Educational Note

UNDERSTANDING AND SELECTING POWER SENSORS

Primer

Products:

► R&S®NRPxxS/SN Three-Path Diode Power Sensors

► R&S®NRX Power Meter

Lawrence Wilson | | Version 2 | 09.2020

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Contents

1 Overview

A power sensor is a fundamental measurement tool in RF engineering. However, today's marketplace is filled with myriad choices, and many are making bold claims about attributes such as measurement speed and readings per second. As a result, it can be difficult to cut through the hyperbole and determine which sensor will actually meet the requirements of a specific measurement.

This primer outlines the basics of RF power sensors and highlights a few key characteristics that will help you select the best one for each application. The narrative has three parts. First, we focus on choosing the right type of sensor: multipath, wideband, average power and thermal can satisfy slightly different measurement needs. The second section covers the five major attributes of sensor performance, and what to look for relative to your requirements. Finally, we outline three ways to integrate a sensor into your measurement application.

2 Choosing the Best Type of Sensor

2.1 Introduction

When measuring power, two fundamental details influence the best choice of power sensor: signal type and required measurements. Three questions clarify the type of signal you are seeking to measure:

► Is it a continuous-wave (CW) signal?

► Is it a gated or pulsed signal?

► Does it carry analog or digital modulation?

The nature of the application -- communications, radar, etc. -- and the focus of your work, be it development, troubleshooting, or production, will determine the range of measurements you need to make:

► Average power of CW or modulated signals

► Power measurements of time-slotted signals

► Envelope power versus time

► Statistical analysis of power such as the cumulative distribution function (CDF), complementary CDF (CCDF) or probability density function (PDF)

Four types of power sensors are commonly used to make these measurements: multipath, wideband, average-power, and thermal (also called thermoelectric). We will take a closer look at each of these, and also introduce two types of specialty power sensors.

2.2 Multipath Sensors

Sometimes called the universal sensor, diode-based multipath units are the most popular type. The name comes from the use of separate paths and diodes for different power ranges. Each path also applies a different amount of input attenuation. Diodes rectify the incoming signal by converting AC to DC, and then the sensor samples the level of the rectified signal.

Multipath models from Rohde & Schwarz use a three-path architecture (Figure 1), and the different paths measure the incoming signal simultaneously. Each path is optimized for a specific power range, and these are designed such that the ranges overlap. Within each path, unique algorithms and weighting processes are applied to the sampled data to determine a measured value. All three values are summed together to ensure an accurate result.

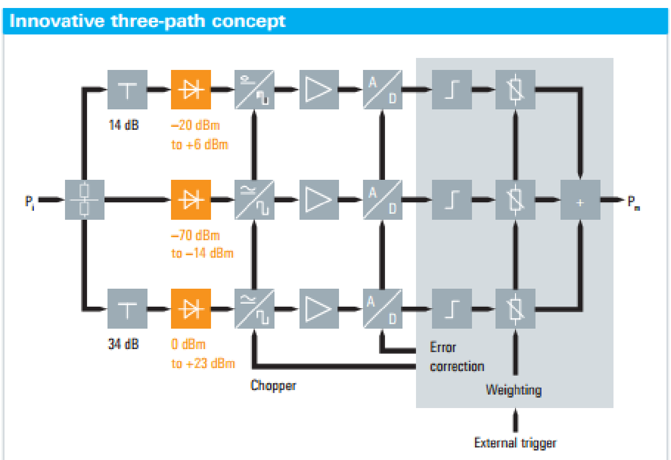

Figure 1: Multipath sensors offer the widest, fastest measurements along with good accuracy, making them an all-around choice that fits many applications.

As a class, multipath sensors can perform a wide range of measurements such as continuous average, burst average, time-slotted, gated, and trace. Figure 2 illustrates a few ways you could configure a multipath sensor to make time-slotted power measurements on a complex signal.

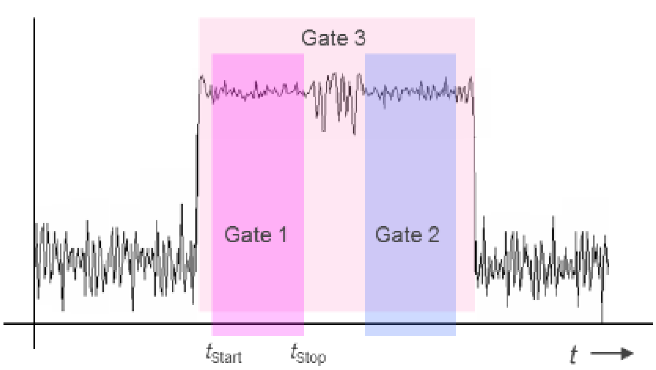

Figure 2. Using multiple gate settings enables the measurement of three different time-slotted measurements.

