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Technologies and approaches for improved mixer measurements

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Measurements of frequency converting devices are always important (e.g., [1]-[2]) and there are a number of variables that can affect the ease and accuracy of these measurements. The purpose of this note is to explore three common measurement topologies, how corrections are applied in each, and what are the dominant uncertainty-related effects. The increasing prevalence of the use of active mixers affect a number of these discussions and some of those impacts will be discussed throughout. The measurement hardware plays a role in all of these areas and thus the first section includes a brief discussion on hardware configuration and orchestration.

Measurement hardware

Central to the mixer measurement is control of two (or more) sources for input (could be RF or IF) and LO (or multiple LOs) and an appropriate set of receivers. There are many ways of configuring these measurements. One of the easier to setup structures uses two internal sources in the VNA and a mixer measurement is possible even with a two port instrument as shown in Fig. 1 using one of the measurement topologies to be discussed in the next section. With four port instruments, loop access need not be used but one does have that flexibility. In addition, one or more external synthesizers can be used (and one is required when working with a single source VNA unless the DUT has an integrated LO). If these external synthesizers must sweep, GPIB control is generally used and the MS464XX can support up to 4 external synthesizers being used simultaneously (in multiple conversion device testing for example).

From a setup point of view, two of the most common issues are:

– LO power and getting enough, particularly for passive mixers. With a wholly external setup, this is often not much of an issue and amplifiers can always be added. With a second internal source and accessing via the front panel loop, extra power is available and can exceed +15 dBm at lower frequencies. For active mixers, the power level is less of a concern but often cannot be neglected.

– Spurious products, embedding admittances, and regeneration. The impedances at the mixer ports at many frequencies can affect performance as reflected spurs, image signals and leakage signals can change DUT conversion, often in complex ways due to the phasing of the various tones and the nonlinear effects that may be involved. With certain active mixer topologies, there are even greater reconversion effects. It is beyond the scope of this note to address all of these effects but one can state that a certain amount of padding (or lossy filtering) can usually mitigate these behaviors.

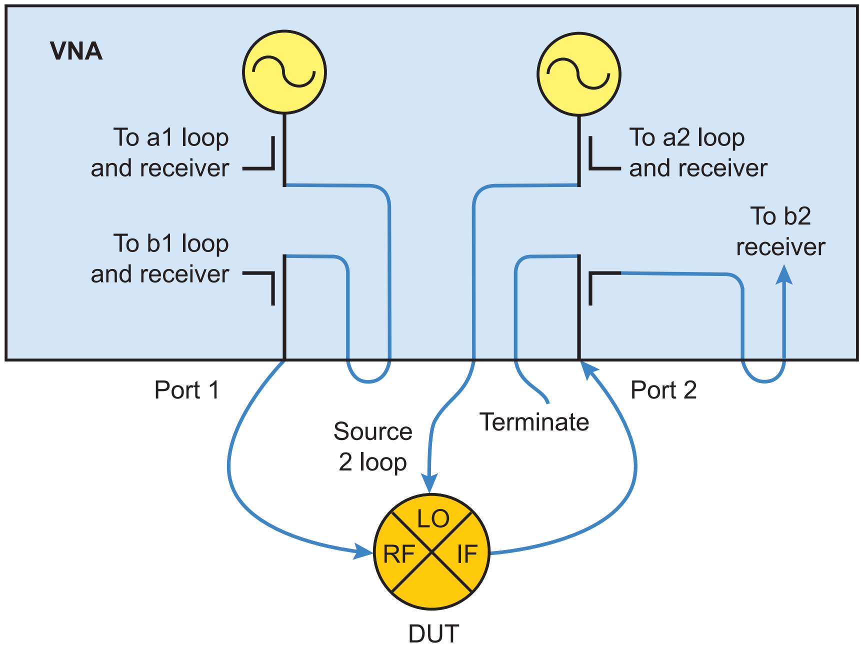


Figure 1. An example mixer measurement setup is shown here for a dual source, two-port VNA. This particular measurement topology is a DUT-only configuration.

Two of the many other possible hardware configurations are suggested in Fig. 2. In the first, external synthesizers with power amplifiers are used for LO drive. As some DUTs may require more than 20 dBm of LO drive and an external synthesizer may be part of the setup for other reasons (e.g., mixer intermodulation distortion measurements), this may make sense. The second shows a DUT with an internal LO whose timebase can be synchronized with that of the instrument. The structure is increasingly popular in monolithic converters. Timebase synchronization may not always be possible and some comments will be made on that topic in a later section.

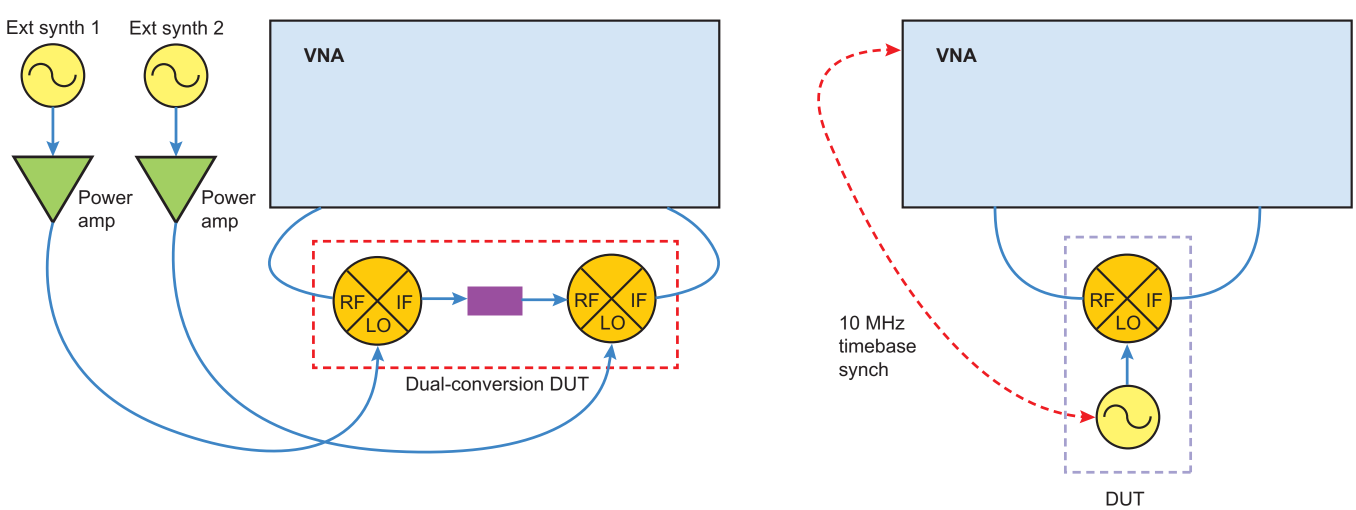


Figure 2. Two additional common setup examples are shown here.

