Effects of Noise Floor, Linearity & Mismatch Error on RF Measurements

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Abstract

As RF measurements today become more and more demanding on semiconductor test, there is a need to revisit the fundamentals on how the characteristics of RF instruments affect the measurements. This article shows how the effects of noise floor, linearity, and mismatch error can affect RF measurements.

1. Introduction

The effects of noise floor, linearity, and mismatch error on RF measurements are different. Detail explanations of the effects are found in numerous publications. The intention of this paper is to summarize the effects and apply them to ATE (Automated Test Equipment).

2. Mismatch Error

Mismatch error will reduce the absolute accuracy of an RF measurement.
Real world RF receivers do not have perfect input impedance, nor do RF source have ideal output impedance. Cables and connectors also do not have ideal impedances. Impedance mismatches produce reflections, which reduce the signal power transferred to the receiver and introduce a measurement uncertainty. The general expression used to calculate mismatch loss in dB is[1]:

$$\text{Loss (dB)} = -20 \log10 (1 \pm |\rho_{load} * \rho_{source}|) - 10 \log10 (1 - |\rho_{load}|^2), \qquad (1)$$

where ρ is the reflection coefficient. In this expression, the mismatch uncertainty in dB is

$$\text{Mismatch Uncertainty (dB)} = -20 \log10 (1 \pm |\rho_{load} * \rho_{source}|) \qquad (2)$$

and the power loss in dB is

$$\text{Power Loss (dB)} = -10 \log10 (1 - |\rho_{load}|^2). \qquad (3)$$

The unitless Reflection Coefficient (ρ) is given by

$$\rho = |(Z-Z_0)/(Z+Z_0)|. \qquad (4)$$

Equation (1) highlights that the mismatch error depends on both the receiver input impedance and the output impedance of the signal source. However, the amount of mismatch uncertainty, calculated as described above, is sometimes only part of the problem. Reflections from adapters or damaged cables and connectors can mean that the real uncertainty contribution in a practical ATE set-up can be larger than the theoretical value.

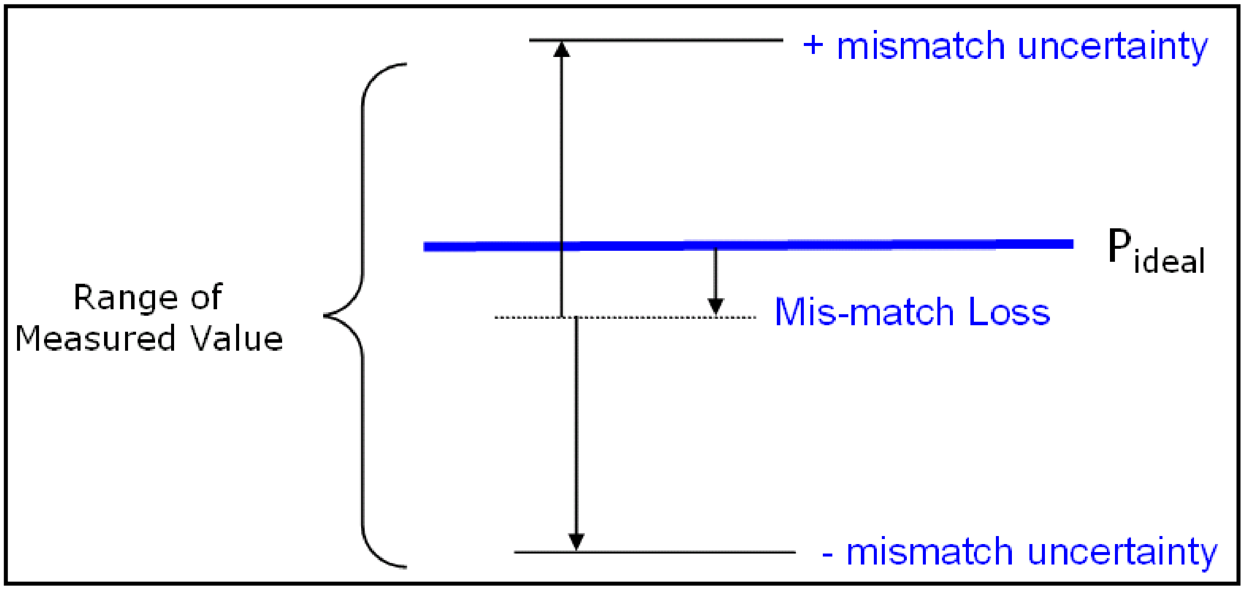

Figure 1: Illustration of mismatch effects on RF measured value.

