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This article first appeared in the
May 2012 issue of Microwave Product Digest (p 52, 76-78, 80).

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New Techniques Simplify Military Frequency-Converter Characterization

by David Ballo, Agilent Technologies

Upconverters and downconverters play fundamental roles in the transmit and receive chains of all defense systems, ranging from EW, ECM, ESM, ELINT, and SIGINT receivers, to satellite terminals and transponders, and radar systems. Two of the key measurements required to characterize converters are port match and transmission response characteristics. For more than a decade, Agilent's PNA and PNA-X vector network analyzers have relied on two very capable techniques for this purpose: scalar mixer/converter (SMC) and vector mixer/converter (VMC). However, Agilent has created a new measurement technique called SMC+Phase that combines the simplicity of SMC with the phase and delay measurement capability of VMC, and eliminates the need for reference and calibration mixers for phase or group delay testing. SMC+Phase can also be used to measure converters with embedded LOs that are difficult or impossible to access. The new technique significantly simplifies and reduces the cost of the measurement test setup.

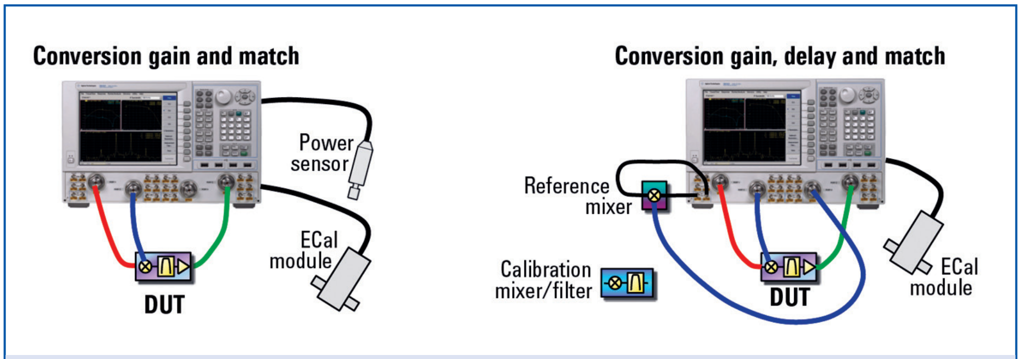

Figure 1: The SMC and VMC techniques each have unique benefits

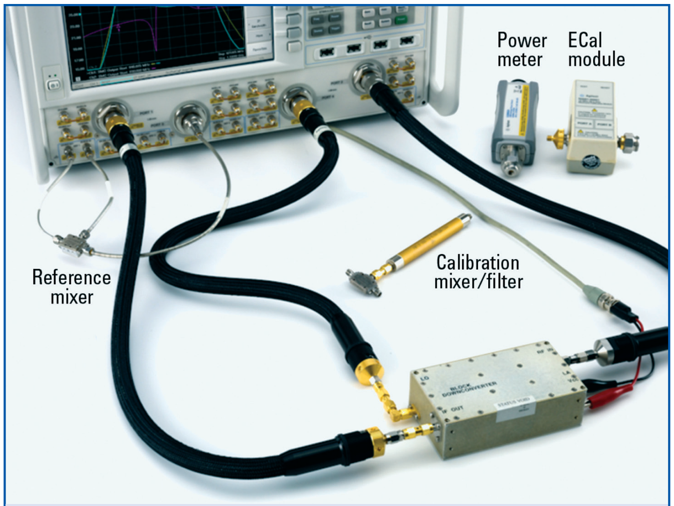

Figure 2: Disadvantages of the VMC technique include limited choice of mixers operating above 26.5 GHz that match the frequency plans of many devices. This applies also to reciprocal calibration mixers and filters for the calibration mixer.

