Mastering Phase Noise Measurements (Part 2)

Application Note

Whether you are new to phase noise or have been measuring phase noise for years it is important to get a good understanding of the basics and to learn of new measurement techniques to improve your designs.

This series of application notes is broken up into three parts:

Part 2: What are the different measurement techniques and their advantages/disadvantages: direct spectrum analyzer, phase detector, delay line discriminator and we introduce our new digital phase demodulator technique

Note: This application is part two of a three part series. See the end of this application note to view the other two parts.

ROHDE & SCHWARZ

Table of Contents

2 Introduction

Phase noise is unintentional phase modulation on a signal that spreads the spectrum and degrades performance in many RF applications. Whether you are new to phase noise or have been measuring phase noise for years it is important to get a good understanding of the basics and to learn of new measurement techniques to improve your designs.

This series of application notes is broken up into three parts:

▪ Part 1: Understanding the basics of phase noise: why it is important, how does it impact different applications, and what causes phase noise

▪ **Part 2: What are the different measurement techniques and their advantages/disadvantages: direct spectrum analyzer, phase detector, delay line discriminator and we introduce our new digital phase demodulator technique**

▪ Part 3: How best to perform advanced measurements: additive phase noise, pulsed phase noise, and AM Noise

We will now cover part 2: Phase Noise Measurement Techniques

3 Phase Noise Measurement Techniques

Let's review the different measurement techniques that can be used for measuring phase noise. This does not represent all the techniques available, however they are the most common ones used nowadays.

3.1 Direct Spectrum Analyzer

The first and most basic technique uses a spectrum analyzer (Figure 2-1). Spectrum analzers have been used to measure phase noise for decades. It's a simple setup. An oscillator signal can be hooked up directly to the analyzer and a measurement is made.
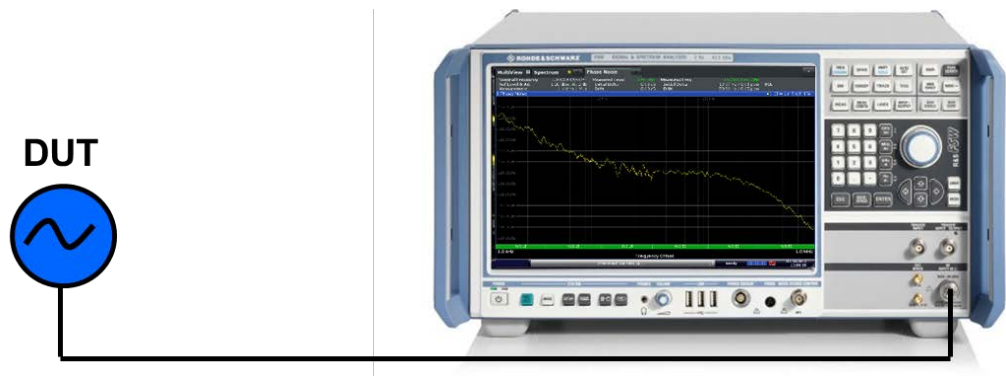

Fig. 2-1; Direct spectrum analyzer measurement setup.

Figure 2-2 shows a generalized block diagram of a modern spectrum analyzer. The incoming signal gets up-converted and down-converted multiple times before it gets to the baseband frequency, where the final signal is analyzed with the DSP hardware. The local oscillator (LO) at each of these stages can contribute phase noise to the overall measurement. For this reason, it is important to make sure that the spectrum analyzer phase noise is lower than the device-under-test (DUT).
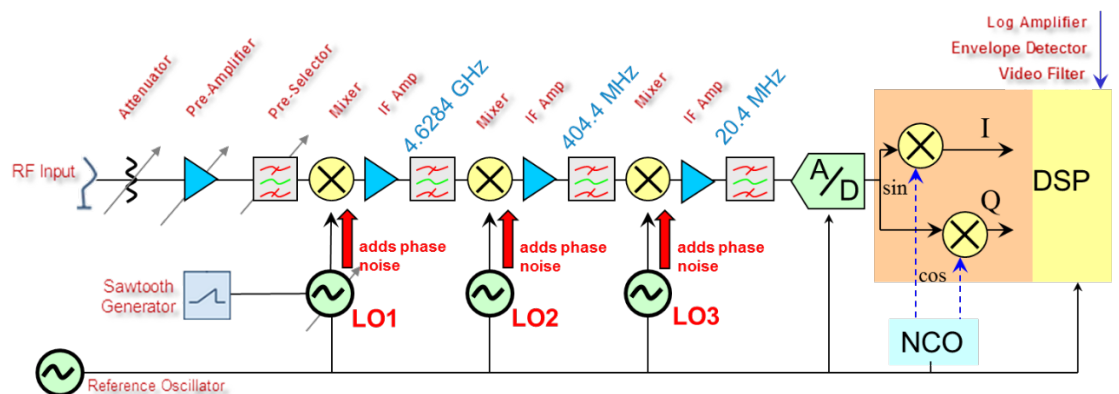

Fig. 2-2: Example direct spectrum analyzer block diagram.

