Optimizing RF Instrumentation for Challenging Measurements

Steve Nichols
NSI-MI Technologies
Motivation to Optimize Performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2005</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theta (Arch)</td>
<td>400 steps</td>
<td>400 steps</td>
</tr>
<tr>
<td>Phi (Azimuth)</td>
<td>800 points</td>
<td>800 points</td>
</tr>
<tr>
<td>Frequencies</td>
<td>4</td>
<td>485</td>
</tr>
<tr>
<td>Polarizations</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>AUT ports</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Total # measurements</td>
<td>$5.12 \times 10^6$</td>
<td>$1.24 \times 10^9$</td>
</tr>
<tr>
<td>Data File size</td>
<td>0.33 GB</td>
<td>81 GB</td>
</tr>
<tr>
<td>Acquisition Time</td>
<td>5 h*</td>
<td>151 h</td>
</tr>
</tbody>
</table>

*Dramatic changes in test requirements

*Positioner speed limited

11m diameter Arch/Azimuth SNF
Simple RF Measurement System

- **Probe**
- **Antenna Under Test**
- **Microwave Signal**
- **Transmit Signal**
- **Vector Network Analyzer**
- **Signal Channel**
- **Internal Transmit Source**
- **Internal Coupler & Reference Channel**
- **Internal LO Source**
- **Internal Mixers**
Measurement Environment

• Test range considerations
  • Motion of test article and/or probes
  • Long, lossy RF cables
  • Indoor/outdoor environmental stability

• Not a simple, bench-top environment
  • Test article located remotely from operator
  • Cable routing and management
  • Inconvenient access to equipment

*The RF instrumentation must overcome the challenges of the measurement environment*
Simple RF Measurement System

Transmit Signal → Microwave Signal → Antenna Under Test

Cable loss reduces available power

Long Cables Reduce Dynamic Range

Cable loss degrades sensitivity

Reduced dynamic range may be acceptable in some cases:
Small chamber with short cables, or low frequency systems
Sensitivity vs. Measurement Speed

- Sensitivity = Thermal Noise Floor + Instrument Noise Figure + 10log(IF BW)
- Every 10 dB improvement in sensitivity costs 10x in measurement speed
Sensitivity Degradation

- 10 dB of cable loss degrades effective sensitivity by 10 dB
- Measure 10x slower to make up the difference

**Rule of thumb:**
cable loss > 10 dB @ highest frequency - consider alternative RF approaches
## Planar Scanner Sizing

*Rule of thumb: cable loss > 10 dB @ highest frequency – consider alternative RF approaches*

<table>
<thead>
<tr>
<th>Highest Frequency</th>
<th>Max. Cable Length (10 dB loss)</th>
<th>Largest Planar Scanner (for max. cable length)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 GHz</td>
<td>23 meters</td>
<td>10m x 10m</td>
</tr>
<tr>
<td>18 GHz</td>
<td>12.6 meters</td>
<td>3.6m x 4.6m</td>
</tr>
<tr>
<td>20 GHz</td>
<td>11.3 meters</td>
<td>3.6m x 3.6m</td>
</tr>
<tr>
<td>40 GHz</td>
<td>4.6 meters</td>
<td>1m x 1m</td>
</tr>
</tbody>
</table>

Maximum Planar Scanner size for simple RF Measurement systems
Alternative RF Approaches for Long Cables

Accept Limitations
- Accept loss of sensitivity
- Accept longer measurement times

Add Amplifiers
- Add transmit amplifier
- Add an LNA at receive antenna output
  - Power drift with temperature changes

Distributed System
- Remote Mixing: maximize sensitivity
- Separate Transmit Source: locate near transmit antenna

Rule of thumb: cable loss > 10 dB @ highest frequency - consider alternative RF approaches
Distributed RF Measurement System

- Transmit Source
- Coupler
-参考接收器
- 探针
- 被测天线
- 载波/中频分配
- 中频处理
- LO/IF分配
- LO源
- 带通滤波器
- 接收子系统
Sensitivity Comparisons

Distributed Systems have better performance

Graph showing sensitivity comparisons for different systems:
- ZVA+cable
- ZVA
- PNA
- PNA Direct Rx
- PNA w/85309B
- MI-750, NSI Panther/DFC

