Keysight Technologies

Comparison of Measurement Performance between Vector Network Analyzer and TDR Oscilloscope

White Paper

Introduction

The bit rate of digital communication standards have dramatically increased in recent years, with multi-Gbps transmission becoming commonplace. For example, USB 3.0 specifies a bit rate of 5 Gbps. With this increase in bit rate, issues not seen in traditional digital systems arise. Issues such as reflection and loss cause distortion in digital signals leading to bit errors. Timing skew of signal paths becomes critical as the acceptable time margin for proper device operation decreases. Radiated electromagnetic waves and coupling due to stray capacitance cause crosstalk leading to errors in device operation. As circuits become smaller and compact, this issue is magnified. To make matters worse, the trend towards lower supply voltages leads to lower signal-to-noise ratio, and more sensitivity of device operation to noise. Although these issues increase the difficulty in digital circuit design, there is constant pressure to shorten development time.

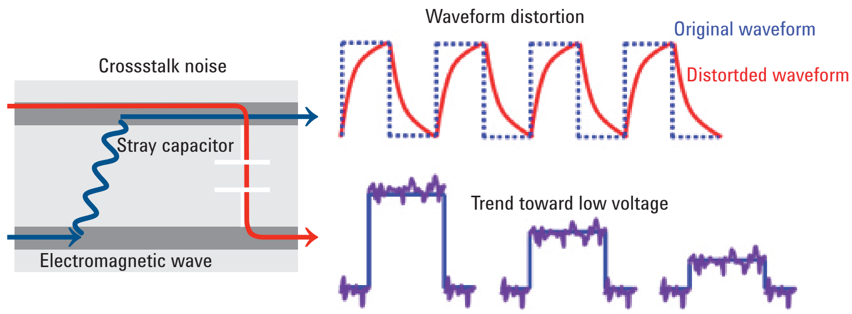

Figure 1. Issues in digital system designs.

Although the aforementioned issues are unavoidable as bit rates increase, detection and characterization of such issues are possible using highly accurate measurement instruments. The measurement requirements needed on the instruments to deal with such issues are the following:

a. High dynamic range across a wide frequency span
   One way to achieve high dynamic range is to lower the noise level. If the instrument noise is minimized, low signal level measurements (i.e. crosstalk) become possible. It is critical to measure the high frequency components accurately, as they are the most common cause of signal integrity issues.

b. Precise synchronization of stimulus signals
   Precise stimulus signal synchronization leads to more accurate measurements when evaluating skew between multiple lines.

c. Fast measurement throughput and display update
   Fast measurement throughput and display update allows for efficient design and increase in throughput in production.

Traditionally, the sampling oscilloscope-based time domain reflectometer (TDR) has been used for evaluation of cables and printed circuit boards. Due to the relatively high noise of the oscilloscope, simultaneously achieving high dynamic range and fast measurements has been difficult. Averaging can be used to lower the noise, but this sacrifices measurement speed. Also, the jitter between the multiple signal sources used to measure skew on an oscilloscope may cause errors. In addition, implementing electrostatic discharge (ESD) protection circuits on the oscilloscope are difficult and TDR oscilloscopes are prone to failure due to ESD.

These issues which are fundamentally difficult to resolve on the TDR oscilloscope can be resolved with a vector network analyzer (VNA) -based TDR solution.

Time Domain Reflectometry Measurements using a Vector Network Analyzer

What does a VNA measure?

A VNA is an instrument which measures the frequency response of the device under test (DUT). A sine wave input to the DUT and the vector magnitude ratio is calculated between the reference and transmitted (S21) or reflected (S11) signals (Figure 2). The frequency response is obtained by sweeping the signal input across frequency (Figure 3). A bandpass filter is located in the receiver to remove noise and unwanted signals from the measurement to improve accuracy.

