New Ultra-Fast Noise Parameter System...
Opening A New Realm of Possibilities in Noise Characterization

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Agenda

- Overview of Noise Measurements
- Noise Parameter Characterization Systems
- Measurement Results
Why Do We Care About Noise?

Noise causes system impairments

• Degrades quality of service of TV, cell phones
• Limits range of radar systems
• Increases bit-error rate in digital systems

Ways to improve system signal-to-noise ratio (SNR)

• Increase transmit power
• Decrease path loss
• Lower receiver-contributed noise
• Generally easier and less expensive to decrease receiver noise than to increase transmitted power

Noise figure is a figure-of-merit that describes the amount of excess noise present in a system. Minimizing the noise in the system reduces system impairments that result from noise. In our personal lives, noise degrades the image quality of TV pictures, and can adversely impact the voice quality of a cell phone call. In military systems like radar, receiver noise limits the effective range of the radar. In digital communications systems, noise can increase the bit-error rate. System designers always try to optimize the overall signal-to-noise ratio (SNR) of the system. This can be done by increasing the signal or by reducing noise. In a transmit/receive system like a radar system, one possibility is to increase the radar’s transmitted power, by using bigger, more powerful amplifiers, and/or by using larger antennas. Decreasing the path loss between the transmitter and receiver would also help increase SNR, but this is usually not under our control. SNR can also be increased by decreasing the receiver-contributed noise, which is usually determined by the quality of the low-noise amplifier (LNA) at the front end of the receiver. In general, it is easier and less expensive to decrease receiver noise (by a better effective noise figure) than by increasing transmitter power.
Noise Figure Definition

Noise figure is defined in terms of SNR degradation:

\[
F = \frac{S_o/N_o}{S_i/N_i} = \frac{N_o}{G \times N_i} \quad \text{(noise factor)}
\]

\[
NF = 10 \times \log (F) \quad \text{(noise figure)}
\]

The definition of noise figure is simple and intuitive. The noise factor (F) of a network is defined as the input SNR divided by the output SNR [F = (S_i/N_i)/(S_o/N_o)]. If an amplifier was perfect, the output noise would be equal to the input noise multiplied by the gain of the amplifier, resulting in the same SNR at both the input and output of the amplifier. For any real-world amplifier, the output noise will be larger than the input noise multiplied by the gain of the amplifier, so the signal-to-noise-ratio at the output will be smaller than that at the input, resulting in F being greater than one. Noise figure (NF) is simply the noise factor expressed in decibels [NF = 10*log(F)].

It is important to note that when measuring and comparing noise figures, the test system is assumed to be 50 ohms. Later, we will discuss the accuracy implications if our test system is not exactly 50 ohms.
Noise Figure Measurement Techniques

Y-factor (hot/cold source)
• Used by NFA and spectrum-analyzer-based solutions
• Uses noise source with a specified “excess noise ratio” (ENR)

\[
\text{Excess noise ratio (ENR)} = \frac{T_{\text{hot}} - T_{\text{cold}}}{290K}
\]

Cold source (direct noise)
• Used by vector network analyzers (VNAs)
• Uses cold (room temperature) termination only
• Allows single connection S-parameters and noise figure (and more)

There are two main techniques for making noise figure measurements. The predominant method is called the Y-factor or hot/cold-source technique, and is used with Agilent’s noise figure analyzers, and spectrum analyzer-based solutions. The Y-factor method uses a calibrated noise source consisting of a diode that can be turned on or off, followed by an attenuator to provide a good output match. When the diode is off (no bias current), the noise source presents a room-temperature termination to the DUT. When the diode is biased in the on state, the avalanche breakdown creates considerable electrical noise, over and above that provided by a room-temperature termination. This amount of extra noise is characterized as an “excess noise ratio” or ENR. Typical ENR values are 5 dB or 15 dB.

