Evaluating signal integrity with a Vector Network Analyzer
Agenda

• Scalar vs. Vector analysis
  • Uses for each
• Transmission Lines
• S-Parameters
  • Wave quantities and wave ratios
  • How S-Parameters are derived from wave quantities
• Network Analyzer Architecture
  • Block diagram of ZVA
• Calibration
  • Importance of calibration
  • Use of calibration manager on the ZVA
• Signal Integrity measurements
  • Time domain
  • Balanced devices
Spectrum Analyzers vs. Vector Network Analyzers

**Spectrum Analyzers:**
- Measure signal amplitude characteristics, carrier level, sidebands, harmonics...
- Can demodulate (+ measure) complex signals
- Spec Ans are receivers only (single channel)
- Can be used for scalar component test (no phase) with tracking gen. or external source

**Network Analyzers:**
- Measure components, devices, circuits, sub-assemblies
- Contains sources and receivers
- Display ratioed amplitude and phase (frequency, power or time sweeps)
- Offers advanced error correction.
Scalar Network Analysis

- Basic scalar analyzer can be a signal generator and a power meter
- Drawbacks are speed, dynamic range and no phase information
- Advantage is cost

Scalar Network Analysis
set up with power meter

Software FreRes(R&S App.Note1MA09)
Scalar Network Analysis

- Basic scalar analysis can be done with a spectrum analyzer, tracking generator or external generator
- Drawback is cost compared to signal generator and sensor
- Still no phase information
- Advantages are speed, dynamic range and spectrum analyzer can be used for other measurements
What Devices do Vector Network Analyzers Test?

Filters
RF Switches
Couplers
Cables
Amplifiers
Antennas
Isolators
Mixers (upconverters, downconverters, also sometimes referred to as transmitters and receivers)

...Most 2 (or more) port devices (and some 1 port devices)
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Optical Analogy to RF Transmission

- Network analyzers measure transmitted and reflected signals relative to the incident signal.
- Scalar analyzers measure magnitude only, vector analyzers measure magnitude and phase of these signals.
Transmission Lines

Parallel Lines

Coax Cable

Microstrip Line

Waveguide
Transmission Line Terminated with Zo

A transmission line terminated in Zo behaves like an infinitely long transmission line.

\[ Z_s = Z_0 \]

\[ V_{\text{refl}} = 0 \] (all the incident power is absorbed in the load)

\[ V_{\text{inc}} \]

Zo = characteristic impedance of transmission line
Transmission Line Terminated with Short, Open

A transmission line terminated in a short or open reflects all power back to source.
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High-Frequency Device Characterization

**REFLECTION**

\[
\frac{\text{Reflected}}{\text{Incident}} = \frac{b_1}{a_1}
\]

- SWR
- S-Parameters $S_{11}, S_{22}$
- Reflection Coefficient $\Gamma, \rho$
- Return Loss
- Impedance, Admittance $R+jX, G+jB$

**TRANSMISSION**

\[
\frac{\text{Transmitted}}{\text{Incident}} = \frac{b_2}{a_1}
\]

- Gain / Loss
- S-Parameters $S_{21}, S_{12}$
- Transmission Coefficient $T, \tau$
- Group Delay
- Insertion Phase

Incident ("a1" receiver)

Reflected ("b1" receiver)

Transmitted ("b2" receiver)
Reflection and transmission
Termination with line impedance (MATCH)

- Current and voltage in phase
- Perfect traveling wave
- No space dependence
- Perfect power transmission from source to drain

\[ Z_A = Z_L \]

\[ \Gamma = 0 \]
Reflection and transmission

Open line: \( (\text{OPEN}) \quad Z_a = \infty \)

- Reactive behavior \( (\Delta \varphi_{U,I} = -90^\circ) \)
- Standing wave
- Current and voltage are space-dependent
- Power oscillates along the line

\[ \Gamma = 1 \]
Reflection and transmission
short-circuited line: (SHORT) \( Z_a = 0 \)

- Reactive behavior \( (\Delta \varphi_{U,I} = +90^\circ) \)
- Standing wave
- Current and voltage are space-dependent
- Power oscillates along the line

\[ \Gamma = -1 \]
S-Parameters, wave quantities and their relationship

S-parameters are the basic measured quantities of a network analyzer. They describe how the DUT modifies a signal that is transmitted or reflected in forward or reverse direction. For a 2-port measurement the signal flow is as follows:

- $S_{11}$ is the input reflection coefficient, defined as the ratio of the wave quantities $b_1/a_1$, measured at PORT 1 (forward measurement with matched output and $a_2 = 0$).
- $S_{21}$ is the forward transmission coefficient, defined as the ratio of the wave quantities $b_2/a_1$ (forward measurement with matched output and $a_2 = 0$).
- $S_{12}$ is the reverse transmission coefficient, defined as the ratio of the wave quantities $b_1$ (reverse measurement with matched input, $b_{1,rev}$ in the figure above and $a_1 = 0$) to $a_2$.
- $S_{22}$ is the output reflection coefficient, defined as the ratio of the wave quantities $b_2$ (reverse measurement with matched input, $b_{2,rev}$ in the figure above and $a_1 = 0$) to $a_2$, measured at PORT 2.

See page 59 of the ZVA user manual
Criteria for Distortionless Transmission

Constant amplitude over bandwidth of interest

Linear phase over bandwidth of interest

Distortion is indicated by:
- Deviation from constant amplitude
- Deviation from linear phase (or stated another way...)
- Non-constant group delay
Group Delay

VNAs calculate group delay from phase measurement across frequency.

Group-delay ripple indicates phase distortion (deviation from linear phase).

Average delay indicates electrical length of DUT.

Aperture of group delay measurement is very important.
Real world example of distortion: OFDMA and EVM

- Consider an OFDMA signal that is 20 MHz wide, 1201 sub-carriers
- With “nearly flat” amplitude and phase response…

• EVM is ~ 55 dBC; a fairly low value.
Real world example of distortion: OFDMA and EVM

- Introduce “linear” amplitude and phase distortion via a channel filter, which primarily impacts the band edges.
  - Approximately 0.5 dB of amplitude response
  - Approximately 2.5 nS of group delay response
  - EVM is now 35 dBc at the band edges
  - Poor EVM can result in lost data, which means retransmission of data, which means lost $$$$$
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Directional Coupler – Directivity

- Directivity is a measure of how well a coupler can separate signals moving in opposite directions.
- A termination at the test port should result in no signal at the b receiver.
- The difference between the coupled signal and the leakage signal is the directivity of the coupler (typical values: 15-25dB).
“a” receiver is also known as reference receiver
“b” receiver is also known as measure receiver
ZVA 2-Port Test Set with direct receiver access (B16)
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Measurement Errors (Calibration)

Drift Errors
- Caused by changes in environment after calibration (temperature, humidity)
- Minimized by controlling test environment

Random Errors
- Caused by instrument noise, switch and connector repeatability
- Not repeatable
- Minimized by high quality equipment and good measurement practices

Systematic Errors
- Due to non-ideal components in the VNA and test setup
- Assumed to be repeatable
- Calibration is used to correct for these errors
- Residual error limited by quality of calibration standards

 puedt

removed (nearly) with calibration
cannot be removed – only minimized
Calibration

- We only want to measure our DUT (device under test) and nothing else!
- Need to remove the phase and amplitude response of our test setup
- Connect known standard (something we know) to the “calibration plane”
Types of Error Correction

- **Response (normalization)**
  - simple to perform
  - only corrects for tracking errors
  - stores reference trace in memory, then does data divided by memory

- **Vector**
  - requires more standards
  - requires an analyzer that can measure phase
  - accounts for all major sources of systematic error
Vector Error Correction

- Process of characterizing systematic error terms
  - Measure known standards
  - Remove effects from subsequent measurements

- 1-port calibration (reflection measurements)
  - Only 3 systematic error terms measured
  - Directivity, source match, and reflection tracking

- Full 2-port calibration (reflection and transmission measurements)
  - 10 systematic error terms measured (crosstalk assumed to be zero)
  - Usually requires 7 measurements on four known standards (TOSM)
  - Thru need not be characterized (unknown thru calibration)

- Standards defined in cal kit definition file
  - Network analyzer contains standard cal kit definitions
  - **CAL KIT DEFINITION MUST MATCH ACTUAL CAL KIT USED!**
  - User-built standards must be characterized and entered into user cal kit
Improvement from a One-Port Calibration

Measurement of match at the end of a 2ft cable
Methods of De-embedding

- Simple delay (port extension)
  - Simply moves reference plane (mathematically)
  - Assumes fixture is ideal transmission line with fixed delay
  - Simple loss model can optionally be included
  - Delay can be entered explicitly or measured with an open or short