The best way to know if a spectrum analyzer is good enough to make your measurement is to look in the datasheet. Figure 2-3 is a datasheet excerpt for the Rohde & Schwarz FSW spectrum analyzer. It shows, for various carrier frequencies, what the phase noise curves look like at various offsets. The table on the right shows how much measurement error to expect, based on the margin between the spectrum analyzer specification and the DUT's measured phase noise.

For example, if the spectrum analyzer is only 3 dB lower in phase noise than the DUT, the resulting measurement error is going to be +1.8 db. It will always read higher; it never reads lower. So this isn't an uncertainty value, this is bias. It actually adds and throws the measurement off by 1.8 dB in this case.

A general guideline would look to have at least 10 dB of margin between the desired DUT performance and the spectrum analyzer's phase noise. From the table it shows less than a 0.5 dB of measurement error. More is always better as far as margin goes.
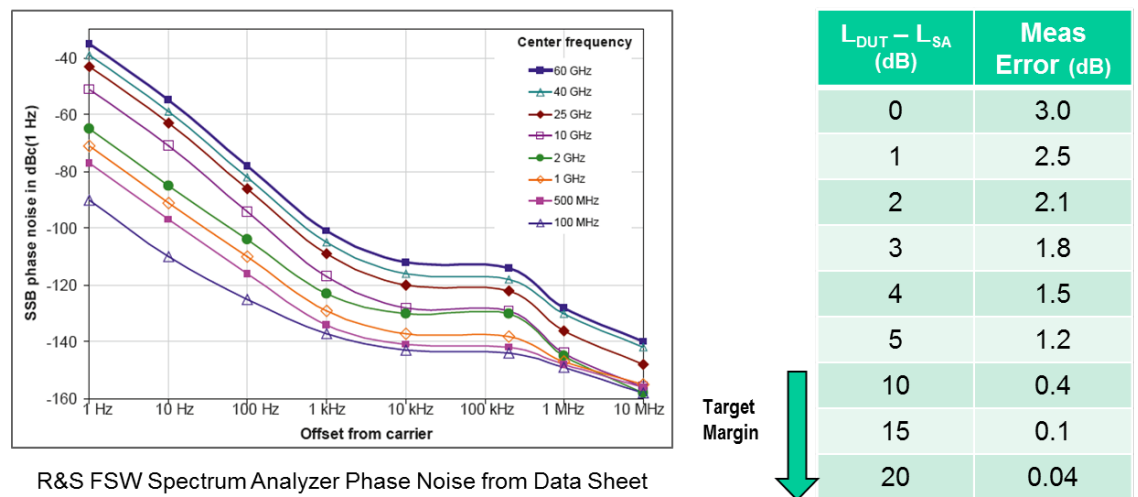

R&S FSW Spectrum Analyzer Phase Noise from Data Sheet

$L_{DUT} - L_{SA}$ (dB)	Meas Error (dB)
0	3.0
1	2.5
2	2.1
3	1.8
4	1.5
5	1.2
10	0.4
15	0.1
20	0.04

Target Margin

Fig. 2-3: Measurement sensitivity is limited by the internal phase noise of the spectrum analyzer.

Spectrum analyzers are usually used in one of two ways: manually or by using a phase noise personality. The manual mode, shown in Figure 2-4, places a marker on the signal peak and moves a second marker at a given offset. Even in manual mode, most spectrum analyzers offer a "phase noise marker", which measures the noise in a given resolution bandwidth and does a correction to normalize to 1 Hz. It also corrects for the Gaussian shaped filters used by the spectrum analyzer, which is called the effective noise bandwidth of the filter.