Multipath sensors offer three key advantages: the widest measurement range, the fastest measurement speeds, and good accuracy. This makes them the best all-around type of sensor and therefore a strong fit with a majority of typical applications. One exception: a noted disadvantage of multipath sensors is a narrow video bandwidth, which can preclude measurements of very fast-pulsed signals.

All of the preceding encapsulates the key attributes to consider when selecting a multipath sensor. One last detail point: in general, multiple-path sensors with overlapping power ranges and simultaneous measurements ensure fast and accurate results.

2.3 Wideband Sensors

Unlike a multipath sensor, a wideband power sensor uses a single diode. Because this creates the potential for nonlinearities, correction factors and built-in digital signal processing are used to compensate for these effects. Consequently, wideband sensors offer very good dynamic range and accuracy.

As the name suggests, this type offers a wider video bandwidth. This makes them better suited to measurements of wideband signals or those that use fast-rising pulses. It also enables more measurement types, including pulse analysis, time-domain analysis, and envelope statistics.

The diagrams in Figure 3 show a few different types of time- and level-related measurements that can be made with a wideband sensor. Overall, these sensors are the ideal choice for analyzing envelope power and performing wideband, time-based analyses of fast-rising pulses. When compared to multipath sensors, wideband models have a bit less measurement range and a slightly higher measurement uncertainty.

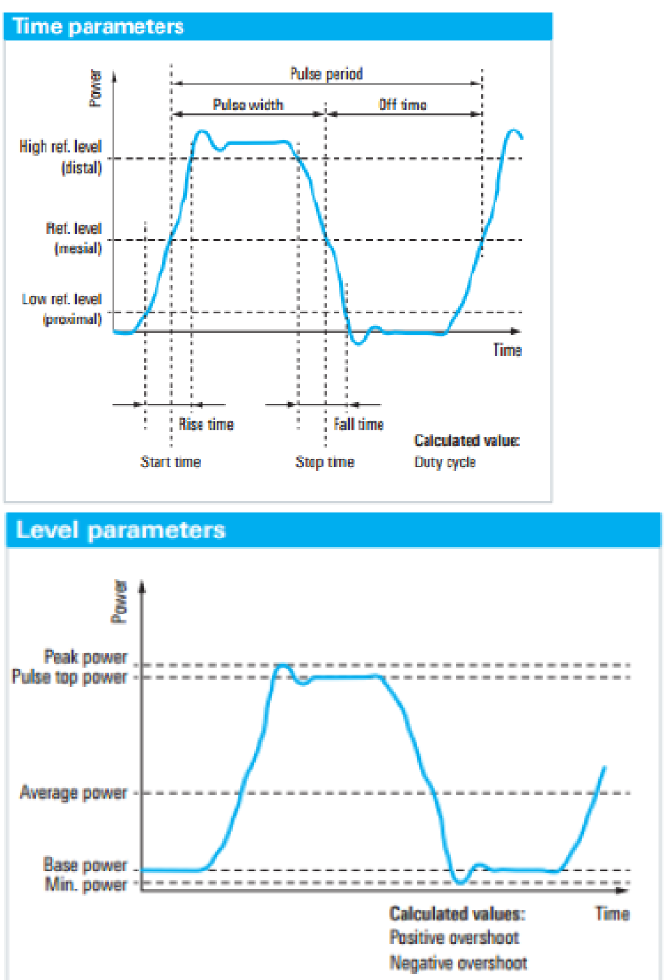

Figure 3. Time and level characteristics are among the many measurements a wideband sensor can make.

2.4 Average-power Sensors

In essence, this type of sensor is a scaled-down version of a multipath sensor. Its capabilities are limited to measuring the average power in CW and modulated signals. As an example, these sensors are well-suited to electromagnetic compatibility (EMC) measurements, which focus on average power in specific frequency ranges.

Typical average-power sensors cover the frequency ranges used in radio telecommunications (e.g., up to 18 GHz) as well as the important lower frequency bands (e.g., down to 8 kHz). Within these ranges, they offer the same properties and benefits as those found in other three-path diode sensors. The disadvantage is the limited measurement functionality.

2.5 Thermal Sensors

These sensors measure power by absorbing RF energy and converting it into heat. Inside the sensor, a thermocouple turns the resulting heat into a voltage that is proportional to the incoming RF power.

This is the most accurate type of sensor. To enhance measurement accuracy, the hardware is designed to minimize measurement noise and enhance immunity to thermal effects from the surrounding environment. These also have the highest frequency coverage, spanning DC to 110 GHz.

Given their high accuracy and wide frequency coverage, thermal power sensors are often used for complex measurement tasks. Ideal applications are in calibration labs or equally demanding settings that require high performance reference measurements (Figure 4).