While it is somewhat outside the scope of this note, there are also a number of choices from a software configuration standpoint. For a somewhat guided approach, mixer setup assistants are available. These dialogs coordinate source selection, frequency and power plans, and advise on a calibration sequence for one mixer measurement or for a complete suite. An example set of dialogs is shown in Fig. 3.

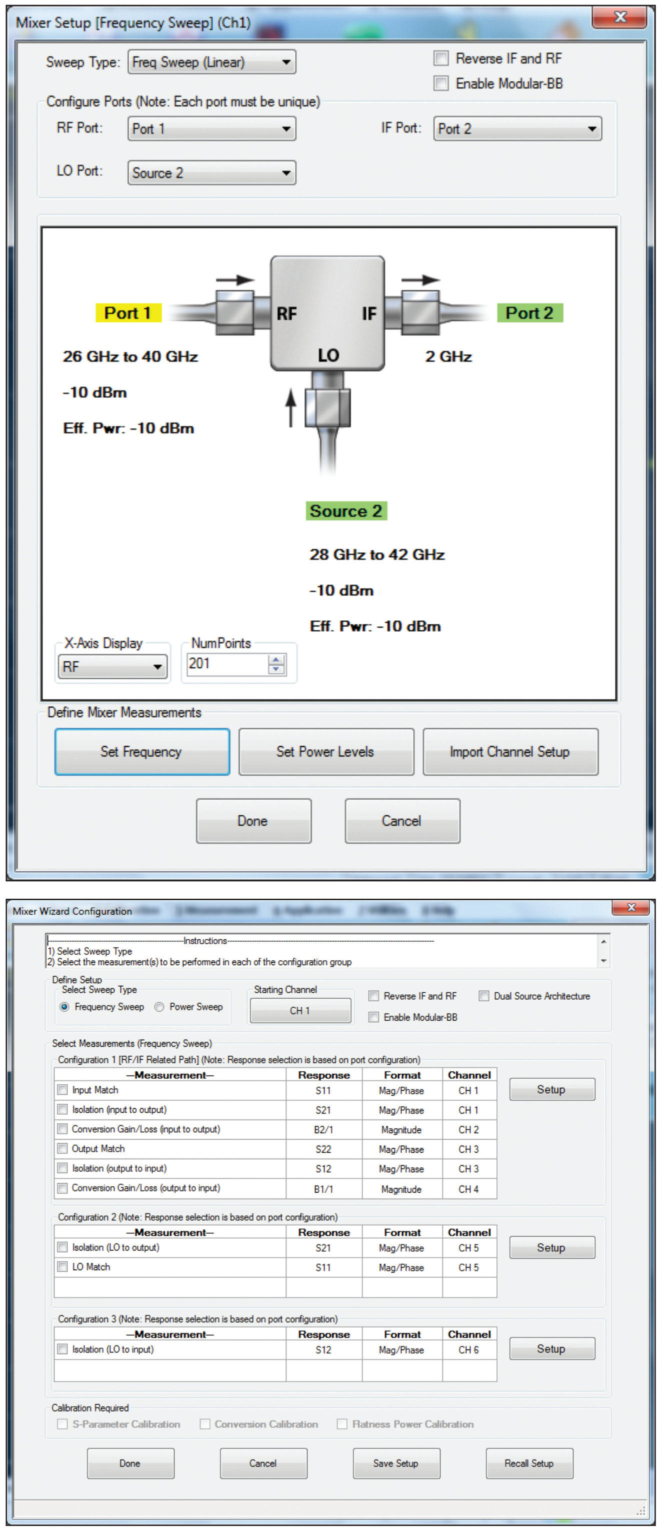
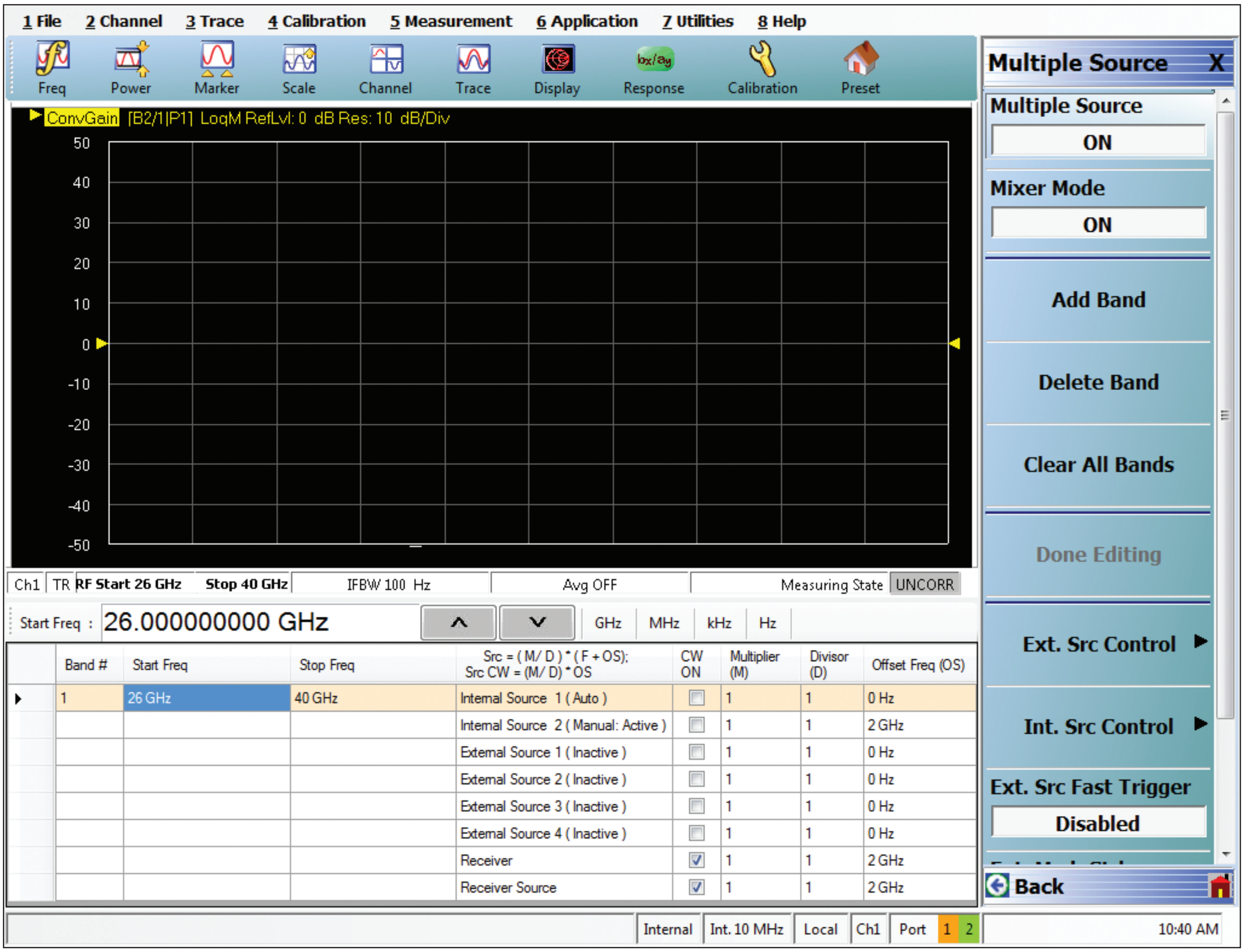


Figure 3. *A variety of mixer setup dialogs are available for configuring sources/receivers, the frequency plan and the desired measurements.*

For more complex setups (e.g., multiple conversions, multiplier or divider involvement), a more flexible, manual control system is available (termed multiple source control [3]). Through a simple set of equations, up to 6 sources and the receiver system can be independently controlled (including the use of mm-wave bands and extensions). The equation matrix is shown in Fig. 4. The central concept is that the receivers and all possible sources are linearly related to a runner frequency variable but can be independent in terms of mode and sweep direction.



