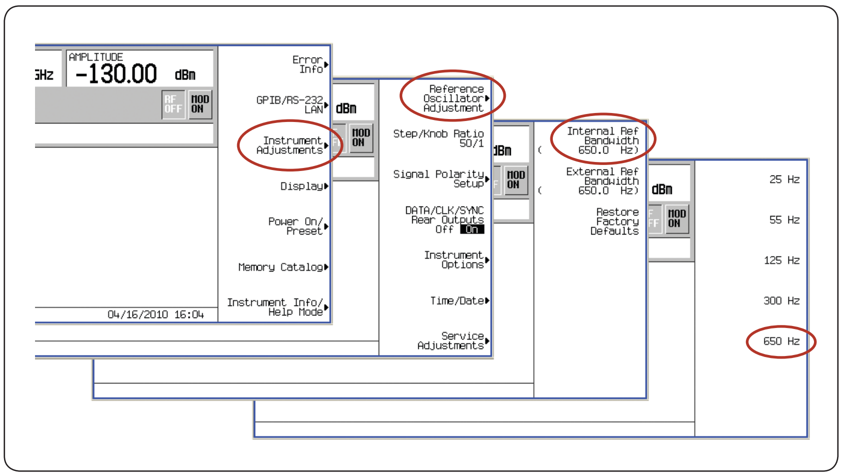


Figure 10. The reference bandwidth setting on the PSG with Option UNX should be set to the widest setting for best phase stability between reference-locked instruments.

Phase Stable PSG with 1 GHz locked reference (Options H1S and H1G)

PSG Options H1S and H1G further improve the phase stability between sources in a phase-stable system. An explanation requires some description of the PSG's reference hardware. The PSG's synthesizer does not use the 10 MHz reference directly; rather it includes an assembly that derives a 1 GHz reference from the 10 MHz reference. This 1 GHz reference is then used to drive the PSG's YIG oscillator-based synthesizer. Options H1S and H1G provide a means to bypass the entire internal reference and provide an external 1 GHz reference, thereby eliminating the relative phase instabilities between the internal 1 GHz reference boards of each PSG. Because different paths are used inside the PSG for different frequencies, Option H1S is necessary for frequencies above 250 MHz and Option H1G for frequencies below 250 MHz (Figure 16).

1. *Found under the Utility > Instrument Adjustments > Reference Oscillator Adjustment keys on the front panel.*

With Options H1S and H1G it is also possible to improve the instrument's overall phase-noise performance. However, since the PSG's internal 1 GHz reference already provides outstanding overall phase-noise performance, the external reference would need to have very high performance. The relative phase instabilities (namely drift), however, are largely improved by sharing a common 1 GHz reference (Figure 12). This is most conveniently done by using one of the PSG's internal 1 GHz reference as the master reference. Figures 11a and 11b show two alternative configurations for sharing a common 1 GHz reference. In Figure 11a, one PSG has Option UNX and the other has Option H1S. Since an instrument with Option UNX includes a 1 GHz reference output, this output can be connected to the 1 GHz reference input of the second unit with Option H1S. Alternatively, if both instruments have Option H1S as in Figure 11b, the 1 GHz reference of the master PSG can be divided and shared amongst multiple PSGs. Although these options will improve the phase stability between instruments, it does not provide full phase coherency.

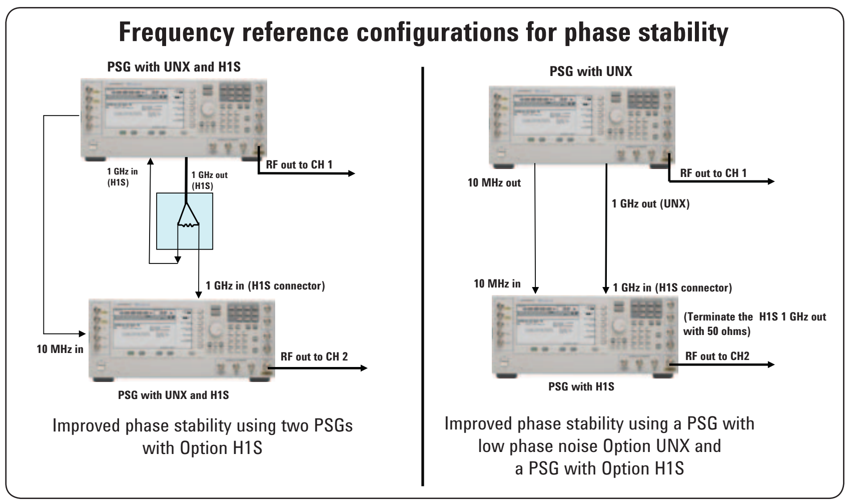


Figure 11. PSGs Options H1S, H1G and UNX provide the ability to improve phase stability between instruments by locking the 1 GHz reference.

