Reducing Effects of LO Cable Movement in Antenna and Long Distance VNA Measurements

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***Abstract*— We evaluate a method for estimating and removing local oscillator cable drift in transmission measurements using a network analyzer. The geometric mean of the measured forward and reverse transmission, including drift, can be used to estimate the actual transmission without drift. This requires the measurement of passive, symmetrical transmission measured with a bi-directional two-port remote-mixing down-converting measurement system. This method is being used in antenna measurements where cable movement is unavoidable. It is viable for other calibrations and measurements using remote-mixing systems and frequency extenders at higher frequencies.**

Keywords*— *antenna measurement; calibration; drift; local oscillator; network analyzer

I. INTRODUCTION

A method has been shown to effectively remove the phase effects of local oscillator (LO) cable drift from remote-mixing vector network analyzer (VNA) measurements [1]. We present the circuit basis for extending this analysis for correcting complex, amplitude and phase, LO drift in measurements [2].

Characterizations of antennas (gain-extrapolation, polarization, and patterns) require antenna movement. Cable drift and movement are direct contributors to errors and increased measurement uncertainties [1-3]. These adverse effects become more significant with increasing frequency and electrical cable length, so frequency conversion is often used to minimize the effect of loss, and cable stress [1,4,5].

Transmitting the signal at the operating radio frequency (RF) though long cables can have large dynamic-range-limiting losses and induce large phase errors which may be both temperature and movement dependent [6]. A reference at lower LO frequency is used to down-convert the higher test RF to a lower intermediate frequency (IF). This lower frequency LO reference and IF measurement can travel farther with better fidelity.

The downside of this approach is that using a remote LO creates a non-linear dependence between LO drift and the desired signal measurement. Ideally, keeping the LO drift small minimizes these errors. Complex systems have been built to measure and compensate for RF, LO and IF drift, which have dramatically reduced these effects [4]. Rather than treating LO drift as a random uncertainty, we estimate it through measurements [1,3,7]. We present a simple method using the geometric mean of forward and reverse measurements through a reciprocal system to estimate actual transmission.

II. TYPICAL ANTENNA MEASUREMENTS

Single direction measurement systems (i.e. only S_{21} or S_{12}) are typically used for antenna measurements as cost, speed and complexity are driving factors. Mixers and cabling for both directions can often be twice the cost, can add more hardware near the antenna (possibly increasing RF scattering) and may require more complex calibration to reduce systematic losses of the measurement system.

Fig. 1. shows several conventional RF setups used in antenna measurements. Fig. 1(a) depicts a common far-field range. Here differential changes in the LO feed network show up directly as differences in the measured IF signal. Fig. 1(b) shows no external frequency conversion. This can lead to excessive loss and RF amplitude phase changes due to the cabling, which become worse as frequency and/or range of movement increases. Fig. 1(c) depicts a single side down conversion. Fig. 1(d) shows a source and receiver conversion RF setup. The LO is split and may drift differently for the reference and antenna under test (AUT).

III. DUAL-DIRECTION REMOTE-MIXING

The National Institute of Standards and Technology (NIST) is using robotic systems to move antennas during the measurement of radiation characteristics from 1-500 GHz. To minimize cable transmission losses at higher frequencies and allow physical separation between the VNA and the antennas, we employ a remote-mixing, frequency-conversion scheme available from many manufacturers. Fig. 2(c) shows the signal

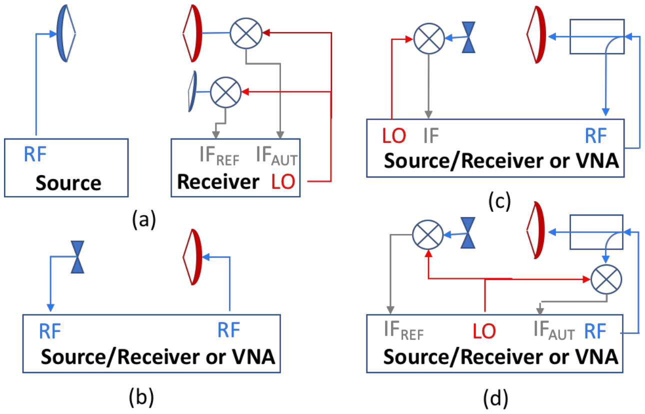

Figure 1. Typical single direction test setups used in antenna measurements. RF signal paths are shown in blue, LO reference paths are red, and IF signal paths are shown in gray.