There are two noteworthy drawbacks. One is poor sensitivity, and this means thermal sensors work best when measuring relatively high levels of power. The other is limited capability: thermal sensors provide only average-power measurements.

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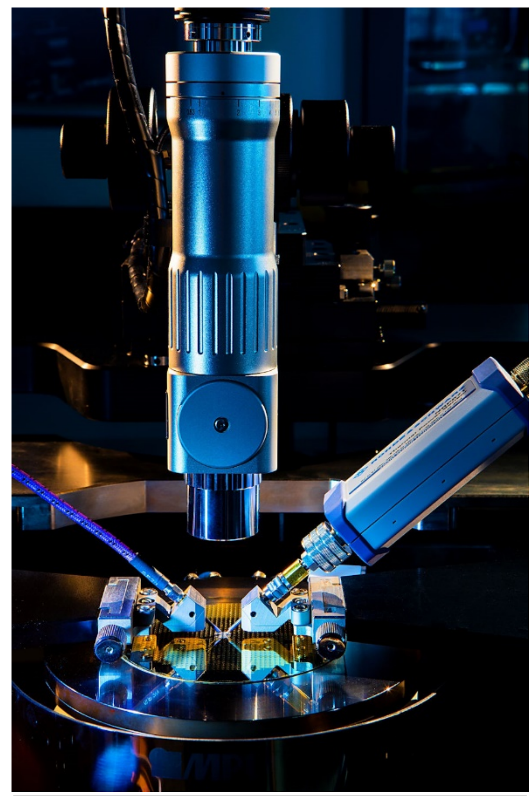

Figure 4. With exceptional linearity and rapid heat dissipation, thermal sensors can deliver excellent performance in reference applications.

2.6 Specialty Sensors

In areas such as mobile communications and phased-array radar systems, it is becoming more difficult to make accurate, repeatable power measurements. Two new types of sensors are designed to meet these challenges: frequency-selective power sensors and integrated antenna modules with internal diode detectors.

2.6.1 Frequency-selective power sensors

When characterizing highly complex wireless signals such as those used in 5G, there is a need to measure individual signals in the presence of nearby RF content. Frequency-selective power sensors are a new category, designed for this type of application.

Based on receiver technology, these sensors can measure the power of one signal in the presence of many others by filtering out nearby signals, thereby reducing noise and improving measurement sensitivity (Figure 5). The inherent filtering enables power measurements on a selected transmission channel down to a noise floor of –130 dBm (typical). Total dynamic range is 150 dB (typical), spanning from –130 dBm to the +20 dBm maximum input level. The resulting sensitivity and dynamic range make this type of sensor equally effective when measuring low-power signals or those that operate across a wide range of power levels.

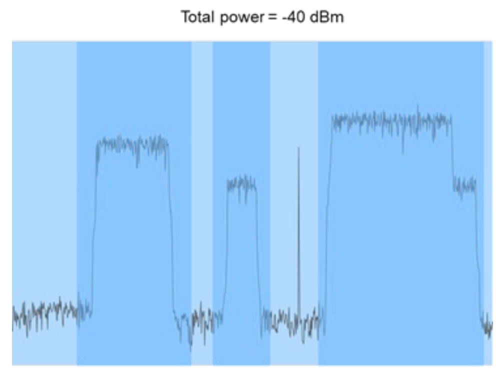

Figure 5. A wideband power sensor measures the total power within its bandwidth, but frequency-selective sensor can make independent measurements that reveal the power present in specific channels.

2.6.2 Integrated antenna modules

With the intense levels of integration used in mobile devices and phased-array antennas, it is often impossible to access transmitted signals using conventional test leads. Instead, characterization requires over-the-air (OTA) measurements via spatially distributed measurement antennas and power sensors. This is especially true in some of the latest applications that utilize millimeter-wave technology.

Combining a wideband antenna and a diode detector in an integrated module eliminates lossy RF cables and adapters (Figure 6). It also enables greater scalability and better spatial resolution in OTA beamforming measurements. Because the modules are self-contained, each one is fully calibrated at the factory across the specified operating ranges for frequency and signal level.

The ability to spatially distribute individual sensor modules across one or more horizontal planes enables direct measurements of power and directionality at the receiving antenna. Further, the number of modules can be easily scaled to meet different test requirements.

Figure 6. Combining a wideband antenna and a diode detector into an integrated module enables greater scalability and better spatial resolution in OTA beamforming measurements.

2.7 Review: Power Sensors

Table 1 displays sensor types onto the types of measurements each can make. As noted earlier, knowing which measurements you need to make is the first step toward determining which type of sensor is best suited to your application.