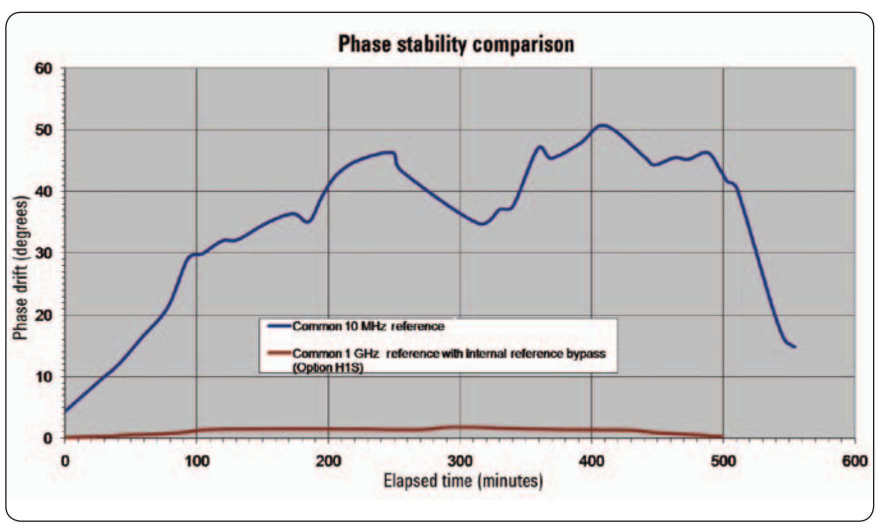


Figure 12. Phase drift comparison of PSGs with 10 MHz reference locked versus 1 GHz references locked (Option H1S).

Agilent N5182A MXG RF Vector Signal Generator

Features fast frequency, amplitude, and waveform switching, high power with an electronic attenuator, and high reliability – all in two rack units (2RU). Agilent MXG vector provides better value for your investment by increasing throughput, improving test yield, maximizing uptime, and saving rack space. With scalable RF and baseband performance, the Agilent MXG vector is easily configured to meet your specific test needs.

- 100 kHz to 3 or 6 GHz
- ≤ 1.2 ms switching speed in SCPI mode; ≤ 900 µs simultaneous frequency, amplitude and waveform switching in list mode
- Internal baseband generator (100 MHz RF BW; up to 125 Msa/s sample rate): arbitrary waveform only
- Supports coherent multi-channel configurations with option

Coherent MXGs with shared LO (Option 012)

The MXG with Option 012 provides a means to coherently lock multiple MXGs together by sharing a common LO through jumpers provided on the back of the instrument. Figure 13a shows a two-unit configuration. The master MXG LO out of one instrument is connected to a two-way splitter. The outputs of the splitter are then connected to the LO inputs of each instrument. Splitting the LO output to more than two instruments, however, would cause too much loss to drive the LO inputs. Three or more MXGs will require an external master LO to provide sufficient amplitude of between 0 to 7 dBm (Figure 13b). In this scenario the signal generator used to generate the master LO must be manually controlled with its frequency set equivalent to the desired output frequency of the system. Because the MXGs now share a common LO, the RF paths of the signal generators are now fully coherent. However, it is also necessary to synchronize the MXG's baseband generators. The first step is to trigger the baseband generators of each MXG to start simultaneously using the Pattern Trigger input. A convenient trigger source is the Event 1 trigger (Figure 13). In its default state the MXG sends a rising-edge trigger out Event 1 at the start of the waveform when played. One MXG should be selected as master and the others designated as slaves. When the master MXG begins to play its waveform it will then trigger the other MXGs to play their waveforms. There will be some trigger delay but this will be compensated for by using the Multi BBG Sync feature of the MXG. For this feature to work, however, the BNC cables connecting the Event 1 trigger output to the Pattern Trigger in should be no more than 30 cm long (the recommended cable length is 23 cm). The 10 MHz references must also be connected.