- Fixture Compensation
  - Models fixture vs. frequency (delay and loss)
  - Does not assume fixture is simple ideal transmission line
  - Compensation can be measured with open, short, or both
  - AFR can also be done

- De-Embedding
  - Models fixture as lumped element network or…
  - Uses measured S-parameters of fixture to de-embed
  - Most accurate, but S-parameters can be difficult to measure for some fixtures
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Introduction – Signal Integrity

- Signal Integrity is a set of measures of the quality of an electrical signal

- Two Key Aspects of SI:
  - Timing which can be quantified as Jitter
  - Signal Quality which can be described with parameters such as ringing, crosstalk, etc.

- Jitter can be measured directly in the time-domain using an oscilloscope or in the frequency-domain using a phase noise analyzer

- Signal Quality can be measured in the time-domain using a high-speed TDR technique or in the frequency-domain using a vector network analyzer (s-parameters).

- IEEE P802.3ap Task Force uses S-parameters as test cases for proposed solutions to the problem of 10 Gbit/s ethernet over backplanes.
Measurement Techniques for Balanced Devices
Balanced Devices

Ideal device responds to differential input signals and rejects common-mode input signals

Differential-mode signal

Common-mode signal (EMI or ground noise)

Balanced to single-ended

Fully balanced
Balanced devices – Why Balanced Design?

Components with balanced design:
- Amplifiers
- Mixers
- Filters (e.g. SAW filters)
- PCB layout in mobile phones
- LAN adapters, converters, filters
- PC components (HDD control, etc)
- Almost all signals high-speed serial data signals

Advantages:
- High noise immunity
  - Minimizes Power and ground plane noise
  - Minimizes EMI susceptibility
  - Minimizes Cross talk
- Low radiated noise
- High integration density
- Lower power consumption
Ideally, balanced devices transmit differential and reject common-mode signals.
Non-Ideal Balanced Device Characteristics

- Non-ideal balanced devices convert modes

  Differential to common-mode conversion

  Generates EMI

  Susceptible to EMI

  Common-mode to differential conversion
Parameters to Test for a Balanced Device

- Performance in pure differential mode
- Performance in pure common mode
- Conversion from differential mode to common mode (in both directions)
- Conversion from common mode to differential mode (in both directions)
Basic Architecture: Definition of Differential Measurements

Measurement Principle

- **VirDi = Virtual differential Mode**
  - Characterization of balanced DUT as single ended DUT with mathematical calculation of mixed-mode S-Parameters from single ended S-Parameters

- **TruDi = True differential Mode**
  - Stimulation of DUT with true differential and common mode signals with calculation of mixed-mode S-Parameters from error corrected mixed mode wave quantities
Virtual Differential Measurement

- Single ended measurements with post processing using linear superposition
- Applicable for all passive devices and active devices operating in their linear region
- Large deviations compared to True Differential in large signal operation, especially in terms of compression curve characteristics
  - Nonlinear behavior of the DUT prohibits linear superposition
ZVA – True Differential Mode

- Coherent sources
  - Generation of true differential and common mode stimulus signals
  - At least one signal output can be adjusted in amplitude and phase with respect to the other
- Simultaneous measurement of two reference signals (a waves) and two measurement signals (b waves)
- Four-port calibration in the reference plane
  - Vector-corrected measurement of single ended waves or voltages
- Calculation of true differential S-Parameters from vector corrected wave quantities
Coherent signals of arbitrary phase and amplitude imbalance are possible

- **Sweep Modes:**
  - Frequency
  - Phase (Phase of the stimulating signal can be swept from 0° to 180°)
  - Magnitude (Variation of the relative magnitude of the differential signals)
- “Classical” VNA calibration techniques sufficient (full two port)
  ⇒ Investigation of the DUT under real conditions
Typical measurements quality parameters

- Differential and common mode insertion loss
- Differential and common mode return loss
- NEXT-Measurements (Near End Crosstalk)
- FEXT-Measurements (Far End Crosstalk)
- Amplitude-Imbalance
- Phase-Imbalance
- Common-Mode Rejection Ratio (CMRR)
Port Configurations for Differential DUT