Band #	Start Freq	Stop Freq	Src = (M/ D) * (F + OS); Src CW = (M/ D) * OS	CW ON	Multiplier (M)	Divisor (D)	Offset Freq (OS)
1	26 GHz	40 GHz	Internal Source 1 (Auto)	☐	1	1	0 Hz
			Internal Source 2 (Manual: Active)	☐	1	1	2 GHz
			External Source 1 (Inactive)	☐	1	1	0 Hz
			External Source 2 (Inactive)	☐	1	1	0 Hz
			External Source 3 (Inactive)	☐	1	1	0 Hz
			External Source 4 (Inactive)	☐	1	1	0 Hz
			Receiver	☑	1	1	2 GHz
			Receiver Source	☑	1	1	2 GHz

Figure 4*. The multiple source system allows for more flexible and custom frequency plan arrangements for more complex measurements. Up to six sources and the receiver system can be independently controlled through a set of simple equations. Full broadband (ME 7838X systems) and mm-wave support are also available here.*

Measurement Topologies

Three common measurement topologies will be discussed. In all of the pictures below, the LO could be from a VNA source, an external synthesizer or (in most cases) internal to the DUT. The DUT RF port is shown on the left but that is, of course, just one possibility.

a) Single mixer

In this case, the DUT is the only external frequency converting device and the VNA internal reference and test channels see different frequencies during the conversion measurements.

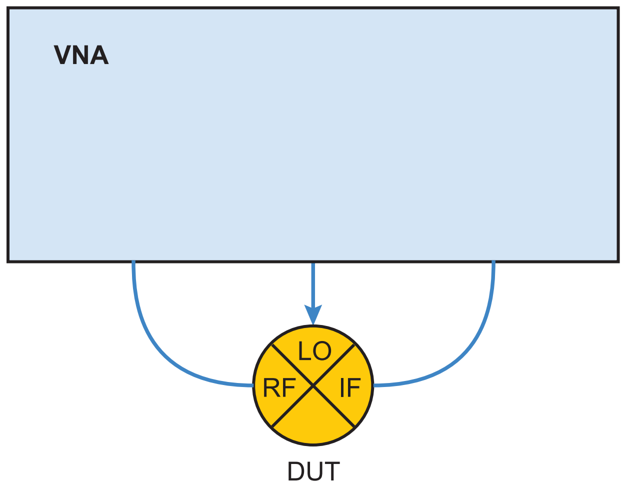


Figure 5. *The single mixer measurement topology.*

b) NxN

In this case, a calibration mixer is used to reconvert the DUT output frequency back to the input frequency. The VNA ports always see the same frequency list and calibrations and phase measurements become much simpler. The 'NxN' name describes how the characteristics of the calibration mixer are found and those details are covered in [4].

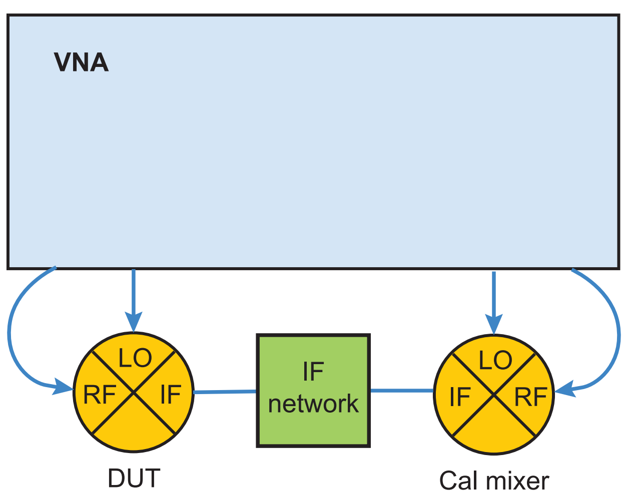


Figure 6. *The NxN measurement topology.*

c) Reference mixer

This is similar to NxN except the calibration mixer is placed in the reference loop of the VNA so that reference and test channels see the same frequency list (again making phase measurements easier). The characterization process for the calibration mixer can take on many forms and the measurement calibration procedure is often a hybrid of that used in single-mixer and NxN approaches.

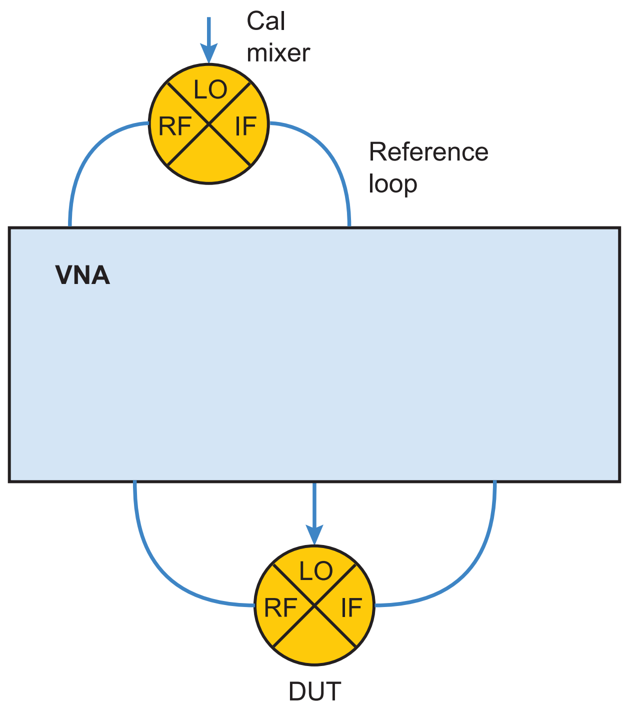


Figure 7. *The reference mixer measurement topology.*

Single mixer setups

The simplest of all configurations requires no auxiliary or calibration mixers at all. The fundamental measurement of conversion has the sources and receivers at different frequencies and the reference and test channels of the VNA at different frequencies (e.g., [3]). As such, conversion phase is often not available but this is still more than a scalar measurement because match information is available. This is quite important since broadband DUT mixer match is normally relatively poor and ripple resulting from that mismatch interacting with the measurement hardware can be a dominant source of uncertainty.