N5182A MXG phase coherency (Option 012)
Two unit configuration

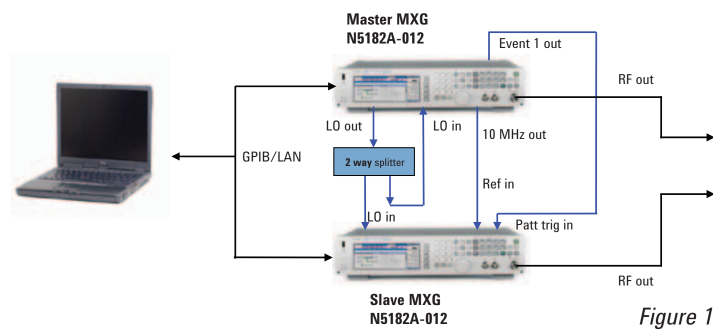


Figure 13a

Phase coherency on N5182A MXG (Option 012)
3 to 16 unit configuration

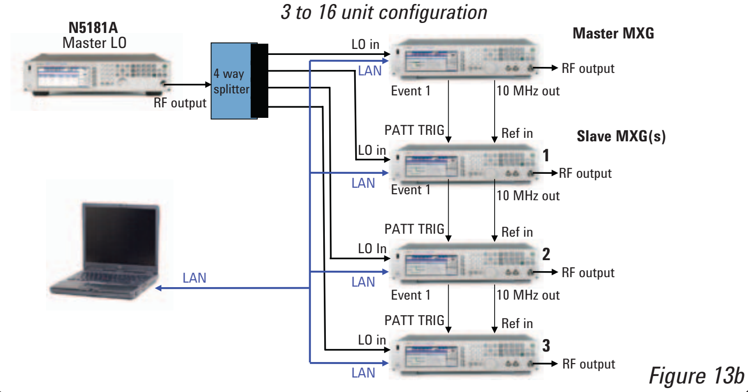


Figure 13b

Figure 13. These coherent multi-MXG configurations use shared LOs (Option 012).

When a BBG receives a trigger, it will latch and start the waveform playback on the next baseband clock cycle after the trigger. Because each BBG has its own clock, the start time of each MXG will therefore be slightly different even if precisely triggered. This difference, as well as any difference due to trigger delay, is corrected using the N5182A MXG's baseband timing-alignment feature.[1] A setup screen will allow you to configure each instrument as either master or slave (Figure 14). The automatic alignment feature will support up to 16 MXGs, one master and 15 slaves. When you designate an instrument as a slave, the arb trigger will automatically set to "external" and the trigger type set to "trigger and run" to await the trigger input from the Event 1 output of the Master MXG. You may receive an error message notifying you of this change when you first designate the MXG as a slave; this is normal.

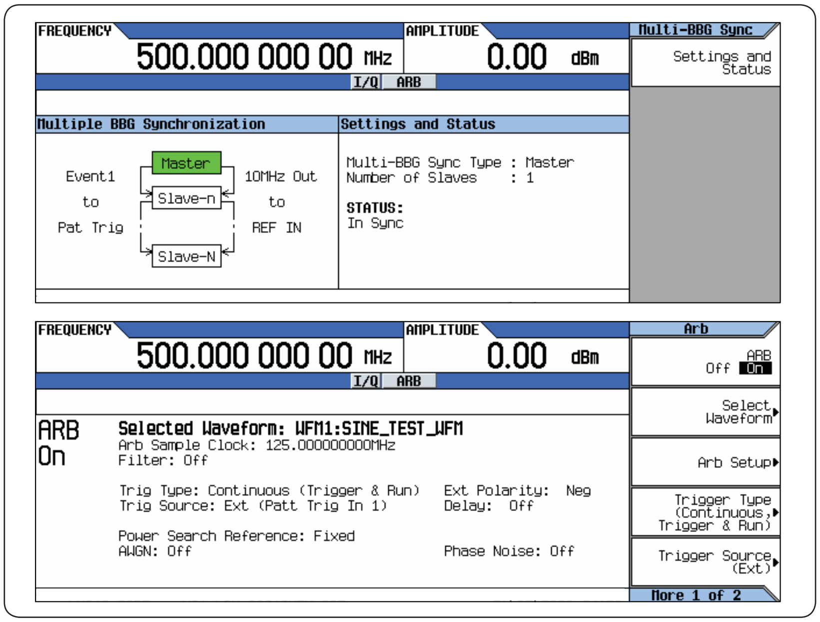


Figure 14. MXG with Option 012 includes the Multi-BBG Synchronization feature, which is used to align the BBGs. One instrument should be designated as master and the others as slaves.