The cold source technique (also called the direct-noise method), only uses a single cold (room temperature) termination, and is used by vector network analyzers. This method is advantageous because one can perform multiple measurements on an amplifier, such as S-parameters and noise figure, with a single set of connections. Next, we will discuss the differences between the two techniques in more detail.

Excess noise ratio (ENR) = \frac{T_{\text{hot}} - T_{\text{cold}}}{290K}
Noise Figure Versus Noise Parameters

- Traditional noise figure gives noise performance at one source impedance (typically 50 ohms).
- Noise parameters provide noise figure versus source impedance (and versus frequency, bias, temperature...)

In this next section, we will discuss accuracy issues for both the Y-factor and cold-source methods.
Why Measure Noise Parameters?

- Optimize match for non-50-ohm devices (e.g. FETs generally have high $Z_{in}$ and low $Z_{out}$)
- Better prediction of system noise performance
  - Nominally matched devices will see non-ideal $Z_{o}$ in actual systems
  - Noise figure is insufficient to predict noise behavior with mismatch
  - Noise parameters account for mismatched sources
Noise Parameters

- Most common noise parameter set consists of four scalar quantities:
  \[
  F_{\text{min}}, R_n, \Gamma_{\text{opt}} (\text{mag}), \Gamma_{\text{opt}} (\text{phase})
  \]

- Noise figure can be expressed in terms of the four noise parameters:
  \[
  F = F_{\text{min}} + \left( \frac{R_n}{G_s} \right) \left| Y_s - Y_{\text{opt}} \right|^2 = F_{\text{min}} + \frac{4R_n}{Z_0} \frac{\left| \Gamma_{\text{opt}} \right| - \left| \Gamma_s \right|^2}{\left| 1 + \Gamma_{\text{opt}} \right|^2 \left( 1 - \left| \Gamma_s \right|^2 \right)}
  \]

The effect of noise correlation and source impedance can be expressed mathematically in the noise-parameter equation. With this equation, we can see that the noise factor (F) varies as a function of source impedance (\(\Gamma_s\)). There are three constants in the equation (two are scalar and one is a vector quantity), corresponding to the four noise parameters. The four noise parameters are \(F_{\text{min}}\) (the minimum noise factor), gamma-opt-magnitude, gamma-opt-phase, and \(R_n\) (noise resistance), which is a sensitivity term that controls how fast noise figure degrades as the source impedance moves away from gamma-opt. The absolute values in the equation are what generates the constant-noise circles.
Two-Port Noise Models

There are multiple ways to mathematically represent noisy two-port networks:

\[
\begin{align*}
V_1 &= Z_{11}I_1 + Z_{12}I_2 + e_1 \\
V_2 &= Z_{21}I_1 + Z_{22}I_2 + e_2 \\
I_1 &= Y_{11}V_1 + Y_{12}V_2 + i_1 \\
I_2 &= Y_{21}V_1 + Y_{22}V_2 + i_2 \\
I_1 &= AV_2 + BI_2 + i \\
V_1 &= CV_2 + DI_2 + e
\end{align*}
\]

Noise sources are generally independent, with varying degrees of correlation.

To understand why the noise figure of a device changes versus input match, we must take a closer look at the noisy two-port model of an amplifier. A noisy two-port network will have two noise sources, one associated with the input port, and one associated with the output port. Mathematically, we can express the noise generators as current or voltage sources, or a mix of both. The bottom representation is popular for noise analysis, because it separates the noise generators from a perfect gain block, and it is easier to understand how source match interacts with the two generators. The two noise sources are generally independent from one another, but typically there is some amount of correlation between them, depending on the physical and the electrical characteristics of the amplifier.
The idea of correlation between noise sources is crucial to understanding noise parameters. If two noise sources are fully correlated, then their instantaneous waveforms (current or voltage) will only differ by a scaling (gain) factor. If they are completely uncorrelated, then each waveform will be truly random and unrelated to the other waveform. For real-world amplifiers, the amount of correlation will be somewhere in between these two extremes, since the noise generators associated with the input and output ports share common active circuitry within the amplifier. These physical noise generators send noise in both the forward and reverse directions (which tends towards correlation), but the magnitude and phase changes in each direction will be different (which tends away from correlation). For example, transistors have gain in one direction, but loss in the other. If there is any correlation between the noise sources, then there will be some value of source impedance (gamma-opt) that provides the right amount of magnitude and phase shift to cause maximum cancellation, which results in a minimum noise figure.
Agenda