Consider a DUT with 5 dB return loss (not that unusual for a broadband passive mixer) and a measurement system with 15 dB return loss (also not that unusual). Ignoring retransmission through the DUT, one might then expect ripple on the order of

$$20 \cdot \log_{10}\left(1 + 10^{-5/20} \cdot 10^{-15/20}\right) > 0.8dB$$

Carrying forward the concepts of traditional VNA error correction, it can be possible to largely correct for these mixer match effects, with some exceptions to be discussed later, using a technique termed the ‘enhanced match calibration’. This becomes something of a bookkeeping chore as error coefficients at both input and output frequencies must be kept track of on both ports. This is illustrated in the diagram of Fig. 8. Here the transmission tracking terms et21 and et12 have been replaced with pseudo-tracking terms (~et21 and ~et12) to denote that they are frequency translating.

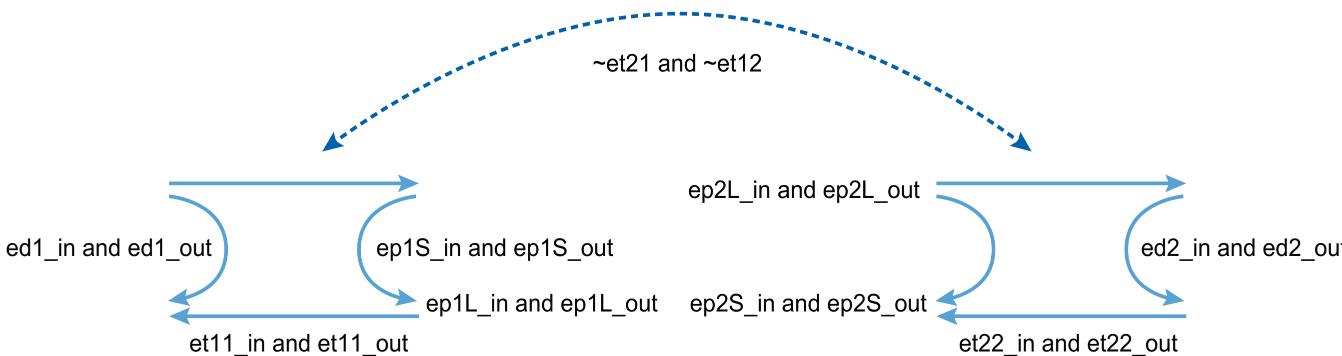


Figure 8. *The error correction diagram for a single mixer measurement is shown here.*

While from the user level, it appears to be a standard full 2-port calibration, there are a number of different frequency sweeps involved and more measurements on the thru standard than one might expect. The process involves the following parts:

– Computing reflectometer error coefficients for both ports at both frequency ranges.

– Performing a receiver calibration for the thru path in both frequency ranges and correcting for system mismatch using the values from the previous step.

– Computing the normalization to account for input drive power and correcting that for system mismatch.

– Measure the DUT conversion, input and output match. Use the above receiver and normalization data with the raw conversion data to calculate a first-pass corrected conversion result. Use the system and DUT match data to make a second level correction.

An example measurement is shown in Fig. 9 where first just a classical receiver calibration plus normalization was performed and then the above enhanced match calibration was performed. This particular DUT had a 4-6 dB return loss in the frequency range of interest so the amount of large scale ripple should not be surprising based on the previous example calculation. The spatial scales of the ripple are related to the electrical lengths in the setup. For this case, there was a short run from the DUT output to the receiver (leading to a high spatial frequency ripple in the norm-only data) and a long run to the DUT input (leading to a low spatial frequency ripple). The enhanced match calibration reduced the amplitude of both input- and output-related ripple.

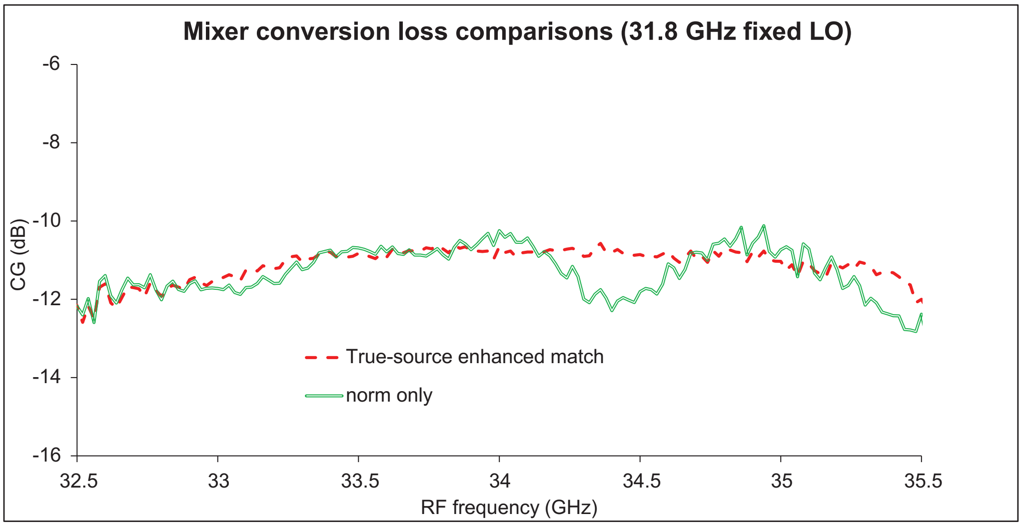


Figure 9. *Example measurements of a typical passive mixer DUT are shown here. The enhanced match version of the measurement was able to correct for DUT mismatch interactions.*

Another example measurement set, again comparing normalization-only to the enhanced match calibration, is shown in Fig. 10. In this measurement, the LO is sweeping with a sliding offset with respect to the input frequency. Note that in fixed output (or fixed input) frequency scenarios there may be less ripple present since the phase of the mismatch on that port does not change over the sweep. The data in that case will be statically shifted by the mismatch effect at the fixed port. The DUT in the case of Fig. 10 had a somewhat wider range of conversion loss over the frequency range and a filter corner (part of the DUT) shows up as well. Again there were different spatial frequencies of ripple that could be largely corrected with the enhanced match approach.