	Sensor Type			
Measurement	**Multipath**	**Wideband**	**Average**	**Thermal**
Average power (CW)	Y	Y	Y	Y
Average power (modulated)	Y	Y	Y	Y
Average power (gated & modulated)	Y	Y		
Pulse power	Y	Y		
Envelope power	Y	Y		
Envelope statistics		Y		
Pulse analysis		Y		
Time analysis		Y		
I/Q data (RF vector signal analysis)				

Table 1. The intersection of power measurement and sensor type can help you identify the best choice for your application.

3 Defining Sensor Performance

Let's now take a look at the four primary specifications that define sensor performance: frequency range, measurement level range, measurement uncertainty, and measurement speed.

3.1 Frequency Range

Frequency range is a fairly straightforward specification. As was the case in the preceding section, the starting point is your signals of interest: all carrier frequencies (and relevant harmonics) should fall within the frequency range of the sensor.

As a reminder, the four most commonly used types of power sensors are not frequency-selective. Unlike spectrum analyzers or frequency-selective power meters, the frequency range cannot be narrowed to measure just the power in specific band or channel. Instead, a power sensor will measure the power of all the signals within its operating range.

3.2 Measurement Level Range

Sometimes called dynamic range, measurement level range is the difference between the maximum and minimum power levels a sensor can measure. Typically, a datasheet will show a range of power specifications from, for example, –70 to +23 dBm. This specification must be considered within the context of the applicable measurements. As discussed earlier, sensors can make different types of measurements and each type will have a specified measurement range.

As an example, Table 2 shows four different measurement level ranges for a Rohde & Schwarz multipath sensor. Each type of measurement has its own specification for measurement range. This is an important factor when measuring low-level signals because the limitations of the different measurement ranges often occur at the lower end of the power range.

Measurement	R&S®NRP8S/N
Continuous average	–70 dBm to +23 dBm
Burst average	–35 dBm to +23 dBm
Timeslot/time-gated average	–65 dBm to +23 dBm
Trace	–57 dBm to +23 dBm

Table 2. As is often the case, the lower end of the measurement range varies by measurement type.

3.3 Measurement Uncertainty

In general, measured values vary from moment to moment and from test to test. This can be expressed statistically, and measurement uncertainty is a well-defined and universally accepted way to quantify the variation.

Two contributors affect measurement uncertainty: sensor uncertainty specifications and external factors. After covering both topics, we will also show how to calculate uncertainty and offer tips for improving measurement uncertainty.

3.3.1 Sensor specifications

The data sheet for a power sensor typically provides an uncertainty specification. This will cover internal factors such as calibration uncertainty, linearity, and changes over temperature. In addition, the specification is given for a defined frequency range, an input power level, and a range of ambient or room temperatures.

Uncertainty specifications are provided in decibels or as a percentage. The equation that transforms percentages to decibels is as follows:

$$U_{dB} = 10 \times \log_{10}(1 + \frac{U_{\%}}{100})$$

Table 3 shows the uncertainty specifications for the same power sensor shown in Table 2 (R&S®NRP8S).

> 2.4 GHz to 8 GHz

0.162	*0.168*	*0.164*	0 °C to +50 °C
0.088	*0.089*	*0.088*	+15 °C to +35 °C
0.065	*0.063*	*0.064*	+20 °C to +25 °C

–70 –20 0 +23

Power level in dBm

Table 3. The uncertainty specification for the R&S®NRP8S is provided as a range of nine values that depend on power level and temperature.

3.3.2 External considerations

A key point: the uncertainty specifications in a datasheet do not reflect the overall measurement uncertainty. Rather, sensor uncertainty specifications are based on factors that are internal to the device. Because these are internal, they are predictable and can be measured while the sensor is being manufactured.

Even so, external factors can have a material effect on measurement uncertainty. First, consider the test setup. Along the signal path, starting with the device-under-test (DUT) and continuing through cables and connectors to the power sensor, voltage standing wave ratio (VSWR) is an important measure of the efficiency of the resulting transmission of power. In any test setup, it is necessary to know the VSWR of the sensor versus that of the DUT.

Any impedance mismatch between these two devices will determine how much power reaches the sensor. With sufficiently high mismatch, the power into the sensor will be a combination of the true power coming out of the device plus a combination of the reflections from the DUT and sensor. This affects the amount of power entering the measurement port of the sensor, thereby altering measurement uncertainty.

The second factor: power sensor characteristics are a consequence of the ways in which the sensor is being used. These include zero offset, zero drift, and measurement noise. Datasheets include these specifications, but the values to use (and their effects on measurement uncertainty) depend on the actual setup. For example, measurement noise may materially affect the results, especially when measuring low-level signals.

Finally, we must also consider sensor settings such as averaging and aperture time. Averaging increases the number of times that the power from the DUT is read before the result is shown. Aperture time determines how long the sensor samples the signal each time it makes a reading. More averages and a longer aperture time will yield a more accurate result. However, because these are user-entered values, they are not included in the uncertainty section of the datasheet.