block diagram of our measurement system. To determine the desired RF signal quantities, a_1, b_1, a_2, b_2, from the ideal VNA inputs, a_1', b_1', a_2', b_2', the error network, Fig. 2(a), needs to be characterized by a calibration. Large physical scans (>100λ) at these frequencies can stress cables that result in changes in receiver measurements not due to the actual antenna measurement. We will show that this is due largely to a mixer network which responds non-linearly to LO cable movement, Fig 2(b).

A. Assumptions, Limitations and Simplications

The major assumptions and limitations for the initial analysis are:

- Both directions are being measured and the antenna measurement is reciprocal, i.e. $S_{21}=S_{12}$. This limits the analysis for active antennas and usage of isolators/circulators.
- LO cable change is the dominant form of drift, i.e. we ignore thermal effects of the VNA or extender head.
- The IF cables are operating at a low enough frequency that amplitude and phase changes due to cable movement at IF can be ignored.
- The RF signal drift is removed by the ratioed S-parameter analysis.
- The system does not systematically change during the forward and reverse scattering parameter measurements. In practice, this is accomplished by limiting the movement of the antennas to no more than $\lambda_{RF}/50$ during the RF measurement.
- There is no movement/drift between the calibration plane and the antenna. This implies avoiding flexible connections between the frequency converter and the antenna. This drift effect can often be more significant than LO cable drift [3].

B. Signals to the Down-Converting Mixers

The standard error model for VNA calibration is dependent on a stable signal path between the test port and the VNA receivers. We assume the error networks in Fig. 2(c) are stable and the mixer networks transmit the coupler output signals, a_1', b_1', a_2', b_2', to the IF inputs of the VNA a_1'', b_1'', a_2'', b_2''.

We will propagate real-time signals from the coupler outputs through the mixer network to determine the effective loss and delay. The error network output signal, a_1', at the RF port of the mixer can be written as:

$$V_{A6}(t) = V_{RFa1}(t) = A_{a1}\sin(\omega_{RF}t + \phi_{a1}) \tag{1}$$

Where ω_{RF} is the angular frequency of the RF test signal, t is time, and A_{xi} and ϕ_{xi} are the amplitude and phase of the signals impingent on the mixers for port i and wave direction x.

The LO signal at the port 1 frequency converter, A2, comes from source, A1, where it may be split and transmits through the LO cable to A2. The received LO signal at the frequency converter, $V_{A2}(t)$, is then sent to a limiting amplifier (depicted in Fig. 2(c) as a saturated amplifier and limiter) and typically filtered to reduce amplifier induced harmonics.

$$V_{A3}(t) = E_{lim1}(L_{LC1}A_{LO})\sin(\omega_{LO}t + \phi_{LO1} + \phi_{LC1} + \phi_{lim1}) \tag{2}$$

where L_{LC1} and ϕ_{LC1} represent the LO cable loss and delay and $E_{lim1}(x)$ and ϕ_{lim1} are the amplitude transfer function and phase delay between the input to the frequency extender and the input to the xn LO up-converting mixer. The output of the up-converting mixer is split and sent to the down-converting mixers at A4, repented by:

$$V_{A4}(t) = C_{MUa1}E_{lim1}(L_{LC1}A_{LO}) \\ \sin[n(\omega_{LO}t + \phi_{LO1} + \phi_{LC1} + \phi_{lim1}) + \phi_{MUa1}] \tag{3}$$

where C_{MUa1} and ϕ_{MUa1} represent the loss and phase delay, including the xn mixer's conversion and splitting loss, between the xn mixer and the input to the down-converting mixers. The xn mixer not only upconverts the LO frequency by a factor of n, but also multiplies any phase shifts after the mixer by the same factor.