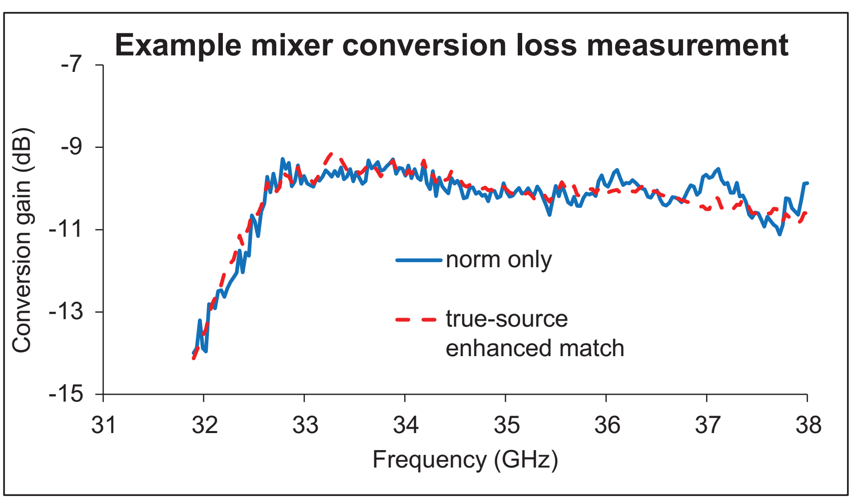
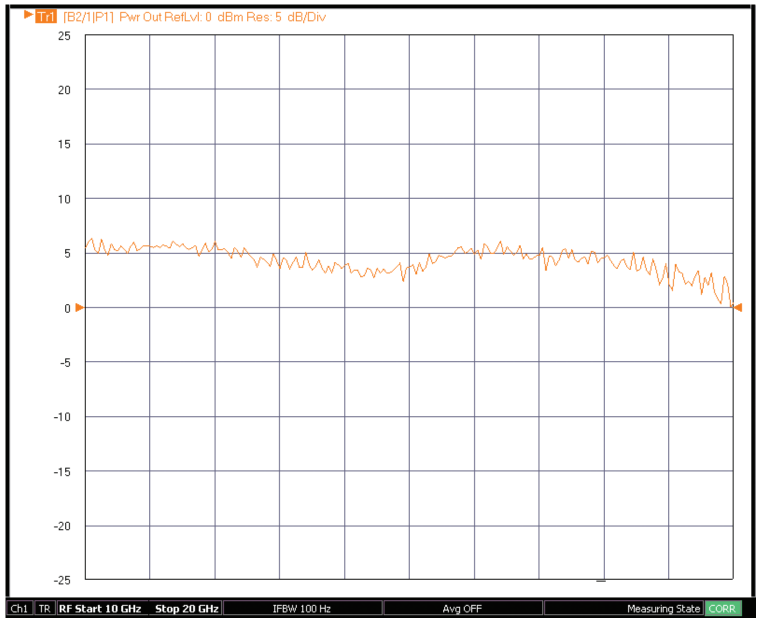


Figure 10. *Another comparison of norm-only vs. enhanced match calibration is illustrated here.*

A third example, this time for an active mixer assembly, is shown in Fig. 11. This test setup was electrically long on both input and output so there is mainly a high spatial frequency ripple in the norm-only data. The low spatial frequency ripple has been replaced with essentially a shift. The enhanced match calibration again reduces these effects.



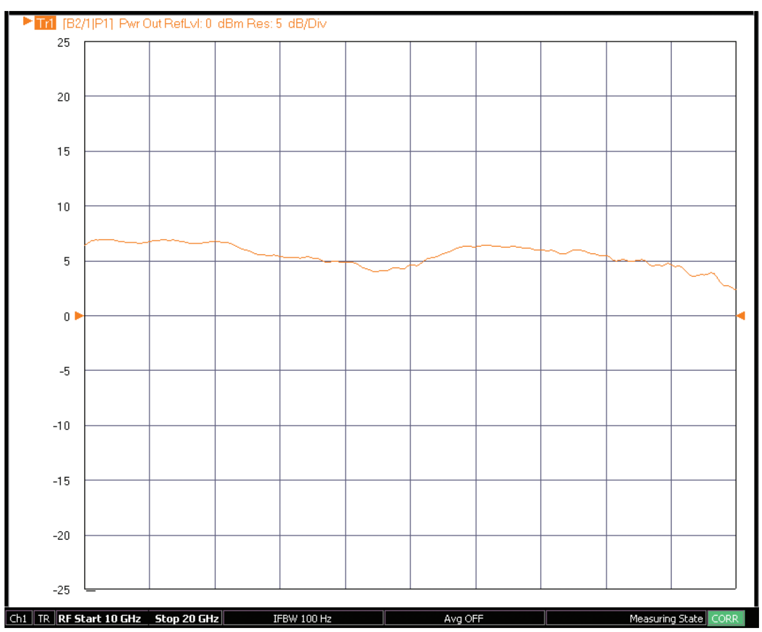


Figure 11. *Measurements of an active mixer conversion are shown here for norm only (top plot) and enhanced match calibration (bottom plot).*

In normal practice, this measurement approach does not handle spurious products that reconvert back to the input or output frequencies (through reverse transmission, transit through the LO system or other paths). Insofar as these spurious or image products can interact with the measurement system (to include the LO) and can readily reconvert in the DUT, errors will be introduced. While more detailed accounting of spurious products at the ports can be performed, keeping track of the embedding admittances at all of those frequencies and the nonlinearities involved can be daunting. From an amelioration point of view, lossy image filtering can often reduce the effects (whether as part of the DUT or as part of the measurement setup).

As an example look at the uncertainties, the normalization-only approach with the single mixer setup tends to be dominated by mismatch interaction between the DUT and the test ports. Other terms include power calibration accuracy and uncertainties introduced in transferring that power calibration to the receivers. As one might expect, adding some padding to the DUT ports can improve the results. As long as the signal levels are not too low (stay ~> –60 to –80 dBm depending on the IFBW being used), there is little signal-to-noise penalty. For a unilateral device, the values shown in Fig. 12 are generated.

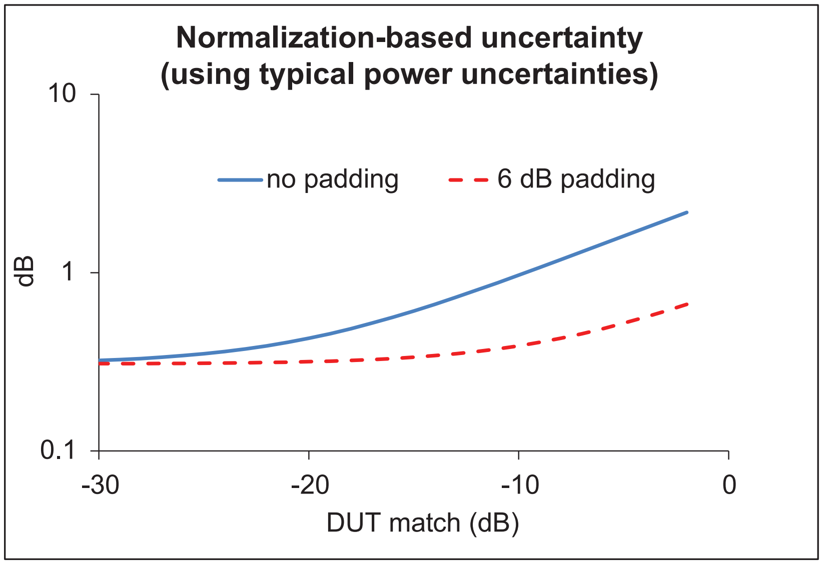


Figure 12. *Conversion uncertainties for the normalization-only approach on the single-mixer setup are plotted here with and without added padding.*

For the enhanced match case, the match component of the uncertainty is greatly reduced as one would expect and the residual is affected by the calibration kit being used. The base receiver calibration transfer uncertainties are also reduced since match corrections are applied to that stage as well. The results for an example setup using a standard K calibration kit are shown in Fig. 13. Note the difference in the vertical scale between Figs. 12 and 13.