3.3.3 Calculating total measurement uncertainty

Combining all these factors makes it possible to determine the overall measurement uncertainty of a test setup. The datasheets for most power sensors provide equations that bring them all together to determine an overall uncertainty value.

Rohde & Schwarz also provides a Windows-based software calculator. As shown in Figure 7, the calculator provides an easy way to enter specific values and quickly determine the overall measurement uncertainty. Results are shown in both percentages and decibels, and the calculator also displays the expected measurement time. This interactive tool helps you find the optimum settings for your power sensor by letting you try different values and then see the resulting changes in measurement uncertainty. Additionally, the software is preloaded with relevant specification data for Rohde & Schwarz power sensors.

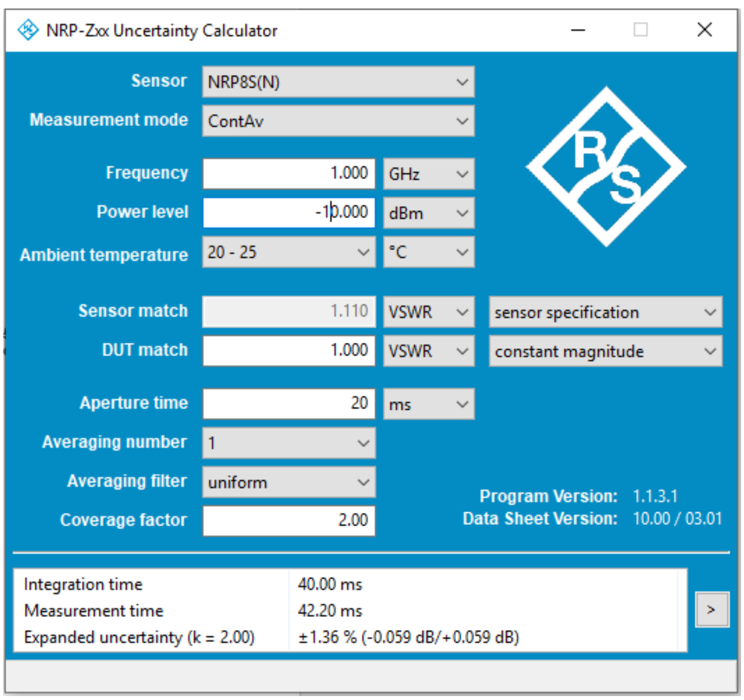

Figure 7. The interactive R&S software calculator helps you optimize power-sensor settings and thereby improve measurement uncertainty.

3.3.4 Improving measurement uncertainty

As noted above in 3.3.2, VSWR can have a substantial impact on measurement uncertainty. Fortunately, we can compensate for its effects. This includes the VSWR of both the sensor and the DUT.

Sensors are able to compensate for the effects of VSWR mismatch using a feature called gamma corrections. Given known values for the reflection coefficients of the sensor and the DUT, the sensor can minimize the effect of mismatch on the overall measurement uncertainty.

Figure 8 provides an example. The upper chart shows a mismatch contribution of nearly 0.3 dB before applying gamma corrections. If the VSWR values of the sensor and DUT are known, they can be entered into the software and the gamma correction feature will adjust the results. The lower chart shows the effect of these corrections: mismatch was reduced to nearly zero and total measurement uncertainty dropped significantly from almost 0.3 dB to just 0.1 dB.

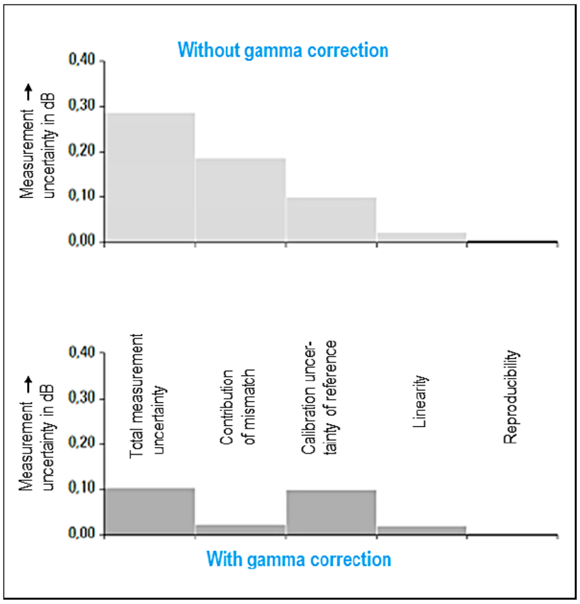

Figure 8. Given known values of VSWR for the DUT and the sensor, gamma correction provides a significant improvement in measurement uncertainty.

Measurement accuracy is also affected by any components in the signal path between DUT and sensor: cables, attenuators, splitters, and so on. These cause reflections and losses that degrade measurement uncertainty.

