MSL Technical Guide 32

An accurate RF reference signal for testing power measuring instruments

Introduction

Power is a fundamental quantity in radio and microwave frequency systems, so it is important to measure it properly. Measuring instruments, such as power sensors, spectrum analysers, measurement receivers, etc, need to be calibrated using an accurately known reference signal.

Providing an accurate reference signal for such calibration work is not always easy. The output characteristics of a signal generator are difficult to measure and the cable, or network, used to connect the device under test to a generator will also affect the power level seen at the device. If these effects cannot be accounted for properly, the accuracy of the reference level will be limited.

This guide describes a simple way to produce an accurate reference signal that uses a resistive power splitter and a pair of power sensors to improve the raw performance of a signal generator and remove the effects of an arbitrary connecting network. For best results, the power splitter and one of the power sensors should be calibrated, although, a traceable reference can still be obtained when only the power sensor has been calibrated. A simpler implementation of the technique can be used to monitor the performance of a suite of power measuring instruments over time.

Making a good signal reference

When a signal generator is connected to a power measuring instrument, the interconnecting network affects the power level at the detector. Some signal is always reflected between the measuring instrument (measurement port) and the signal generator. These reflections give rise to interference effects that can change the measured power level. Some power is also dissipated as the signal propagates through the network.

To correct for network effects, a resistive power splitter can be placed at the end of the network, as shown in Figure 1. In this configuration, the generator output must be adjusted to maintain a stable signal on one splitter port, while the other port can be used as a reference.

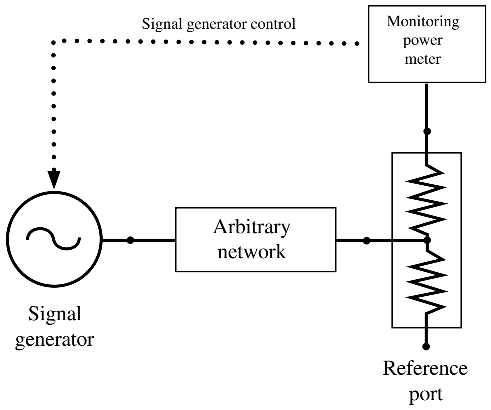

Figure 1: A stable reference signal can be obtained at the reference port by adjusting the generator to maintain a constant level on the monitoring arm.

To establish the reference level, a calibrated sensor must first be connected to the reference port and the generator adjusted to obtain the desired power level on that sensor. At this generator setting, the level on the monitored arm of the splitter should be noted. Then, when any other device is connected to the reference port, the generator should be adjusted to restore this reading on the monitored arm.[1]

> *This re-adjustment is the key to improving the characteristics of the reference port.*

Importantly, when this procedure is followed, the effective reflection coefficient looking into the reference port is *independent of the network connecting the generator to the splitter* and will usually be smaller than the raw reflection coefficient of the signal generator itself. The reflection coefficient depends only on the splitter characteristics, which can be measured independently of the generator and connecting network.

The reference level obtained this way is well-defined, because it is based on traceable measurements with a calibrated power sensor.

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[1] The re-adjustment can be performed by hand when continuous feedback control is not available.

The reference port

The reference port reflection coefficient

The effective[2] reflection coefficient $\boldsymbol{\Gamma}_{\mathrm{g}}$ of the splitter reference port is determined by the complex S-parameters of the splitter[3]

$$\boldsymbol{\Gamma}_{\mathrm{g}} = \boldsymbol{S}_{22} - \frac{\boldsymbol{S}_{21}\boldsymbol{S}_{32}}{\boldsymbol{S}_{31}} \ .$$

A perfect splitter has the following S-parameters

$$\begin{array}{cc} \boldsymbol{S}_{22} = \frac{1}{4} & \boldsymbol{S}_{21} = \frac{1}{2} \\ \boldsymbol{S}_{32} = \frac{1}{4} & \boldsymbol{S}_{31} = \frac{1}{2} \end{array}$$

so

$$\boldsymbol{\Gamma}_{\mathrm{g}} = 0 \ .$$

In practice, $\boldsymbol{\Gamma}_{\mathrm{g}}$ can be very small, which is why the method is effective: a small reflection coefficient keeps interference effects to a minimum.

Mismatch

When a sensor is connected directly to the reference signal source, the reflection coefficients of the source and sensor affect the signal level at the sensor. The equivalent network consists of a pair of facing terminations, each reflecting a portion of the signal falling on them (Figure 2).

