The Hidden Challenge of MIMO Test

Today, engineers can combine modern RF signal analyzers with a basic understanding of digital downconversion to produce a tightly synchronized MIMO measurement solution.

By David A. Hall, National Instruments

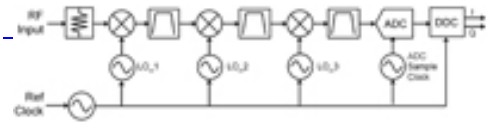

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Figure 1. Architecture of a simplified three-stage superheterodyne vector signal analyzer

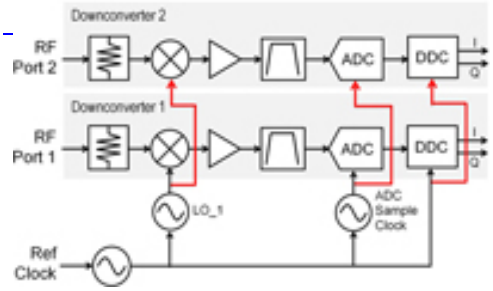
As an increasing number of wireless communications standards use MIMO (multiple input multiple output) antenna systems, new wireless transceivers are required to support a wider range of MIMO configurations than ever before. As a result, engineers designing next generation radios not only have to consider single-carrier measurements such as power and spectrum mask, but must also consider multichannel RF measurements such as phase offset and crosstalk. Unfortunately, multichannel, phase-coherent RF measurement systems remain a significant challenge.

While the superheterodyne vector signal analyzer (VSA) architecture yields many benefits such as intermediate frequency (IF) image rejection, this architecture is not a natural fit for MIMO test. In this article, we will explain how one can perform phase-coherent RF measurements by synchronizing multiple downconverter signal chains. Note that while each of the measurements described in this article were performed with modular, software-defined PXI instrumentation using NI LabVIEW, the same principles apply to all RF vector signal analyzers.

Synchronizing RF Instrumentation

While baseband synchronization has long been addressed in lower frequency direct sampling instrumentation such as high-speed digitizers and data acquisition modules, the challenges of synchronization at RF frequencies is becoming increasingly relevant. Not only do RF signals require tight sample clock synchronization, but they also require synchronization of all synthesized local oscillators (LOs). For example, consider the case of a phase-coherent RF signal acquisition with a traditional RF signal analyzer. Historically, traditional RF vector signal analyzers downconverted signals from RF to baseband by means of a three-stage superheterodyne downconversion process. This method of downconversion uses three local oscillators - with the last stage downconverting to a low intermediate frequency (IF). Once downconverted to IF, the signal is sampled by an ADC and then digitally downconverted (using direct downconversion) to baseband. A block diagram of a superheterodyne vector signal analyzer is shown in Figure 1.

As we observe in Figure 1, the use of multiple clock signals introduces a significant synchronization challenge. If one were to synchronize two analyzers that use the three-stage architecture depicted in Figure 1, each clock or LO signal must be shared between each downconverter signal chain. More specifically, the analyzers would have to share signals such as "Ref Clock," LO_1 (first local oscillator), LO_2 (second local oscillator), LO_3 (third local oscillator), and the ADC sample clock.



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Today, most traditional RF vector signal analyzers allow you to share signals such as the reference clock (usually 10 MHz) and occasionally a start trigger. While sharing these clock signals is sufficient to guarantee simultaneous signal acquisition, it does not guarantee true phase coherency in an RF sense. For example, consider the case where only a 10 MHz reference clock is shared between two VSAs. In this scenario, the two analyzers will independently derive their local oscillators from a common 10 MHz clock. Over time, it would be possible for each analyzer to maintain a relatively constant phase offset. However, because each LO is derived independently from a 10 MHz reference, the phase-locked loop (PLL) noise that is introduced when synthesizing each LO will be independent from one channel to the next. As a result, a multichannel RF acquisition system with only a shared 10 MHz reference will be characterized by substantial channel-to-channel phase skew.

Phase Coherency and Single Stage Downconversion

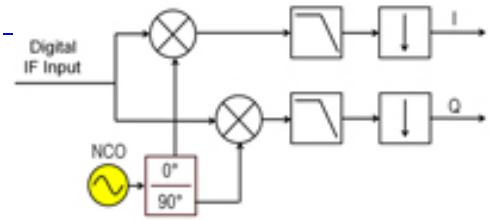
Achieving true phase coherency between multiple channels of RF signal acquisition requires all clock signals to be shared directly between each downconverter and ADC. Moreover, the synchronization becomes an easier challenge with simpler downconversion architecture. Systems using direct downconversion (zero-IF) or single stage downconversion involve fewer local oscillators. In many cases, LO signals can be shared directly between downconverters - yielding the potential for phase-coherent measurements.