Whether the S-parameter values for these accessories are known or have been measured using a network analyzer, the information can be entered into the power sensor, which will apply corrections (Figure 9). Adjusting for component S-parameters and reducing their effect will shift the measurement plane from the input of the sensor to the output of the DUT, providing another way to improve accuracy (lower panel, Figure 9).

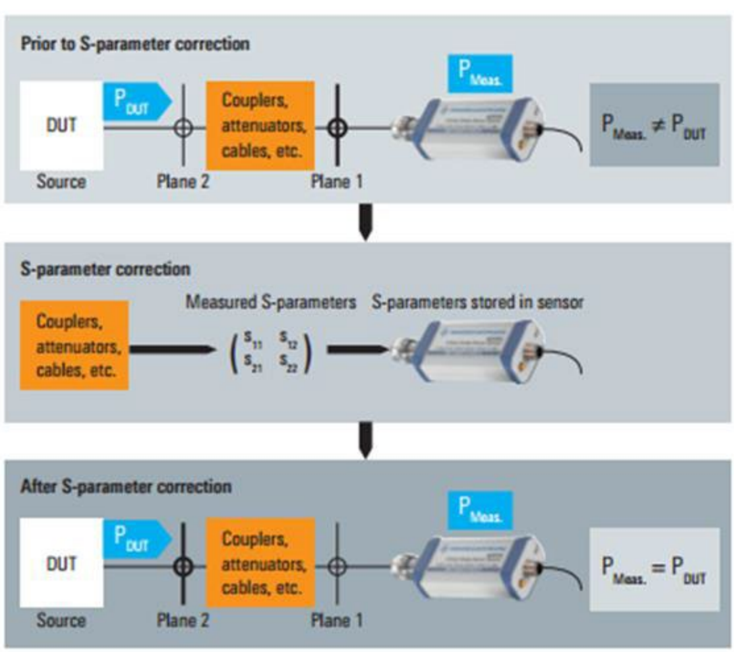

Figure 9. Applying S-parameter corrections offsets the effects of intermediate components and shifts the measurement plane downstream to the DUT output (lower panel).

3.4 Measurement Speed

It is very common for sensor manufacturers to advertise fast speeds and vast amounts of data collected per second. Even though performance can be specified as "readings per second," this is not the same as "measurements per second." One *reading* is the time needed to make a single power measurement of the DUT. One *measurement* comprises a sufficient number of readings averaged together to achieve the desired accuracy. The key point: the time to needed produce an accurate result depends on much more than just the "speed" specification.

A measurement example will help illustrate the interaction between speed and accuracy. In this case, the goal was to measure a signal at –60 dBm with an accuracy of ±0.1 dB. For this measurement we used two sensors with the assumption each provided the same measurement speed and had identical uncertainty specifications.

Figure 10 shows the respective results. On the left, Sensor #1 had a noise floor of –67 dBm; on the right, Sensor #2 had a noise floor of –70 dBm. As context, the y-axis shows the power level and the white bar between the blue boxes is the desired ±0.1 dB tolerance level.

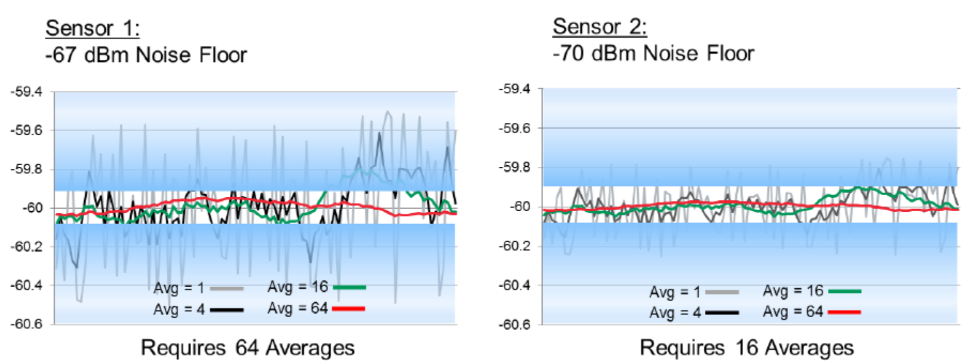

Figure 10. For the same DUT, different sensors required different numbers of averages to achieve a desired tolerance level.

Starting with Sensor #1, making one measurement with one average produced readings that varied widely (gray line). Changing to four averages reduced the variation (black line), but not enough to stay within the ±0.1 dB tolerance range. Not until the number of averages was increased to 64 did the result reside within the target window (red line).

Turning to Sensor #2, we measured the same signal and again made measurements with 1, 4, 16 and 64 averages. With its lower noise floor, this sensor needed just 16 averages to achieve a result that met the desired tolerance level (green line). Allowing for processing overhead, this was roughly four times faster than the 64 averages needed with Sensor #1.

