Configuring Phase-Coherent RF Measurement Systems: From MIMO to Beamforming

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Overview

Ever since the first radio waves were transmitted, engineers have continually sought new ways to use electromagnetic microwave signals. While RF signals have been incorporated in a wide variety of applications, two specific applications that use one common technology are wireless communications and Radio Detection and Ranging (RADAR). In essence, both applications are unique in that they use the spatial dimension of electromagnetic waves. Today, many wireless communications systems incorporate multiple input, multiple output (MIMO) antenna schemes to take advantage of the multipath signal propagation. In addition, many of today's modern RADAR systems use electromagnetic beam steering as replacement for the traditionally mechanically steered transmit signal. These applications and others are some of the primary drivers behind the demand for multichannel phase-coherent RF measurement systems.

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Introduction

The modular architectures of PXI RF instruments such as the NI PXIe-5663 6.6 GHz RF vector signal analyzer and NI PXIe-5673 6.6 GHz RF vector signal generator lend themselves to the phase-coherent RF measurements required for MIMO and beamforming applications. Figure 1 illustrates a typical measurement system with four synchronized RF analyzers and two synchronized RF signal generators in an NI PXI-1075 18-slot chassis.

Figure 1. Typical PXI Phase-Coherent RF Measurement System

This white paper examines the technical requirements for configuring a phase-coherent RF generation or acquisition system. In addition, it walks through a step-by-step process of calibrating the phase delay between multiple RF analyzers to achieve the best possible performance.

1. Phase-Coherent RF Signal Generation

The configuration of any phase-coherent RF system requires synchronization of every clock signal present on the devices. With the NI PXIe-5673 6.6 RF vector signal generator, direct upconversion is used to translate baseband waveforms into RF signals. Figure 2 illustrates the basic architecture of a two-channel RF vector signal generator. Note that both baseband sample clocks and the local oscillators (LOs) must be shared between both channels.

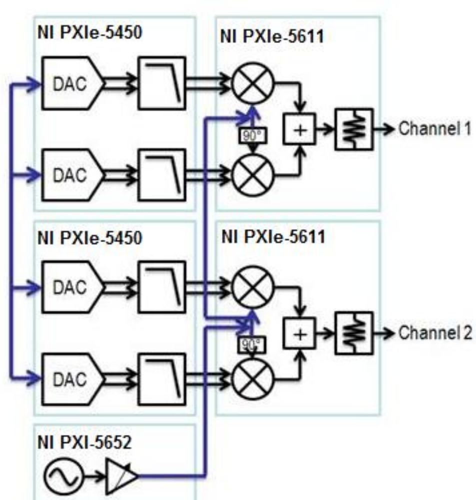

Figure 2. Synchronization of Two RF Generation Channels

In Figure 2, observe that the NI PXIe-5673 consists of three modules: the NI PXI-5652 continuous wave synthesizer, the NI PXIe-5450 arbitrary waveform generator, and the NI PXIe-5611 RF modulator. You can use these modules together as a single-channel RF vector signal generator or combine them with additional arbitrary waveform generators and RF upconverters for multichannel signal generation applications. In Figure 2, a standard NI PXIe-5673 (consisting of three modules) is combined with an NI PXIe-5673 MIMO extension kit. The extension kit includes an additional arbitrary waveform generator and modulator that enable the second channel of signal generation.

2. Phase-Coherent RF Signal Acquisition

In addition to the NI PXIe-5673 RF vector signal generator, you can configure the NI PXIe-5663 RF vector signal analyzer for multichannel applications. When configuring multiple NI PXIe-5663 modules for phase-coherent RF signal acquisition, you must ensure that both the LO and baseband/intermediate frequency (IF) signals are synchronized. The NI PXIe-5663 uses signal stage downconversion to IF and digital downconversion to baseband. This architecture is one of the simplest to configure for phase-coherent applications because, unlike a traditional three-stage superheterodyne vector signal analyzer, only a single LO must be synchronized between each channel. To synchronize multiple NI PXI-5663 analyzers, you must distribute a shared IF sample clock and LO between each analyzer to ensure that each channel is configured in a phase-coherent manner. An example two-channel system is shown in Figure 3.

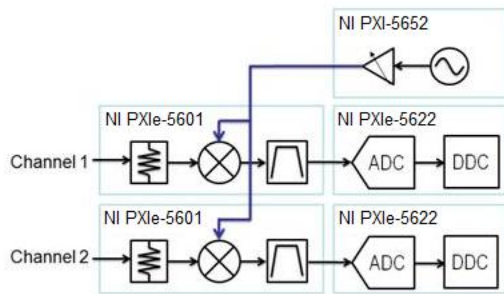

Figure 3. Synchronization of a Two-Channel Vector Signal Analyzer System

Figure 3 shows that the NI PXIe-5663 RF vector signal analyzer consists of the NI PXI-5652 continuous wave synthesizer, the NI PXIe-5601 RF downconverter, and the NI PXIe-5622 IF digitizer. When you combine this vector signal analyzer with an additional NI PXIe-5663 MIMO extension kit, you add a downconverter and digitizer to complete the two-channel RF acquisition system.

