Application Note

GROUP DELAY MEASUREMENT ON FREQUENCY CONVERTING DEVICES

Products:

► R&S®ZNA26

► R&S®ZNA43

Thilo Bednorz | 1EZ81 | Version 1e | 02.2022

Note:

Please find the most up-to-date document on our homepage https://www.rohde-schwarz.com/applications/1ez81

Contents

1 Overview

Frequency converters e.g. in satellite transponders need to be characterized not only in terms of amplitude transmission but also in terms of phase transmission or group delay, especially with the transition to digital modulation schemes. They often do not provide access to the internal local oscillators. This application note describes a method using the R&S®ZNA analyzer family to measure group delay of mixers and frequency converters with an embedded local oscillator very accurately. The key aspect of this new technique is that the network analyzer applies a 2-tone signal to the frequency converter. By measuring the phase differences between the two signals at the input and at the output, it calculates group delay and relative phase.

2 Abstract

Mixers are one of the fundamental components of many receiver or transmitter, especially in the microwave range. Any mixer-based receiving or transmitting system requires that the system has well-controlled amplitude, phase and group-delay responses. Especially phase-linearity and constant group-delay are essential for low bit error rates of data transmission or high target resolution for phased antenna array modules of surveillance systems.

A key measurement is the relative and/or absolute group delay for frequency converters. **Relative phase** and **group delay** can be measured using the so-called reference or golden mixer technique, as long as the local oscillator is accessible. However, due to increasing integration and miniaturization often neither the local oscillator (LO) nor a common reference frequency signal are accessible.

This application note describes a technique for measurements on frequency converters with an embedded LO source and without direct access to a common reference signal. Key for this technique is, that the network analyzer stimulates the device under test with a 2-tone signal. By measuring the phase differences between these two signals at both the input and the output, the network analyzer calculates the phase transfer function or the group delay of the device under test.

The measurement accuracy does not depend on the embedded LO's frequency stability as long as the deviation is within the measurement bandwidth of the network analyzer's receivers.

3 Theoretical Background

Group delay measurements are based on phase measurements. The measurement procedure corresponds to the definition of group delay τ_{gr} as the negative derivative of the phase φ (in degrees) with respect to frequency f:

$$\tau_{gr} = -\frac{1}{360°} \bullet \frac{d\varphi}{df}$$

For practical reasons, Vector Network Analyzers measure a difference coefficient of the transmission parameter S_{21} instead of the differential coefficient, which yields a good approximation to the wanted group delay τ_{gr}, as long as the variation of phase φ can be assumed to be linear in the observed frequency range Δf, which is called the aperture.

$$\tau_{gr} = -\frac{1}{360°} \bullet \frac{\Delta\varphi}{\Delta f}$$

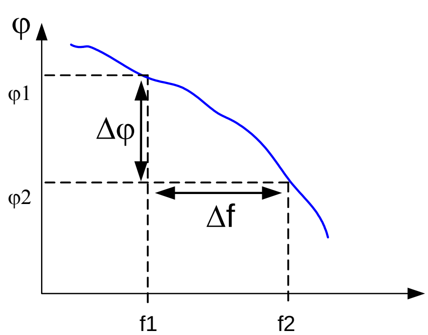


Figure 1: Definition of phase shift and $\Delta\varphi = \varphi_2 - \varphi_1$ and $\Delta f = f_2 - f_1$

The figure above shows the terms $\Delta\varphi = \varphi_2 - \varphi_1$ and $\Delta f = f_2 - f_1$ for linearly decreasing phase response, e.g. of a delay line.

For non-frequency converting devices the measurements of S_{21} at two different frequencies can happen sequentially. This works fine for non-frequency converting DUTs such as filters and amplifiers.

With frequency converting devices like mixers, the phase between the input and output signal cannot be measured directly, because the frequencies are different. Also, the phase is not only influenced by the component itself, but also by the phase of the local oscillator for the MUT (mixer under test).

Therefore, phase and group delay measurements on mixers use so-called reference mixer technique. The reference mixer uses the same local oscillator as the device under test to reconvert either the RF or IF signal in order to get identical frequencies at the reference and measurement receivers of the VNA. This technique also helps to get rid of phase instabilities of the local oscillator.

