Understanding the Effect of Uncorrelated Phase Noise on Multi-channel RF Vector Signal Generators and Analysers

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Introduction

With growth of applications such as beamforming, MIMO (multiple input multiple output) communications systems and even phase-array RADAR, the need for phase-coherent signal generation and acquisition systems is increasing. However, engineers still face challenges such as system size, cost and complexity. While you can use modular PXI instrumentation to solve many of the size and cost issues associated with phase coherency, calibrating MIMO systems is still a unique challenge. In figure 1, observe PXI system that has been configured for a 2x4 MIMO test application. As figure 1 illustrates, and as the block diagram in figure 2 illustrates, phase coherent measurement systems require each instrument to share a variety of timing and synchronisation signals.

Figure 1. Diagram of 2x4 Phase-Coherent Test System

In figure 1, a 2x4 MIMO test system requires 2 channels of phase-coherent RF generation and 4 channels of phase-coherent RF acquisition. In the case of MIMO, the challenge producing phase-coherent RF signals exists not only with transmitters and receivers, but also with the instrumentation used to test them. Generally, you must perform sophisticated calibration techniques to remove any phase offsets between each RF channel. In this tutorial, we explain the technical requirements for configuration of phase-coherent RF generation and acquisition systems. In addition, we walk through a step-by-step process of calibrating the phase delay between multiple RF analyzers to achieve the best possible performance. The techniques described are applicable both to generic test instrumentation and to RF transceivers. As a result, you will learn how small adjustments to a digital downconverter (DDC) can be used to account for phase delays between multiple RF channels.

Configuring Systems for Phase-Coherent RF Generation

The configuration of any phase-coherent RF generation system requires synchronisation of every stage – from a shared sample clock at baseband or intermediate frequency (IF), to a shared local oscillator (LO) at RF. While devices using either superheterodyne or a direct RF upconversion architecture can be synchronised, the simplest architecture when configuring multiple phase-coherent RF transmitters is direct upconversion. Using direct RF upconversion, engineers can create systems which maximise the bandwidth of the signal being generated.

A typical implementation of synchronised RF vector signal generators requires each channel to have shared baseband I and Q sample clocks as well as a shared LO at the desired centre frequency. In this configuration, baseband I and Q signals are mixed to RF in two direct quadrature modulators – which share a common LO. Note that it is also possible to use independent LOs with a shared 10 MHz. While this configuration will prevent the phase of each RF signal from independently drifting over time, this configuration yields a scenario where phase noise between each channel is uncorrlelated. Thus, the most accurate method is to use a common LO that is distributed to multiple RF generators. Many RF vector signal generators, including the new NI PXIe-5673 shown in figure 1, can accept external LO inputs as well as share baseband sample clocks with other instruments. Thus, the scenario shown in figure 2 applies not only to PXI instrumentation, but to traditional instrumentation as well.

Configuring Systems for Phase-Coherent RF Acquisition

When configuring multiple analysers for phase-coherent RF acquisition, you must take similar care to ensure that both the LO and baseband/IF signals are synchronised. Again, while either direct RF downconversion or heterodyne downconversion architectures are feasible, most modern VSAs (vector signal analysers) employ heterodyne RF downconversion. In our discussion, we explain synchronisation techniques required for multiple single-stage RF vector signal analysers. This architecture is one of the simplest to configure, because unlike a three-stage superheterodyne vector signal analyser, only a single LO must be shared between each channel.

Similar to phase-coherent RF generation systems, a shared IF sample clock and LO must be distributed between each analyser to ensure that each channel is configured in a phase-coherent manner. Figure 2 shows an example configuration for a 2-channel acquisition system.