Consider, for example, a 75-ohm cable used in 50-ohm impedance environment. In this situation,

$$\rho_{load} = \rho_{source} = |(Z-Z_0)/(Z+Z_0)| = (50-75)/(50+75) = 0.2. \quad (5)$$

Using Equation (2),

$$\text{Mismatch Uncertainty} = -20\log10\ (1 \pm |\rho_{load} * \rho_{source}|) \quad (6)$$

and

$$\text{Mismatch uncertainty} = -20\log10\ (1 \pm |0.2*0.2|) \quad (7)$$

would give an uncertainty of +0.34 & -0.35 dB. This is a peak to peak variation of about 0.7 dB! Hence, for high accuracy & lower system to system variation, keeping the unnecessary mismatch uncertainty contribution under control is necessary. Care should be taken to ensure the cables used are in good condition, torque and connected properly. If the reduction of reflections is not possible, one way to reduce reflections is to use the use of attenuation at the input of the receiver. This improves the input impedance match conditions and it can be easily done in the V93000 PSRF receiver. For best amplitude accuracy, use an input attenuator of more than 10 dB.

In summary, each mismatch in the system adds to the measurement uncertainty, even after calibration. Therefore the user needs to make a model of the entire system that is being measured and take into account each mismatch error and add it to the overall error.

3. Noise Floor

The noise floor of an instrument determines the lowest possible signal that can be measured or sourced by the instrument. This also determines the dynamic range of the instrument. In addition, the noise floor in comparison to the signal amplitude will affect the standard deviation or repeatability of the measurement. A high repeatability is always desired in ATE as that will allow for a smaller guard band on the limits of the test. A smaller guard band will allow more marginal device to be considered to be known good device, resulting in higher yield.

Looking closer at the effect of noise, for any RF measurement, the V93000 receiver is measuring the sum of all signal energy present in the requested bandwidth. Therefore, the measured amplitude of the signal is actually signal plus noise. Depending upon the signal level relative to the noise level, the inaccuracy in assuming that the "measured" amplitude equals the "signal" amplitude may be small or large.

When measuring large signals, measurement uncertainty (error) is not as much of a concern as when the signals being measured are close to the noise floor of the ATE. In cases where the signal is close to the noise floor, the measurement uncertainty is described, as shown in Figure 2, by

$$\text{Measurement Uncertainty (dB)} = 20\log\{1 \pm [1/10^{(SNR_{dB}/20)}]\}, \qquad (8)$$

where SNR_{dB} is the signal to noise ratio of the signal from the DUT (Device Under Test) compared to the noise floor of the ATE in dB [2].