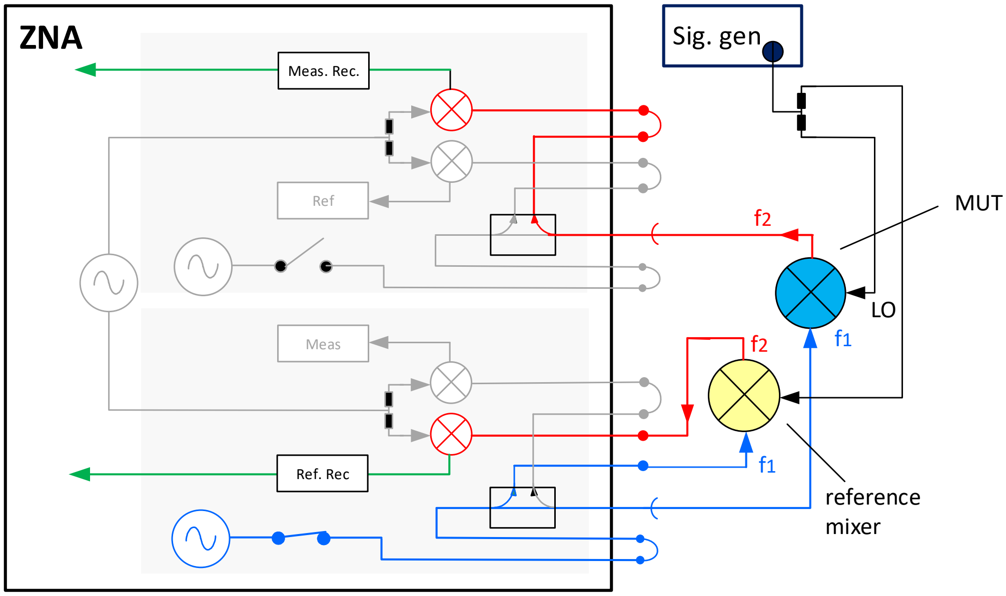


Figure 2: Group delay measurement using the reference mixer technique

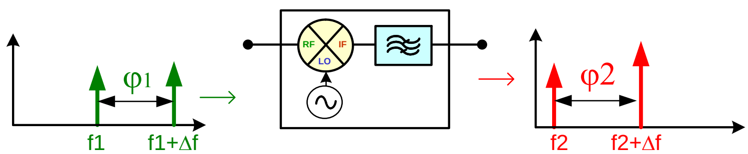
This measurement delivers phase and group delay relative to a calibration- or golden mixer used for calibration instead of the mixer under test.
The mixer for calibration can be a passive mixer as golden mixer that is assumed to be ideal or it is characterized using R&S®ZNA-K5 option.

If the LO of the device under test is not accessible, group delay measurements are not possible using a reference mixer technique, because any frequency difference between the DUT's LO and the LO for the reference mixer are directly converted into a phase error.
One solution is to use AM or FM modulated signals, other methods try to reconstruct the LO. The "LO reconstruction technique" uses an internal or external signal source as LO for the reference mixer and try to tune the source frequency until the phase drift versus time of the IF is minimized.
These techniques have limitations in terms of dynamic range, measurement accuracy and speed. In addition, internal local oscillators of the device under test often are not very stable, which makes it hard for the signal source to follow.

The R&S®ZNA uses a different approach, which overcomes the problems of the former techniques.

4 The Two-Tone Method

This method offered with option R&S®ZNA-K9 uses a two-tone signal, to stimulate the device under test.

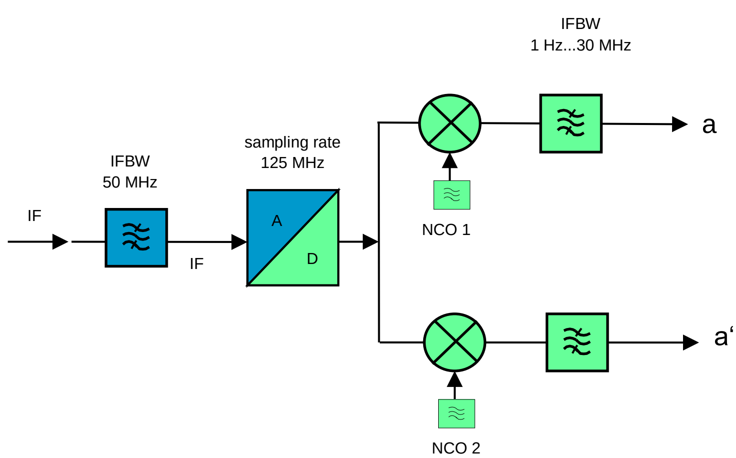


The R&S®ZNA measures the phase differences between both carriers simultaneously first at the input and then at the output of the device under test. Then, the group delay is calculated as:

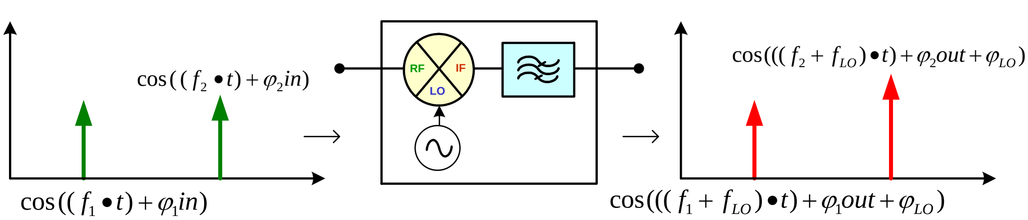
$$\tau = \frac{-1}{360^\circ} \bullet \frac{\Delta\varphi}{\Delta f} \qquad with \quad \Delta\varphi = \varphi 2 - \varphi 1;$$

The frequency difference Δf between both carriers is called the aperture.

To measure the phase difference of two carriers, the R&S®ZNA provides for each analogue receiver channel two digital receivers that measure both signals simultaneously.



This technique works also in case of a frequency converting DUT, because frequency and phase instabilities of the DUT's LO are cancelled out, when calculating Δφ.