- Physical single ending ports → logical balanced ports

- Different impedances for common-mode and differential-mode
  - differential-mode (ideally matched) → 100 Ω ( =2*Z₀ )
  - common-mode (ideally matched) → 25 Ω ( =1/2*Z₀ )
Modal Decomposition Method
Mixed Mode S-Parameter Matrix

DUT

Logical Port 1  Logical Port 2

Differential-Mode stimulus
Port 1  Port 2

Common-Mode stimulus
Port 1  Port 2

Differential-Mode Response
Port 1  Port 2

Common-Mode Response
Port 1  Port 2

Naming Convention: $S_{mode\ meas., \ mode\ stim., \ port\ meas., \ port\ stim.}$
Mixed Mode S-Matrix: DD Quadrant

- Describes fundamental performance in pure differential-mode operation
### Mixed Mode S-Matrix: CC Quadrant

The Mixed Mode S-Matrix describes the fundamental performance in pure common-mode operation. The matrix is structured to illustrate the input reflection, reverse transmission, forward transmission, and output reflection scenarios. Each element in the matrix corresponds to a specific characteristic of the system, with indices indicating the input and output ports.

The S-Matrix is given by:

\[
\begin{bmatrix}
S_{dd} & S_{dc} & S_{dd} & S_{dc} \\
S_{dd} & S_{cc} & S_{dd} & S_{cc} \\
S_{cd} & S_{cd} & S_{cc} & S_{cd} \\
S_{cd} & S_{cd} & S_{cd} & S_{cc}
\end{bmatrix}
\]

- **S_{dd}**: Describes the direct transmission from input to output in the same mode.
- **S_{dc}**: Describes the reverse transmission from input to output in the opposite mode.
- **S_{cc}**: Describes the forward transmission from input to output in the same mode.
- **S_{cd}**: Describes the output reflection from input to output in the opposite mode.

This matrix is crucial for analyzing and designing mixed-mode systems in electronics and communications engineering.
Mixed Mode S-Matrix: DC Quadrant

- Describes conversion of a common-mode stimulus to a differential-mode response
- Terms are ideally equal to zero with perfect symmetry
- Related to the generation to EMI
Mixed Mode S-Matrix: CD Quadrant

- Describes conversion of a differential-mode stimulus to a common-mode response
- Terms are ideally equal to zero with perfect symmetry
- Related to the susceptibility of EMI
Example 1: Tunable Active Filter

True differential power axis has been shifted by -3 dB to equalize voltage amplitudes
Summary: TruDi vs. VirDi

- Passive Devices/Linear operation
  - TruDi and VirDi give exactly the same results

- Active Devices/Non-linear operation
  - Significant difference between TruDi and VirDi
  - TruDi represents the real operating conditions of a device

- TruDi Measurements
  - Requires two phase coherent sources
  - Ability to set amplitude and phase independently
  - Relative phase stability of VNA sources is crucial for reproducible results
Measurement Techniques for TDR
Applications of TDR

 Localization of Faults in Transmission Lines

- This is the 1st application that I think of for TDR measurements
- Examples include localizing a fault on an underground cable or a cable running up a tower
- Test to see if an antenna is properly connected
- Check if an amplifier or filter is presenting the expected impedance
Applications of TDR

Moving the Reference Plane of RL measurements

- This is the second most common use for TDR
- In the frequency domain we see “all” the reflected signals. By separating the results in the time domain, we can determine the source of the reflections.
But what is a TDR measurement?

- In a TDR measurement, we send a pulse down a transmission line, and then we record (in time) the reflections that come back out of the transmission line.
- This can be done with a “fast” power supply and a “fast” oscilloscope.
- The goal is to measure the transient traveling waves on the transmission line leading to the device under test.

- The time delay tells us the distance to the load.
- The reflected wave (magnitude and phase) tells us the impedance of the load.
And what are the challenges

- Generating a very clean and fast pulse
  
  1. A stepped pulse in the time domain generates *all* frequencies in the frequency domain.
  2. The pulse generator needs to be matched to the transmission line. Mismatches need to be “calibrated” out of the measurement.
  3. The oscilloscope needs to sample at a very high frequency. These pulses are traveling at the speed of light if the transmission line has an air dielectric.
  4. The oscilloscope also needs to be matched to the transmission line.