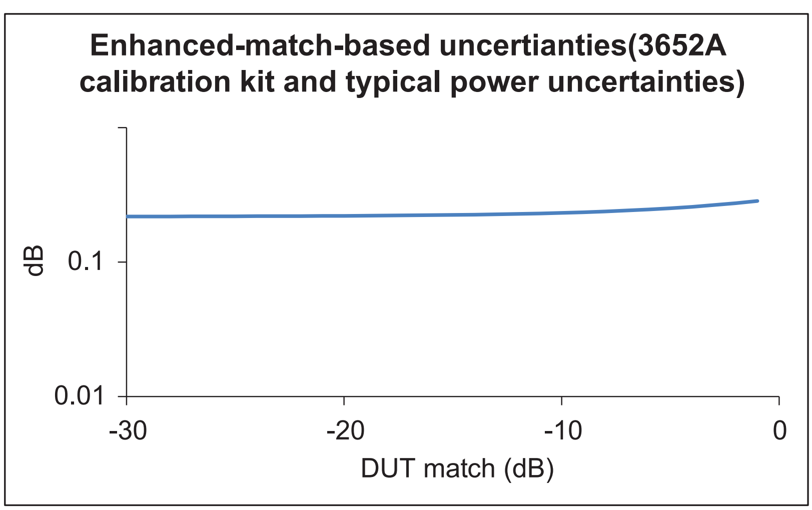


Figure 13. *An example uncertainty curve for conversion measurements using the enhanced-match calibration approach with the single-mixer setup is shown here.*

The above analysis strictly only holds for a unilateral DUT but it will be close if there are any gain stages in the DUT and it usually holds true for active mixer designs. For a purely passive mixer, the uncertainties will be higher since there will be some level of reconversion and interaction between input and output match levels. While such an analysis is possible, it is outside the scope of this note.

NxN

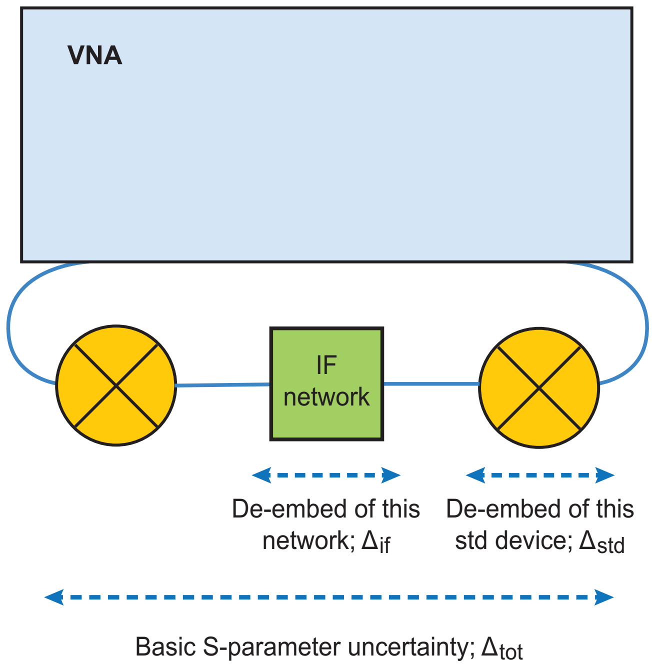


Figure 14. *The NxN setup is repeated here. In terms of uncertainties, some components are related to the de-embedded sections and others are related to the overall measurement and to section interaction.*

This particular technique is covered in some detail in [4] and [5] so only brief details will be provided here. The central concept is that by reconverting the DUT output frequency back to the input, using a calibrated mixer, the VNA sees no frequency translation so calibrations and phase measurements are much simpler. The calibration mixer, and any image/spur rejecting IF network, must be de-embedded to get the desired result.

This technique can quite accurately arrive at transmission phase/group delay, conversion loss and input match but cannot directly find output match. In addition, inner plane mismatch can have an important effect on uncertainty so some padding or lossy filtering is desirable there. As with all of the techniques, spurious and image reconversion can have a significant effect so the IF network here typically includes some filtering.

For the more classical DUT measurement approach, there are several main components to the uncertainty:

1) The basic S-parameter measurement of the combined network. This follows from the basic VNA and calibration kit parameters and is often in the few tenths of a dB range for default settings and reasonable (>10 dB) DUT return loss. Note that the S-parameter measurement is fully corrected from the VNAs point-of-view so standard uncertainty calculations apply to that portion.

2) Uncertainty in the IF network parameters to be de-embedded. Assuming the loss is not extremely high (~<20 dB), the uncertainty in this network knowledge will propagate directly to the net DUT parameters.

3) Uncertainty in the calibration mixer parameters to be de-embedded. Again if the loss is not too high, this uncertainty will propagate directly to the DUT values. If the losses are higher, there can be an additional signal-to-noise term (which will vary with IFBW and averaging).

The characterization of the calibration mixer is often done with a round-robin measurement of 3 mixers (one of which may be the DUT) in the same setup as the diagram which does require that one of the mixers, usually ‘the calibration mixer,’ be reciprocal. These measurements are then combined to yield the characteristics of the calibration device

$$\sqrt{\frac{M1 \cdot M2}{M3}} \approx \sqrt{\frac{M1'(1+\Delta_1)M2'(1+\Delta_2)}{M3'(1+\Delta_3)}}$$

Here the ‘M’ measurements are the S21 values of composite transmission. The Δs (representing errors) have two components: the basic S21 uncertainty from the VNA’s point of view (which normally will be around 0.1-0.3 dB for typical match levels) and the error in assuming that each M measurement of transmission is equal to the product of the individual transmissions.

4) Uncertainty in the transmission-only de-embedding process. Much like in the standard device solving process, this is determined by the degree of match interaction at the IF level. The transmission through the IF can be expressed as

$$\frac{S_{21}}{1-\left(S_{11}\Gamma_1 + S_{22}\Gamma_2 + S_{21}S_{12}\Gamma_1\Gamma_2\right) + S_{11}S_{22}\Gamma_1\Gamma_2}$$

Where the S-parameters are those of the IF network and the Γs are the mixer match terms (at the IF frequency). Often the phase of the match interaction is assumed to be uniformly distributed and a worst-case or Monte-Carlo analysis can be performed to determine the net effect.

Complicating the composite analysis somewhat is that some of these terms (particularly #3 and #4 above) can be correlated so it is possible to incorrectly combine the uncertainty components. This correlation increases with mismatch levels in the IF region. If the IF network is relatively well-matched and the electrical lengths are not very short, then one can treat the terms as uncorrelated.