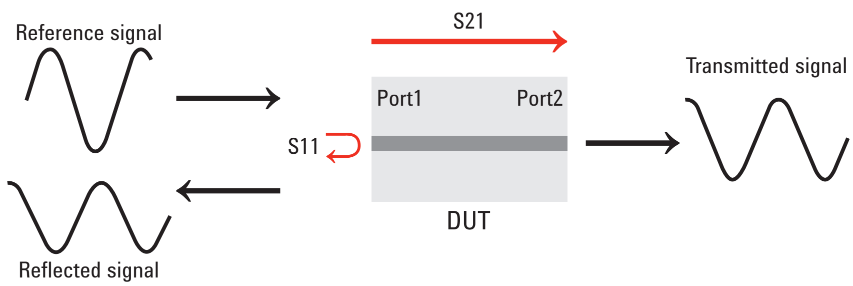

Figure 2. Diagram of reference, reflection, and transmission signals.

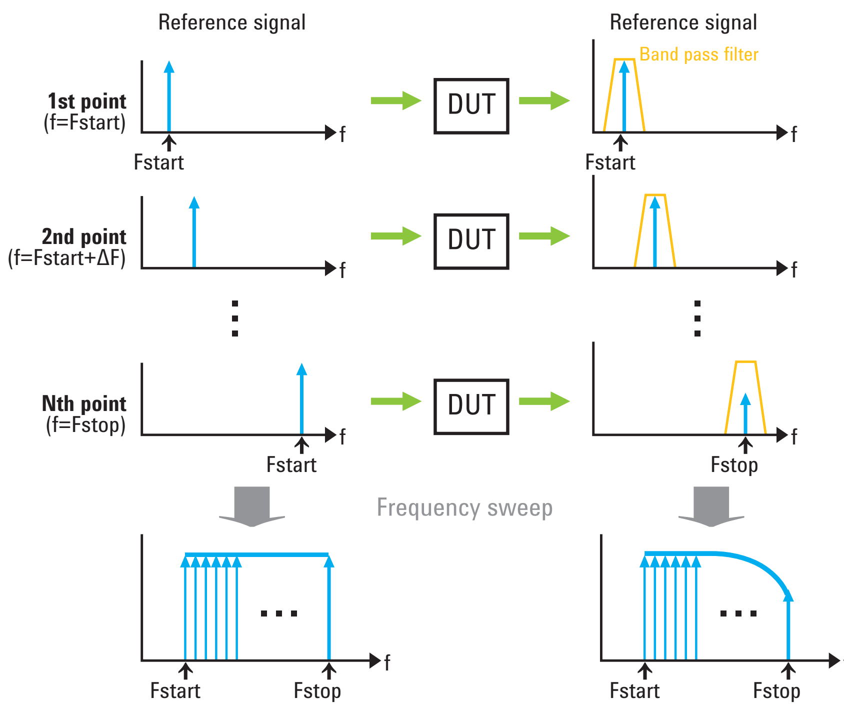

Figure 3. Sine wave stimulus signal is swept across frequency to obtain the frequency response on the VNA.

Converting from Frequency Domain to Time Domain (Inverse Fourier Transform)

It is well known that the relationship between the frequency and time domains can be described by the Fourier theory. By applying the inverse Fourier transform to the reflected and transmitted frequency response obtained with a VNA, the time domain impulse response can be obtained (Figure 4). By integrating the impulse response, the step response can be obtained. This is the same response that can be observed on a TDR oscilloscope. Since the integration calculation is time consuming, the actual implementation is done in the frequency domain using the convolution theorem of the Fourier transform. The Fourier transform of the input signal is calculated and convolved with the frequency response of the DUT. Then, the inverse Fourier transform is applied. Since integration in the time domain is also described by convolution in the frequency domain, fast calculation of the step response is possible.