The manual mode often requires the use of averaging to smooth out the noise. It is important to use power averaging and not log averaging. Years ago, log averaging was the only averaging available on spectrum analyzers, but today modern analyzers will average in the power domain, the voltage domain, the linear domain or the log domain.
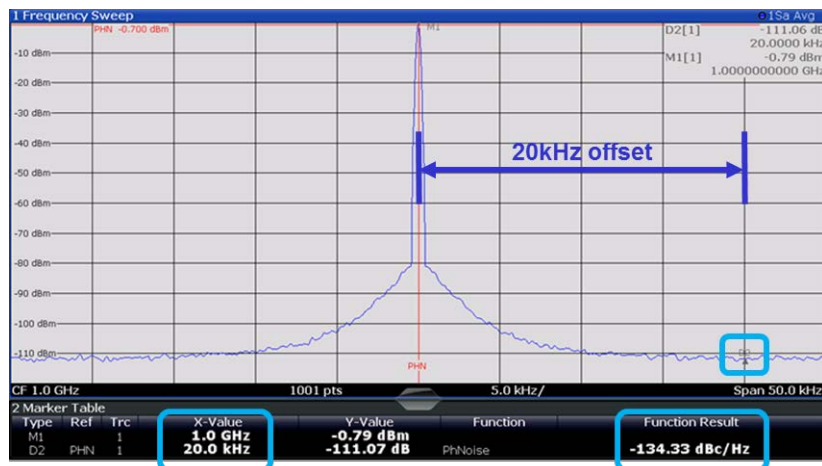
Fig. 2-4: Manual spot noise measurement.

Most spectrum analyzers today offer a phase noise measurement personality, which is typically an add-on option. It takes care of much of the instrument setup and displays the measurement in the typical phase noise format (Figure 2-5). The personality can list spot noise, show a spur list and the residual calculations such as FM, PM, jitter, and so forth.
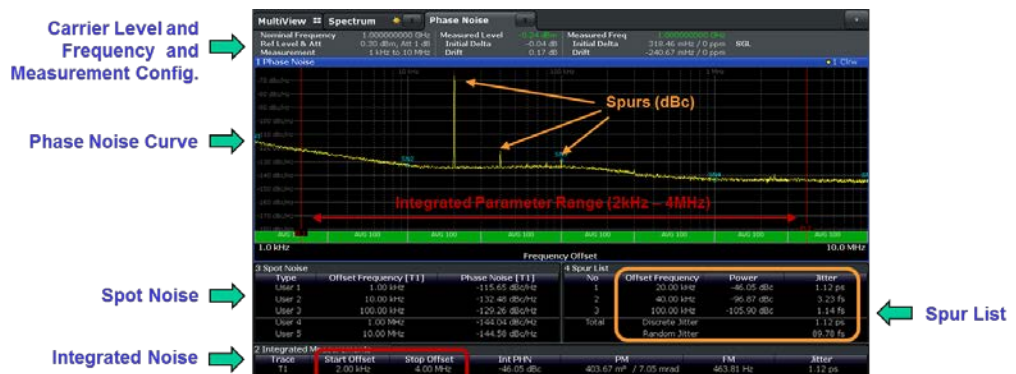

Fig. 2-5: A spectrum analyzer's phase noise measurement personality takes care of much of the instrument setup and displays the measurement in the typical phase noise format.

Spectrum analyzers do have a few limitations. They're scaler instruments, so they generally don't discern the difference between phase noise and AM noise. Normally that's not a problem because AM noise is much lower than the phase noise, especially close in.

Also, even the best spectrum analyzers have only a minimum resolution balance of 1 Hz. Trying to measure close in to a carrier in the neighborhood of 1 Hz or less can't be resolved. Not many applications need to measure that close, but there are some applications where it's important.

In summary, direct spectrum analyzer measurements are fast and easy to setup, especially if using a phase noise personality. Plus, a spectrum analyzer offers something that a dedicated phase noise analyzer may not offer – the ability to measure

other things on an oscillator, such as harmonics, adjacent channel power, or spurious and so forth.

A spectrum analyzer is a very versatile instrument, but remember that the sensitivity is limited by the internal phase noise of the spectrum analyzer itself. The datasheet can be used to determine whether it's an issue for you or not.