- Overview of Noise Measurements
- Noise Parameter Characterization Systems
- Measurement Results
Motivation for Change

• Speed up the measurement (traditionally slow)

• Simplify the measurement (traditionally difficult)
General Method for Measuring Noise Parameters

- Set four values of $\Gamma_s$
- For each $\Gamma_s$, measure $F$
- Solve four simultaneous equations based on the four measured values

$$F = F_{\text{min}} + 4r_n \frac{|\Gamma_s - \Gamma_{\text{opt}}|^2}{|1 + \Gamma_{\text{opt}}|^2 (1 - |\Gamma_s|^2)}$$
Practical Method for Measuring Noise Parameters

- Measurement is sensitive to small errors
- Use over-determined data
  - Measure at more than four $\Gamma_s$ values
  - Use least-mean-squares to reduce data
Refinement to Practical Method

Use noise-power equation:

- Provides rigorous solution
- Accounts for $\Gamma_{\text{hot}}$ and $\Gamma_{\text{cold}}$ of noise source
- Allows hot/cold or cold-only approaches

\[ P_n = kB\left([T_{NS} + T_0(F_1-1)]G_{a1} + T_0(F_2-1)\right)G_{t2} \]

- $P_n$ = noise power
- $k$ = Boltzmann's constant
- $B$ = system bandwidth
- $T$ = effective noise temperature
- $T_0$ = reference temperature (290 K)
- $F$ = noise figure
- $G_a$ = available gain
- $G_t$ = transducer gain

Noise source $\to$ DUT $\to$ Noise receiver
Noise Parameter Measurement Sequence

1. **System S-parameter calibration**
   - Tuners, noise source, deembedding

2. **Noise receiver calibration**
   - Noise and gain parameters of noise receiver

3. **DUT measurement**
Traditional Noise Parameter Setup

![Diagram showing the setup involving a Network Analyzer, Noise Source, Bias Tee, Tuner, DUT, Bias Tee, and Noise Figure Meter.](image-url)
Traditional Noise Parameter Calibration

- **System calibration**
  - Characterize tuners over entire Smith chart
  - Perform characterization at one frequency at a time
- **Receiver calibration and DUT measurement**
  - Measure at one frequency at a time
  - Allows ideal impedance pattern
Limitations of Traditional Method

- **Time-consuming procedure**
  - Tuner probe is moved many, many times during calibration and measurements
  - More likely to encounter errors due to drift
- **System calibrations**
  - Used for a long period to save test time
  - Calibrating parts separately increases errors
History

Heavy objects are hard to move
Innovation

Once seen, wheels are obvious!
New Method for Noise Parameter Measurements*

- Characterize only one set of tuner states (positions)
- Sweep frequency at each state
- Take advantage of fast sweep times of modern instruments like the PNA-X

* Patent pending
New Noise Parameter Method

**Problem:**
Maintaining proper impedance patterns at all frequencies

![Diagram showing impedance patterns at different frequencies](image-url)
New Noise Parameter Method

Solution:
Use non-uniform phase spacing

0.800 GHz F1

1.700 GHz F1

2.700 GHz F1
Here is the block diagram of a two-port PNA-X with the noise figure option. In addition to the noise receivers shown on the right side of the diagram, two mechanical switches are included. One is used to switch the noise receivers in and out of the measurement path, and the other is used to either include or bypass the ECal module on the source loop at test port one of the analyzer.
System Setup For New Method