Without delving into product differences, it is apparent that two sensors with similar speeds and uncertainties will provide substantial differences in overall measurement time (e.g., a factor of four in this case). Here, because Sensor #2 had a noise floor 3 dB lower than that of Sensor #1, it reached the desired measurement result after just 16 averages rather than 64. Thus, no matter how fast a sensor may be operating, the ability to deliver good results in fewer averages means shorter measurement times.

3.5 Review: Sensor Performance

The preceding example showed a clear relationship between speed and accuracy. When searching for a power sensor that can produce accurate results quickly, three factors stand out.

First, look for an accurate sensor with the lowest measurement uncertainty. Second, look for the lowest noise floor values for all of the measurement types you will need to make. Finally, identify the one that can make readings quickly (i.e., the speed specification).

The key takeaway is to evaluate all the performance characteristics of a sensor, keeping in mind that they are interrelated. In particular, accuracy, speed, and noise floor all affect how quickly a sensor will produce accurate results. Also, as a rule of thumb, every 3 dB reduction in the noise floor means 50 percent less noise, a difference that is significant when using averaging and when measuring low-level signals.

4 Integrating a Sensor

Turning to practical matters, let's consider the different ways a power sensor can be operated. Also, the best sensor for your application may depend on how you want to integrate the sensor into your application: using USB, Ethernet or a traditional base unit.

4.1 USB Interface Control

Today, most sensors are USB-based. As an aside, Rohde & Schwarz introduced the first USB sensor more than fifteen years ago.

With a USB sensor, all of the measurements are made in the sensor head itself, meaning it can be operated without the use of a traditional power meter (i.e., "traditional base unit"). These sensors can be controlled manually from dedicated software on a PC, or can be commanded remotely in an automated test equipment (ATE) system.

4.2 Direct Ethernet Control

As a more recent development, many sensors can be controlled over Ethernet through an integrated LAN port. These models deliver the same measurement performance and capabilities as a USB-based sensor. Control via Ethernet makes the sensor accessible through a network, ranging from isolated system networks to a corporate intranet or the public Internet (Figure 11).

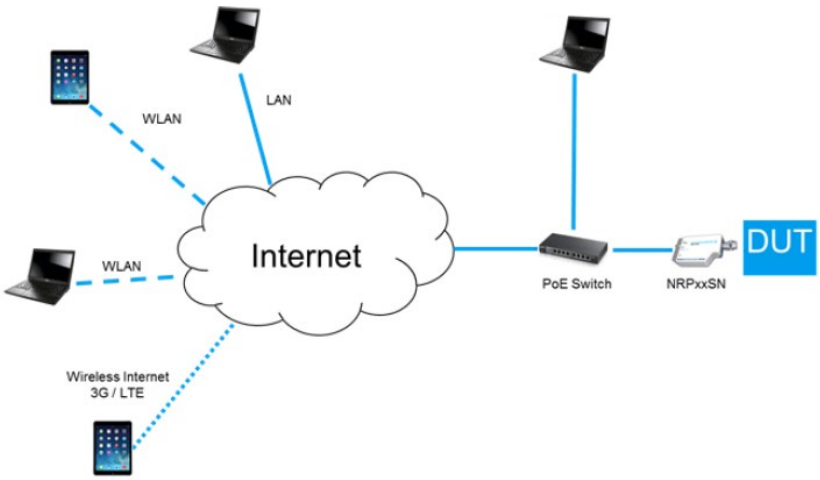

Figure 11. Ethernet-based connectivity enables a wide range of usage scenarios through many types of end-user devices.

This type of sensor is ideal for ATE systems, which are making increasing use of Ethernet for programmatic control. And, as with a USB sensor, using Ethernet for sensor control removes the need for a standalone power meter.

Ethernet control is also very useful when working with remote monitoring sites. This could be a transmission tower in the field or on top of a building, with a power sensor installed and connected to the Ethernet. In this scenario there is no need to travel to the site to make measurements. Instead, you can log in from any one of your devices – laptop, smartphone or tablet – and make measurements in real time (Figure 12). What's more, many of the leading LAN sensors have a built-in Web server, greatly simplifying the process of making manual measurements in remote-access scenarios.