To understand the method of synchronization between multiple RF vector signal analyzers, consider a more detailed block diagram of the NI PXIe-5663 RF signal analyzer. In Figure 4, observe that even though a single LO is used to downconvert from RF to IF, each analyzer must share three clocks.

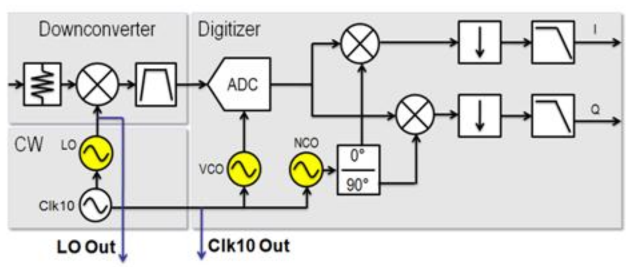

Figure 4. Detailed Block Diagram of an NI PXIe-5663 RF Vector Signal Analyzer

As Figure 4 illustrates, the LO, analog-to-digital converter (ADC) sample clock, and digital downconverter (DDC) numerically controlled oscillator (NCO) must be shared between each RF channel. Figure 4 also shows that it is sufficient to merely share a common 10 MHz clock between each digitizer. While sharing only a 10 MHz reference between each digitizer introduces uncorrelated channel-to-channel phase jitter, the level of phase noise introduced at IF is masked by the phase noise of the LO at RF.

3. Characteristics of Digital Downconversion

Before you can determine the precise methods for calibrating phase-coherent RF acquisition systems, you need to understand how you can observe signal characteristics at RF at baseband. For example, consider the scenario where a vector signal generator and vector signal analyzer are configured in a loopback mode at the exact same center frequency. As shown in Figure 5, a downconverted RF signal that is precisely at the analyzer's center frequency appears as a DC signal at baseband. In addition, because the baseband signal is a complex waveform, you can also analyze the phase (Θ) of the signal as a function of time. Figure 5 shows that the phase versus time waveform appears as a constant phase offset so long as the RF vector signal generator and analyzer are in-phase with one another.

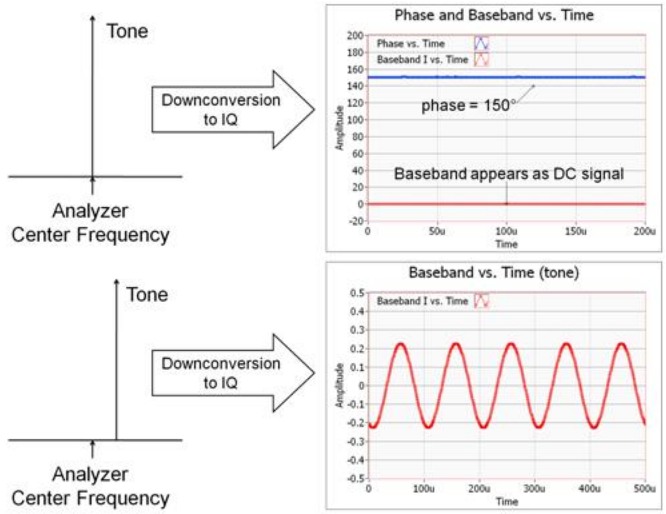

Figure 5. Understanding the Effect of Frequency Offset on Baseband Signals

By contrast, a RF tone that is slightly offset from the center frequency of the analyzer yields a different result. When downconverted to baseband, an offset tone produces baseband I (and also Q) signals that are sinusoidal. In addition, the frequency of the baseband sinusoid is equal to the frequency difference between the input tone and the center frequency of the analyzer. As a result, a phase versus time graph appears as a linear relationship, which is shown in Figure 6.

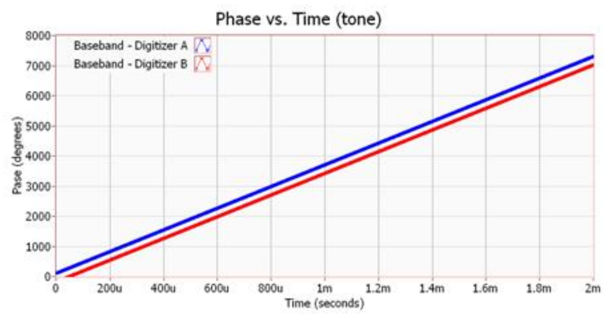

Figure 6. Phase versus Time for 10 MHz Tones in an Uncalibrated System

Figure 6 illustrates that phase increases by approximately 360 degrees every microsecond, indicating that the generated tone is exactly 1 MHz offset from the center frequency of the analyzer. Also notice that a small but constant phase difference is maintained between two simultaneously sampling digitizers. This discrete phase difference is caused by differences in cable length between the LO sourcing each downconverter. In the following section, learn how you can easily compensate for this phase difference by adjusting the start phase of the downconverter for one of the RF channels.