Y-axis: Sensitivity (dBm)
X-axis: IF Bandwidth/Measurement Speed (Hz)
Sensitivity Impact to Measurement Uncertainty

- **Peak SNR = 60 dB**
  - Uncertainty: +/- 0.01 dB
- **Side Lobe SNR = 40 dB**
  - Uncertainty: +/- 0.1 dB
- **Null SNR = 20 dB**
  - Uncertainty: +/- 1.0 dB

**SNR = Signal to Noise Ratio**
Sensitivity/Speed Comparisons

Example:
Peak SNR = 60 dB
Peak power = -40 dBm

Required sensitivity = -100 dBm
Example: Spherical Near-Field/Far-Field System

Applications
• Stationary Device Under Test
• High frequency, low gain antennas
• Near-Field <200 GHz
• Far-Field <500 GHz
• Small or on-chip antennas

Description
<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction</td>
<td>Theta, phi, and pol rotation stages with steel interconnect structure</td>
</tr>
<tr>
<td>Drive System</td>
<td>Precision Stepper Motors</td>
</tr>
<tr>
<td>Scan Area</td>
<td>360° Phi and 360° Theta</td>
</tr>
<tr>
<td>Scan Radius</td>
<td>500 mm (with WR15 probe)</td>
</tr>
<tr>
<td>Probe</td>
<td>OEWG, Std. Gain Horn</td>
</tr>
<tr>
<td>Rotary Joints</td>
<td>DC-40 GHz (Phi, Theta)</td>
</tr>
</tbody>
</table>
Alternative Solutions for 18 - 40 GHz

- RF Cables: 12m to probe, 6m to DUT
- Cable/RJ loss: 32 dB @ 18 GHz, 49 dB @ 40 GHz
Alternative Solutions for 18 - 40 GHz

• RF Cables: 12m to probe, 6m to DUT
• Cable/RJ loss: 32 dB @ 18 GHz, 49 dB @ 40 GHz

Peak SNR at 1 kHz IF Bandwidth

<table>
<thead>
<tr>
<th>Peak Signal to Noise Ratio (dB)</th>
<th>VNA with cables only</th>
<th>VNA with Remote Mixing</th>
<th>VNA with LNA</th>
<th>Panther/750 Remote Mixing</th>
</tr>
</thead>
<tbody>
<tr>
<td>18 GHz</td>
<td>90 Hz</td>
<td>50 kHz</td>
<td>260 kHz</td>
<td>790 kHz</td>
</tr>
<tr>
<td>40 GHz</td>
<td>N/A</td>
<td>45 Hz</td>
<td>160 Hz</td>
<td>1.8 kHz</td>
</tr>
</tbody>
</table>

Measurement Speed for 60 dB Peak SNR
Distributed mmWave System (>40 GHz)

- Transmit Source
- mmWave Module
- Probe
- Microwave Signal
- mmWave Module
- Antenna Under Test
- Receive Subsystem
- IF Processing
- LO/IF Distribution
- LO Source
- Signal Channel
- Reference Channel
Harmonic Mixer Modules

- Mixer produces harmonics of the LO input
  - Closest multiple combines with the RF signal to produce the IF
- High conversion loss – low performance
- LNA may improve performance
Fundamental Mixer Modules

**LO multiplier before mixer improves performance**

Full VNA Extension Modules
- Flexible: easy Tx/Rx range reversal
- Coupler loss impacts measurement sensitivity

*Block diagrams courtesy of Virginia Diodes, Inc.*
Peak Signal to Noise Ratio for mmWave

- Compare module performance for SNF/FF system

Peak SNR at 1 kHz IF Bandwidth

<table>
<thead>
<tr>
<th>Peak Signal to Noise Ratio (dB)</th>
<th>Harmonic Mixing</th>
<th>Fundamental Mixing</th>
<th>Fundamental Mixing</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 GHz</td>
<td>60 GHz</td>
<td>60 GHz</td>
<td>60 GHz</td>
</tr>
<tr>
<td>90 GHz</td>
<td>90 GHz</td>
<td>90 GHz</td>
<td>90 GHz</td>
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</table>
Measurement Speed for mmWave

- Compare module performance for SNF/FF system

Peak SNR at 1 kHz IF Bandwidth

<table>
<thead>
<tr>
<th>Harmonic Mixing</th>
<th>Fundamental Mixing</th>
<th>Fundamental Mixing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full VNA Extension</td>
<td>High Sensitivity</td>
<td></td>
</tr>
</tbody>
</table>

- Peak Signal to Noise Ratio (dB)
  - 5 kHz
  - 1.6 kHz
  - 25 kHz
  - 10 kHz

Max. Max.

