Understanding and Testing Multi-Channel RF Systems with Signal Generators

Part 1: Timing Synchronization

Most wireless systems, whether in commercial applications, or aerospace and defense, employ multi-antenna techniques. These techniques include antenna diversity, MIMO (multi-input, multi-output) spatial multiplexing, beamforming, or phased-array radar. Engineers use multi-antenna techniques to achieve diversity, multiplexing, or antenna gains. Wireless systems can increase a receiver’s data throughput and signal-to-noise ratio (SNR) through these gains.

However, as the number of antennas grows, test complexity also increases. As a result, it is necessary to generate multiple RF channels for receiver testing and to analyze multiple RF channels for transmitter testing. Generating and analyzing multiple synchronized RF signals are potentially challenging. This white paper discusses test signal requirements for the evaluation of multi-channel RF systems and how to configure instruments for these test requirements.
Multi-Antenna Techniques

As the higher throughput applications grow sharply, there is a need for wider bandwidth in wireless systems. Given limited spectrum allocation, engineers must look for a way to improve spectral efficiency. Most wireless communication systems use multi-antenna techniques to increase the receiver’s robustness, data throughput, and signal-to-noise ratio (SNR). Let’s take a look at some important and commonly used multi-antenna techniques.

Spatial Diversity Systems

In wireless communication systems, multipath results in radio signals reaching the receiver’s antenna with two or more paths. When multipath signals arrive at a receiver, they will combine either constructively or destructively depending on their relative phase. Spatial diversity, also known as antenna diversity, offers a solution to the signal multi-path problem. It uses two or more antennas to improve the quality and reliability of a wireless link with channel switching, signal weighting, or time delay.

Figure 1(a) shows a simple switching which involves a combination of received signals either at RF, Intermediate frequency (IF), or digital baseband. Figure 1(b) shows a diagram of maximal ratio combining where the received signals’ magnitudes are weighted before combining them. The weighting algorithm sets gain to maximize a metric such as receiver power or signal-to-noise ratio. Figure 1(c) is a type of beamforming system at the receiver side where a digital automatic delay equalizer is used to align the signals with delays and a combination. This paper will address the beamforming technique later.

To simulate the multipath signals for receiver testing, you need a signal generator and a multi-port RF fader to simulate the multi-path scenario. Another approach is to have multiple baseband generators (such as Keysight PXB N5106A) to simulate the scenario and use several signal generators to upconvert baseband multipath signals to RF signals.

Figure 1. Spatial Diversity Techniques.
Spatial Multiplexing Systems

Spatial multiplexing systems, also called MIMO systems, use multiple transmit and receive antennas to exploit multipath propagation. A MIMO system encodes data onto the transmit signals and the receiver is then able to process and break multipath channels to recover the original data. In order to recover original data, MIMO systems use computationally inverse channel property estimation algorithms. Figure 2 represents a 2x2 MIMO diagram where two bits are transmitted simultaneously for double the data throughput. A simple formula appears below.

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

If the wireless channel (the h matrix) can be estimated, the receiver can recover the transmit signals (s1 and s2) through signal processing:

\[
\begin{bmatrix}
  s_1 \\
  s_2
\end{bmatrix} = \frac{1}{h_{00}h_{11} - h_{01}h_{10}} \begin{bmatrix}
  h_{11} & -h_{01} \\
  -h_{10} & h_{00}
\end{bmatrix}
\begin{bmatrix}
  r_1 \\
  r_2
\end{bmatrix}
\]

Figure 2. A 2x2 (two transmitters and two receivers) MIMO system.

The calculation above is based on timing-aligned signals and the use of a common LO to up-convert or down-convert multi-channel signals. This technique increases test challenges for simulating multi-channel RF signals as most commercial signal generators possess an individual baseband generator and LO.

Fun fact

If channels are correlated, and no multipath or antennas are too close), the \(1/(h_{00}h_{11} - h_{01}h_{10})\) approaches to infinity making it hard to recover the original signals. Spatial multiplexing uses multipath propagation instead of removing it.
Beamforming Systems

Another important capability in using multiple antennas involves forming a narrow antenna beam. Coherently-driven antennas with the appropriate phase delay between antenna elements can form signal beams. Phased array antennas use delays created 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 antennas 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 3. The delays improve receivers’ SNR and reduce overall interference in the area.