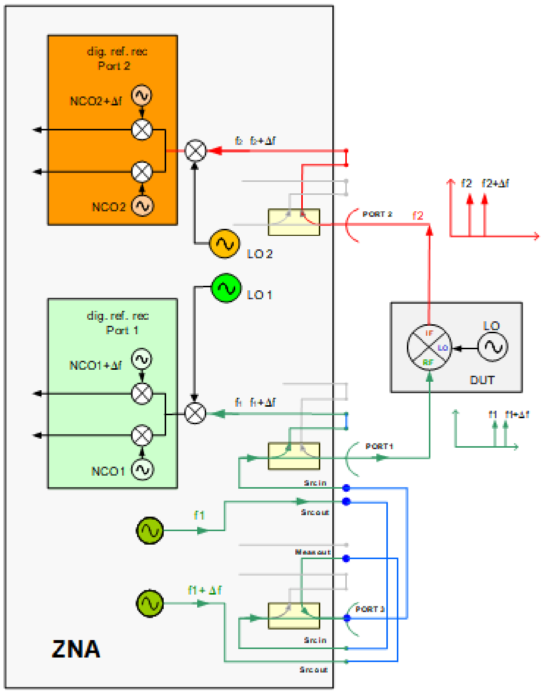


$$\Delta\varphi = (\varphi_{2out} + \varphi_{LO} - \varphi_{1out} - \varphi_{LO}) - (\varphi_{2in} - \varphi_{1in})$$

Beside group delay, the R&S®ZNA also calculates the relative phase of the DUT by integration of the group delay. Using a mixer with known group delay for calibration, e.g. characterized with R&S®ZNA-K5 option, provides absolute group delay. If only relative group delay is necessary, a **golden mixer** is sufficient for calibration.

The measurements of the phase differences between the carriers at input and output happen sequentially, first with the reference receiver at RF frequency f_1 and then with the measurement receiver at IF frequency

f_2. With hardware option R&S®ZNA-B5, that provides two internal local oscillators (LO 1 and LO 2) for the ZNA receivers, both measurements on RF- an IF-frequency of the MUT can happen simultaneously. This decreases measurement time by factor 2 and improves trace noise significantly. LO 1 is routed to the receivers of Port 1 and Port 3, while LO 2 is routed to the receivers of Port 2 and Port 4. Therefore, it is recommended to connect the input of the DUT to Port 1 or Port 3 and the output to Port 2 or Port 4.



4.1 Test Setup

The following accessories are required:

Designation	Type
Vector Network Analyzer	R&S®ZNA 4-port
Direct Generator / Receiver Access	R&S®ZNA-B16
Frequency Conversion	R&S®ZNA-K4
Embedded LO Mixer Delay Measurement	R&S®ZNA-K9
Cable Set for ZNA-K9 (recommended)	R&S®ZNA-B9
2nd internal LO (recommended)	R&S®ZNA-B5
Calibration mixer	R&S®ZV-ZM292

This example measures a converter with the following settings:

Swept RF and IF, fixed LO, IF=RF-LO

RF frequency: 1.5 GHz to 1.8 GHz
LO frequency: 1 GHz
IF frequency: 500 MHz to 800 MHz

4.1.1 The Hardware Setup

For accurate measurements, it is necessary to generate a two tone signal with an accurate and stable frequency offset. The R&S®ZNA provides this signal by using two sources of a 4-port model. The two tone signal is generated by using an external combiner or using one of the ZNA's internal couplers as combiner.

For that purpose, perform the following connections:

Src Out (Port 1) -> Src In (Port 3)
Src Out (Port 3) -> Meas Out (Port 3)
Port 3 -> Src In (Port 1)

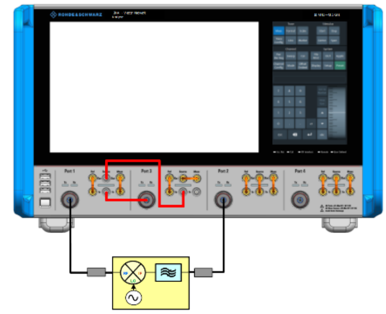


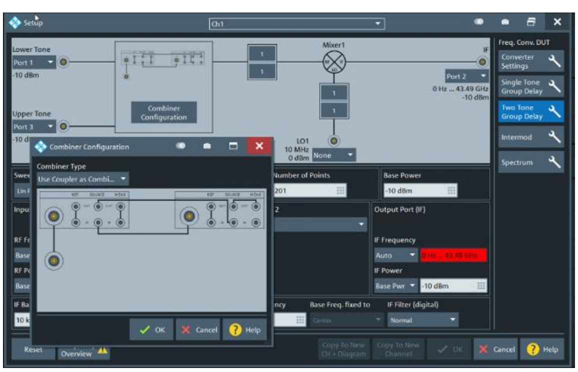
Figure 3: Setup using the internal coupler as combiner

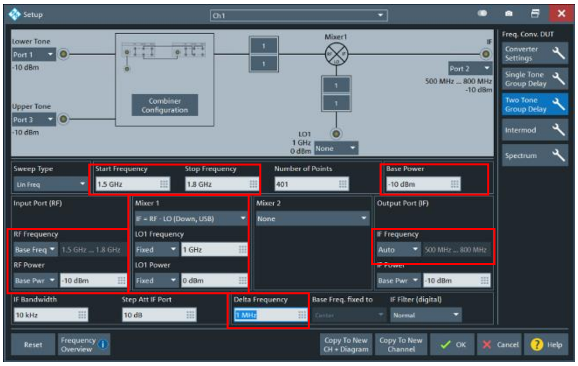
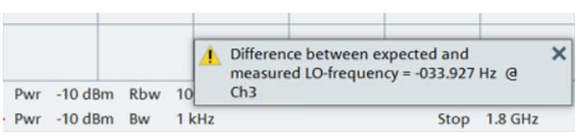
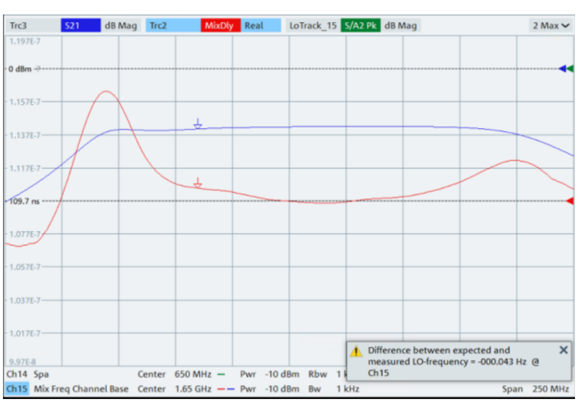
Rohde & Schwarz offers with the R&S®ZNA-B9 a cable set for the different types of ZNA (see order information).