One of the most accurate methods to measure the phase offset between two analyzers involves generating a single tone at the center frequency of both analyzers, as shown in Figure 7.

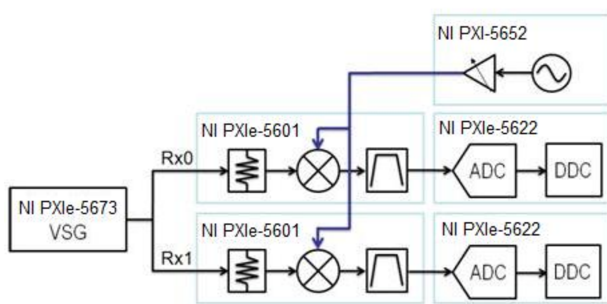

Figure 7. Test Setup for Calibrating the Phase of a Two-Channel RF Analyzer

Using a splitter and matched cable lengths, you can measure the phase versus time for each analyzer. Assuming that the signal generators and analyzers are centered at the same RF frequency, you can observe a constant phase versus time plot for each analyzer. This is illustrated in Figure 8.

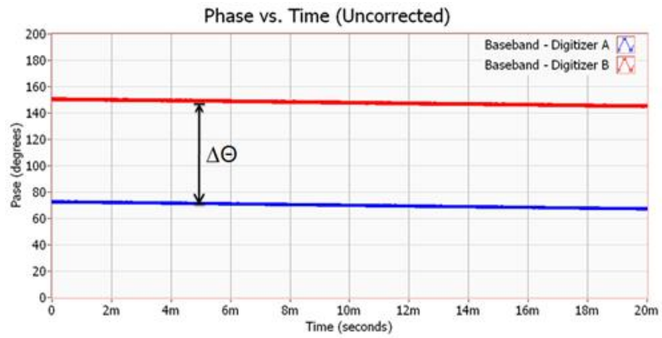

Figure 8. Each simultaneously sampled ADC has a constant phase offset.

Figure 8 shows that two analyzers sharing the same LO and IF sample clock maintain a constant phase offset over time. You can measure and compensate for the phase difference between each analyzer ($\Delta\Theta$ = 71.2 degrees in Figure 8) by adjusting the start phase of the NCO in the DDC. An NCO is essentially a digital sinusoid at the IF center frequency that is used to produce the resulting baseband I and Q signals. In Figure 8, you see that the daisy-chained RF analyzers produce a carrier phase difference of 71.2 degrees at a particular center frequency. The exact phase offset is determined by a combination of cable length to the second LO and by the center frequency that is used. By applying a phase delay of 71.2 degrees to the NCO of the master DDC, you can successfully align the phase of the baseband signals of both channels, as shown in Figure 9.

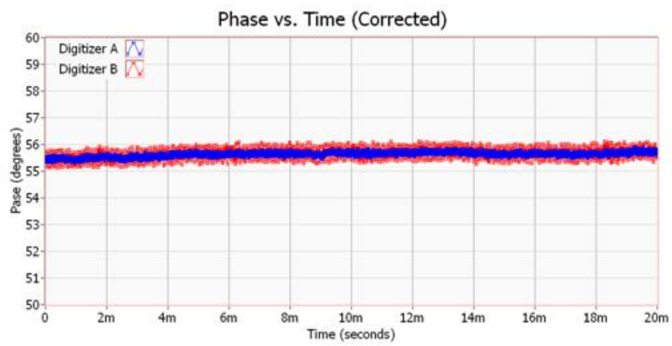

Figure 9. Phase versus Time for Calibrated Phase-Coherent RF Acquisition Channels

Once you have calibrated the NCO of each analyzer, your RF analyzer system is capable of two or more channels of phase-coherent RF acquisition. You can synchronize up to four NI PXIe-5663 RF vector signal analyzers for multichannel applications.

Conclusion

While emerging technologies such as MIMO and beamforming produce new challenges for test engineers, modular RF instrumentation provides a cost-effective and accurate measurement solution to this challenge. In fact, you can configure PXI instruments such as the NI PXIe-5663 and NI PXIe-5673 for up to 4x4 MIMO and phase-coherent RF measurement applications. For more information, see the following:

- INL: Do You Know Where Your Radios Are? (http://zone.ni.com/devzone/cda/pub/p/id/1010)
- RF Resources (http://www.ni.com/rf/)
- Preconfigured MIMO Test System (http://sine.ni.com/nips/cds/view/p/lang/en/nid/207234)
- RF Synchronization Example Code (http://ftp.ni.com/pub/devzone/tut/rf_synchronization_suite.zip)
- Overview of RF Phase-Coherent Applications (http://ni.com/mimo/)