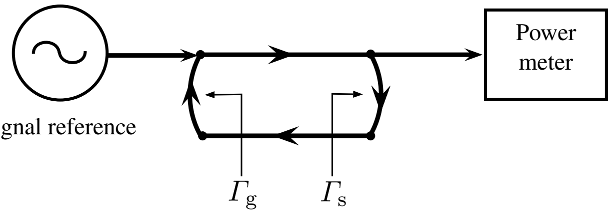

Figure 2: The signal flow diagram of a power meter connected directly to a signal source. The signal source and meter each have non-zero reflection coefficients.

The power incident on the sensor in this configuration is

$$P_{\mathrm{i}} = P_{\mathrm{g}} \frac{1}{|1 - \boldsymbol{\Gamma}_{\mathrm{g}}\boldsymbol{\Gamma}_{\mathrm{s}}|^2} = \frac{P_{\mathrm{g}}}{M_{\mathrm{gs}}} \ ,$$

where P_{g} is the power that would be delivered in the absence of reflections, $\boldsymbol{\Gamma}_{\mathrm{g}}$ is the complex reflection coefficient of the source port and $\boldsymbol{\Gamma}_{\mathrm{s}}$ is the reflection coefficient of the sensor.

Having $\boldsymbol{\Gamma}_{\mathrm{g}}$ small helps keep the mismatch factor

$$M_{\mathrm{gs}} = |1 - \boldsymbol{\Gamma}_{\mathrm{g}}\boldsymbol{\Gamma}_{\mathrm{s}}|^2$$

close to the ideal value of unity.

When the reflection coefficients are known, the mismatch factor can be calculated and a correction applied to P_{i}, to obtain a better estimate of P_{g}.

When $\boldsymbol{\Gamma}_{\mathrm{g}}$ and $\boldsymbol{\Gamma}_{\mathrm{s}}$ are not known, uncertainty in the value of $|1 - \boldsymbol{\Gamma}_{\mathrm{g}}\boldsymbol{\Gamma}_{\mathrm{s}}|^2$ makes a significant contribution to the measurement accuracy.

How the method works

A resistive power splitter is a passive 3-port device, comprised of two resistances. A splitter has one input port and two output ports, as shown in Figure 3.

When the ports are terminated in the characteristic impedance of the network, the reflection coefficient looking at the input port is zero and a signal impinging on the input will be shared equally between the output ports. The output ports behave differently. The reflection coefficient looking at an output port is $1/4$ and $1/4$ of any signal incident on that port is transmitted to the other (while $1/2$ is transmitted to the input). These properties are exploited, by the method described above, to provide a stable reference using feedback.

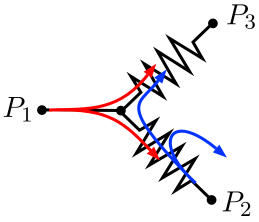

Figure 3: Signal impinging on the input is shared equally between the output ports (red lines). Any power impinging on an output port is both reflected and transmitted to the other output port in equal proportions (blue lines).

Suppose that a signal is applied to (the input) port 1 and that port 3 is monitored. Signal variations at port 2 (the reference port) can arise for two reasons: the input signal changes or an (unwanted) signal impinges on port 2 (due to mismatch).

In the first case, any change of input signal appears equally on both splitter output arms, so the input correction needed to maintain the reference port 2 constant will be obtained by keeping the level on the monitoring arm constant.

In the second case, $1/4$ of a signal impinging on port 2 is reflected and the same amount is transmitted to port 3. So the superposition of reflected and transmitted signals at port 3 reproduces the superposition of signals at port 2.

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[2] The term *effective* is used because this value is only obtained when the feedback adjustment process is carried out.

[3] The indices in this equation assume that the reference port is splitter port 2, port 1 is the input port and port 3 the monitor port.

Once again, controlling the level on the monitoring port corrects variations at the reference port.

Finally, half of any signal impinging on port 2 is transmitted to the input port and, from there, propagates through the network to the signal generator. Some of this signal will be reflected back to the splitter, where it affects the input signal. However, as explained in the first case, changes of input level will be corrected.

Some words of warning

Use of a resistive splitter in this way is straightforward, however there are some pitfalls to avoid.

Generator adjustment is necessary

To obtain the desired performance enhancement, the monitoring arm power must be maintained at the required level by adjusting the input level: simply adding a splitter to the network is not enough. Indeed, doing so might even harm the performance. The reflection of the raw splitter output port (0.25) is rather large.

Don't pad the output

As we have seen, resistive splitters are cleverly designed so that changes at one output port are mirrored at the other. This balance can be upset if one of the outputs is modified. For instance, the common practice of 'padding' with an attenuator to reduce mismatch should be avoided.