Comparing SMC and VMC

The SMC technique is the most accurate way to measure conversion loss and gain. It corrects for mismatch errors during calibration and measurements by combining one-port and power-meter calibrations. The technique is simple to set up and calibrate, and requires a power meter during calibration along with the usual open, short, load and thru standards. SMC corrects for DUT mismatch during transmission measurements by taking advantage of the VNA's ability to measure its source and load match during calibration as well as the DUT's input and output match. Benefits of the two techniques are shown in Figure 1.

The VMC technique delivers the most accurate phase and absolute group delay measurements and calibrates the test system's transmission phase response as well as providing mismatch correction at the input and output of the DUT. However, the technique has several inherent drawbacks (Figure 2). It is more complicated and requires more external components than SMC as two additional mixers are needed for reference and calibration. VMC uses a characterized mixer as a calibration thru standard along with the usual open, short, and load standards, and removes magnitude and phase errors for transmission and reflection measurements.

An external reference mixer is used as a phase reference, but is not needed for phase-locking the source and receivers with a frequency offset, as offset sweeps are achieved with the instrument's internal sources. As both calibration techniques perform corrections for mismatches, external attenuators are rarely needed. While VMC provides the ability to evaluate deviation from linear phase and absolute group delay, mixers that match the frequency range of the DUT are harder to obtain above 26.5 GHz as are filters with acceptable performance. In addition, many mixers may be required to evaluate DUTs with diverse frequency plans, so several calibrations must often be performed to cover all bands.

SMC+Phase Explained

The SMC+Phase technique (Figure 3) uses simple setup and calibration, requires no external signal source or reference and calibration mixers, provides the most accurate conversion-loss/gain and phase/delay measurements, and removes mismatch errors during calibration and measurement. Not surprisingly, it will likely replace VMC for most frequency converter measurement applications.

In contrast to VMC that uses ratios of test and reference signals at the same frequency (thus the required reference mixer), the SMC+Phase technique ratios single-receiver phase measurements performed at the DUT's input and output. It also replaces the calibration mixer with a comb generator as a phase standard, and magnitude measurements are performed the same way as SMC, using a power sensor as a calibration standard. Mismatch correction at the

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input and output frequencies is still performed.

By eliminating the reference and calibration mixers, SMC+Phase simplifies and reduces the cost of the converter measurement system. For example, to test single-stage converters that require an external LO, only three cables are required, one each for input, output, and LO signals. For dual-stage converters, the second LO signal can be supplied by an external signal generator routed from the rear panel to test port three or four of the PNA or PNA-X. For converters with embedded LOs, only input and output cables are needed. Calibration is simple, as three broadband coaxial standards are used to calibrate the entire frequency range of the instrument: a power meter for a magnitude standard, a comb generator for a phase standard, and an S-parameter calibration kit. The latter can be a mechanical-standards-based kit or an electronic Agilent ECal module. The technique makes it possible to test any frequency converter within the frequency range of the instrument.