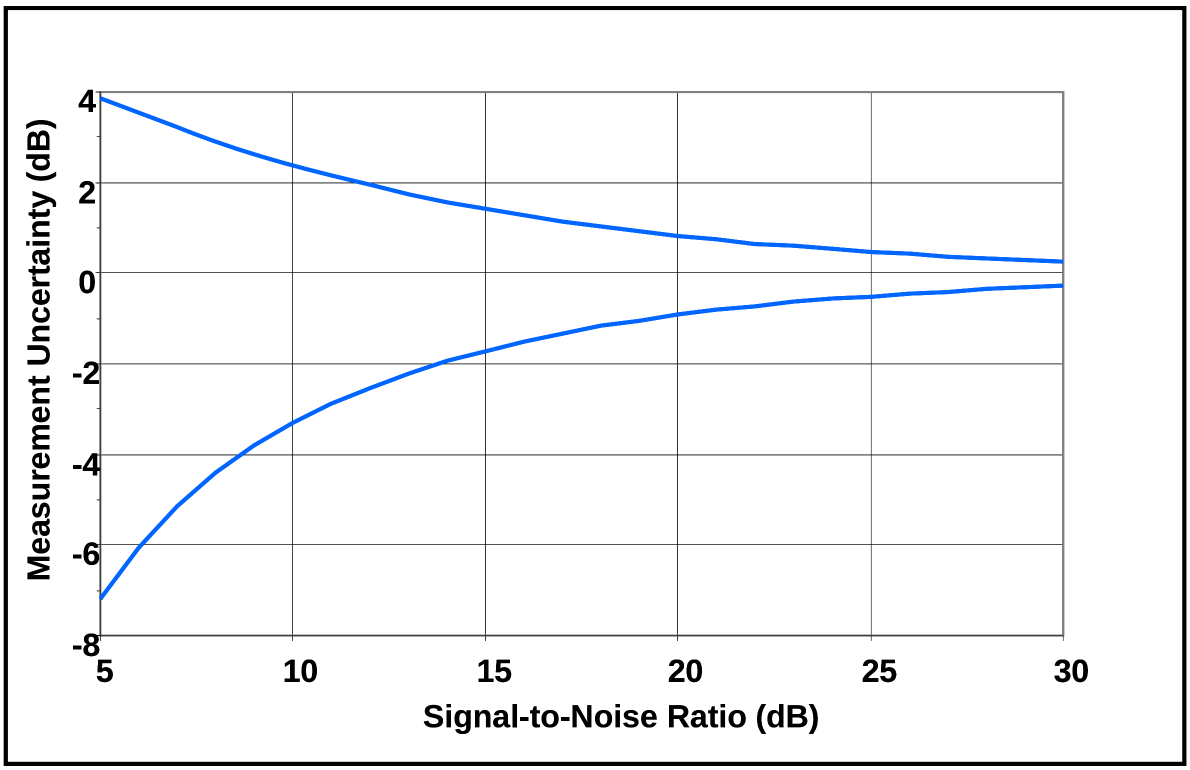

Figure 2: Measurement Uncertainty vs. Signal to Noise Ratio

Notice in Figure 2 that for an SNR of 20 dB, the measurement uncertainty is approximately 0.9 dB. This is commonly about the lowest signal-to-noise ratio that one would want in an ATE environment. Having an SNR of 30dB yields a measurement uncertainty of +/-0.3 dB which is much more appropriate for production testing. At times, low SNR values cannot be avoided. In these cases, although the measurement accuracy may be sacrificed, it may be acceptable if a repeatable measurement can be obtained. This can be achieved using averaging.

Variations of measured values due to the Measurement Uncertainty could cause bad parts to pass. Guard bands are required to insure that the parts meet the manufacturer's specifications. The size of the guard band can be determined from the standard deviation of the measurement and the allowable probability of passing a bad part. Taking the standard normal distribution, the probability table is given below:

Multiple of Standard Deviation	1	2	3	4	5	6
Max Probability of passing 1 bad part (%)	15.9	2.3	0.13	3.2e-3	28e-6	99e-9

The table above is based on the probability that a bad device falls within the pass limits. You can use the table above, together with Figure 2 to determine guard band. For example, to allow the chance of 0.13% of a bad part being determined as a good bad, the guard band for a power measurement with a SNR of 20 dB is 0.92*3 = 2.7 dB. A guard band this wide, would unfortunately classified a lot of good parts as bad. Fortunately, for a good ATE RF receiver, the measurement SNR values are typically much better than 30 dB. This allows for a much narrower guard band.

In general, as the bandwidth of the measurement gets wider, more noise is being added. This results in a lower signal to noise ratio. Hence, we should not use an unnecessary wider bandwidth for lower signal power level measurement.

4. Linearity

Linearity or the lack of it, non-linearity, is the cause of distortion effects. Typically, the non-linearity effect will creep when the signal power is compressing the instrument's amplifier. It is important to keep within the instrument's linear range to ensure that the signal does not distort. While the noise floor determines the lowest possible signal that can be sourced or measured, the linearity of the instrument determines the upper limits. A compressed signal on the receiver path would obviously result in an error in the measured power value but also distortion to the resulting waveform.

In ATE production testing, many of the waveforms can have higher peak-to-average rms power levels compared to a CW signal. Not recognizing the peak to average rms value of the waveform would frequently result in unwanted compression of the measured signal giving unwanted distortion.