As an example, suppose the DUT and standard converter mixers all had 10 dB return loss and roughly 7 dB conversion loss. Suppose the IF network had a 20 dB return loss and 6 dB insertion loss. The basic S-parameter (95%) uncertainty for #1 is ~0.015 and is perhaps 0.01 for #2 (at a lower frequency). The values for #3 and #4 work out to ~0.094 and 0.068 respectively (all are expressed ratiometrically). The combination would then work to ~0.116 or about 0.95 dB if the four terms above are treated as uncorrelated. If terms #3 and #4 are correlated, this value could rise to about 1.3 dB.

Using the above IF network parameters but allowing the DUT match to vary (assuming worst-case phasing but otherwise assuming uncorrelated errors), one can get an uncertainty profile as shown in Fig, 15. Clearly the match interaction is still dominant and a better match environment on the interior would help. For well-matched DUTs, the uncertainties do not deviate that much from those for the enhanced match (or well-padded) singe mixer approaches but they do diverge for higher levels of mismatch.

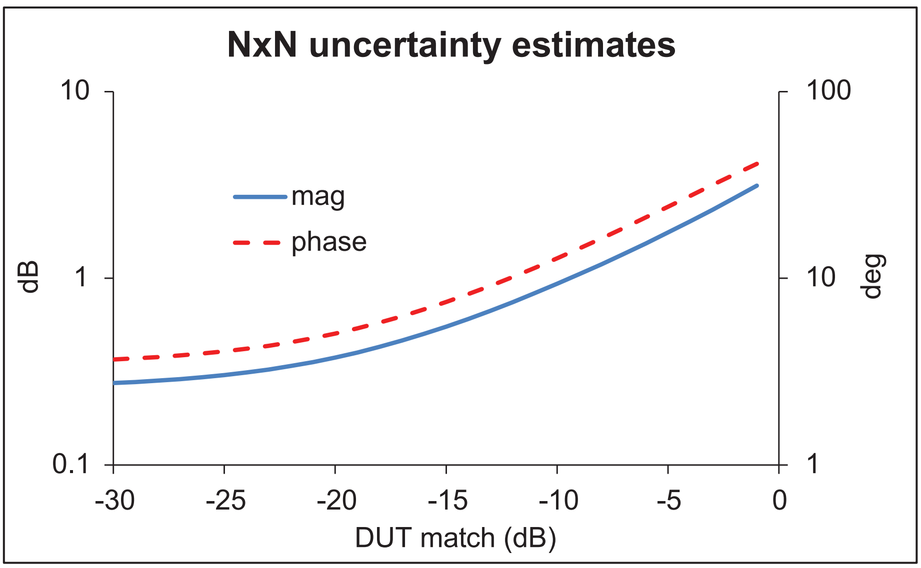


Figure 15. *Uncertainty estimates (conversion magnitude and relative phase) for the NxN method are show here assuming the IF network discussed in the text, ~7 dB DUT conversion loss and a 3652A-based calibration.*

One may note the addition of a phase curve in Fig. 15 and the availability of this measurement is one reason for using the NxN measurement. It should be noted that this is a relative phase uncertainty (which can be readily converted into group delay uncertainty) since there is an ambiguity in converter absolute phase due to an unknown phase state of the LO.

In terms of practical setups, the LO has not been discussed at length. Often a common synthesizer (internal or external) and a splitter are used to drive both sides. If the DUT has an internal LO, then clearly a separate synthesizer (or the VNA's other internal source) must be used for the calibration device. If timebase references cannot be locked, then a wider IFBW on the VNA is often used along with peak tracking to take into account any relative drift.

Reference mixer measurements

Reference mixer measurements have been discussed extensively in the literature (e.g., [6]) and, on a high level, the concept is related to that of the last section: by having reference and test receivers of the VNA seeing the same frequencies, ratioing and easier phase measurements are possible. The topology is shifted in this case so that only some S-parameters are instantaneously available and the calibration details become somewhat more complicated although many variations exist [6]. The advantage is that match interactions can be better controlled. Again, a variety of LO configurations are possible and a splitter/common LO is present in the below figure.

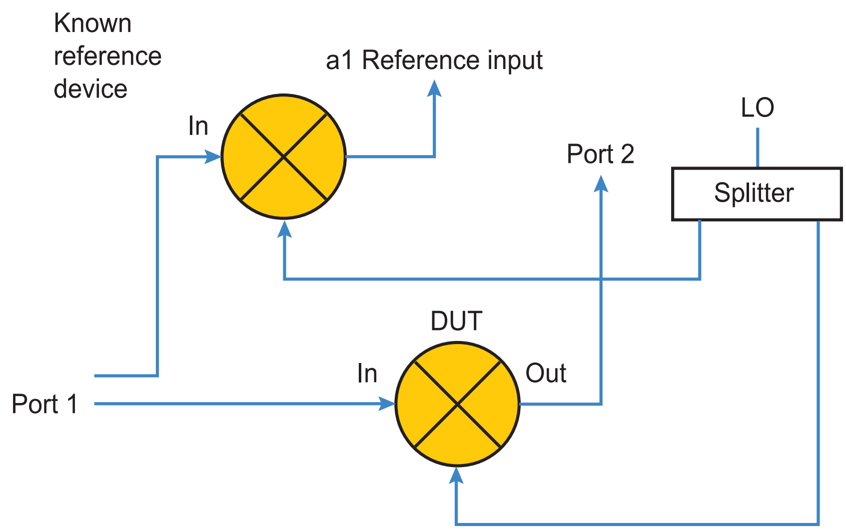


Figure 16. *An example of the reference mixer setup is shown here. In terms of uncertainties, the interactions of the reference mixer with the reference ports must be considered.*

The match correction for the conversion measurement often works much like the enhanced match calibration for single-mixer setups. Since the reference mixer was not present for the port analysis steps, uncertainties in its characterization and the characterization of the reference port mismatches will map through directly to the final uncertainty. This is an additional term, beyond that in the enhanced match calibration, that will vary in significance depending on those match levels. Of course, reconversion in both paths will be a potential issue as usual. The benefit over the single mixer approach is that phase information is now available with similar uncertainty adders as with the conversion magnitude measurement.

Using the same protocol as before, we can calculate an estimate of uncertainties for this measurement. Here the DUT and the reference mixer are assumed to have similar return losses and that interaction of the reference mixer with the reference ports does cause some elevation at higher mismatch levels.