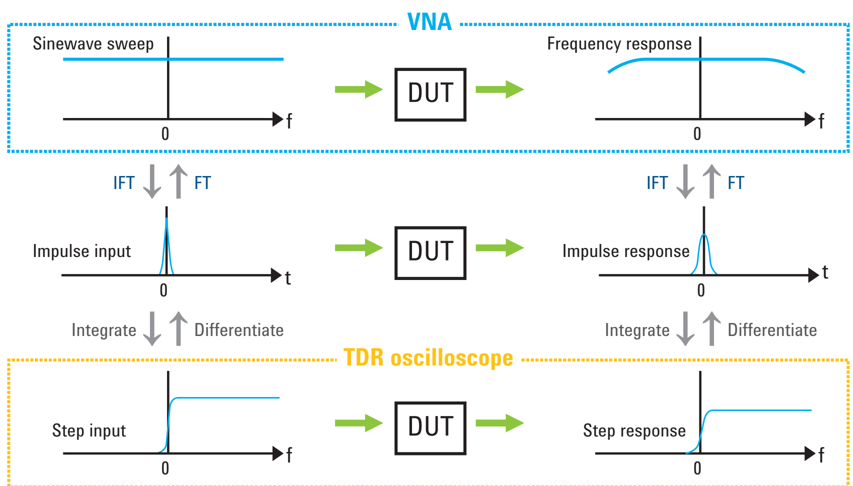

Figure 4. Relationship between the step and impulse response derived from the inverse Fourier transform.

The time resolution and time span obtained with the inverse Fourier transform correspond respectively to the inverse of the maximum frequency and the inverse of the frequency step (Figure 5). For example, for a maximum frequency of 10 GHz, the time resolution is 100 psec. It may seem that the time span can be increased without bound by increasing the frequency step, but there is a limit. Since the frequency data used in the inverse Fourier transform needs to be equally spaced in the frequency domain, the inverse Fourier transform cannot be performed for frequency steps smaller than the minimum frequency of the VNA. For example, if the minimum frequency for the VNA is 100 kHz, the maximum time span is 10 usec. This is more than sufficient for TDR measurements.

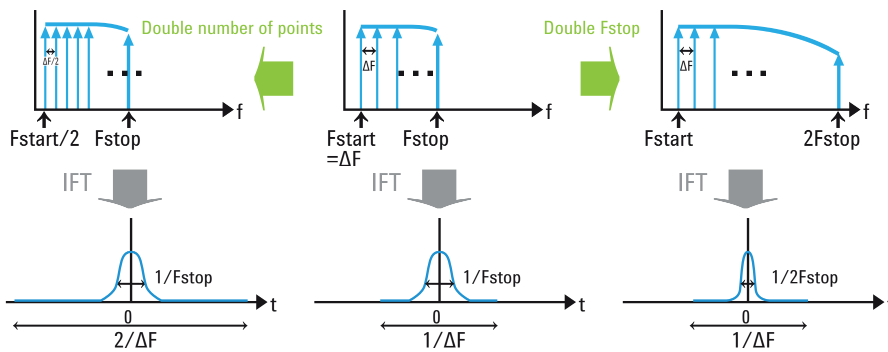

Figure 5. Relationship between the time domain parameters (time resolution and measurement time) and frequency domain parameters (maximum frequency and frequency step).

Correlation between the VNA-based and oscilloscope-based TDR response is shown in Figure 6. The same DUT (test fixture and cable from Hosiden) was measured with the Keysight Technologies, Inc. ENA E5071C VNA and Keysight DCA 86100C TDR Sampling Oscilloscope. The measurement result format is impedance and there is < 0.4 Ω difference between the two measurement results.