Thus, the two tone signal runs via the reference receiver of Port 1 to the input of the DUT.

Thus, the two tone signal runs via the reference receiver of Port 1 to the input of the DUT. This setup is recommended for all R&S®ZNA models, as long as IF and RF frequencies are above 200 MHz. For Input or output frequencies below 200 MHz, the loss of the internal coupler roll off for the reference and/or the measurement paths at low frequencies will decrease the signal-to-noise ratio and thus increase the trace noise. If this is too high, alternative setups are recommended as indicated within the appendix. In case the DUT has poor port match it is recommended to improve the excellent raw test port match of R&S®ZNA furthermore with well-matched 6 dB to 10 dB attenuators at both ports directly in the measurement plane.
Typically the LO of the DUT differs slightly from the LO assumed for the settings, not only because of drift but also due to the finite frequency accuracy of the R&S®ZNA and the DUT. The R&S®ZNA has an internal LO tracking functionality that measures the frequency offset and changes the settings of the R&S®ZNA accordingly to ensure a stable trace so that small IF bandwidths can be used for better signal to noise ratio.

4.1.2 The Instrument Settings

	Configure the mixer measurement. Press **MEAS** - FREQUENCY CONVERTING – TWO TONE GROUP DELAY – SETUP FREQUENCY CONVERTING DUT Select how to connect the MUT to the ZNA and the ports providing the 2-tone signal; Here Port 1 and Port 3 use the internal coupler of port 3 as combiner for the two tone signal and Port 2 for the output of the DUT. Select the LO source; Because the LO of the DUT is internal, “NONE” is selected

 *The dialog can be closed by OK to apply the settigs to the active channel. A new channel can be added, by closing the dialog with COPY TO NEW CHANNEL or a new channel in a new diagram is added with COPY TO NEW CHANNEL AND DIAGRAM.*	Configure the frequencies and conversion type. Usually the input frequency is selected as Base Frequency and Base Power, that is also displayed on the frequency axis. **RF Frequency**: Base Freq **Start Frequency**: 1.5 GHz **Stop Frequency**: 1.8 GHz Base Power: -10 dBm Set the frequency aperture to e.g. 1 MHz in the **Delta Frequency** field. Conversion Mixer 1: IF=RF-LO (Down, USB) The IF Frequency (Auto) is calculated *The IF bandwidth should be as wide as the uncertainty of the DUT's internal LO.*
	After closing the dialog with OK, the conversion loss trace is displayed. It might be unstable due to the unknown LO. Switch on LO Tracking via: **MODE** - MODE – TRACK LO "On". The LO deviation is measured and displayed. The trace is stable now, the bandwidth can be decreased.
	Add a trace via: TRACE CONFIG – TRACES – Add Trace Select Group Delay via: **MEAS** – TWO TONE GROUP DELAY- TWO TONE GROUP DELAY RF->IF Conversion Loss (S21) and Group Delay (MixDly) are displayed

	Add a trace **TRACE CONFIG**-ADD TRACE Measure Conversion Phase **MEAS**-TWO TONE GROUP DELAY-CONVERSION PHASE Conversion Loss (S21) Group Delay and relative Phase are displayed
	Apply linearity Deviation to the phase trace to get deviation from linear phase. **TRACE CONFIG** – LINEARITY DEVIATION – AUTO LINEARITY DEVIATION – TRACKING ON

Alternatively, an external generator can be used instead of a 2nd source of R&S®ZNA but is not recommended. The reason is that high phase stability of the sources is critical.
The selected aperture in this example is 1 MHz. This means that the frequency offset Δf between both carriers is 1 MHz. The aperture for the mixer group delay measurement can be changed in this dialog only, not in the Format menu, which is only dedicated to select the aperture for ratios and S-parameters.
The measurement bandwidth should be as wide as the embedded LO's frequency stability or frequency deviation, and can be decreased after applying LO tracking. Normal selectivity is sufficient, as long as the aperture is about 50 times wider than the measurement bandwidth. If the aperture is very small, selective IF-filters have to be used. Normally R&S®ZNA uses IF filters for fast settling and fast sweep speed. These filters have comparable high side lobes what might become a problem for measurements. For these cases, R&S®ZNA offers high selectivity IF filters with high side lobe suppression.