The splitter outputs are not the same

It may be tempting to use a calibrated power sensor on the monitoring output arm of the splitter and dispense with the second power sensor altogether. However, to do so introduces additional measurement errors. In real splitters, the level detected on the monitoring arm differs from the level on the other arm by an amount called the 'tracking error'. Manufactures sometimes specify a maximum tracking error, but the actual value depends in a complicated way on the splitter characteristics and the devices connected to it.

Different implementations

There could be different motives for improving the quality of a signal reference. Depending on the need, the implementation of the technique will be different.

Best accuracy: splitter and sensor calibrated

To obtain the highest accuracy, and full metrological traceability, the power sensor and the resistive splitter should be calibrated and the complex value of the sensor reflection coefficient $\boldsymbol{\Gamma}_\mathrm{s}$ must be known.

The mismatch factor M_gs, when the reference and the calibrated sensor are connected, can be calculated and used to find the required indication on the calibrated power sensor during the set-up phase

$$P_\mathrm{i} = \frac{P_\mathrm{g}}{M_\mathrm{gs}} ,$$

where P_g is the desired reference signal level. This level for P_i must be obtained by adjusting the generator; the corresponding level on the monitoring sensor should then be noted.

The measurement uncertainty associated with the reference level obtained, as an estimate of P_g, can be calculated. Please contact us if further details are required.

Note that the mismatch factor will change when a device is connected to the reference port. So, the complex reflection coefficient of the device under test should be measured as well, and used to calculate the mismatch factor needed to correct power level indicated on the device.

Good accuracy: sensor calibrated

Metrological traceability can still be obtained without calibrating the splitter, although the reference level will be less accurately known because the uncertainties associated with mismatch will be larger.

In this case, the sensor must be calibrated but only the magnitude of the sensor reflection coefficient $|\boldsymbol{\Gamma}_\mathrm{s}|$ is needed, not the full complex value. The magnitude of the effective splitter reflection coefficient $|\boldsymbol{\Gamma}_\mathrm{g}|$ will not be known, but a value taken from manufacturer specifications may be used.

The mismatch factor must now be estimated as unity, $M_\mathrm{gs} \approx 1$. So, during set-up the generator output is adjusted to obtain an indication of P_g on the sensor.

The uncertainty of this setting, as an estimate of a true source with power level P_g, will be dominated by the uncertainty component $u(M_\mathrm{gs})$ due to the approximation $M_\mathrm{gs} \approx 1$. The relative standard uncertainty is then

$$\frac{u(P_\mathrm{g})}{P_\mathrm{g}} = \sqrt{2}|\boldsymbol{\Gamma}_\mathrm{s}||\boldsymbol{\Gamma}_\mathrm{g}| .$$

Example

Consider a setup in which the splitter manufacturer reports an 'equivalent output SWR' of 1.20 (equivalent to

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[4] If a manufacturer does not report 'equivalent output SWR', use the specification for splitter input SWR.

0.091 in linear units) in the device specifications.[4]

The sensor calibration report gives a reflection coefficient magnitude of $|\boldsymbol{\Gamma}_{\mathrm{s}}| = 0.13$ at the measurement frequency.

With these numbers,

$$\begin{aligned}\frac{u(P_{\mathrm{g}})}{P_{\mathrm{g}}} &= \sqrt{2}|\boldsymbol{\Gamma}_{\mathrm{s}}||\boldsymbol{\Gamma}_{\mathrm{g}}| \\ &= \sqrt{2} \times 0.091 \times 0.130 \\ &= 0.017\ .\end{aligned}$$

So the relative standard uncertainty is 1.7%.

No accuracy: splitter and sensor uncalibrated

Metrological traceability cannot be claimed when neither the sensor nor the splitter have been calibrated, because there is no way of establishing the power level. Nevertheless, provided the power sensor response is stable over long periods of time, the method could still be used to check the stability of other instruments.

For instance, a suite of spectrum analysers might be calibrated by a calibration laboratory at regular intervals. Between calibrations, the technique could provide a useful routine check of the instruments' performance.

In this case, only the power sensor connected to the monitoring arm of the splitter is needed.

A particular monitor level should be chosen and maintained by adjusting the signal generator each time a device is connected to the reference port.

The power level indicated on a device under test should be recorded and compared with historical values. It is important that the measurements are made with *exactly* the same splitter and sensor each time and that the same power level is obtained on the monitoring arm of the splitter.

The repeatability of this method can be evaluated by performing the set-up and measurement sequence a number of times and looking at the variability of the results.

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