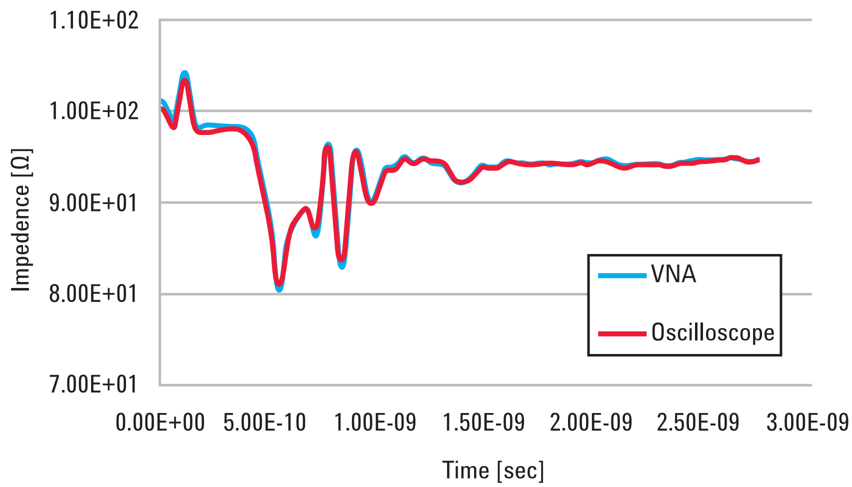

Figure 6. Correlation between measurements taken on a VNA (E5071C) and TDR oscilloscope (86100C) (averaging = 16 is applied to the TDR oscilloscope measurement).

Dynamic Range Comparison between the VNA and TDR Oscilloscope

Previous literature has covered the limitations and accuracies of a VNA and TDR oscilloscope. This discussion will focus on the theoretical comparison of dynamic range due to the difference in architecture between the VNA and TDR oscilloscope.

The following assumptions have been made to simplify the discussion:

– The noise and bandwidth (f_C) of the systems are equal

– The noise is assumed to be uniform (white noise) from DC to fC and the observed power is b^2.

– The max signal power (a^2) of the TDR oscilloscope step input and the VNA sine wave input is equal.

– No loss in transmission channel between the signal source and receiver.

– Normalized impedance is used to simplify the numerical expressions.

First the dynamic range is compared for a single measurement. The time domain response from a TDR oscilloscope consists of the step stimulus and noise. The power of each component is defined as a^2 and b^2 respectively. The dynamic range is simply the ratio of these components. For the VNA, the bandpass filter passes the signal without loss and thus the signal power is a^2. The noise component is attenuated in the stopband of the bandpass filter. If the bandpass filter bandwidth is f_{IF}, the noise at the output of the filter is attenuated by f_{IF}/f_C. Since the reduction in noise is directly proportional to dynamic range, the dynamic range increases by 10 log (f_C/f_{IF}) dB. Since this relationship is independent of stimulus frequency, the dynamic range of the time domain response obtained by the inverse Fourier transform will also improve by 10 log (f_C/f_{IF}) dB compared to the TDR oscilloscope.

1. Keysight Technologies, Limitations and Accuracies of Time and Frequency Domain Analysis of Physical Layer Devices, Literature Number 5988-2421EN

2. Since the negative frequency component is the complex conjugate of the positive frequency component, the actual data points required is M/2.