3.2 Phase Detector

So what happens when the DUT has lower phase noise than your spectrum analyzer? Luckily, the phase detector technique has been around for almost as long as spectrum analyzers. An example block diagram of a phase detector based solution or as they are known, a phase noise analyzer, is shown in Figure 2-6.
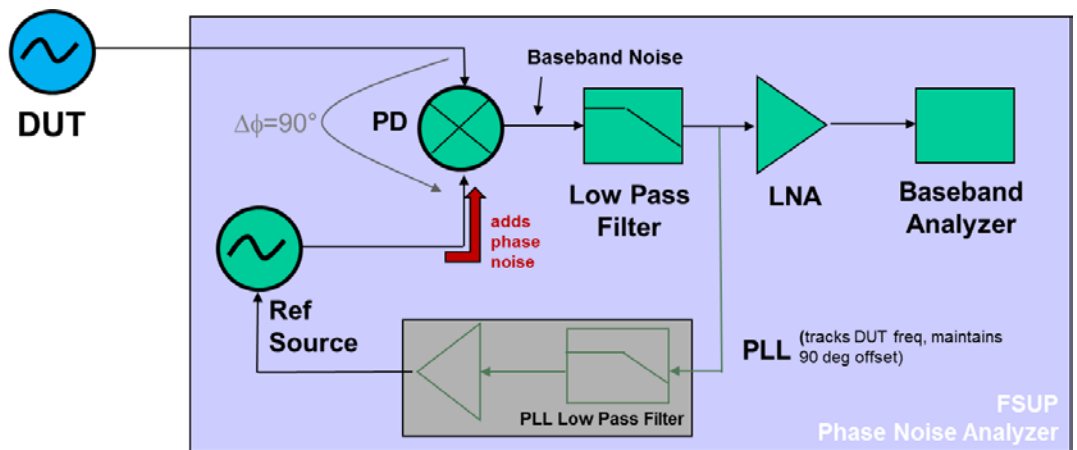

Fig. 2-6: Phase detector block diagram.

The phase detector is basically an RF mixer that has the same frequency going into both inputs. With mixers, the output signal is the sum and difference of the two input frequencies. In this case, where the two frequencies are equal, we get 2x of the frequency and the difference, which is zero or DC.

A benefit of this technique is that the carrier is not present anymore, only low level baseband noise. This reduces the need for high dynamic range. The 2x term is removed with a low pass filter. Adding a high gain, low noise amplifier further improves the sensitivity.

The reference source still adds phase noise, but since it is only a single conversion – not the three or four stages of conversion on a spectrum analyzer. With only one stage, the reference source can be tuned to be very low phase noise.

The phase noise analyzer has a phase lock loop in its design. This keeps the reference source frequency and phase locked to the incoming DUT signal. These two signals are phase locked at 90 degrees out-of-phase. They are kept in quadrature to each other to get the most sensitivity, which occurs right at that 90 degree point.

There is a downside to the phase lock loop. At offset frequencies below the phase lock loop bandwidth, it's also tracking the noise. The loop bandwidth is set as low as possible to still maintain tracking. When trying to make measurements below the loop bandwidth there's going to be some suppression of the DUT noise. Luckily, we know what that suppression characteristic is and can apply an inverse correction to it. A problem occurs when you get more than one to two decades below that loop bandwidth, the correction gets rather large and the uncertainty starts to increase. Try not to make measurements that offset it more than one or two decades below that loop bandwidth value.

Finally, because we no longer need to worry about the minimum resolution bandwidth filter, this technique is able to measure very close offsets since the carrier is no longer present. Down to 0.01 Hz is a typical value on this type of analyzer.

As with the spectrum analyzer technique, it is important to look at the margin between the device under test and the reference source, or the analyzer's inherent phase noise. The table from Figure 2-3 still applies and it is important to have 10 dB margin between the desired DUT performance and the measurement solution, just to keep the error down.

The output of a phase noise analyzer may be formatted differently on the display screen, but it contains all of the same information – spurs, a spot noise table, and residual calculations (Figure 2-7). The key benefit is the better sensitivity and better rejection of AM using this technique.

One final comment on this technique via a phase noise analyzer is that it is a specialized instrument. A key advantage of the spectrum analyzer technique is that it can also measure harmonics, adjacent channel power, digital modulations, etc.
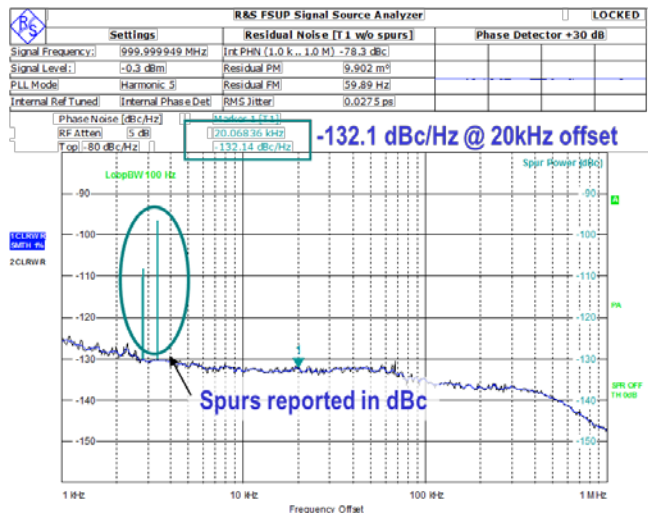