The output of the down-converting mixer, A8, is the product of the two inputs to the mixer with a conversion loss:

$$V_{A8}(t) = \frac{C_{MDa1}A_{a1}C_{MUa1}E_{lim1}(L_{LC1}A_{LO})}{2} \\ cos[(\omega_{RF} - n\omega_{LO})t - n(\phi_{LO1} + \phi_{LC1} + \phi_{lim1}) + \phi_{MUa1} \\ + \phi_{a1} + \phi_{MDa1}] \tag{4}$$

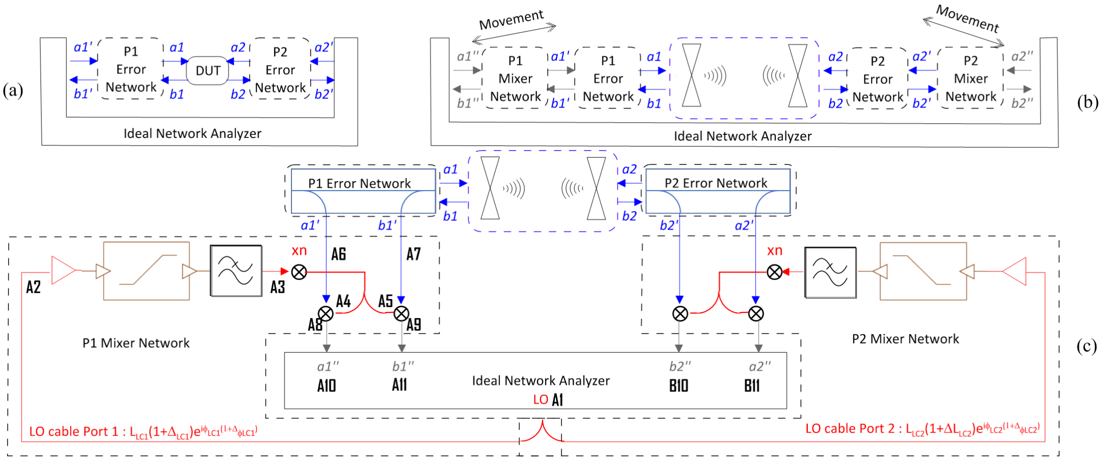

Figure 2. Block diagrams of the ideal VNA calibration with a static error network between the VNA and the test ports(a), (b) a changing error network due to movement such as during an antenna test, and (c) a signal flow model of the down-conversion to get the signal between the frequency extenders and the VNA.

where C_{MDa1} and ϕ_{MDa1} are the mixer down-conversion loss and phase delay between A6 and A8. The upper mixing product, $(\omega_{RF}+n\omega_{LO})$, is filtered out by the mixer and the IF cabling leaving the IF signal $(\omega_{RF}-n\omega_{LO})$. The signal at A10 or the VNA receiver, a_1'', is the signal at A8 with the IF cable loss, L_{IFa1}, and phase delay, ϕ_{IFa1}, at the IF frequency.

$$V_{A10}(t)=a_1''=\frac{L_{IFa1}C_{MDa1}A_{a1}C_{MUa1}E_{lim1}(L_{LC1}A_{LO})}{2} \quad (5)$$
$$cos[(\omega_{RF}-n\omega_{LO})t-n\phi_{LC1}+\phi_{a1}+\phi_{MUa1}+\phi_{MDa1}+\phi_{IFa1}]$$

If we can assume thermal and mechanical stability except for the LO cable, and that at IF, the movement of the IF cables cause minimal change in complex loss, we can simply (5) to:

$$V_{A10}(t)=a_1''=A_{a1}K_{a1}E_{lim1}(L_{LC1}A_{LO})\,cos[(\omega_{RF}-n\omega_{LO})t-n\phi_{LC1}+\phi_{a1}+\phi_{Ka1}] \quad (6)$$

IV. HOW LO CHANGES AFFECT A CALIBRATION

VNA calibration is accomplished by employing standards with "known" scattering parameters and measuring the response of the VNA with the attached error network and then removing the effects of the error network [8-10]. (6) shows a linear amplitude and phase relationship between the RF signal input and the VNA receivers as long as the LO cable stays constant. However, we see that LO cable changes in L_{LC1} and ϕ_{LC1} affect the relationship between a_1'' and a_1'.

A. Response Calibration

The simplest two-port error network characterization is using the response or "thru" calibration. The measurement ports are connected via a known transmission network, often a flush zero-loss device, and the source and transmission are measured relative to the"thru".