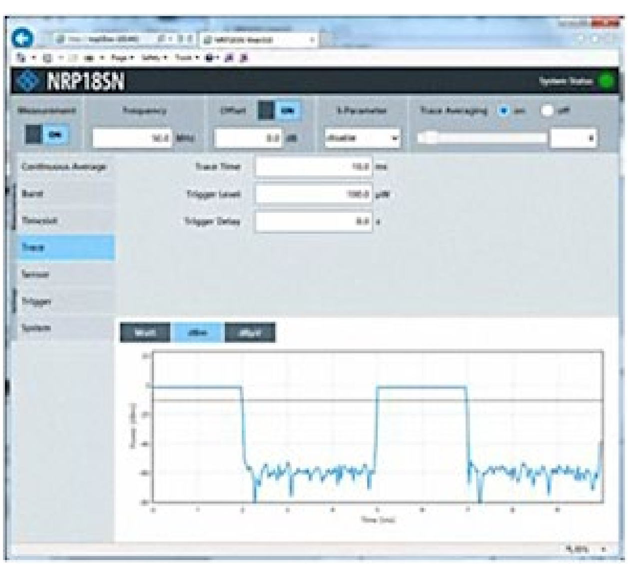

Figure 12. LAN-capable sensors with built-in Web servers enable real-time monitoring and manual control from multiple locations.

4.3 Traditional Base Unit

To view the readings from a power sensor, it must be connected to another device that provides a display. This may be a PC with the necessary software, or it can be another piece of test equipment such as a compatible signal analyzer or a dedicated device called a power meter.

A traditional base unit is designed for manual or programmatic control, displaying results on its front panel or sending them via USB, LAN or GPIB. The base unit does not actually make the measurements, it simply provides control and display (Figure 13).

Figure 13. Base units such as the R&S®NRX power meter have a touchscreen for intuitive control and display.

One benefit of using a base unit: it can provide a single point of control for multiple sensors. In this configuration a single trigger into the base unit can simultaneously trigger multiple sensors (typically four).

For programmatic or remote control, most base units can be accessed over USB, LAN or GPIB. Some also have a built-in reference source that can be used to check the operation and performance of an attached power sensor. This eliminates the cost and complexity of adding a separate external signal generator.

Also relevant to programmatic control, many base units provide an emulation mode that enables them to be drop-in replacements for older, legacy power meters. This is useful because many previous generations of base units are still operational but are no longer actively supported by the manufacturer. Today, current-generation Rohde & Schwarz base units equipped with the R&S®LegacyPro Emulation Mode can support a variety of widely used legacy power meters from Rohde & Schwarz and other manufacturers.

If these older units are controlled via test software, replacing them usually requires software changes, a process that is costly and time-consuming (and may require requalification of the test system). Instead, emulation mode eliminates the need to modify existing software. As an added benefit, a new base unit enables use of newer power sensors, potentially improving measurement accuracy and system throughput.

5 Summary

The first step in deciding which type of sensor you need is clarifying the relevant signal types and measurement requirements: CW, gated or pulsed? Analog or digital modulation? Average power? Power of time-slotted signals? Envelope power versus time? CDF, CCDF or PDF?

The next step is comparing the performance, specifications and advantages of the different types of sensors: multipath, wideband, average-power, thermal, and specialty (e.g., frequency-selective and integrated antenna modules). This comparison goes far beyond the banner specifications often touted by manufacturers. For example, frequency range is important; however, measurement level range varies with measurement type, and this can affect the ability to accurately characterize low-level signals. As another example, a 3 dB difference in noise floor can improve measurement speed by reducing the number of averages needed to achieve the desired accuracy.

Measurement uncertainty is another key topic, and it depends on sensor specifications and external factors. The ability to compensate for factors such as VSWR mismatch and S-parameters helps ensure exceptional measurement accuracy. Tools such as the Rohde & Schwarz uncertainty calculator can help you find the optimum settings for a power sensor by letting you try different values and observe the resulting changes in measurement uncertainty.

Rohde & Schwarz has a portfolio of power sensors and base units, with leading performance, lowest noise floor, lowest measurement uncertainty factors, and fastest measurement speed. What's more, this performance is combined with outstanding usability capabilities such as touchscreen base units, LAN interfaces, built-in triggering, and emulation of legacy power meters.

For more information on our power sensors and power meters plus application notes, selection guides, and the uncertainty calculator, please visit

www.rohde-schwarz.com/products/test-and-measurement/power-meters-voltmeters/overview_63672.html

6 Literature

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7 Ordering Information

Designation	Type	Order No.
Three-path diode power sensor, USB	R&S®NRP33S	1419.0064.02
Three-path diode power sensor, USB/LAN	R&S®NRP33SN	1419.0070.02
Frequency-selective power sensor	R&S®NRQ6	1421.3509.02
Three-channel sensor module	R&S®NRPM3	1425.8563.02
Single-polarized antenna module	R&S®NRPM-A90	1426.7760.02
Dual-polarized antenna module	R&S®NRPM-A90D	1426.7777.02
Power meter	R&S®NRX	1424.7005.02

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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PAD-T-M: 3572.7186.00/01.00/EN

| Version 2 | 09.2020
Educational Note | Understanding and Selecting Power Sensors
Data without tolerance limits is not binding | Subject to change