Fig. 2-7: Phase detector display presents results of phase noise, spot noise, integrated calculations, and spur detection (in dBc).

3.3 Phase Detector with Cross-Correlation

What happens if phase detection is still not sensitive enough to measure a super-quiet oscillator? Within the last 15 years or so, a new technique of adding a cross-correlation function has been introduced to improve the sensitivity of the phase detector technique even more.

The cross-correlation technique adds a duplicate set of hardware, a second identical path that includes a different reference oscillator (Figure 2-8). Why is this done? The Reference 1 and Reference 2 oscillators are uncorrelated from each other. By cross-correlating the results of the two measurements over time, the uncorrelated noise from Ref 1 and Ref 2 will tend to diminish, whereas the common noise from the DUT will not diminish. With enough cross-correlation, the measurement effectively reduces the phase noise of the two reference oscillators. If we perform 100 cross-correlations, it results in an effective 10 dB reduction in the reference phase noise. If we perform 10,000 cross-correlations, then it's 20 dB of reduction. This becomes a very sensitive way to make really low phase noise measurements using the phase detector technique with cross-correlation.
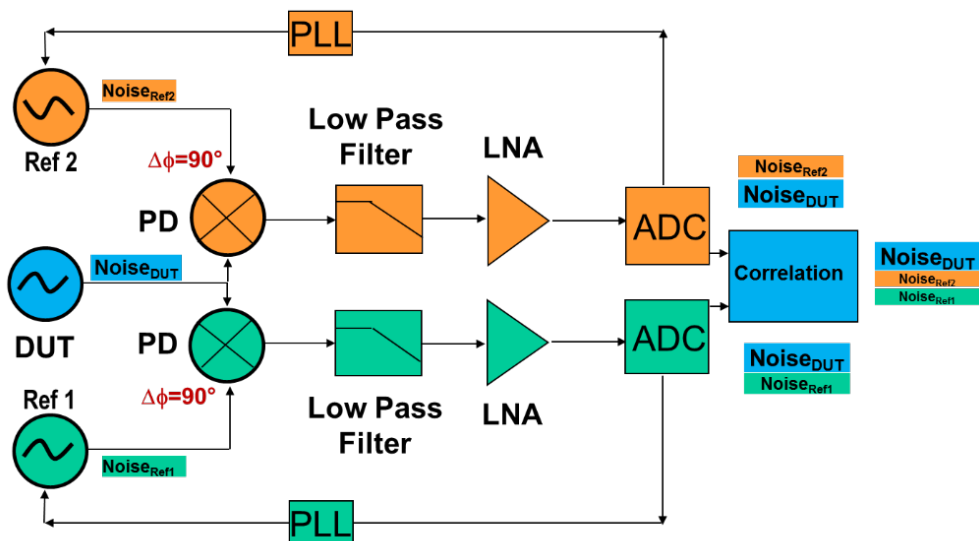

Fig. 2-8: Phase detector with cross correlation block diagram.

Figure 2-9 shows the result of a screenshot from an analyzer that uses cross-correlation. The DUT results are from the same oscillator as the one without cross-correlation (Figure 2-7). That measurement was about -132 dBc/Hz. With the same oscillator using cross-correlation, the result is -140, that's an 8 dB improvement in this example. Note that the measurement sensitivity improved by 20 dB, which resulted in a more accurate phase noise measurement showing an 8 dB improvement. This improvement actually matches the spec for that particular signal source.
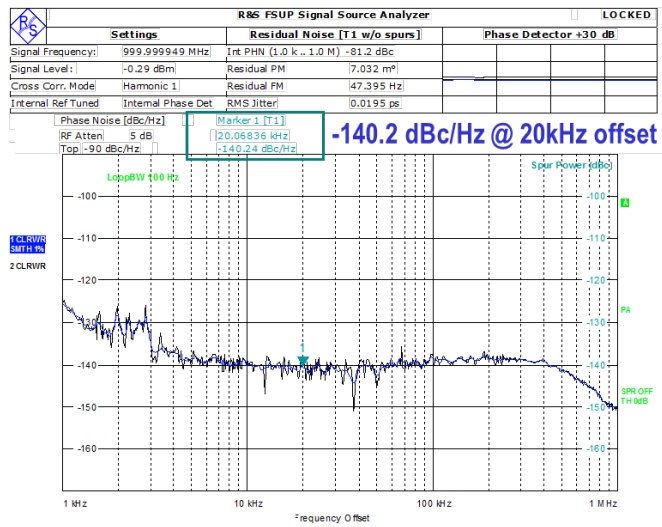
Fig. 2-9: Adding cross-correlation improves measurement sensitivity by 20 dB, resulting in a more accurate phase noise measurement.