![Beamforming Network](image)

Figure 3. A phased array of antennas forms a beam by adjusting the phase between coherent antennas.

The three multi-antenna techniques require precise baseband timing alignment and a common LO that distributes to multiple channels, so they can perform efficiently and increase the diversity, multiplexing, or antenna gain. However, this scenario is at odds with simulating multi-channel signals and commercial signal generators. Most signal generators have an independent baseband generator and synthesizer which is ideal for generating single-channel RF systems. All the baseband generators must be synchronized, and all the synthesizers must be phase-coherent between all signal generators.

Next, you will learn how to synchronize multiple baseband generators to ensure all the channels can be transmitted at the same time.
Timing Synchronization Test System

When considering multiple signal generators using standalone instruments, it is important to understand the timing alignment of the baseband signals. RF vector signal generators (VSG) use dual arbitrary waveform generators (AWG) to generate complex baseband I/Q signals. The dual AWG controls the playback sequence of waveform segments that have been written into the memory in the internal baseband generator. Just like an MP3 player converts an audio file to an analog signal, the generator enables you to play, rename, delete, store, and load waveform files in addition to building waveform sequences. It also offers markers, triggering, clipping, and scaling capabilities.

Understand the “Master/Slave” Operation

Many wireless applications require more than one stimulus signal and those signals must be synchronized. Synchronizing multiple instruments requires a “master-slave” operation in which one of the instruments is the “master” and generates a trigger signal to enable other “slave” instruments. The slave instruments begin generating or acquiring signals after a trigger event is detected.

Waveform Markers

Vector signal generators provide waveform markers to mark specific points on a waveform segment. You can turn on markers at specific sample points manually or download a marker file with the waveform file to the baseband generator. When the signal generator encounters an enabled marker, an auxiliary signal is routed to a real panel event output that corresponds to the marker number (from 1 to 4), as shown in Figure 4.

![Waveform Markers Diagram]

Figure 4. Represents the I and Q components of the waveform and the marker points.

The auxiliary output signal is capable of synchronizing an additional signal generator or can serve as a trigger signal to enable a measurement. Typically, a fine channel skew control allows for precise time alignment between all signal generators or other instruments, including the effects of cabling and other accessories.
Trigger Delay

Cabling and external devices can affect how long it takes a trigger signal to reach each instrument. This effect is called trigger delay and needs to be accounted for, so your instruments can transmit and receive at the same time. Using a channel skew control on your master instrument allows for precise time synchronization between all channels. Figure 5 shows two AWGs and their synchronization setup. To remove the effects of master-to-slave delay, it is necessary to delay the signal generated by the master.

![Figure 5. A setup of two AWGs (master and slave) to generate time-aligned signals.](image)

Sampling Clock

Even if differences of sampling clock are tiny, they will accumulate over time.

Figure 5 shows an additional signal called the frequency reference. When you synchronize multiple baseband generators, make sure you have this common frequency reference. Sharing the same frequency reference across multiple generators results in the same sampling rate for all the instruments. This is important because once the slave generators receive trigger signal, they will start playing waveforms from the rising edge of next sampling clock. With the same sampling clock, all instruments may not start generating signals at the same time, but all the signals start at fixed time offsets. Additional timing alignment is necessary to remove the time offsets.

Timing Alignment

Beyond sampling clock synchronization, it is important to ensure waveforms from different baseband generators are properly time-aligned. This is because the initial phase for each sampling clock is random, but constant during any given generation session. The alignment requires an additional measurement on the signals and adjustment for the delay on each generator.
For example, Keysight MXG N5182B vector signal generators can be set up as shown in Figure 6 for synchronizing multiple baseband generators (BBG). The multiple BBG synchronization feature offers a system for synchronizing the waveform generation capability of up to 16 signal generators within a characteristic value of ± 8 ns between the master and the last slave. The minor amount of delay (± 8 ns) can be reduced further to picosecond resolution by using the I/Q Delay adjustment. The delay value includes compensation for cables that have less than 1 ns of propagation delay between the EVENT 1 and PAT TRIG connector. The use of cables with greater propagation delay may not allow the signal generators to properly synchronize. In addition, you will need to connect a frequency reference using daisy-chain topology.