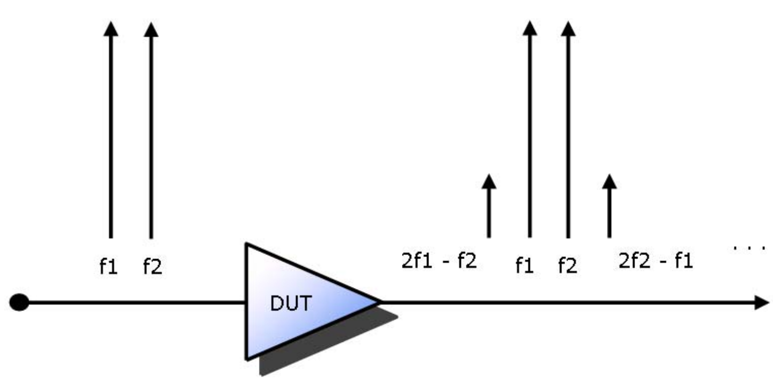

Figure 3: A 2 two-tone distortion test

For example, in Figure 3, a two-tone test signals are often used for characterizing amplifiers for linearity of their amplification. If the amplification is non-linear, two pure input signals of f1 and f2 result in inter-modulation signals at the output, of the form 2f1 – f2, 2f2 – f1, and many more. The test is a very sensitive indicator of amplifier linearity. Measuring power of such tones needs user analysis because the phase of the two carriers adds or cancels at the rate of the offset frequency. In this two-tone example, the constructive addition of tones can result in a peak carrier of two, twice the single tone, which is a peak power of four times the single tone. In a modulated waveform such as in OFDM modulation waveforms, which can be viewed as numerous tones being generated, such peak-to-average rms ratio can be very large. Caution should be taken to ensure that the peaks of such waveforms do not exceed the instruments' maximum range specification.

Figure 4 demonstrates the transfer function of an instrument measuring an RF signal with various peak-to-average power ratios (PAR). Notice the deviation of the orange trace as the instrument exhibits non-linear (compression) at higher input power levels. For the case of a CW (Continuous Wave, i.e., sinusoid) signal or modulated signal with low PAR, the signal falls within the linear mode of operation of the instrument. In the case of the high PAR modulated signal, some of the signal content falls in the compression (non-linear) region of the instrument. Care should be taken to avoid this in practice.

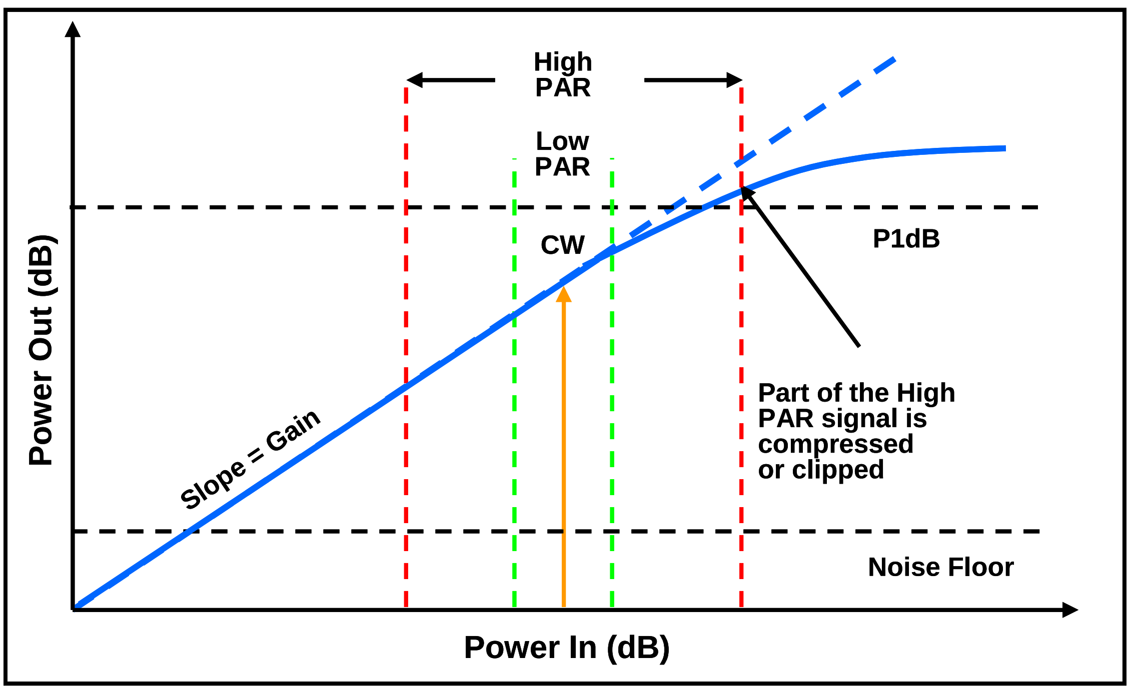

Figure 4: CW, Low-PAR, and High-PAR signals shown on the transfer function of an RF measuring instrument.

5. Conclusion

The effects of noise floor, linearity & mismatch error on accuracy, repeatability and distortion are explained and summarized. Mitigation and precautions for avoiding these effects in production test environments are also explained.

6. References

[1] Agilent Technologies, “Fundamentals of RF and Microwave Power Measurements” Agilent Application Note 64-1A
[2] Agilent Technologies, “Optimizing RF and Microwave Spectrum Analyzer Dynamic Range,” Agilent Application Note 1315 (2000).

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