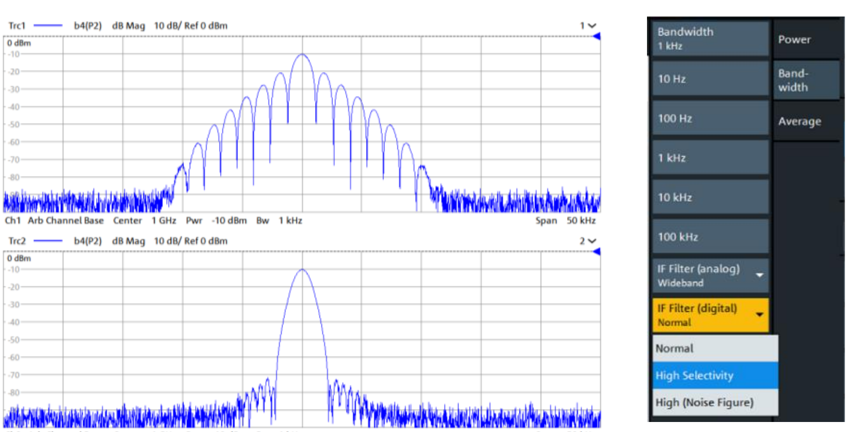
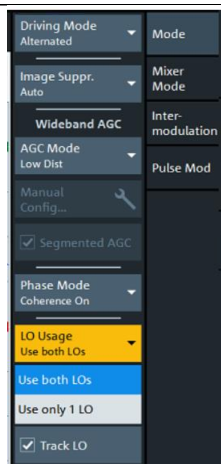


Figure 4: Sidelobe suppression of normal and high selectivity filters

4.1.3 Find Optimum Settings for Low Trace Noise

As soon as R&S®ZNA is equipped with a 2nd internal receiver LO (Option R&S®ZNA-B5) the two partial measurements of the input and the output signals are sampled simultaneously to provide minimum trace noise. This setting is selected by default and can be changed manually within the mode menu. The LO optimization should be set to “Use both LOs”. If the trace noise is still too high, perform one of the following measures.

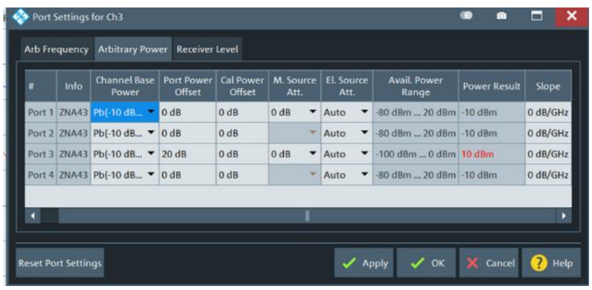
<table>
<tr><td>
</td><td>MODE – LO Optimization – Use Both LOs</td></tr>
<tr><td>
</td><td>Trace noise improvement using simultaneous measurements of input and output signals

Blue - Use only 1 LO

Red - Use both LOs</td></tr>
</table>

4.1.3.1 Increase the Power Level of Source 3

Using the cable set R&S®ZNA-B9 the source of Port 3 is injected into the coupler of Port 3 via Meas Out. Due to the coupling loss of about 10 dB, the signal is reduced by 10 dB. This means, that the power of the carrier from source 3 is lower than the carrier from source 1. The power of port 1 remains nearly unaffected. Increasing the power of source 3 will improve the trace noise. This can be done in the port configuration. In cases where Port 3 is not equipped with receiver step attenuator option R&S®ZNAxy-B33, a fixed attenuator in the Meas coupler path increases the attenuation to 20 dB. In this case the power has to be increased by 20 dB.

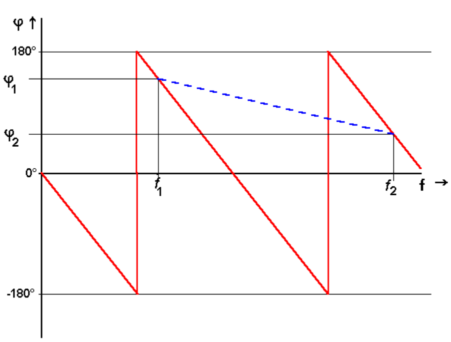
	Press: **CHANNEL CONFIG** – PORT CONFIG – Port Settings…
	Enter a 10 dB offset (or 20 dB offset in case without receiver step attenuator at Port 3) and close the dialog with ok. The power of port 1 is increased now by 10 dB (or 20 dB).

4.1.3.2 Apply Averaging

Reducing the IF bandwidth might help, but can lead to worse results if the embedded LO is unstable. Applying averaging instead, improves the trace noise without reducing the bandwidth.

4.1.3.3 Increase the Aperture

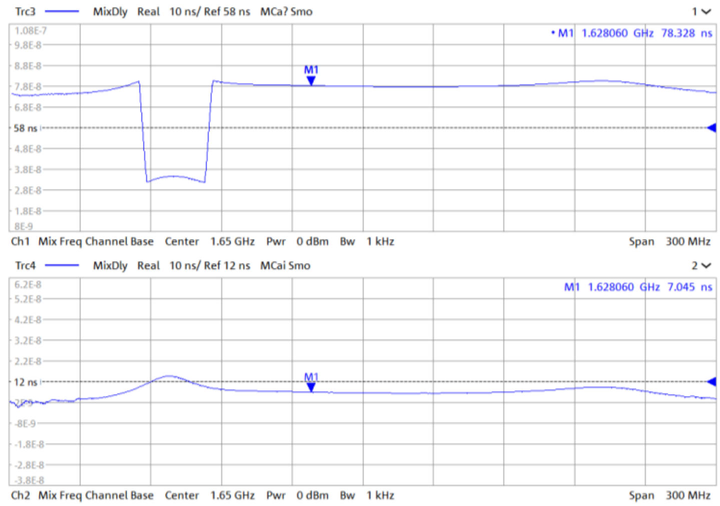
Increasing the aperture will also improve the trace noise. But there are limitations. Increasing the aperture, increases also the phase difference of the two tones. This phase difference should not exceed 180° otherwise the result is incorrect.