With the BBG synchronization feature the alignment error will be within a characteristic value of ±8 ns. If necessary, this minor delay can be reduced further to picosecond resolution by manually measuring and adjusting the I/Q delay. Figure 15 shows an example of measuring and making fine-alignment adjustments by using a two-channel oscilloscope to capture the start of two complex signals generated from two coherent MXGs.[2]

1. *The alignment feature is turned on by selecting [Mode], Dual Arb > Arb Setup > More 1 of 2 > Multi-BBG sync setup > On.*
2. *The timing is adjusted by selecting [I/Q] I/Q Adjustments > Internal Baseband Adjustments > More > I/Q delay. For more information on adjusting the delay, see "I/Q Adjustments" in the Agilent MXG Signal Generator User's Guide.*

Now that the multi-MXG configuration is fully aligned and coherent, it may be necessary or desirable to shift the phase of each signal relative to the other. For example, you may wish to set the relative phase of each signal generator to simulate an arriving wavefront. With a VSG this can be done using the BBG by modifying the phase of the AWG waveform. Details on how to adjust the phasing using the AWG waveform can be found in a section below. However, with the MXG the built in I/Q phase shift feature can also be used to adjust the phase without the need to modify the waveform file.[1] Using this feature allows independent control of the phase of each instrument relative to the other instruments in the system. (This feature should not be confused with the analog phase adjustment feature found under Freq > Mode > Adjust phase, which is designed to shift the phase of an MXG signal in standalone operation and will have no effect on the relative phase between instruments.)

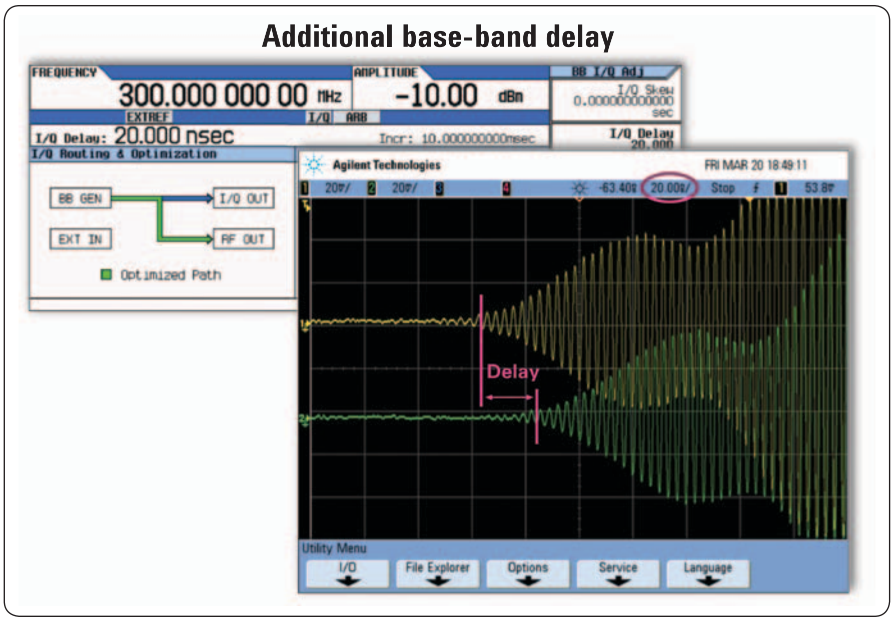


Figure 15. MXG with Option 012 includes Multi-BBG Synchronization feature used to align the BBGs. Each instrument should be designated as master or slave.