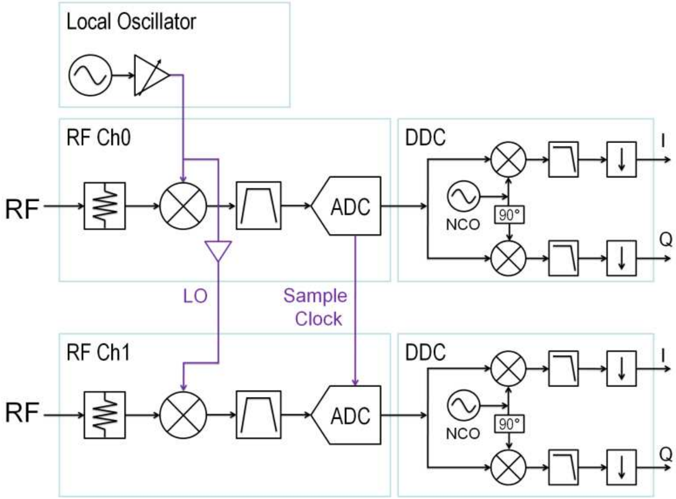


Figure 2. Synchronisation of 2-channel VSA system

From figure 2, note that a digital downconverter (DDC) translates IF signals into baseband I and Q components. Digital downconversion is not only a necessary step to provide useable baseband waveforms, but it also provides a tunable NCO (numerically controlled oscillator). As you will observe in figure 3, a tunable NCO is a crucial DDC characteristic because it enables you to precisely control adjust the phase of the baseband waveform.

Characteristics of Digital Downconversion

Before we investigate the precise methods you can use to calibrate phase-coherent RF acquisition systems, you must first understand how signal characteristics at radio frequencies can be observed at baseband. More precisely, by understanding differences between a vector signal generator (VSG) and vector signal analyser (VSA) at baseband, you can more easily understand basic methods for calibrating phase offsets between multiple analysers.

To illustrate this principle, consider a scenario where a VSG and VSA are configured in a loopback mode at the exact same centre frequency. In this case, a downconverted RF signal that is exactly at the analyser's centre frequency appears as a DC signal at baseband. In addition, because the baseband signal is a complex waveform, you can also analyse the phase (Θ) component of the waveform as a function of time. In fact, the phase vs. time waveform will appear as a constant phase offset whenever the RF vector signal generator and analyser are operating at the same centre frequency.

By contrast, generating an RF tone that is slightly offset from the centre frequency of the analyser yields a different result. When downconverted to baseband, a tone that is offset from the carrier produces baseband I and 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 centre frequency of the analyser. As a result, a phase versus time graph appears as linear relationship for an offset tone.

While any signal shared between two synchronised analysers will yield a discrete phase difference over time, it is easiest to calibrate the system with minimal frequency offset. Thus when calibrating a phase coherent analysis system, the best stimulus is a single tone that is centred precisely at the centre frequency of both analysers. Using a splitter and matched cable lengths connected to each analyser, you can compare the phase versus time for each channel.

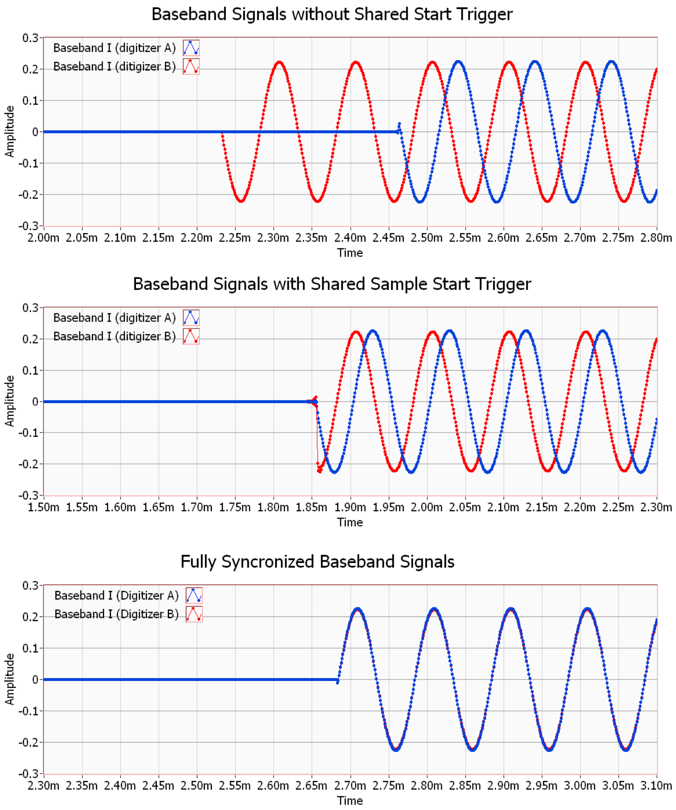
Calibrating Phase-Coherent RF Acquisition Systems