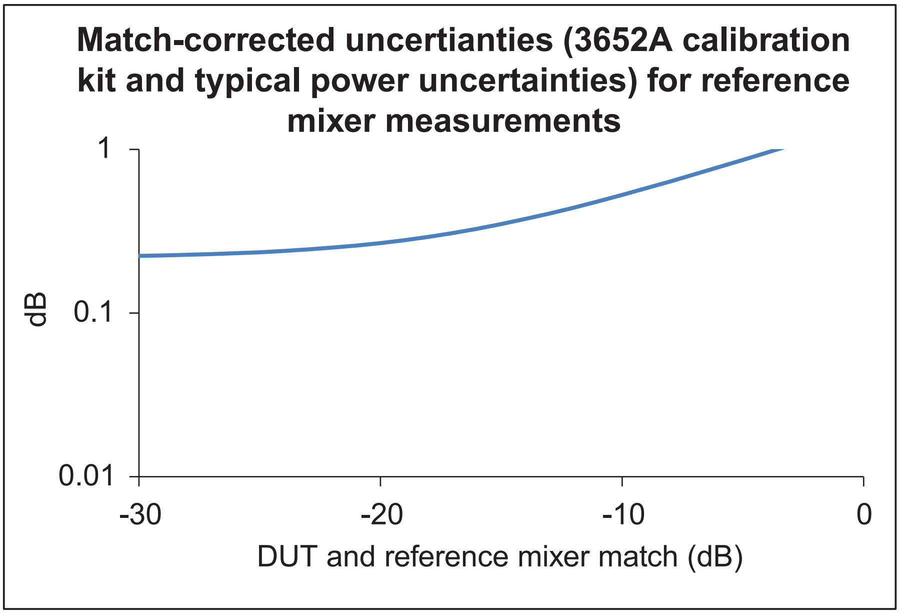


Figure 17. *An estimate of uncertainty for a reference mixer method using similar match correction to the enhanced match approach discussed earlier is plotted here. While phase information is available with this method, there is some uncertainty penalty for higher DUT mismatch levels.*

As with the other techniques, there are complications when measuring a DUT with an integrated LO where there is no timebase synchronization access. If the drift rate is slow (~< 10 kHz/min) then it can be practical to perform the measurement asynchronously using a wide IFBW. This can allow sufficient time to make measurements before the converted signal has wandered off (relative to the VNA) from where it started. In terms of group delay, this alone is not enough as phase will continue to move based on any remaining offset. The use of a marker tracking function, however, can be used to adjust for this quasi-real-time. As an example of such a measurement, a group delay measurement was made with a reference mixer setup both when the DUT (with internal LO) was initially on-frequency with respect to the VNA and when it had drifted off by about 1 kHz (~0.3 ppm LO change). These results are overlaid in Fig. 18. The peak deviation was about 100ps on this electrically long DUT.

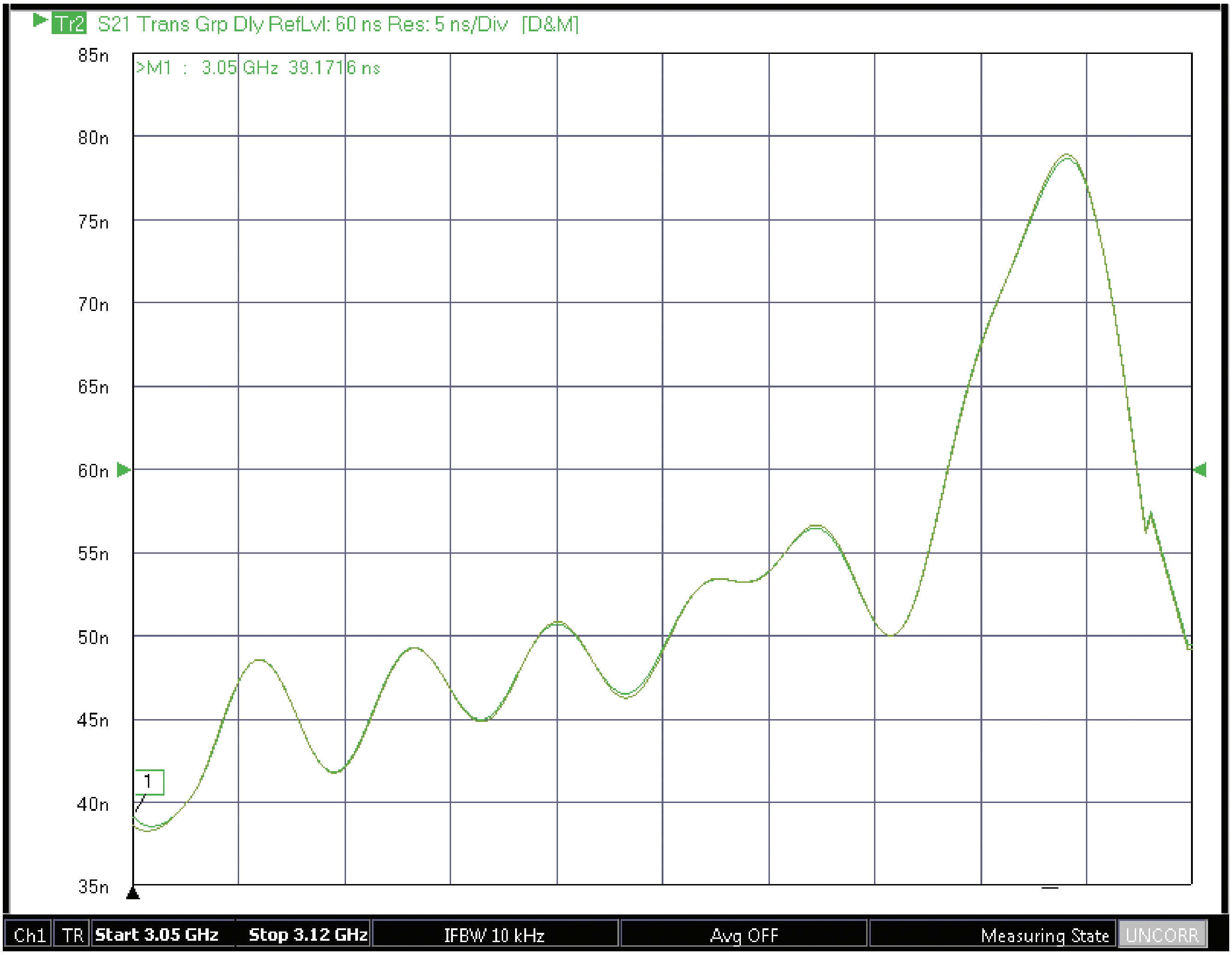


Figure 18. *A group delay measurement on a DUT with integrated LO is shown here for both when the DUT LO matched the system LO frequency and when it had drifted about 1 kHz.*

Summary

A variety of mixer measurement topologies have been discussed along with some of the related calibration and uncertainty issues. In general, uncertainties increase with DUT mismatch but some topologies are more affected than others (single-mixer methods among the least affected) but this must be viewed in the context of available measurements and setup complexity.

References

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[2] L. Dunleavy, T. Weller, E. Grimes and J. Culver, “Mixer Measurements using Network and Spectrum Analysis,” 48th ARFTG Conf. Dig., Dec. 1996, pp. 16-27.

[3] “VectorStar MS464xB Calibration and Measurement Guide,” Anritsu publication 10410-00318D, May 2014.

[4] “Mixer VNA Measurements,” Anritsu Application Note 11410-00519, July 2009.

[5] ”Lighting 37000 Series Vector Network Analyzers Application Note: Measuring Frequency Conversion Devices,” Anritsu Application Note 11410-00197, April 1998.

[6] J. Dunsmore, “Novel Method for Vector Mixer Characterization and Mixer Test System Vector Error Correction”, 2002 Int. Micr. Symp. Dig. , June 2002.

Notes

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