$$\Delta\varphi(f) = -360 \bullet \Delta f \bullet \tau$$

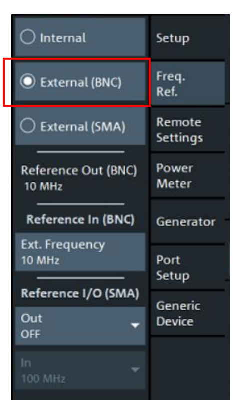
$$\Delta\varphi_{max} = 180° \Rightarrow \Delta f_{max} = \frac{0.5}{\tau}$$

The higher the group delay, the lower the maximum aperture. A DUT with 100 ns limits the maximum aperture to 5 MHz. The setup has to be recalibrated if the calibration is changed. An aperture too large will result in non continuous group delay measurement. In the screenshot below, the upper trace is measured with wrong aperture, the steps can be seen. The lower trace is measured with the correct aperture.



4.2 Calibration

The calibration is done with an ideally assumed mixer e.g. ZN-ZM292. This mixer has a flat group delay with a deviation of typical 100 ps. As alternative, any mixer can be characterized with the R&S®ZNA -K5 option beforehand. R&S®ZNA-K5 is an option to measure vector error corrected phase and group delay of mixers. Often absolute group delay is not required, but only relative group delay and group delay ripple. In these cases it is sufficient to use a mixer with linear phase and flat group delay for calibration an assumption that is valid for most cases.



Select a suitable aperture for the measurement before starting the calibration. Changing the aperture between calibration and measurement decreases the measurement accuracy. Connect the golden or calibration mixer instead of the DUT. Use a source of R&S®ZNA (in case the R&S®ZNA has four sources) or an external signal generator as LO if necessary. Set the frequency and the power level. Lock the reference frequencies of the external signal generator to the R&S®ZNA.

To lock the ZNA to the sig. gen connect a BNC cable and press:

SETUP – FREQ.-REF. - External **(BNC)**

Set the IF bandwidth to 100 Hz

PWR BW AVG – BANDWIDTH:

Meas Bandwidth: 100 Hz

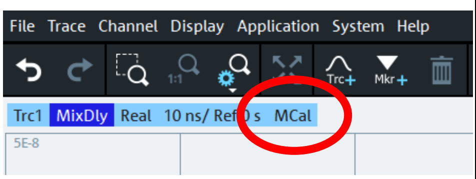
AVERAGE:
AVERAGE FACTOR: 10
AVERAGE ON

<table>
<tr>
<td>
</td>
<td>Press:

MEAS - TWO TONE GROUP DELAY

For absolute group delay, the delay of the calibration mixer has to be entered, either a fixed value or as an *.csv file with frequency dependent data.
For relative group delay, a constant Delay of 0 ns for the calibration mixer is assumed.

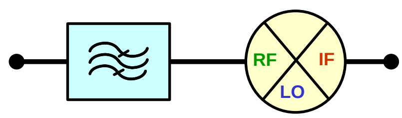
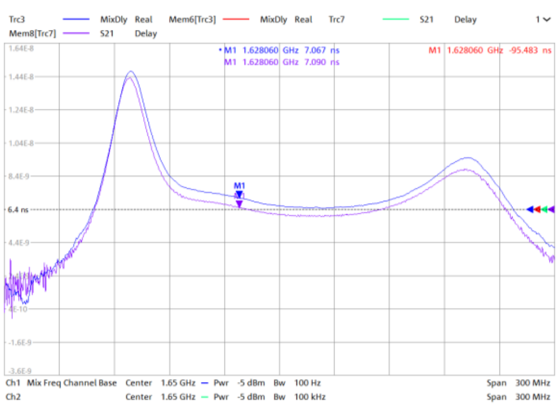
Connect the mixer for calibration and press:

MIXER DELAY CAL</td>
</tr>
<tr>
<td>
</td>
<td>MCAL In the trace line shows that the trace is calibrated for group delay.</td>
</tr>
</table>

5 Test Results

5.1 Measurement of a Converter

To prove the accuracy, the group delay of S21 of a filter, measured with full 2-port calibration is compared to the group delay of a combination of this filter with a mixer using the two tone technique.

<table>
<tr>
<td>
</td>
<td>The measurement results of the filter and the combination of filter and mixer are compared.</td>
</tr>
<tr>
<td>
</td>
<td>The purple trace shows the full two port calibrated measurement of the filter (in non frequency converting mode).

The blue trace shows the group delay of the entire converter, after calibrating with a golden mixer.

The maximum deviation of all measurements is less than 100 ps.</td>
</tr>
</table>

6 Conclusion

In the past, group delay and phase measurements of frequency-converting components without LO access were only possible if the DUT's internal LO satisfied high stability requirements. The two-tone technique of R&S®ZNA overcomes these problems and provides high accuracy independent whether the DUT's LO is unstable or drifting. An automated LO tracking functionality compensates even high frequency deviations. R&S®ZNA's new receiver concept, allowing simultaneous measurements of the input and the output signals doubles the measurement speed and drastically reduces the trace noise. This technique simplifies also measurement on frequency converters with multiple LO stages with and without LO access.