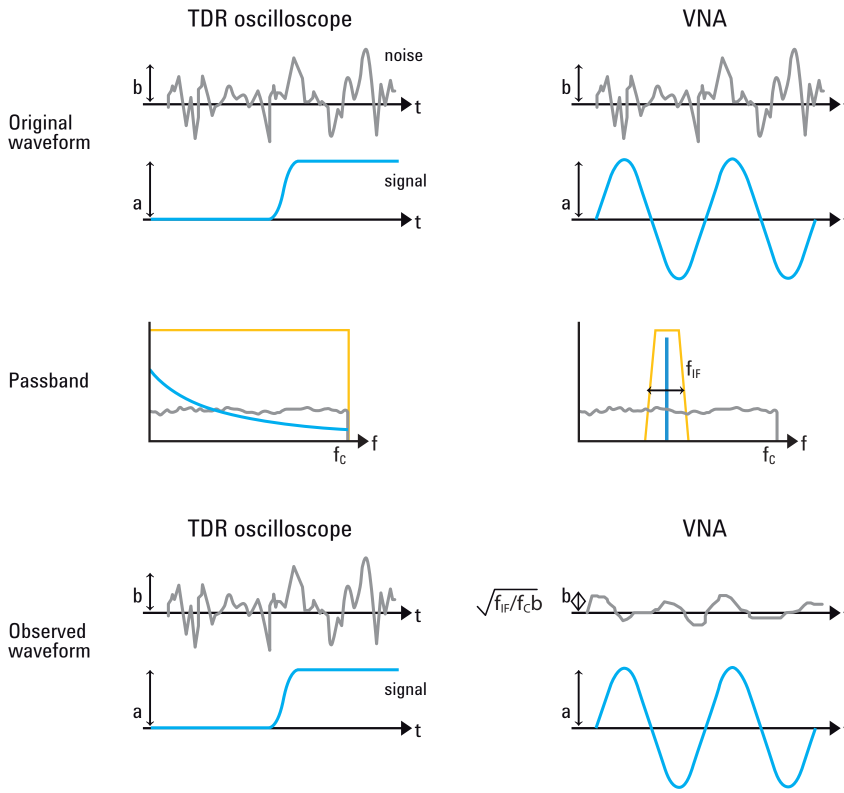

Figure 7. Noise reduction mechanism on the VNA.

Next, the measurement time to obtain the time domain response with the same time span (T) and time resolution is compared.

For the TDR oscilloscope, to obtain an equivalent sampling frequency f_E with physical sampling frequency f_P, the measurement will take f_E/f_P times longer (Figure 7). $T \times f_E$ data points (M) are required for a time span of T and the measurement time is $T \times f_E/f_P$. A frequency step of 1/T and M[*1] data points are required to obtain the same time domain response on the VNA (Figure 9). The measurement time for a single point is predominantly determined by the bandpass filter and is $1/f_{IF}$. Thus, the total measurement time is $M \times 1/f_{IF}$, which is equivalent to $(T \times f_E) \times 1/f_{IF}$.

Comparing the results, the TDR oscilloscope measures f_P/f_{IF} times during a single measurement sweep on the VNA. Since averaging a signal waveform L times results in noise reduction proportional to $\sqrt{L}$, the TDR scope is able to improve the dynamic range by 10 $\log(f_P/f_{IF})$ dB compared to a VNA.

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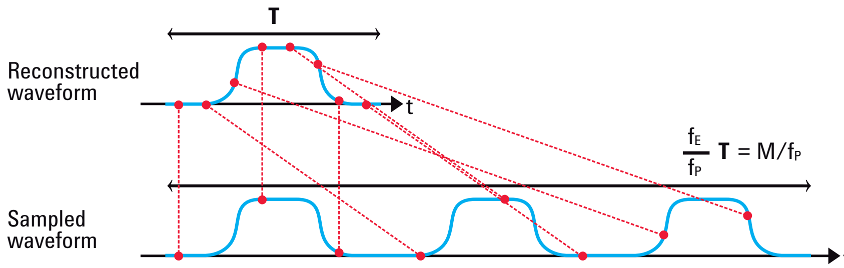

Figure 8. Relationship between the reconstructed waveform and measurement time on a sampling oscilloscope.

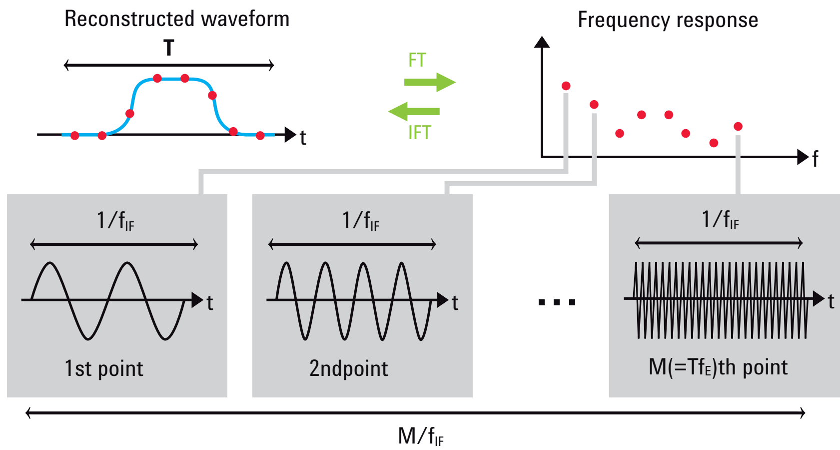

Figure 9. Relationship between the reconstructed waveform and measurement time on a VNA.

