3 Tactics for Configuring Phase-Coherent RF Signal Generation

How to overcome multi-antenna system test challenges
Overview

As the number of higher throughput applications grows, there is a need for wider bandwidth and network coverage in wireless systems. However, given limited spectrum allocation, you must look for ways to improve spectral efficiency and signal-to-noise ratio (SNR). Multi-antenna techniques, such as multi-input multi-output (MIMO), and beamforming can help you achieve diversity, multiplexing, and antenna gain in order to improve spectral efficiency and SNR.

This white paper will help you understand phase coherence and why it matters, and offer tactics for generating phase-coherent signals.

Testing multi-antenna systems requires a test system capable of providing multiple signals and a constant phase relationship between the signals. Employing different tactics for configuring phase-coherent signal generation leads to different measurement results.
What Is Phase Coherence?

Two signals are coherent if they have a constant relative phase at all times. Figure 1a illustrates two non-coherent signals with phase varies and 1b shows coherent signals with fixed phase offset. When present together, coherent signals will combine constructively or destructively depending on their relative phase.

In cases where you characterize a multi-channel component such as a phased-array antenna, you need to control the phase angle relationship precisely between the channels (Figure 1c). For digitally modulated signals, phase coherence indicates both timing synchronization between baseband generators and phase coherence between RF carriers (see Figure 1d). Similarly, radar pulses require precise timing of the pulse bursts to simulate the appropriate spatial delays (see Figure 1e).

Figure 1. Phase relations between two signals
Why Phase Coherence Matters

Most wireless systems, whether in commercial applications or aerospace and defense, use multi-antennas techniques at the receiver, transmitter, or both to improve overall system performance. These techniques include spatial diversity, spatial multiplexing, and beamforming. Engineers use multi-antenna techniques to achieve diversity, multiplexing, or antenna gains. Wireless systems can increase a receiver’s data throughput and SNR through these gains.

Spatial Diversity

In wireless communications systems, multipath effect results in radio signals reaching a receiver’s antenna with two or more paths. When multipath signals arrive at a receiver, the signals will combine either constructively or destructively depending on their relative phase. Spatial diversity, also known as antenna diversity, offers a solution to multipath interference. By using two or more antennas, you can achieve improvements in the quality and reliability of a wireless link. You can accomplish this with channel switching, signal weighting, time delay, or transmit diversity, as shown in Figure 2.

Figure 2. Spatial diversity techniques for receiver diversity and transmitter diversity
To simulate the multipath signals for spatial diversity tests, you need a signal generator and a channel emulator to simulate the multipath scenario for receiver diversity tests (Figure 3a). You need multiple signal generators and a channel emulator for transmit diversity tests (Figure 3b). To accurately emulate the multipath scenarios, you must synchronize both signal generators’ baseband and align the phase of both carriers.

![Receiver diversity test](image)

(a) Receiver diversity test

![Receiver test for transmit diversity](image)

(b) Receiver test for transmit diversity

**Figure 3. Spatial diversity test setups**

**Spatial multiplexing**

Spatial multiplexing is a transmission technique for a MIMO system. The system splits transmit data into multiple encoded data streams. The system transmits all data streams simultaneously over the same radio channel through different antennas. In order to recover the original data at the receiver, MIMO systems use computationally inverse channel property estimation algorithms. Figure 4 represents a 2x2 (two transmitters and two receivers) MIMO diagram where two symbols (b1 and b2) transmit simultaneously for double the data throughput. A simple formula appears below:

\[
\begin{bmatrix}
  r_1 \\
  r_2
\end{bmatrix} =
\begin{bmatrix}
  h_{00} & h_{01} \\
  h_{10} & h_{11}
\end{bmatrix}
\begin{bmatrix}
  s_1 \\
  s_2
\end{bmatrix}
\]

Where \( r \) is the received signal, \( s \) is the source signal, and \( h \) is the wireless channel response.

The receiver can perform channel estimation (the \( h \) matrix above) using training sequence algorithms. You can recover the transmit signals \( (s_1, \ s_2) \) through signal processing using the formula below:

\[
\begin{bmatrix}
  s_1 \\
  s_2
\end{bmatrix} = \frac{1}{h_{00} h_{11} - h_{01} h_{10}}
\begin{bmatrix}
  h_{11} & -h_{01} \\
  -h_{10} & -h_{00}
\end{bmatrix}
\begin{bmatrix}
  r_1 \\
  r_2
\end{bmatrix}
\]
The calculation above uses timing-aligned signals and a common local oscillator (LO) to up-convert and down-convert multi-channel signals. This technique increases test challenges for simulating multi-channel RF signals and the channel matrix, as most commercial signal generators have an individual baseband generator and a LO.

To simulate the MIMO multipath signals for spatial multiplexing performance tests, you need multiple signal generators and channel simulators to emulate the multipath scenarios and inject additive white Gaussian noise (AWGN) to emulate the desired SNR. Figure 5 shows 5G NR base station performance tests with MIMO fading and AWGN.

**Figure 4.** A 2x2 MIMO system diagram

**Figure 5.** 5G NR gNB MIMO 2x4 performance tests with channel emulation
Antenna Array – Beamforming

An antenna array is a set of antenna elements that are used to transmit or receive signals. Coherently-driven antennas with the appropriate phase delay between antenna elements can form signal beams. Phased array antennas use phase shifters in the beamforming network (BFN) to produce a uniform wave front traveling in a specific direction. The uniform wave front allows a group of low directivity antenna elements to behave like a highly directional antenna for either transmit or receive applications. The phase delays between the channels decide the antenna pattern as shown in Figure 6.

\[ \sum \]

Figure 6. A phased array of antennas forms a beam by adjusting the phase between coherent antennas
Figure 7 illustrates the impact of using multiple antenna elements at a specific spacing. As you increase the number of antenna elements by a half wavelength separation, the antenna beamwidth gets narrower (Figures 7a to 7d). By applying a 90-degree phase shift to the signal at each antenna, you can change the direction of the beam as shown in Figure 6e. By changing phase shifts between elements in different amounts, you are able to steer the beam in a range of directions. To simulate such multi-channel signals, you need to precisely control the phase difference between the channels for both transmitter and receiver tests.