1. *This feature is found under the [I/Q] I/Q adjustments > Internal Baseband Adjustments > I/Q phase. Make sure I/Q adjustment is turned on.*

Coherent PSGs with shared LO (Options HCC)

An Agilent PSG with Option HCC provides the means to lock multiple PSG signal generators coherently by sharing LOs similar to Option 012 on the MXG. Option HCC works for signals above 250 MHz and is available on both the analog (E8257D) and vector (E8267D) PSGs. Option HCC loops the LO paths out the rear panel of the PSG using two pairs of connectors: one pair (LO input and LO output) for the low-band path (250 MHz to 3.2 GHz), and another pair for the high-band path (> 3.2 GHz) (Figure 16).

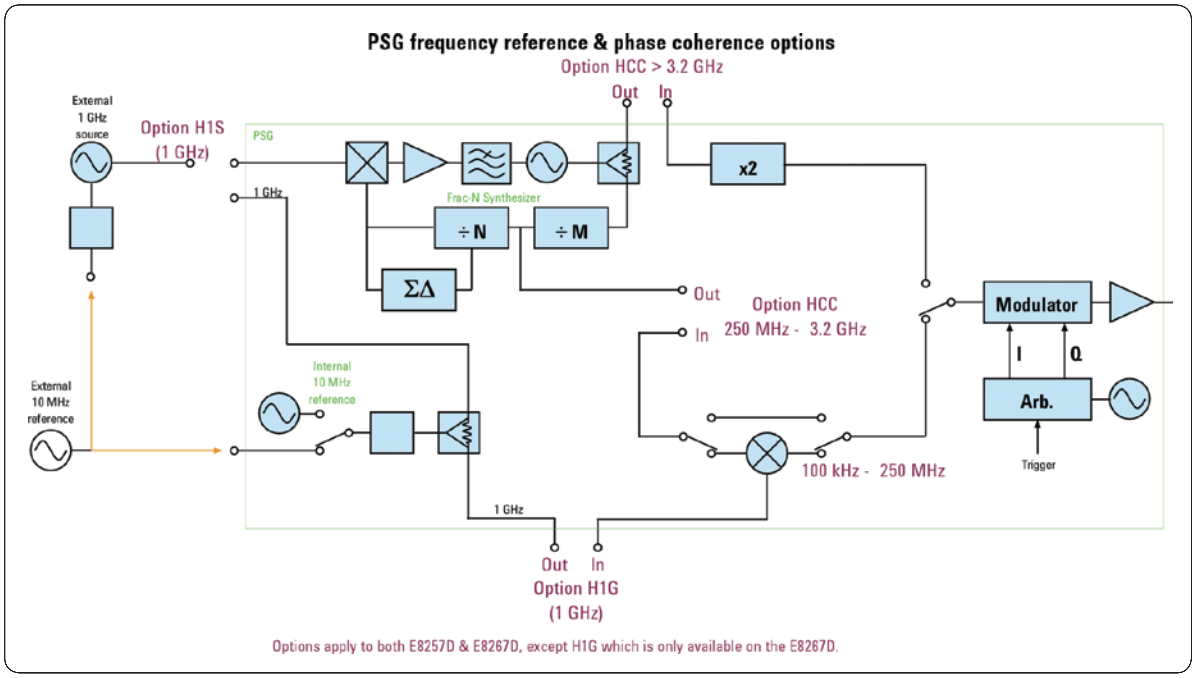


Figure 16. Option HCC provides access to PSGs LO from the rear panel for both low-band and high-band paths. Option H1S and H1G provide the ability to use a 1 GHz reference.

The system is configured by connecting the LO outputs from a master PSG to a distribution amplifier and then distributing the LOs back to the LO inputs of all the PSGs, including the master (Figure 17). The distribution amplifier, referred to as the "lock box," is required to coherently split and amplify the LO signals to supply adequate LO power to the LO inputs and is available from Agilent as part number Z5623A. The lock box can be custom configured to support the required number of instruments and LO paths.