For a true comparison of dynamic range, it is necessary to compare the dynamic range obtained with the same measurement time. Therefore, both the improvement due to the bandpass filter on the VNA and the improvement due to averaging on the TDR oscilloscope needs to be considered.

In general, the physical sampling frequency (f_P) is much lower than the cutoff frequency (f_C) on the TDR oscilloscope. Thus, the VNA has higher dynamic range than the TDR oscilloscope by a factor of 10 log (f_C/f_P) dB (Table 1). To obtain the same dynamic range as the VNA on a TDR oscilloscope by averaging, measurement time will be longer by a factor of f_C/f_P.

Table 1. Comparison of dynamic range (DR) between the VNA and TDR oscilloscope.

	VNA	TDR oscilloscope
DR improvement ratio for single measurement	$10 \log\left(\frac{f_C}{f_{IF}}\right)$	1
Ratio of measurement time	1	f_P/f_{IF}
DR improvement ratio for equivalent measurement time	$10 \log\left(\frac{f_C}{f_{IF}}\right)$	$10 \log\left(\frac{f_P}{f_{IF}}\right)$

The discussion so far has focused on the time domain response. Frequency domain measurements are becoming a necessity in modern high-speed digital communication systems. For example, to measure the effects of crosstalk, the accurate measurements of the high frequency response is critical and it is necessary to use an instrument with high dynamic range at high frequencies. Therefore, the dynamic range comparison in the frequency domain is considered next. The key points and results are covered in this section. Refer to the appendix for detailed analysis on this topic.

Because the stimulus signal power is assumed constant across frequency, the same dynamic range can be obtained across the entire frequency on the VNA. The Fourier transform of the step stimulus on the TDR oscilloscope is $\delta(f)/2+1/(2\pi jf)$, which has a large DC component and decreases inversely proportional to frequency. (Figure 10) compares the dynamic range with the same frequency span and resolution on the VNA and TDR oscilloscope. For measurements on N points, the difference in dynamic range 10 log (f_C/f_P) dB occurs at the $\sqrt{N}/2\pi$ th point. For higher frequencies, the VNA advantage in dynamic range increases (refer to appendix for details).

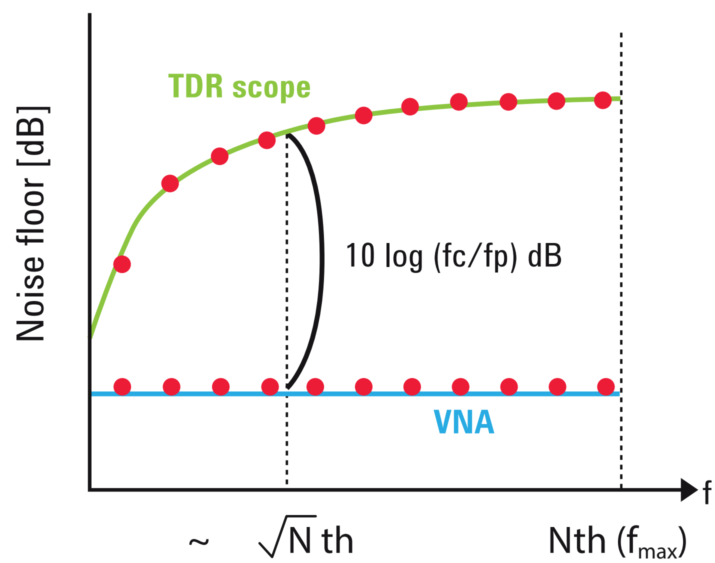

Figure 10. Comparison of dynamic range of the VNA and oscilloscope in the frequency domain.