- PNA-X with Noise Option + Maury Noise Software
- Noise Source
- Cal Plane
- Maury Tuner
- DUT
- DUT Cal Planes

Noise Source Cal Plane
New Measurement System is Simple!
Noise Parameter Steps for New Method

- **System calibration**
  - Perform 2-port S-parameter cal at DUT planes
  - Perform 1-port S-parameter cal at noise source plane
  - Perform tuner characterization (~ 3 - 4 minutes, 73 frequencies)
- **Noise receiver cal** (< 2 minutes, 73 frequencies)
- **DUT measurement** (< 2 minutes, 73 frequencies)

Note: For manufacturing test, this can be even faster with fewer frequencies
Less Operator Skill Required

**Traditional Method**
- Measurement much more complex than S-parameters
- Many connections and components required
  (external RF switches, bias tees, more cables, etc.)
- 4 to 6 S-parameter calibrations required
- Many opportunities for operator error

**New Method**
- Connections very similar to S-parameter calibrations
- Required skill of operator equal to S-parameter measurements
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Noise Parameter Results from Old Method

73 frequencies
30 hours, start to finish!
Smaller Frequency Steps Gives Aliased Results

Same data with 0.5 GHz steps
Noise Parameter Results from New Method

Same 73 frequencies, but now 224 times faster!
(8 minutes, including system calibration)
### Measurement Example with 401 Frequencies

<table>
<thead>
<tr>
<th></th>
<th>Traditional method (hr:min:sec)</th>
<th>New method (hr:min:sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>System cal</td>
<td>139:59:xx</td>
<td>00:03:12</td>
</tr>
<tr>
<td>Noise receiver cal</td>
<td>13:13:xx</td>
<td>00:10:44</td>
</tr>
<tr>
<td>DUT measurement</td>
<td>13:02:xx</td>
<td>00:10:54</td>
</tr>
<tr>
<td><strong>Total time (excluding connections)</strong></td>
<td><strong>166:14:xx</strong></td>
<td><strong>00:24:50</strong></td>
</tr>
<tr>
<td>Speed improvement</td>
<td></td>
<td><strong>400x!</strong></td>
</tr>
</tbody>
</table>
Accomplishment

- Success for motivation:
  - Two orders of magnitude faster!
  - Setup and measurement are much simpler!
- And, results are more accurate!
How Do We Get Better Accuracy?

- **Simpler setup**
  - Fewer cables and connections
- Always do full **in-situ calibration**
  - Removes accumulated errors of multiple S-parameter cals
  - Removes connection errors
- **Minimal drift** due to shorter calibration and measurement times
- Always use **dense frequency selection** to eliminate aliasing
Summary

New ultra-fast noise parameter measurement solution...

- Based on Agilent PNA-X and Maury tuners and software
- Industry breakthrough speed (224 times faster with 73 freqs)
- Better accuracy compared to legacy systems
- Simpler setup and measurements
- Less operator skill required

Opens up new possibilities!

- R&D engineers
  - No longer have to compromise accuracy for speed
  - Can iterate and verify designs much faster
  - Can perform system noise simulations with increased accuracy
- Test engineers
  - Can verify noise performance in production
  - Can specify noise of amplifiers under different mismatch conditions
Load Dependent X-parameters

- Leverage your PNA-X* and Maury tuners to form an NVNA system
- Fully characterize the nonlinear behavior of transistors and amplifiers at any arbitrary load impedance
- X-parameters load directly into PHD model of Agilent’s ADS for full nonlinear simulation

* NVNA application requires a 4-port PNA-X plus additional accessories
Contact Information

Interested? Have a need? Like to know more?

Maury Microwave Sales Department
• (909) 987-4715 (press “1” when prompted)
• www.maurymw.com

Agilent Technologies Test and Measurement Contact Center
• (800) 829-4444
• www.agilent.com/find/pnax

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