3.4 Delay Line Discriminator

Another technique is the delay line discriminator, but it's not supported in Rohde & Schwarz equipment. This technique doesn't use a reference source, instead the DUT feeds into a power splitter, which goes to a long delay line on one side and a phase shifter on the other (Figure 2-10). The rest of the setup is similar to the other techniques.

The delay line converts frequency fluctuations to phase fluctuations, then the phase detector converts the phase fluctuations to voltage fluctuations. The phase shifter role is to achieve the 90 degree phase shift needed to maximize sensitivity.
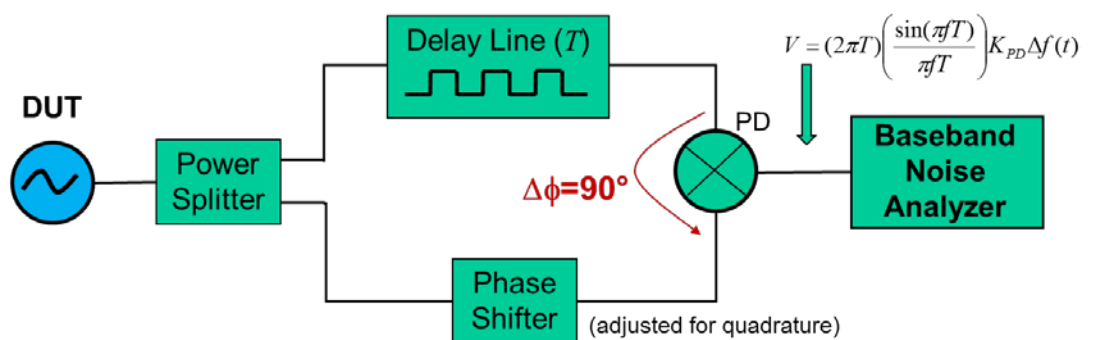

Fig. 2-10: Delay line discriminator block diagram.

This technique is good for noisy or drifting DUTs since no reference source is required. However, there's a reason that this isn't used that commonly and that is the delay line is going to have a lot of loss. This loss works against the sensitivity of the phase detector.

While the longer delay gives better sensitivity, it reduces the maximum usable frequency offset. In Figure 2-10 there is an equation in the upper right with a sin(x)/x term. This sin(x)/x term starts weighting the function down and, at high offsets, strange nulls in the phase noise curve appear (Figure 2-11). These aren't really a feature of the DUT, but a feature of the measurement technique. There is a limitation of this technique up to a frequency of 1/2π times the delay line length.
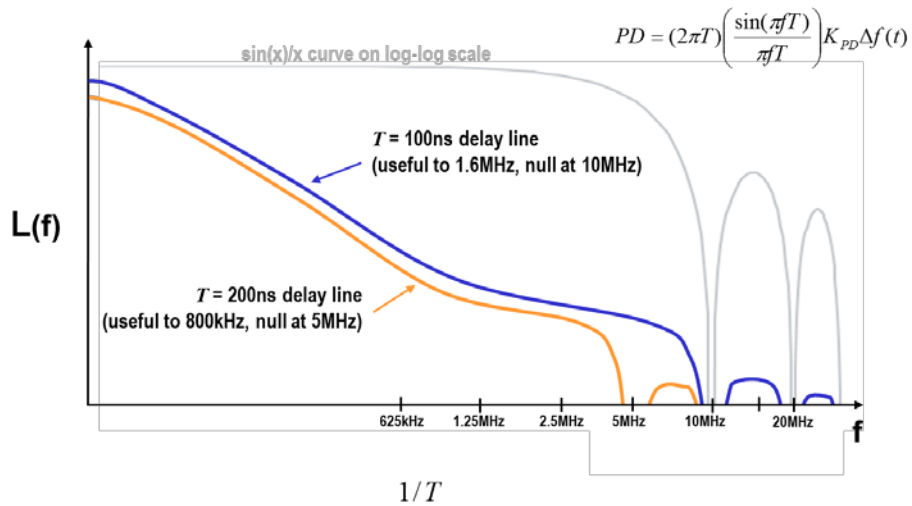