7 Ordering Information

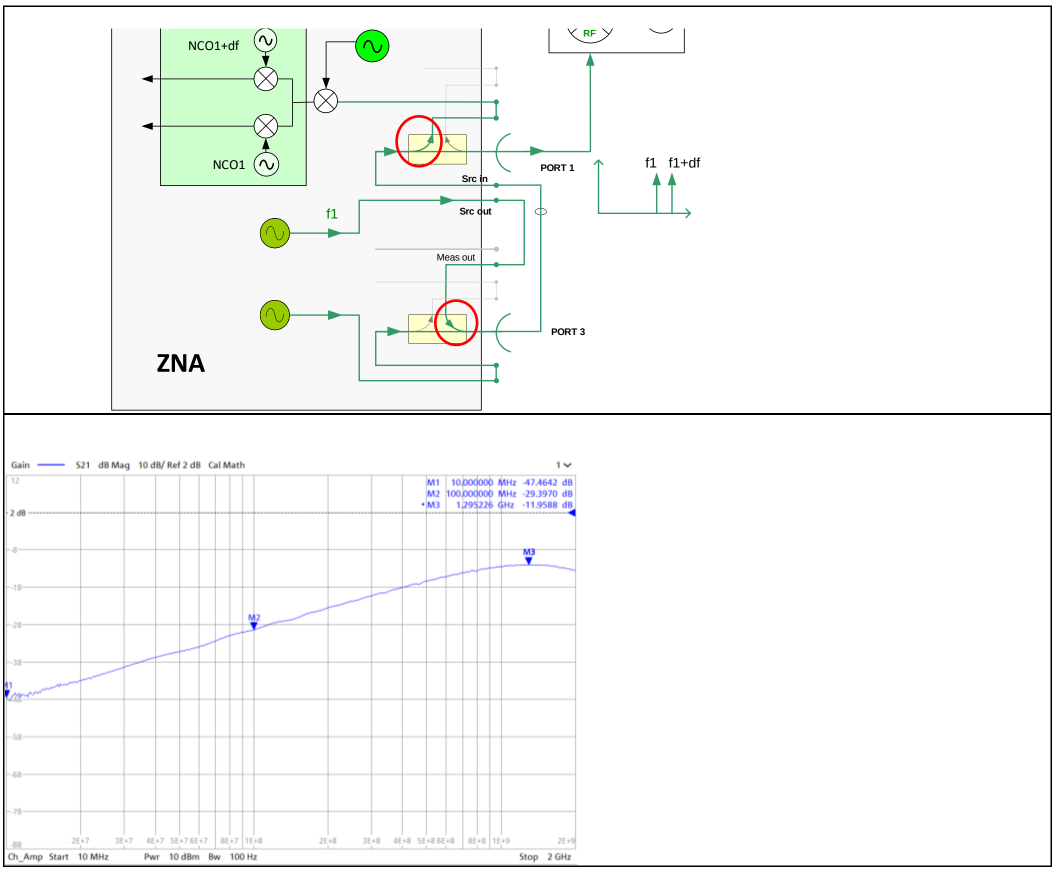
Designation	Type	Order No.
Vector Network Analyzer 4 Ports 26,5 GHz 3.5 mm connectors	R&S®ZNA26	1332.4500.24
Vector Network Analyzer 4 Ports, 43,5 GHz 2.92 mm connectors	R&S®ZNA43	1332.4500.44
Vector Network Analyzer 4 Ports, 43,5 GHz 2.4 mm connectors	R&S®ZNA43	1332.4500.45
Direct Source and Receiver Access for 4-port R&S®ZNA26	R&S®ZNA26-B16	1332.4581.24
Direct Source and Receiver Access for 4-port R&S®ZNA43	R&S®ZNA43-B16	1332.4581.44
3rd and 4th internal source for R&S®ZNA26 (4 ports)	R&S®ZNA26-B3	1332.4523.02
3rd and 4th internal source for R&S®ZNA43 (4 ports)	R&S®ZNA43-B3	1332.4617.02
2nd internal LO source for R&S®ZNA (4 ports)	R&S®ZNA-B5	1332.4675.02
Scalar mixer and arbitrary frequency-converting measurements	R&S®ZNA-K4	1164.1863.02
Group delay measurements on frequency converters without LO access[1]	R&S®ZNA-K9	1332.5394.02
Vector corrected converter measurements	R&S®ZNA-K5	1332.5359.02
Calibration mixer, 2.92 mm (f)	R&S®ZN-ZM292	1339.3800.02
Cable set for R&S®ZNA-K9 (3.5 mm for R&S®ZNA26	R&S®ZNA26-Z9	1332.4730.26
Cable set for R&S®ZNA-K9 (2.92 mm for R&S®ZNA43)	R&S®ZNA43-Z9	1332.4730.43
Cable set for R&S®ZNA-K9 (2.4 mm for R&S®ZNA43)	R&S®ZNA43-Z9	1332.4730.44

[1] Requires ZNA-K4

8 Appendix

A.1 Setup for Input Frequencies Below 200 MHz (Up-Conversion)

This case, with input frequencies below 1 GHz might have the biggest impact on the trace noise. The reason is, that the source from port 1 is attenuated by the loss of the coupler of port 3 that is used as combiner. The loss is about 10 dB above 1 GHz. With decreasing frequency, the loss increases to 50 dB at 10 MHz. This causes a bad S/N at the a1 receiver and thus a high trace noise. Minimizing the measurement bandwidth would improve the S/N but will become a problem in the case of DUTs with large LO drift.



In this case it is recommended to use two power splitters instead of the coupler to combine the two tones and two get a reference signal.