To minimize notation, we can re-write (6) at the IF in amplitude and phase notation with the frequency suppressed:

$$\begin{aligned} a_1'' &= a_1'K_{a1}E_{lim1}(L_{LC1}A_{LO})\angle(-n\phi_{LC1}+\phi_{Ka1}) \\ b_1'' &= b_1'K_{b1}E_{lim1}(L_{LC1}A_{LO})\angle(-n\phi_{LC1}+\phi_{Kb1}) \\ a_2'' &= a_2'K_{a2}E_{lim2}(L_{LC2}A_{LO})\angle(-n\phi_{LC2}+\phi_{Ka2}) \\ b_2'' &= b_2'K_{b2}E_{lim2}(L_{LC2}A_{LO})\angle(-n\phi_{LC2}+\phi_{Kb2})\ . \end{aligned} \quad (7)$$

The reference value of the response calibration, with transmission $T\angle\phi_T$, is calculated at what is assumed to be the nominal state of the LO cables.

$$S_{21_{ref}}=\frac{b_2}{a_{1_{ref}}}=T\angle\phi_T=\frac{b_2''}{a_1''}_{ref}K_{21_{ref}}=$$
$$K_{21_{ref}}\frac{b_2'}{a_{1_{ref}}'}\frac{K_{b2}E_{lim2}(L_{LC2}A_{LO})\angle(-n\phi_{LC2}+\phi_{Kb2})}{K_{a1}E_{lim1}(L_{LC1}A_{LO})\angle(-n\phi_{LC1}+\phi_{Ka1})} \quad (8)$$

$$S_{12_{ref}}=\frac{b_2}{a_{1_{ref}}}=T\angle\phi_T=\frac{b_1''}{a_2''}_{ref}K_{12_{ref}}=$$
$$K_{12_{ref}}\frac{b_1'}{a_{2_{ref}}'}\frac{K_{b1}E_{lim1}(L_{LC1}A_{LO})\angle(-n\phi_{LC1}+\phi_{Kb1})}{K_{a2}E_{lim2}(L_{LC2}A_{LO})\angle(-n\phi_{LC2}+\phi_{Ka2})}$$

A calibrated response measurement can be made by solving for $K_{21_{ref}}$

$$K_{21_{ref}}=T\angle\phi_T/\left(\frac{b_2''}{a_1''}_{ref}\right),\ K_{12_{ref}}=T\angle\phi_T/\left(\frac{b_1''}{a_2''}_{ref}\right) \quad (9)$$

If a differential change is now added to the LO cables, as happens in moving antenna measurements, we see an amplitude and phase change (e.g. the port 1 LO cable transmission, $L_{LC1}\angle\phi_{LC1}$, becomes $L_{LC1}(1+\Delta_{LC1})\angle\phi_{LC1}(1+\Delta\phi_{LC1})$). This effects the single-direction measurement of S_{21}:

$$S_{21_{meas}}=\frac{b_2}{a_1}\sim\frac{b_2''}{a_1''}K_{21_{ref}}=\frac{b_2''}{a_1''}T\angle\phi_T/\left(\frac{b_2''}{a_1''}_{ref}\right)=\frac{b_2'}{a_1'}$$
$$\frac{K_{b2}E_{lim2}(L_{LC2}(1+\Delta_{LC2})A_{LO})\angle(-n\phi_{LC2}(1+\Delta\phi_{LC2})+\phi_{Kb2})}{K_{a1}E_{lim1}(L_{LC1}(1+\Delta_{LC1})A_{LO})\angle(-n\phi_{LC1}(1+\Delta\phi_{LC1})+\phi_{Ka1})}$$
$$T\angle\phi_T\frac{a_1'}{b_{2_{ref}}'}\left[\frac{K_{a1}E_{lim1}(L_{LC1}A_{LO})\angle(-n\phi_{LC1}+\phi_{Ka1})}{K_{b2}E_{lim2}(L_{LC2}A_{LO})\angle(-n\phi_{LC2}+\phi_{Kb2})}\right]. \quad (10)$$

If there are no changes in the LO cables, (10) reduces to the standard calibrated thru result. However, changes in either of the LO cables will directly translate into changes in the measured transmission: the standard side-effect of using a single-direction measurement. So, the measurement of just S_{21} or S_{12} using the VNA receivers may be compromised.