$$PD = (2\pi T)\left(\frac{\sin(\pi f T)}{\pi f T}\right)K_{PD}\Delta f(t)$$

sin(x)/x curve on log-log scale

$L(f)$

T = 100ns delay line
(useful to 1.6MHz, null at 10MHz)

T = 200ns delay line
(useful to 800kHz, null at 5MHz)

625kHz 1.25MHz 2.5MHz 5MHz 10MHz 20MHz f

$1/T$

Fig. 2-11: The longer delay gives better sensitivity, but reduces the maximum usable frequency offset.

3.5 Digital Phase Demodulator

Rohde and Schwarz have introduced a new technique for measuring phase noise that is called the digital phase demodulator technique. Figure 2-12 shows a very simplified block diagram of our FSWP Phase Noise Analyzer. The DUT interface is similar to the spectrum analyzer setup and it accepts inputs from 1 MHz up to 50 GHz. The incoming DUT signal is spilt into two IQ mixers channels. We still use low pass filters and LNAs, but then the signal flows into a digitizer. This is where some really low-noise, high-speed hardware does a very high sensitivity, digital frequency demodulation, which is then converted to phase demodulation, and finally converted to phase noise.
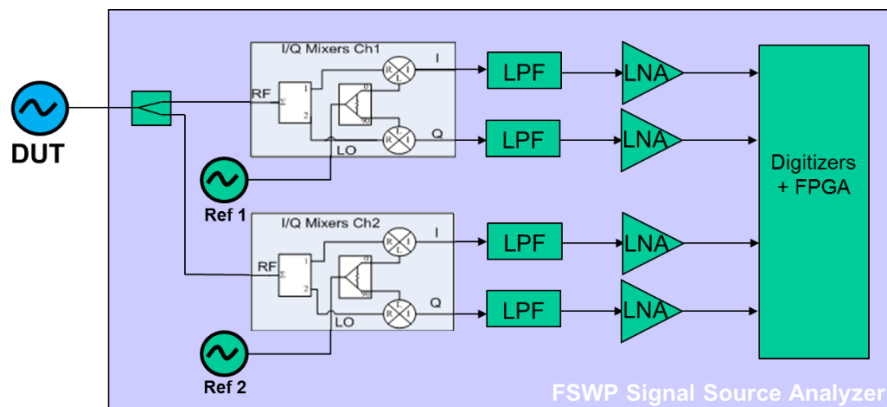

Fig. 2-12: Digital phase demodulator block diagram.

One advantage of this technique is that it does not use a phase detector. Therefore, it does not require a phase lock loop and the associated loop bandwidth correction, which greatly simplifies calibration and speeds up the overall measurement time.

In addition, our design uses very low-noise reference sources and very high-speed cross-correlation, which delivers state-of-the-art sensitivity. As a result, we can measure the phase noise on a low-level signal in the presence of a larger one. That's difficult to do with a phase detector. In section 3 we'll discuss new advantages when measuring additive, pulsed, and AM noise.

This digital phase demodulator technique offers a measurement speed improvement of more than 10x over traditional techniques. Figure 2-13 shows a very sensitive measurement of a 100 MHz crystal oscillator, which took less than 30 seconds. At a 10kHz offset we are measuring -174 dBc/Hz! This same measurement on a currently available phase detector cross-correlation system would take 10 minutes or more to get that level of sensitivity. It's a very fast and sensitive technique, with offsets available from 0.01 Hz out to 300 MHz.