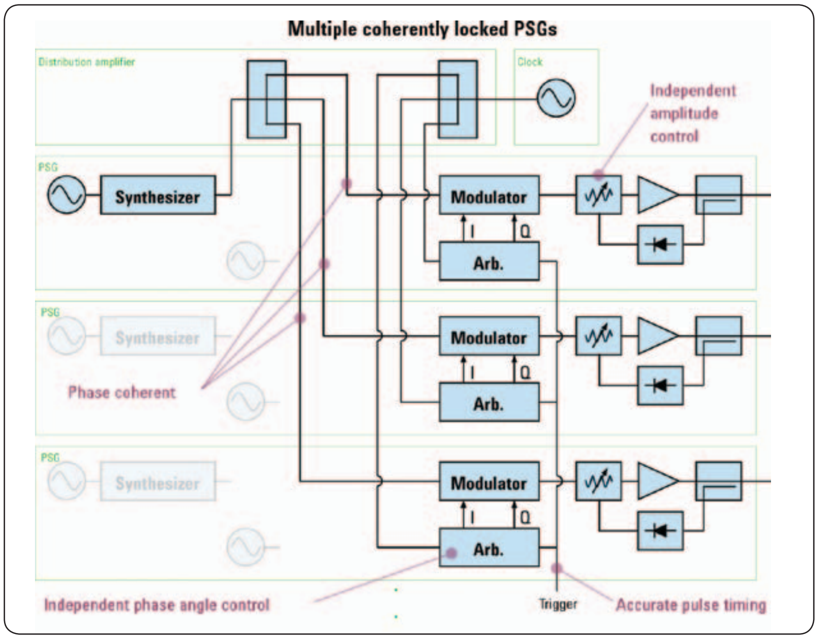


Figure 17. Simplified block diagram of coherently locked and synchronized PSG vector signal generators.

With this configuration the PSGs are now coherent. For the analog PSG (or vector PSG used in analog mode), the signals will be coherent with a static phase shift or delay between signals due the differences in the delay paths of each instrument. There is no built-in means to adjust the fixed delay or phase shift between analog instruments. With the vector PSG the BBG can be used to control the phase and time delay between instruments as well as generate coherent complex signals. However, the BBGs must first be aligned and synchronized. The vector PSGs are synchronized by simultaneously triggering the baseband generators using the Pattern Trigger in, as explained for the MXGs. The baseband triggers for all the slave instruments (and master if using a separate master trigger source) should be set to "trigger and run" and "ext" so that they will all start to play the waveform on the trigger event.[1]

For convenience, the Event 1 trigger of the master PSG can be used as the master trigger for all of the slaves. In the factory default state, the Event 1 trigger output will send a trigger at the start of the waveform. Hence, when the master PSG starts to play a waveform the Event 1 trigger occurs and starts the slave PSGs simultaneously. However, due to the trigger delay of the Event 1 trigger (typically around 50 ns), the waveforms won't be fully aligned without other adjustments. The PSG does not have an automatic multi-BBG sync setup feature like the MXG; it is therefore generally recommended to use a separate external trigger source with equal length cables to trigger all the PSGs simultaneously.

1. *This can be set by selecting [Mode]Dual Arb > Trigger Type > Continuous > Trigger and Run; [Mode]Dual Arb > Trigger Source > Ext.*

Although the instruments are simultaneously triggered, there will still be some alignment error between the BBGs if the baseband clocks are not synchronized, as explained previously in the Approaches to Coherency Problems section and the MXG Option 012 section. Unlike the MXG solution, however, the PSG does not have a built-in BBG synchronization function. However, the PSG's BBG does allow for an external BBG clock source to ensure the BB clock samples are aligned. The external clock input must be a continuous wave (CW) signal with frequency of 200 to 400 MHz and should have an amplitude of approximately 0 to 6 dBm. The PSG will use the baseband clock to oversample by a factor of four. As an example, an input of 400 MHz will result in a sample rate of 100 MSa/s.

Because the PSGs are now sharing a common baseband clock, the latch time of all BBGs will occur simultaneously on trigger input and will be fully synchronized and aligned with one exception. The exception has to do with how the waveform sample points are interpolated onto the oversampled points. Because the PSG uses four-times oversampling, each sample point is converted into multiple oversampled points. This may or may not occur consistently between each PSG and may result in small alignment errors at four discreet time offsets of 2.5 ns at the full sample rate of 100 MSa/s. These will vary each time the waveforms are started. Currently, the only way to correct for this offset is by trial and error, repeatedly restarting the waveform or using the "Align DACs" function until the waveforms align.

Now that the multi-PSG configuration is fully aligned and coherent, it may be necessary or desirable to shift the phase of each signal relative to each other. This can be done by modifying the BBG waveform files. A description of how to do this is included below.