However, if we can assume that the antenna measurement is reciprocal, $S_{21}=S_{12}$, or $b_2/a_1=b_1/a_2$, we can look at (10) and see that S_{12} has an inverse relationship with LO changes from S_{21}. If both directions are measured and the geometric mean of the results are taken, it can cancel out the LO drift effects:

$$\sqrt{S_{21_{meas}}S_{12_{meas}}}=\sqrt{\frac{b_2''}{a_1''}K_{21_{ref}}\frac{b_1''}{a_2''}K_{12_{ref}}}$$
$$=\sqrt{\frac{b_2''}{a_1''}\left(T/\left(\frac{b_2''}{a_1''}_{ref}\right)\right)\frac{b_1''}{a_2''}\left(T/\left(\frac{b_1''}{a_2''}_{ref}\right)\right)}=\Bigg\{\frac{b_2'}{a_1'}$$
$$\left[\frac{K_{b2}E_{lim2}(L_{LC2}(1+\Delta_{LC2})A_{LO})\angle(-n\phi_{LC2}(1+\Delta\phi_{LC2})+\phi_{Kb2})}{K_{a1}E_{lim1}(L_{LC1}(1+\Delta_{LC1})A_{LO})\angle(-n\phi_{LC1}(1+\Delta\phi_{LC1})+\phi_{Ka1})}\right]$$
$$T\angle\phi_T\frac{a_1'}{b_{2_{ref}}'}\left[\frac{K_{a1}E_{lim1}(L_{LC1}A_{LO})\angle(-n\phi_{LC1}+\phi_{Ka1})}{K_{b2}E_{lim2}(L_{LC2}A_{LO})\angle(-n\phi_{LC2}+\phi_{Kb2})}\right]\frac{b_1'}{a_2'}, \quad (11)$$
$$\left[\frac{K_{b1}E_{lim1}(L_{LC1}(1+\Delta_{LC1})A_{LO})\angle(-n\phi_{LC1}(1+\Delta\phi_{LC1})+\phi_{Kb1})}{K_{a2}E_{lim2}(L_{LC2}(1+\Delta_{LC2})A_{LO})\angle(-n\phi_{LC2}(1+\Delta\phi_{LC2})+\phi_{Ka2})}\right]$$
$$T\angle\phi_T\frac{a_2'}{b_{1_{ref}}'}\frac{K_{a2}E_{lim1}(L_{LC2}A_{LO})\angle(-n\phi_{LC2}+\phi_{Ka2})}{K_{b1}E_{lim1}(L_{LC1}A_{LO})\angle(-n\phi_{LC1}+\phi_{Kb1})}\Bigg\}^{\frac{1}{2}}$$

$$=\sqrt{\frac{b_2'}{a_1'}\left(T/\left(\frac{b_2'}{a_{1_{ref}}'}\right)\right)\frac{b_1'}{a_2'}\left(T/\left(\frac{b_1'}{a_{2_{ref}}'}\right)\right)}=\sqrt{\frac{b_2}{a_1}\frac{b_1}{a_2}}=\sqrt{S_{21}S_{12}}=S_{12}=S_{21}$$

B. Practial Implementation

Equation (11) shows that measured geometric mean of the forward and reverse measurements can be an estimate of the transmission through a passive, bi-directional, down-converting receiver setup. However, (11) has multiple solutions to the phase of the transmission signal [1]. If the net LO phase changes, $n(\Delta\phi_{LC1}-\Delta\phi_{LC2})>\pi$, there can be an angle ambiguity, Fig. 3, because there are two solutions to square root in (11) that are separated by π. The correct branch can be found by keeping the movements small between RF measurements so to track the best branch, or by taking a broad frequency sweep so the correct solution can be chosen to keep the phase consistent.

C. Reflection Measurments

Since reflection measurements use a single port, they only require one LO cable. Re-writing (11) for one-port results in:

$$S_{11} = \frac{b_1}{a_1} \propto \frac{b_1'}{a_1'} \frac{K_{a_1'} E_{limA}(L_{LOA} A_{LO}) \angle\left(-n\phi_{LOA} + \phi_{a_1'}\right)}{K_{b_1'} E_{limA}(L_{LOA} A_{LO}) \angle\left(-n\phi_{LOA} + \phi_{b_1'}\right)}. \quad (12)$$

(12) shows that the single-port scattering parameters are primarily dependent on one LO cable, so drift effects are normalized and reduced.