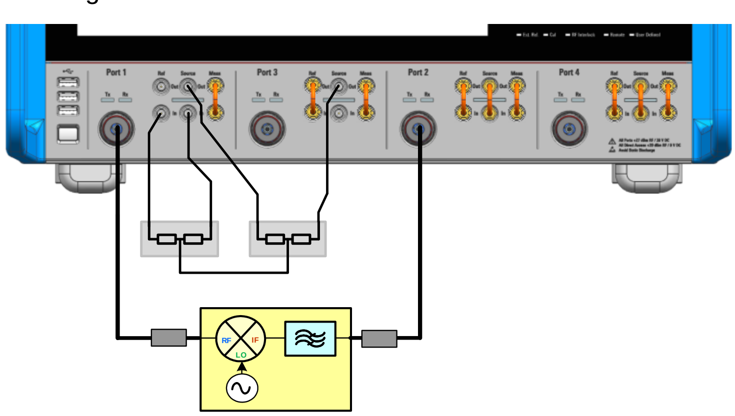
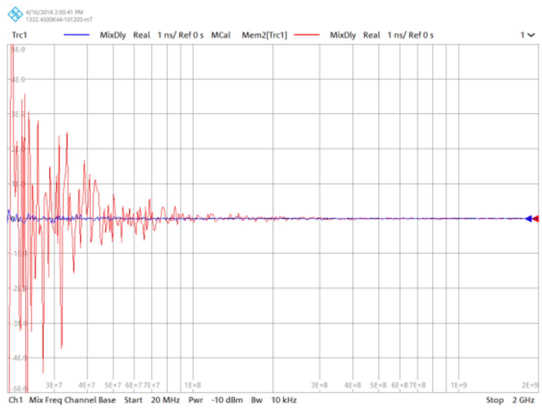
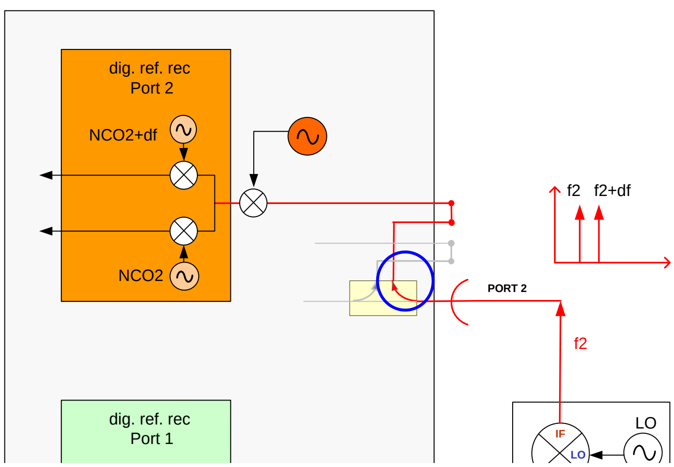


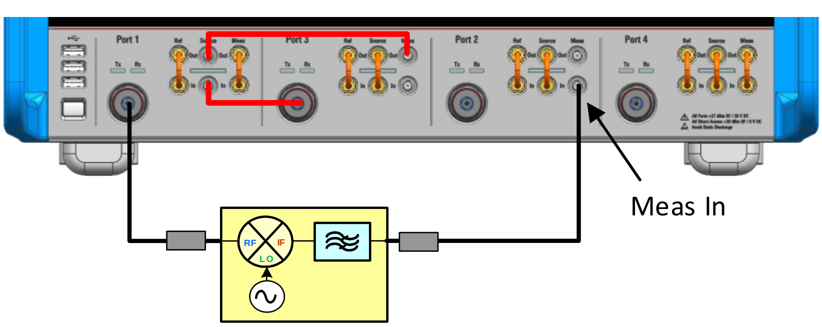
Figure 5: Improvement of trace noise using power splitters instead of the coupler as combiner

	Red: Conversion loss using the couplers Blue: Conversion loss using external power splitters Settings: Pin -10 dBm IFBw 10 kHz Freq.apert. 10 MHz

A.2 Setup for Output Frequencies Below 200 MHz (Down-Conversion)



To avoid the coupler loss at Port 2, the direct receiver access can be used. The output of the DUT then is connected to **Meas In** of Port 2 to access the receiver of Port 2 directly.



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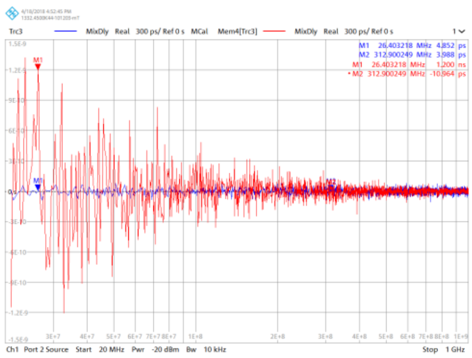
<tr>
<td>


</td>
<td>
Red: Conversion loss measuring Pout at the test port

Blue: Conversion loss measuring Pout at direct receiver input b2

Settings: Pout -20 dBm
IFBw 10 kHz
Freq.apert. 5 MHz
</td>
</tr>
</table>

Rohde & Schwarz

The Rohde & Schwarz electronics group offers innovative solutions in the following business fields: test and measurement, broadcast and media, secure communications, cybersecurity, monitoring and network testing. Founded more than 80 years ago, the independent company which is headquartered in Munich, Germany, has an extensive sales and service network with locations in more than 70 countries.

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Application Note | Group Delay Measurement on Frequency Converting Devices