- These challenges match up well with the features of modern vector network analyzers.
Aliasing in the time domain

- Aliasing results from the fact that the Network Analyzer measures the spectrum at a finite number of discrete measurement points.
- In the time domain, this results in the time response being copied at regular intervals (Fourier transform of a comb spectrum is a comb spectrum).
- Ambiguity range: $\Delta t = 1 / \Delta f$
  where $\Delta f = \text{spacing of measurement points}$
Aliasing in the time domain

3001 Points

301 points
Tradeoffs and settings

- We need to pick a frequency span and number of points
  - We will end up with an alias free range, and a time resolution.
  - A spreadsheet can help us with this.
- We then pick a window function in the frequency domain
  - We end up with a minimum pulse width, and a certain amount of side lobe suppression or ringing.
  - What are we trying to measure, high dynamic range, or a high amount of precision on the distance or time axis.
Example: Distance to Fault (DTF)

**SETTINGS and CONSTANTS**

- Span (Hz): $9.99 \times 10^9$
- # of Points: 1001
- Dielectric Constant of Cable: 2
- Lowpass Mode: 2, Bandpass Mode: 1
- Speed of Light (m/s): $3.00 \times 10^8$
- Meters to Feet Conversion: $3.28$

**LIMITATIONS**

- Max Measurable Cable Length (ft): 69.72
- Max Measurable Time (s): $1.00 \times 10^{-7}$
- Distance Resolution (in): 0.255
- Time Resolution (s): $4.25 \times 10^{-2}$
Time Gating

- Time Gating opens up a whole new range of applications for the Time Domain option of a Network Analyzer.
- Typical application is to filter out certain parts of the response and display back into the Frequency Domain.

Measure the return loss looking into this adaptor, even though the cable is terminated with an open circuit.
Impulse and Step Response Examples

SHORT               OPEN

Impulse

Impulse

Step

Step
S11 measurement with no gating

-70 -60 -50 -40 -30 -20 -10 0 10 0 10 0 10

Pb Time Domain

Ch1 Trc1 S11 dB Mag 10 dB / Ref 0 dB
Trc2 S11 Real 50 mU/ Ref 150 mU

S11

M1 797.0000 ps 287.43 mU

11/3/2014, 12:49 PM

10.11.2014 Introduction and Fundamentals of VNA’s 110
S11 measurement with gating

Trc1 S11 dB Mag 10 dB / Ref 0 dB Gat
Trc2 S11 Real 50 mU / Ref 150 mU

S11

M1 797.0000 ps 258.66 mU

Ch1 fb Start 19.900498 MHz Pb 0 dBm
Trc2 fb Start -1 ns Time Domain
Stop 4 GHz Stop 4 ns

11/3/2014, 12:48 PM
Summary of VNA Settings

- The **Span** determines the *Time Resolution* as follows:
  - When in Bandpass Mode: Resolution = 2 / Span
  - When in Lowpass Mode: Resolution = 1 / Span

- The **# of Points** and **Span** determine the *Ambiguity Range* by the following relation:
  \[
  \text{Range} = \frac{1}{\Delta f} = \frac{1}{(\text{Span} / \text{# of points})}
  \]

- Use **Lowpass Mode** if the sign of the Real Part of $\Gamma$ is important (e.g. for a Short Circuit Response). **Bandpass Mode** can be used when only concerned with Magnitude measurements.

- **Frequency Windowing** affects the shape of the main and side lobe responses in the Time Domain.

- Use **Time Gating** to filter out undesired discontinuities of the DUT.

- **Time Gate Windowing** affects the shape of the main and side lobe responses in the Frequency Domain.
What is the Measurement Frequency?

The max frequency for the VNA can be calculated from the required rise time of the data.

<table>
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<tr>
<th>Product</th>
<th>Max Frequency</th>
<th>Rise Time</th>
</tr>
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<tbody>
<tr>
<td>ZNB8</td>
<td>8.5 GHz</td>
<td>59 ps</td>
</tr>
<tr>
<td>ZVA24</td>
<td>24 GHz</td>
<td>21 ps</td>
</tr>
<tr>
<td>ZVA40</td>
<td>40 GHz</td>
<td>13 ps</td>
</tr>
<tr>
<td>ZVA50</td>
<td>50 GHz</td>
<td>10 ps</td>
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<tr>
<td>ZVA67</td>
<td>67 GHz</td>
<td>7.5 ps</td>
</tr>
<tr>
<td>ZVA110</td>
<td>110 GHz</td>
<td>4.5 ps</td>
</tr>
</tbody>
</table>
Thank you!