D. Other Calbration Methods

As the dominant term in the transmission error correction in most two-port calibrations is the transmission coefficient of the reference thru, a form of (10) is relevant in systems similar to Fig. 2(c). Estimating the transmission using $\sqrt{S_{21}S_{12}}$ with LO cable drift can be used for other two-port calibration methods such as TRL[9], SOLT, and "Unknown-Thru"[9]. A major advantage of using the "unknown-thru" in antenna measurements is that VNA calibrations can be done with the test antennas in place: this avoids the need for a mechanical-thru connection between the test ports, limiting port movement when measuring the standards during RF calibration.

V. MEASURED DATA

We performed a two-port LRL calibration in WR-05 from 140-180 GHz. The xn up-conversion factor was 12 and the IF was set at 100 MHz. A power calibration was performed to ensure the LO was in the proper power range for the frequency converters. Fig 4. Shows the results viewing the flush-thru after calibration, so all data should be 0 dB and 0°. Moving the LO cable for each port shows minimal amplitude change but large phase changes. Using the measured $\sqrt{S_{21}S_{12}}$ to estimate S_{12} shows promise even when a 2-cm 2-dB pad is inserted into the LO line.

VI. UNCERTAINITY IMPLICATIONS

The random sampling noise in $\sqrt{S_{21}S_{12}}$ has the potential to be larger than in S_{12} or S_{21}. So, for systems with small levels of LO stress this may increase uncertainty in the transmission results.

VII. CONCLUSION

The geometric mean of the measured forward and reverse transmission, in a system that has drift due to LO cable movement, can be used to estimate the actual drift-free transmission. This method requires a measurement of a passive and reciprocal system using a bi-directional remote down-converting receiver system. This method is especially useful when LO cable stresses are expected to be electrically large, as in antenna measurements and high-frequency measurements where movement of the test ports is much greater than a wavelength.

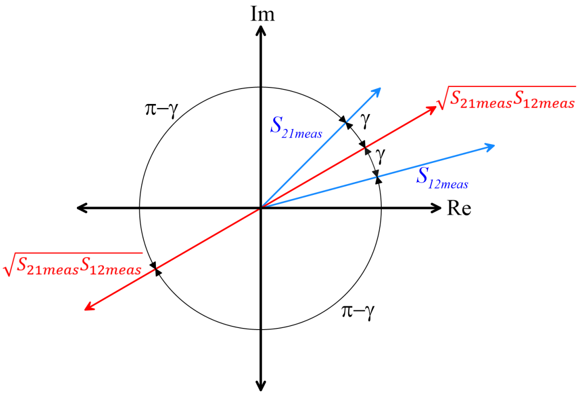

Figure 3. Geometric mean of the forward and reverse transmission measurement showing both solutions.

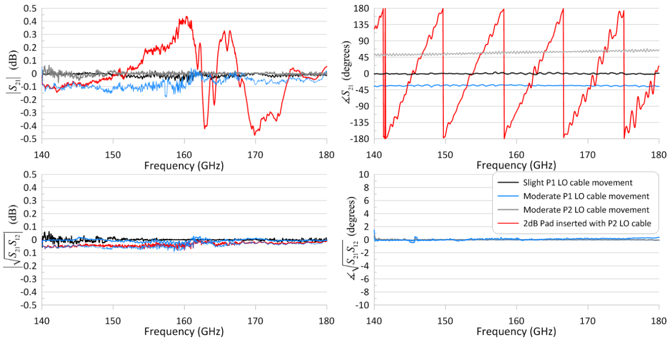

Figure 4. Transmission estimation of a flush thru using the measured $S_{21}$and $\sqrt{S_{21}S_{12}}$ with LO cable movement and inserting a 2 dB pad into the LO line. The majority of amplitude errors are reduced by the limiter in the converter, phase and residual amplitude errors are reduced by $\sqrt{S_{21}S_{12}}$.

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