One unique feature of the FSWP can be seen in the gray area below the phase noise curve. What this shows is the measurement margin. The user can adjust the amount of cross-correlation necessary to assure the needed signal-to-noise ratio for accurate results. This reduces the need to look up the specs of this analyzer.
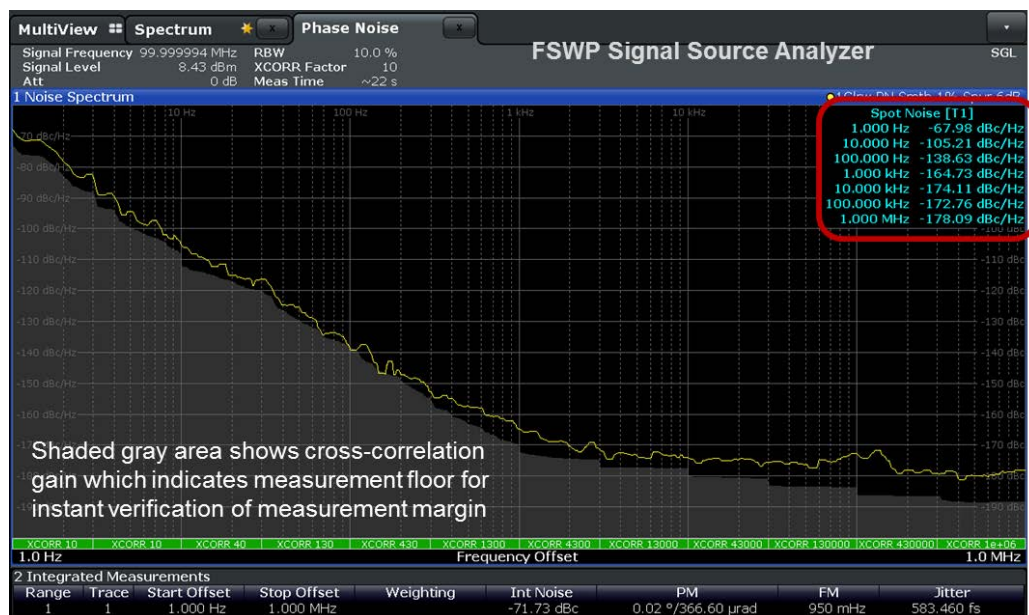

Fig. 2-13: Along with improved sensitivity the digital phase demodulator technique offers a measurement speed improvement of more than 10x over traditional techniques.

4 Summary

Minimizing phase noise is critical to achieving the performance required by many of today's RF applications. Part 1 of this series of application notes has covered the basics of phase noise, and in this Part 2 of the series, we looked at several traditional measurement techniques and introduced a new technique using the R&S FSWP. While the traditional techniques have been used for years, they are hindered by cumbersome calibration and often require additional hardware. Our new digital phase demodulation technique provides really low-noise reference sources and achieves fast correlations with simple setups that deliver state-of-the-art sensitivity and speed.

In Part 3 of this series, we will introduce some of the advanced phase noise measurements used to evaluate special device-under-tests (DUT) situations.

Please follow this link for more information on the R&S®FSWP Phase Noise Analyzer and VCO Tester.

▪ Part 1: Understanding the basics of phase noise: why it is important, how does it impact different applications, and what causes phase noise

▪ Part 2: What are the different measurement techniques and their advantages/disadvantages: direct spectrum analyzer, phase detector, delay line discriminator and we introduce our new digital phase demodulator technique

▪ Part 3: How best to perform advanced measurements: additive phase noise, pulsed phase noise, and AM Noise

Rohde & Schwarz

The Rohde & Schwarz electronics group offers innovative solutions in the following business fields: test and measurement, broadcast and media, secure communications, cybersecurity, radiomonitoring and radiolocation. Founded more than 80 years ago, this independent company has an extensive sales and service network and is present in more than 70 countries.

The electronics group is among the world market leaders in its established business fields. The company is headquartered in Munich, Germany. It also has regional headquarters in Singapore and Columbia, Maryland, USA, to manage its operations in these regions.

Regional contact

Europe, Africa, Middle East
+49 89 4129 12345
customersupport@rohde-schwarz.com

North America
1 888 TEST RSA (1 888 837 87 72)
customer.support@rsa.rohde-schwarz.com

Latin America
+1 410 910 79 88
customersupport.la@rohde-schwarz.com

Asia Pacific
+65 65 13 04 88
customersupport.asia@rohde-schwarz.com

China
+86 800 810 82 28 |+86 400 650 58 96
customersupport.china@rohde-schwarz.com

Sustainable product design

▌ Environmental compatibility and eco-footprint

▌ Energy efficiency and low emissions

▌ Longevity and optimized total cost of ownership

Certified Quality Management
ISO 9001

Certified Environmental Management
ISO 14001

This and the supplied programs may only be used subject to the conditions of use set forth in the download area of the Rohde & Schwarz website.