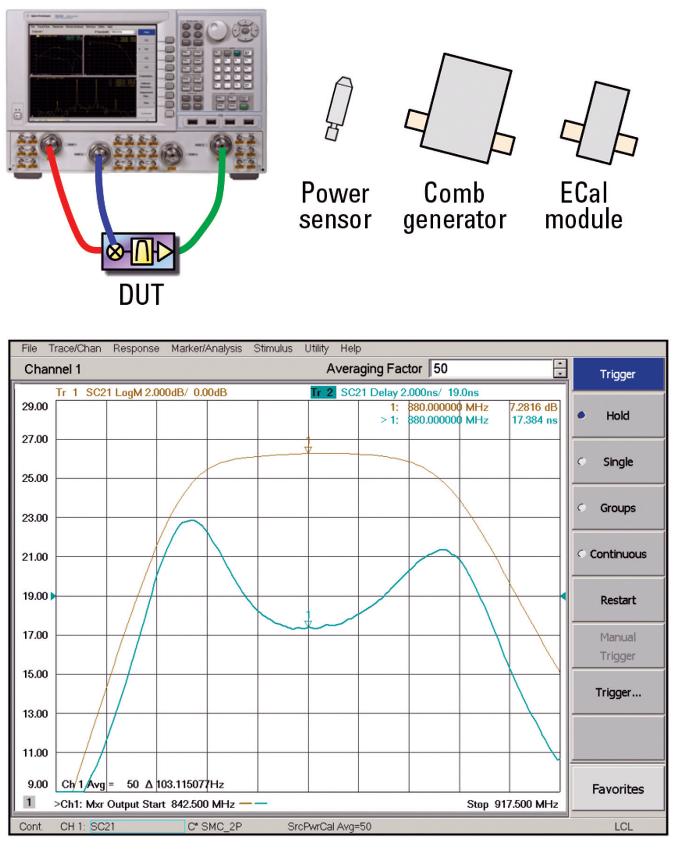

Figure 3: Advantages of the SMC+Phase technique include simplified setup and elimination of an external signal source and reference and calibration mixers

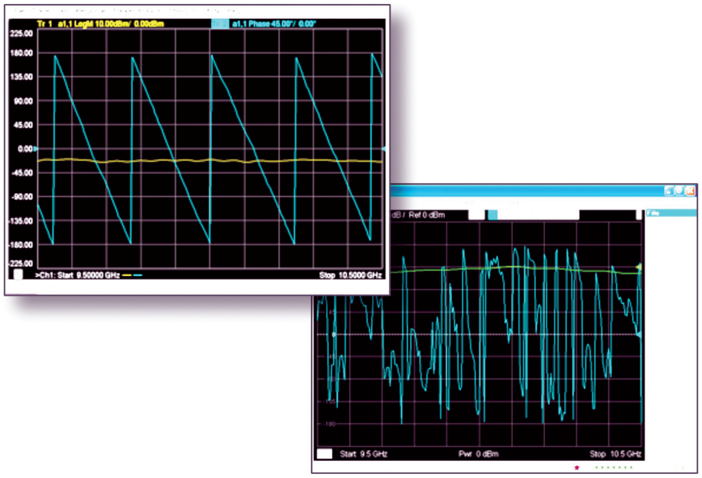

Figure 4: The high-modulus, fractional-N synthesizer and integrated phase accumulator in the PNA and PNA-X allows single-receiver phase coherent (un-ratioed) measurements to be made over frequency (top left) which cannot be achieved with most other VNAs (lower right)

How It Works

The phase-measurement technique employed by SMC+Phase relies on the phase coherency of the signal sources in the instruments' fractional-N-based synthesis architecture to eliminate the reference mixer (**Figure 4**). This is an advantage of the PNA and PNA-X over other VNAs that do not have such phase coherency over their frequency range for single-receiver measurements. In the PNA and PNA-X, relative phase coherency is maintained across a frequency sweep by digitally incrementing the phase accumulators embedded in the fractional-N hardware and by employing synchronous IF detection and digital signal processing.

At band-crossings where changing synthesizer-divide numbers causes discrete phase jumps, phase is mathematically "stitched together" to maintain phase coherency across the sweep. Sweep-to-sweep starting-phase variation is removed by normalizing one point in the phase sweep to zero, which allows sweep averaging to be employed as an effective noise-reduction technique. Normalizing one point of the phase sweep does not affect measurements of deviation from linear phase or group delay calculated from the change in phase from point to point.

For calibration of test system transmission phase response and delay, SMC+Phase offers three approaches, one of which is new. The first is to use a mixer with known delay that uses a fixed value of delay (the average of mixer delay versus frequency) with delay determined from simulation or measurement. The second choice is use of a characterized mixer and uses actual delay data versus frequency and relies on the same characterization method as VMC, based on reflection measurements. It requires a reciprocal mixer and filter for selecting the desired conversion product. The new third choice is the use of a comb generator as a phase standard with a two-step approach in which the first step is power and phase calibration and the second requires only S-parameter calibration (**Figure 5**).