Measurement Speed for 60 dB Peak SNR
Practical Receiver Speed Impact

- Receiver speed is not the only factor
- 23% speedup for 8 dB sensitivity loss

![Graph showing the relationship between full acquisition time and sensitivity for different IF bandwidth/measurement speeds.]

- 1.2 billion measurements
- Data output: 81 GB
Frequency Switching Speed Impact

- This test has nearly 500 frequencies
- Large gains can be made with faster sources

<table>
<thead>
<tr>
<th>Source Type</th>
<th>Full Acquisition Time (Hours)</th>
<th>Switching Speed (μS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source 1</td>
<td>151 (h)</td>
<td>200</td>
</tr>
<tr>
<td>Source 2</td>
<td>97</td>
<td>50</td>
</tr>
<tr>
<td>Source 3</td>
<td>78</td>
<td>1</td>
</tr>
</tbody>
</table>

1.2 billion measurements
Data output: 81 GB

11m diameter Arch/Azimuth SNF
Multi-Channel Using Multiplexers

- Multiplexer combinations are measured sequentially in time

- Dual-polarized probe
- 2-port Multiplexer
- Coupler
- Signal Source
- Receiver
- AUT with 4 ports
- Multiple RF paths
- 4-port Multiplexer
- Vertical
- Horizontal
- Single RF Path
- Mixer
- Test input
- Reference input
- 1 RF cable
Multi-Channel Using Parallel Hardware

- Four channels + Reference measured simultaneously
- Sequential polarizations

Diagram:
- Dual-polarized probe
- 2-port Multiplexer
- Coupler
- Signal Source
- Mixer
- Reference input
- Multiple RF paths
- 4 Mixers
- 4 RF cables
- AUT with 4 ports
- 5-Channel Receiver

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Combinations of Improvements

- A >20x reduction in test time is possible

<table>
<thead>
<tr>
<th>Combo</th>
<th>IF BW</th>
<th>Source Speed</th>
<th>2 port Mux</th>
<th>4 port Mux</th>
<th>5 chan Rcvr</th>
<th>Total Test Time (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>10 kHz</td>
<td>200 μS</td>
<td></td>
<td></td>
<td></td>
<td>151</td>
</tr>
<tr>
<td>1</td>
<td>68 kHz</td>
<td>200 μS</td>
<td></td>
<td></td>
<td></td>
<td>117</td>
</tr>
<tr>
<td>2</td>
<td>68 kHz</td>
<td>50 μS</td>
<td></td>
<td></td>
<td></td>
<td>63</td>
</tr>
<tr>
<td>3</td>
<td>10 kHz</td>
<td>50 μS</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
<td>48</td>
</tr>
<tr>
<td>4</td>
<td>68 kHz</td>
<td>50 μS</td>
<td>Yes</td>
<td></td>
<td>Yes</td>
<td>9</td>
</tr>
<tr>
<td>5</td>
<td>68 kHz</td>
<td>1 μS</td>
<td>Yes</td>
<td></td>
<td>Yes</td>
<td>7</td>
</tr>
</tbody>
</table>

1.2 billion measurements
Data output: 81 GB

11m diameter
Arch/Azimuth SNF
Conclusion: Addressing Measurement Challenges

• Tools for your toolbox
  • Not every tool applies to every problem
• Match RF instrumentation to the measurement challenge
  • Simple RF equipment for low frequency test or no time pressure
• Higher test frequencies require distributed systems
• Locate equipment to minimize RF cable losses
• Low noise figure receiver
• Fast frequency switching speed
• Apply multi-channel measurement techniques
• Trade off sensitivity and measurement speed