Figure 7. Antenna pattern vs. the number of antenna elements
Generate Multiple Phase Coherent Signals

Testing multi-antenna systems such as spatial diversity, spatial multiplexing, and antenna array requires a test system capable of providing multiple signals with stable phase relationships between them. However, a commercial signal generator has an independent synthesizer to upconvert an intermediate frequency (IF) signal to a radio frequency (RF) signal. To simulate the multi-channel test signals, the phase between test signals must be coherent and controllable. We explore different tactics to generate multi-channel signals below and assess the pros and cons of these tactics.

Independent Local Oscillator

The easiest way to achieve a certain amount of phase stability between signal generators is to lock a 10 MHz frequency reference. Figure 8 shows two signal generators with synchronized baseband generators using a triggering signal and a common 10 MHz time base. To learn more about time synchronization between instruments, download the white paper “Understanding and Testing Multi-Channel RF Systems with Signal Generators Part 1.”

Figure 8. Two signal generators with a common reference clock
**Phase Drift**

The signal generators have separate oscillators, each with its phase-locked loops (PLL). This will result in phase drift between the signal generators. Most of the time, PLL can lock the phase drift within the constraints of the loop bandwidth, or the PLL’s loop filter. However, PLL cannot completely track out higher-order responses.

In MIMO test systems, slow phase drift between channels is less of an issue as the receivers can remove linear errors via adaptive equalizers. Test channels that share a common frequency reference may deliver acceptable performance for system-level tests.

**Phase Noise**

Uncorrelated phase noise contributes to phase error between reference-locked signal generators. Inside the loop bandwidth of PLL, the frequency reference has the most impact on phase noise performance. Outside the loop bandwidth, the PLL’s oscillator determines the phase noise.

By using high-quality stable references and instruments with low phase noise, you can improve phase drift and phase error. Applications such as MIMO and spatial diversity can use these “phase-stable” multi-channel signals for testing. However, for precise component characteristics testing, a common LO still is appropriate in order to achieve the best measurement results.
Share a Common Local Oscillator

To minimize the sources of coherency errors, use a common LO for multiple signal generators. Figure 9 represents two Keysight MXG N5182B vector signal generators (VSG) that are set up for a phase-coherent test system. The system takes the LO of the top signal generator, splits it, and uses it as the LO input (see red lines) for both signal generators. With this configuration, the RF paths of the two signal generators are fully coherent. The fully coherent configuration appears on the right side of Figure 9, where you can see the phase difference between the two signal generators is less than one degree.

Figure 9. Setup for two phase-coherent RF channels with a common LO

Phase Shift

Even if you are using a shared LO, you will still encounter some static time and phase skew between instrument channels. Cable lengths and connectors cause static time and phase variations. The delays and phase shifts skew the phase relationship between the channels. You will need to correct these offsets and ensure the measured differences come from the device under test, and not from the test system. Use a wide-bandwidth oscilloscope as shown in Figure 10 to measure static time and the phase skew of multiple VSGs.

Figure 10. Measure channels, time, and phase skew with an oscilloscope
Direct Digital Synthesis

Direct digital synthesis (DDS) produces an analog waveform by generating a time-varying signal in digital form and then performing a digital-to-analog conversion. DDS architecture provides an optimal path to low phase noise and fast frequency switching speed, along with extremely fine frequency tuning resolution.

DDS maintains a fixed phase relationship between its output for each frequency. The synchronization requires initial clock alignment using a common reference clock as shown in Figure 11. Synchronous reset, illustrated by the green line, to the phase accumulator achieves the phase alignment. You can apply this reset on every frequency update. The synchronous reset of the phase produces a fixed and repeatable phase relationship for each channel.

Next-generation dual-channel signal generators such as Keysight VXG vector signal generators have two DDS units on a synthesizer board. The Keysight M9484C VXG provides up to four coherent channels in one box with time alignment < 10 ps without touching any hardware, as shown in Figure 12. You can cascade multiple VXGs with Keysight's advanced synchronization technology for high channel count applications. Table 1 below summarizes the tactics for generating phase-coherent signals.

![Diagram](image-url)

**Figure 11.** Shared a high-frequency reference clock for two DDSs
Figure 12. M9484C VXG enables quad-channel coherent operation

Table 1. Various implementations for testing multi-antenna RF systems

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1. Keysight VXG vector signal generators use enhanced high-performance reference at 19.2 GHz as DDS’s reference clock.
Conclusion

As multi-antenna technology matures and the demand for diversity, multiplexing, and antenna gains grows, test systems require tightly aligned channels for accurate tests. When performing a characterization test, you need to accurately recreate the operational environment. In order to accomplish this, you must create signals in such a way that they will coherently combine to simulate their real-world behavior.

For various multi-antenna test applications and requirements, there are different tactics for generating phase-coherent or phase-stable signals. Always strive to minimize errors that various tactics may cause. In addition, ensure test instruments are phase-coherent and phase-controllable for your test applications, such as beamforming, phased array antennas.

References

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

White Paper: Understanding and Testing Multi-Channel RF Systems with Signal Generators Part 1


White Paper: Calibration Techniques for Improved MIMO and Beamsteering Characterization