In the first step of this new method, the VNA receivers are calibrated for absolute power and phase relative to the test ports without test cables or other system interconnects attached. The second step is a simple S-parameter calibration that removes the effects of test cables, adapters, attenuators, and wafer probes. The comb generator creates a repetitive, negative-going impulse in the

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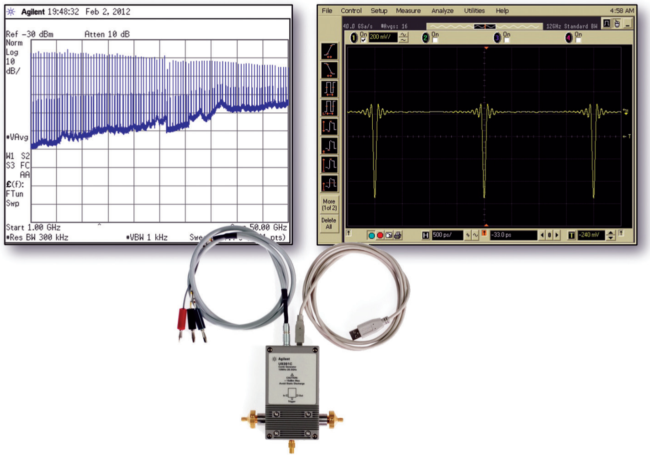

Figure 5: The comb generator provides a broadband, phase-calibrated "comb" of signals that is used to calibrate the phase of the VNA's receivers. The phase calibration method is derived from electro-optical sampling and is traceable to NIST.

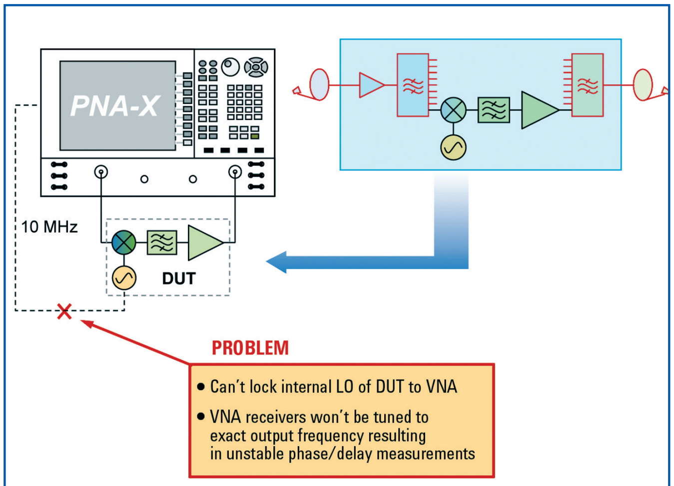

Figure 6: Embedded LOs, a fact of life in satellite transponders, make it impossible to provide coherent frequency synchronization of the VNA and the transponder, which has until now eliminated the VNA as a measurement tool for this application. This problem has been solved with the PNA Series by using sophisticated tuning algorithms to compensate for the frequency offset of the embedded LO.

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time domain, which provides a broadband phase-calibrated frequency spectrum (i.e., a "comb" of signals) that is used to calibrate the phase of the VNA receivers.

The calibration performed during the first step calibrates the VNA receivers for absolute power using a power sensor and phase using a comb generator. It is typically performed directly at the reference plane of the instrument's test ports or with adapters connected to them. This eliminates the effect of test cables, making the calibration more accurate and repeatable. Calibration is typically performed over the full frequency range of the instrument and can be performed infrequently because of the instruments' stability.

The S-parameter calibration performed in the second step includes the system interconnect hardware that was not included in the first step and is performed at the end of the test cables, adapters, or wafer probes that connect to the DUT. For coaxial calibrations in which the ECal module connectors match those of the DUT, this calibration can be done as a single step.