Coherent PSG with shared LO (Options HCC, 016) and synchronized external wideband AWG (N8241A)

The vector PSG (E8267D) with internal AWG BBG provides up to 80 MHz of bandwidth. If wider bandwidths are required the PSG can be configured with Option 016 to work with the N6030A or N8241A wideband AWG to provide up to 1 GHz of bandwidth for frequencies from 3.2 GHz to 44 GHz. For this case, the PSG's LOs should be distributed and configured as described above. The wideband AWGs should also be aligned and synchronized. This is done by using the Marker Out 2 trigger output of one of the AWGs as the master to simultaneously trigger each AWG waveform playback and by sharing the baseband clocks. Since the N6030A and N8241A each have two channels—one for I and one for Q—the clocks for each channel should be shared. The rest of the system should be configured in the same way a standard PSG with external wideband AWG is configured—by connecting the differential outputs of channels one and two of the AWG to the differential I and Q inputs provided on the rear of a vector PSG with Option 016. A complete connection block diagram with configuration for two PSGs and two wideband AWGs is shown in Figure 18.

Agilent N8241A Arbitrary Waveform Generator

The Agilent N8241A arbitrary waveform generator combines the unprecedented performance of Agilent's AWGs with the unsurpassed flexibility of scalable modules. High sampling rates of either 1.25 GSa/s or 625 MSa/s, and high bit resolution enable designers to create ideal waveforms for accurate test of radar, satellite, digital-radio and frequency-agile systems.

- LXI class-A compliant
- Simultaneously delivers 1.25 GSa/s and 15 bits of vertical resolution
- Optional dynamic sequencing direct digital synthesis (DDS) engine
- Dual-channel, single-ended and differential outputs with 500 or 250 MHz of instantaneous analog bandwidth per channel
- Compatible with the E8267D PSG vector signal generator for generating 1 GHz bandwidth to 44 GHz

For 1 GHz bandwidth signals below 3.2 GHz, Option H18 is required and works by adding an additional downconverter to the PSG to reconvert the wideband signals to frequencies below 3.2 GHz. However, because the Option H18 down-converter uses a separate LO the system would not be fully coherent. However, it would be phase-stable.

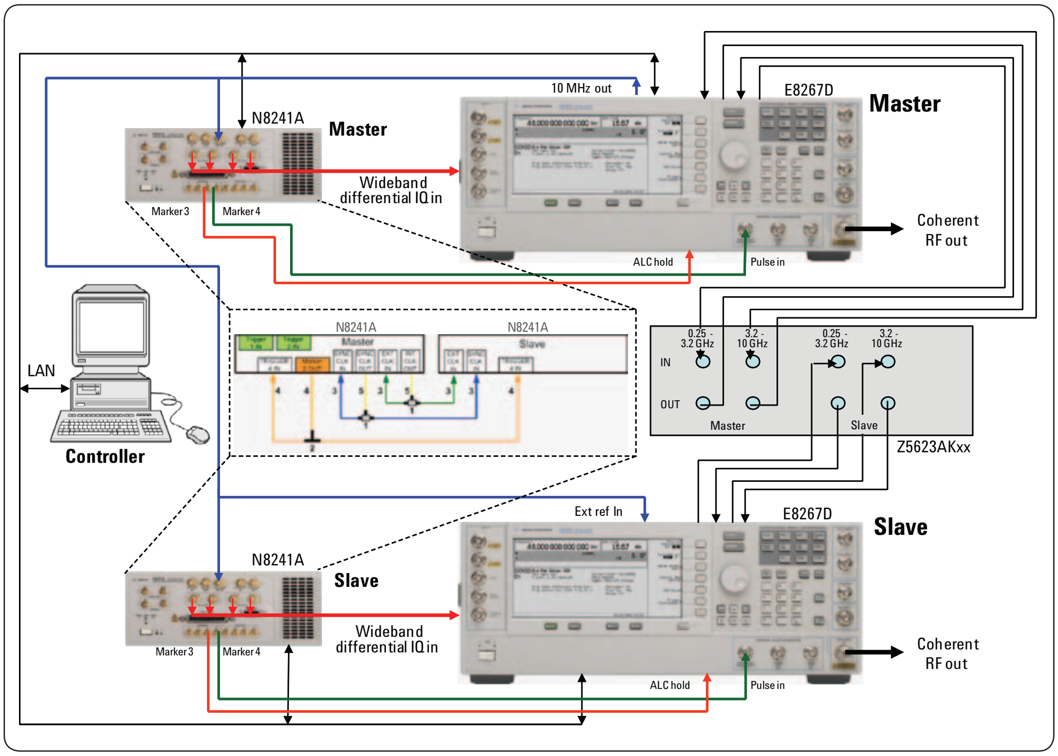


Figure 18. These are the connections for two coherent wideband VSGs using an E8267D PSG and an N8241A external AWG.