For example, consider the case of synchronizing two RF signal analyzers that use single stage downconversion architecture. In the case of the NI PXIe-5663 6.6 GHz RF vector signal analyzer, the LO can be derived from an onboard voltage controlled oscillator (VCO), -or it can be accepted from an external source. In the latter case, a common LO can also be shared between two separate analyzers - as shown in Figure 2.

As we observe in Figure 2, a single VCO supplies a common LO to each of the

mixers of Downconverters 1 and 2. By sharing the LO directly, one can ensure that any phase noise introduced by the LO is correlated between the two channels. However, the LO isn't the only clock that must be shared. We also observe that the sample clock must be shared between each downconverter signal chain. Finally, observe that each DDC (digital downconverter) must also share a common reference clock to maintain phase coherency. This requirement occurs because the numerically controlled oscillator (NCO) present in the DDC introduces a digital carrier, and its start phase influences the measured phase of the resulting baseband signal.

Evaluating Synchronization in Phase-Coherent Measurement Systems



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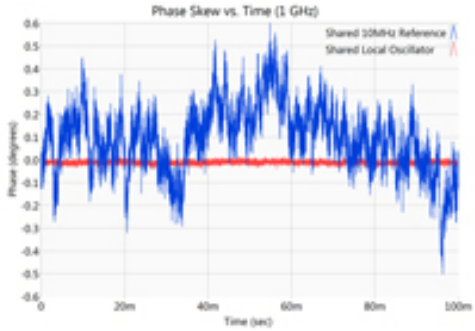
To understand the method of calibrating phase between multiple RF signal analyzers, it is important to investigate a more detailed block diagram of a typical digital downconverter. Figure 3 shows a diagram of a DDC - which translates the digital IF carrier to baseband.

As we observe in Figure 3, the intermediate signal is digitally downconverted to baseband by mixing (mathematical multiplication) it with in-phase and quadrature-phase digital carriers: a process called direct downconversion. Note that the digital carrier is produced by a numerically controlled oscillator (in yellow). Because the NCO is a digital carrier, its start phase and frequency influence the measured phase of the baseband IQ waveform. After the IF is mixed (multiplied) with the digital carrier, the resulting digital baseband I and Q digital signals are decimated (downsampled) to the requested IQ sample rate.

Visualizing Phase-Coherent Measurements in the Time Domain

With a basic understanding of phase-coherent downconversion and DSP techniques such as digital downconversion, we can investigate sophisticated methods of calibrating a phase-coherent measurement system. Using a power splitter, a vector signal generator is connected to our two-channel phase-coherent measurement system. With all RF front ends tuned to the same center frequency, we can calibrate the measurement system simply by analyzing each analyzer's downconverted baseband waveform.



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Fortunately, baseband I and Q samples provide us with direct access to the phase information of an acquired waveform. Viewed in the Cartesian coordinate domain, each I and Q sample pair contains both magnitude and phase information. In LabVIEW, we can calculate the phase information (&Theta) of each sample by computing the arctangent of Q/I. By observing the phase information from an IQ waveform, we are able to accomplish two important tasks. First, using measured phase information, one can make fine adjustments to the start phase of each NCO, thereby compensating for variation in cable length to the two analyzers. Note that this phase alignment or calibration to remove residual skew needs only to be performed once, since any phase skew is a function of cable length. Once this source of error is accounted for, each channel of the two-channel measurement device can be used to measure two RF channels in a phase-coherent manner.

By subtracting the phase of Channel 1 from Channel 2, we can report the phase difference over time between the two channels. In Figure 4, observe the channel-to-channel skew when using two different synchronization approaches. The blue trace shows the phase difference over time when each analyzer shares only a 10 MHz reference clock and does not share the LO. The red trace illustrates the phase difference between each channel when the local oscillator is shared directly between each downconverter signal chain.

Note from Figure 4 that sharing the LO directly enables significantly tighter sycnhronization than when merely sharing a 10 MHz reference. When the LO is directly shared, each downconverter shares the same phase noise. When each downconverter derives its own LO from a common 10 MHz clock, the resulting uncorrelated phase noise appears as channel-to-channel phase skew. In either case, a constant phase skew versus time plot indicates that the two downconverter chains are completely synchronized. As a result, the measurement system can now be used for multi-channel phase-coherent RF measurements.

Conclusion

In the same way that emerging wireless technologies such as MIMO antenna systems have profoundly influenced transceiver designs, they've also left their mark on RF instrumentation as well. Thus, while multi-channel phase-coherent RF measurements were traditionally difficult, today's modular instrumentation has evolved to meet the new measurement requirements of MIMO systems. Today, engineers can combine modern RF signal analyzers with a basic understanding of digital downconversion to produce a tightly synchronized MIMO measurement

solution. For more information on PXI-based MIMO test systems from National Instruments, please see www.ni.com/automatedtest/MIMO.

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