With both RF analysers channels sharing the same start trigger, ADC (analog-to-digital converter) sample clock and LO, each resulting baseband waveform will have a phase offset that is directly proportional to the LO cable length. In other words, the second RF channel will have a slight phase delay due to the longer cable length of a cascaded LO. To account for this phase offset, you can measure the phase difference between each channel by subtracting the phase component of the baseband waveform on a point-by-point basis. Taking the mean of this value, you can determine the mean phase offset induced by the longer, cascaded LO cable. The example shown in figure 3 has a precise phase offset (ΔΘ) of 71.2°.

As figure 2 illustrated, a heterodyne architecture utilises digital downconversion to translate IF signals to baseband. Many DDCs, such as the one on the NI PXIe-5622 IF digitiser, implement downconversion in real-time on an FPGA. In this case, you can adjust the phase of the resulting RF signal by changing the start phase of the DDC's numerically controlled oscillator (NCO). An NCO is essentially a digital sinusoid at the IF centre frequency that is used to produce the resulting baseband I and Q signals. By delaying the start phase of the first analyser's DDC by 71.2°, the measured phase difference, you can adjust the phase of the resulting baseband waveform by the appropriate phase offset.

Effects of Synchronisation on Phase Coherency

To illustrate the importance and methodology of synchronisation between phase-coherent RF acquisition channels, you can observe several configurations with varying levels of synchronisation. For example, consider the case of two VSAs where the LO and sample clock are shared but the start trigger used by each ADC is independent. In this scenario, a shared LO maintains a constant phase difference between each channel. However, the delay between each ADC results in each channel having a different power envelope. In figure 3, observe a pulsed 10 kHz tone that is slightly offset from the centre frequency of the analyser.


Baseband Signals without Shared Start Trigger

Baseband Signals with Shared Sample Start Trigger

Fully Syncronized Baseband Signals

Figure 3. Baseband I Signals with Varying Levels of Synchronisation

As the figure illustrates, the trigger delay between each ADC skews the power envelope of the resulting baseband waveform. In this scenario, we gain little from measuring the phase offset between each analyser because without a shared start trigger, the phase offset will vary from one acquisition to the next.

Next, observe the scenario where the LO, ADC sample clock and start trigger are shared between two RF analysers. As we see in figure 3, sharing a start trigger between each IF digitiser correctly aligns the power envelope of the resulting baseband signals. However, figure 3 also illustrates that a constant phase offset between the two channels still remains. In order to configure two (or more) channels of phase-coherent RF analysis, this phase offset must be removed. Utilising the approach described above, you can adjust the start phase of the first channel's DDC by 71.2°. Only then will each channel be phase-coherent.

Observing figure 3, you can see that adjusting the NCO start phase can be used to correct any discrete phase offset between each channel. In fact, figure 3 illustrates two baseband waveforms once phase-coherent calibration is complete. Visually, you can observe that these waveforms are synchronised to less than 1°. Mathematically, however, you can verify that the standard deviation of the phase difference between each channel is actually less than 0.1°. Moreover, as the phase offsets are induced purely by differences in cable length and are not dynamic, phase coherency between each RF channel can be preserved over an extended period of time

Conclusion

As emerging communications systems continue to experiment with MIMO and beamforming technology, the technical expertise required to calibrate phase-coherent generation and acquisition systems becomes increasingly important. As you see in the discussion above, you can apply basic knowledge of DDC signal processing and a few simple measurements to achieve highly accurate phase-coherent acquisition systems. While the system illustrated in this illustration was designed for 1x2 or 2x2 MIMO scenario, you can use the same calibration procedure to configure 4x4 and 8x8 MIMO systems. Also, note that while the instrumentation described in the system above used modular components of the NI PXIe-5663 RF vector signal analyser from National Instruments, you can use the same calibration techniques for traditional RF vector signal analysers as well as custom phase-coherent RF acquisition systems.