Tackling Embedded LOs

Embedded LOs are common in converters used in satellite transponders because of the spacecraft's size and weight limitations and to eliminate or greatly reduce spurious signals. As a result, it is impossible to access the DUT's LO or its time base and thus also impossible to make the necessary connections to provide coherent frequency synchronization of the VNA and the transponder (**Figure 6**). This is why VNAs have traditionally not been used for these measurements, which has hindered efforts to reduce the time required for transponder characterization. Agilent has created a way to circumvent this problem that makes it possible to make very accurate VNA-based converter measurements in these situations.

There are four basic obstacles that must be surmounted in order to make possible VNA-based measurements of embedded LOs. The first is frequency stability, which is not an issue for most transponders, as their LOs are locked to highly-stable crystal oscillators and have low phase noise. The second issue is establishing frequency coherency because the narrowband VNA receivers must be tuned to frequencies that exactly match the output frequencies of the DUT. The VNA's LO must also be stable enough relative to the DUT's LO to ensure that errors caused by non-ratioed phase are not excessive.

The next issue is phase stability that arises because even when the frequencies are the same there will be sweep-to-sweep variations in absolute phase response caused by the architecture of the instrument. Fortunately, phase can be normalized at each sweep to an arbitrary phase reference so that averaging can be used just as effectively as with a common time-base. Finally, as the phase noise of the LOs in the VNA and DUT cannot be "ratioed out", averaging and smoothing can be used to lower the noise of the group delay measurements.

In order to establish the appropriate pseudo-coherent phase relationship between the DUT and the test instrument, the PNA or PNA-X breaks down the measurement of the converter's effective LO into coarse and fine measurements. This two-step approach quickly achieves the needed frequency accuracy. Coarse tuning is achieved by first setting the RF stimulus to an appropriate CW frequency within the defined input frequency band, and the instrument calculates the output frequency corresponding to the input frequency and the nominal value of the DUT's LO.

The instrument's internal receivers are swept around the expected center frequency of the DUT's output. The difference between the peak of the actual signal and the expected signal (based on the nominal value of the DUT's LO) gives a frequency-offset value for adjusting the nominal LO value of the mixing plan. The VNA is then tuned very close to the DUT's actual output frequency. The frequency span of the course receiver sweep can be set by the user up to 10 MHz. The coarse-tune process gets the instrument close to the

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desired output frequency but not close enough to stop phase slippage between the VNA and the DUT. The necessary frequency accuracy can be obtained by taking a different measurement approach for the fine sweep.

Once the coarse offset is applied, the PNA performs a ratioed phase-versus-time sweep between the DUT and test receivers at a fixed input frequency and with the test receiver fix-tuned to the output frequency of the DUT derived with the coarse sweep. Any small residual frequency offset will show up as a linear phase change versus time. The slope of this phase change can be accurately estimated, which gives the fine offset value. This fine-tune process can be repeated multiple times to get a good sub-hertz estimate of the DUT's LO frequency.

Minimizing the phase shift versus time until the phase response has a flat slope over the measurement period provides a pseudo-locked condition and places the two local oscillators in a fixed phase relationship. This method is much faster than performing a narrowband sweep of the VNA's receivers with a large number of data points. Both coarse and fine tuning can be performed at every sweep of the group delay measurement, creating a coherent relationship between instrument and the DUT.

Summary

Fully characterizing a frequency converter is a necessity, and traditional methods have typically been cumbersome, costly, and time-consuming. Two essential measurements required to characterize converters, port match and transmission response characteristics, have been performed with excellent results, but Agilent's new SMC+Phase technique streamlines the process, reduces the complexity of the test setup, requires neither reference nor calibration mixers, and provides the same or better levels of accuracy as previous methods.

In addition, Agilent's PNA and PNA-X VNAs can characterize converters even when the DUT's LO is not accessible, which is often the case with transponders employed in communications satellites. Together these techniques represent significant advances in converter characterization that are likely to become the standard for the way these measurements are made in the future.

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Published in USA, August 2, 2014
5991-1367EN