Z2090B-3xx single or multi-channel coherent signal simulator

The Z2090B multi-channel coherent signal simulator system is available from Agilent as a turnkey solution. The Z2090B is built to order based on customer requirements and can be configured with two or more PSG signal generators and wideband AWGs.

Modifying the Baseband Arbitrary Generator Waveform File to Add a Phase Shift

A VSG is a very flexible tool for waveform creation. In a coherent multi-channel system the flexibility of the AWG can be used to create a desired phase delay between signals. This section will discuss how to modify a waveform file to create a phase delay between two waveform files.

The waveform file consists of I/Q pairs of data that describe the voltage level of a waveform in the real and imaginary coordinates for points in time. The waveform can therefore be described in complex terms:

$$A = I + jQ$$

I and Q are arrays of voltage levels.

The magnitude of the waveform is then $|A| = \sqrt{(I^2 + Q^2)}$

The phase is $\theta = tan^{-1} I/Q$

The waveform can be described in polar coordinates as $A = |A|(cos\ \theta + j\ sin\theta)$

A phase offset of φ can be added by modifying the above to

$$A = |A|(cos\ (\theta + \varphi) + j(sin\ \theta + \varphi))$$

Mathematically, this can be done for all I/Q points by multiplying

$$|A|(cos\ \theta + jsin\ \theta)\ by\ (cos\varphi + jsin\varphi)$$

The resulting waveform file can then be converted back to the $A' = I' + jQ'$ form using the formulas

$$I' = |A'|cos\theta'$$
$$Q' = A\ |'|sin\theta'$$

Scaling the amplitude |A′| may be necessary if it must remain equal to the original amplitude |A|.

The resulting I′ and Q′ pairs can then be loaded back into the BBG or AWG. This computation can be easily performed using a tool such as MATLAB®. The waveform can be readily downloaded into the MXG or PSG using the Agilent-provided download assistant available at **www.agilent.com/find/psg**.

Which System Do I Need?

At this point it is common to ask, "Which system is sufficient for my needs?" Do you need a coherent system, phase-adjustable system or a simple phase-stable system? Do you need a PSG configuration, or will a more economical MXG system suffice?

Many variables will affect the answer to these questions, not the least of which is the performance requirements of the system you are designing or testing. Other factors include the technology you are working with and the type of tests or simulations you are performing. While it is impossible to provide a full answer, some common use cases and suggested configurations are offered.

Use case	**Suggested instrument configuration**
Simple MIMO receiver stimulus	10 MHz-locked MXGs
MIMO receiver channel estimation algorithm verification	Coherent MXGs with Option 012
Simulations for direction-finding equipment	Coherent PSGs with Option HCC UNX
Providing test LOs for multi-stage coherent converters in high end military equipment	PSG with Option H1S and UNX
Beam forming for radar application	Coherent PSGs with Option HCC and UNX
Beam forming for commercial SDMA application	Coherent MXGs with Option 012 or phase-stable PSGs with Option H1S
Simulation for commercial switched-diversity system	10 MHz-locked MXGs
Simulation for military switched-diversity system	PSG with Option H1S and UNX
DADE algorithm development for diversity system	MXGs with Option 012

Conclusion

With multi-channel technologies becoming more common, the need to accurately and efficiently create test signals to exercise these systems is of growing importance.

In this application note we have discussed the test challenges for multi-channel systems and the reasons that coherent systems are needed; we have outlined key differences between phase-stable sources, phase-coherent systems and phase-adjustable coherent systems.

We've presented a number of solutions available from Agilent including 10 MHz reference-locked signal generators, 1 GHz reference-locked signal generators, signal generators that share common LOs, and vector signal generators that use synchronized BBGs to control the phase.

We have also offered some suggested test configurations to be used for different applications

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