![Figure 6. Multiple baseband synchronization setups.](image)

**Modular Instruments Can Make Implementation Easier**

The growth of higher data throughput drives the need for high-order MIMO configuration and test channels. While the number of synchronized channels increases, the cabling between the instruments becomes much more complicated and achieving proper time-synchronization can take a significant amount of time. Modular instruments are based on standard instrumentation buses such as PXI, AXIe, and VXI. These instruments can share clocks and trigger signals through a backplane bus. This makes it easier to implement synchronization and the trigger events more repeatable because the test environment is controlled with minimal cabling.

For example, a PXI trigger bus consists of eight trigger lines spanning the backplane connectors. The trigger lines (0-7) are divided into three trigger bus segments, slot numbers 1-6, 7-12 and 13-18 as shown in Figure 7. The trigger routing direction (blue arrow) between the segment of each trigger line can also be configured.
Figure 7. PXI trigger setup using Keysight I/O library software.

Figure 8 shows two PXI chassis deployed as a WLAN 802.11ax test solution that fully supports 8x8 MIMO. The PXI backplane bus routes trigger signals to target modules (Keysight M9421A VXT PXIe Vector Transceiver) for eight-channel signal generation and analysis. This system takes advantage of the PXI standards that lower a chassis’ slot-to-slot trigger time and clock skew to hundreds of picoseconds. This results in accurate timing synchronization which eliminates the need to adjust MIMO transmitter and receiver testing.

Figure 8. WLAN 802.11ax test solution that fully supports 8x8 MIMO configuration in two PXI chassis.
Independent Local Oscillator (LO) – Phase-Stable Test System

Multi-antenna RF systems employ a common LO that distributes to multiple channels. To simulate or analyze the multi-antenna RF system, you need to have the same structure. However, a commercial signal generator has an independent synthesizer to upconvert IF signal to RF signal. Using commercial signal generators to simulate multi-channel RF systems may result in errors even with a common reference clock, such as phase draft and uncorrelated phase noise. Let us take a two-channel RF system as an example.

Figure 9 shows two signal generators with baseband generators synchronized and a common 10 MHz time base. The signal generators have separate oscillators, each with their own phase-locked loops (PLL) which results in phase drift as shown in the right of Figure 9. For the most part, the drift will track out within the constraints of the loop bandwidth and tracking ability of the generator’s synthesizer. Typically, the frequencies are well within the loop bandwidth (the PLL’s loop filter) so that tracking can perform well, but the high order responses cannot be tracked out completely.

In addition, each synthesizer has its own phase noise performance. The uncorrelated phase noise contributes to the phase error between the reference-locked signal generators. Phase noise degrades the signal’s modulation quality (such as error vector magnitude, EVM) and results in poor receiver sensitivity.

Figure 9. System block diagram shows the measured phase drift of two 10 MHz-locked signal generators.

Phase drift and error can be improved by using high-quality stable references and instruments with low phase noise. This “phase-stable” multi-channel signal can be used for some applications such as MIMO and spatial diversity.

For example, there is less than 0.1% difference in EVM reading (802.11n signals) for independent and common LO using Keysight MXG N5182B VSGs. The phase noise from the signal generators is not a significant factor in an EVM measurement at this level. However, for precise component characteristics testing, a common local oscillator may still be appropriate in order to reach the best performance.
**Trigger and Time Synchronization Leads to Better Testing**

To test multi-channel devices effectively, you must perform highly synchronized, multi-channel signal generation and analysis. Accurate triggering among the instruments helps ensure that all measurements start precisely at the right time. To simplify your test synchronization for high channel count, consider a modular test system that enables streamlined integration of multiple instruments into a multi-channel test system.

In Part 2 of this whitepaper, you will learn about phase relation between signals and how to achieve multiple vector signal generators phase-coherent and phase-controllable, an important step for some applications such as beamforming systems.

For more tips on making better measurements, visit the [RF Test blog](www.keysight.com/find/sg). For more information about Keysight signal generators, visit [www.keysight.com/find/sg](www.keysight.com/find/sg).

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