Signal Synchronization Comparison

To evaluate the signal skew between multiple transmission channels, time synchronization between the measurement results of each channel is required. The method to synchronize the results is different on the VNA and TDR oscilloscope. This section will investigate the effects of this difference on measurement accuracy. (Figure 11) compares the stimulus signal for VNA and TDR oscilloscope when measuring multiport devices. The TDR oscilloscope has a stimulus source for each port and independently generates a step stimulus. Therefore, it is necessary to synchronize the stimulus signals to evaluate skew between the different channels. If the stimulus is synchronized at a certain point in time, any time fluctuation of the stimulus will cause jitter in the measurement results.

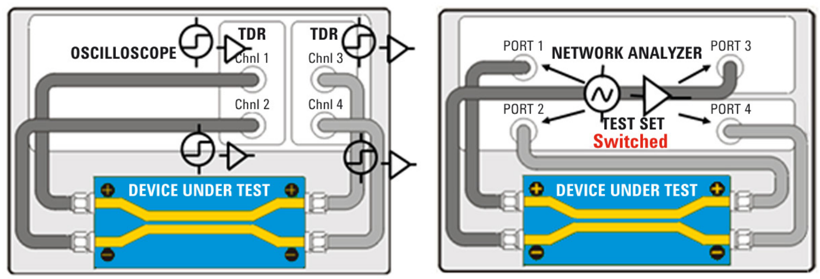

Figure 11. Block diagram of stimulus settings on the TDR oscilloscope (left) and VNA (right) when measuring multiport devices.

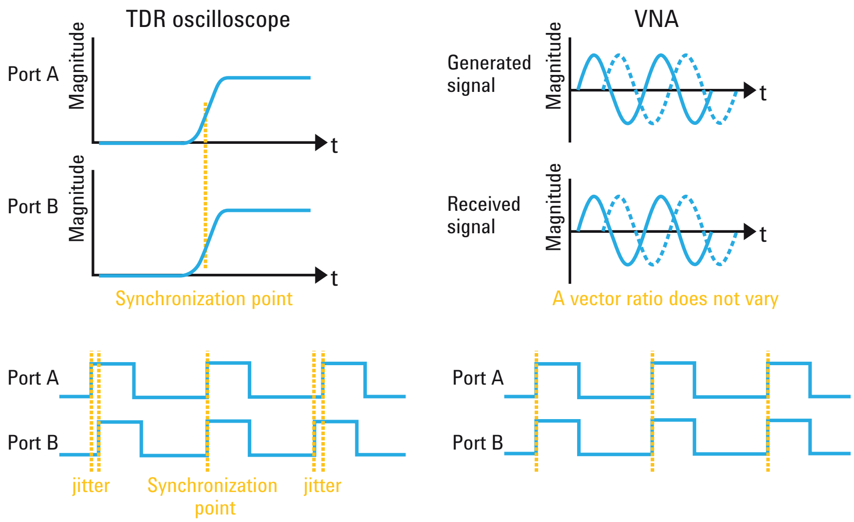

Figure 12. Time synchronization of multiple sources on the TDR oscilloscope (left). Adjusting for phase delay on the VNA for time synchronization (right).

With a VNA, measurements are taken in the frequency domain and the inverse Fourier transform is calculated to obtain the time domain response. Phase delay in the frequency domain corresponds to time delay in the time domain. But with the VNA, there are many calibration methods available to compensate for the phase delay. In addition, the VNA measurement results are not affected by the fluctuations on the stimulus. Since the VNA measures the vector ratio between the input and output signals, any fluctuations on the input are cancelled out. As a result, the time domain response measured on the VNA does not contain errors due to fluctuations of the stimulus and the results are as if a perfect stimulus with no fluctuations was used.

Static Damage Sensitivity

TDR oscilloscopes are prone to failure due to electrostatic discharge (ESD), because ESD protection circuits are difficult to implement on the instrument due to the internal structure. A block diagram of the TDR oscilloscope is shown in (Figure 11). The sampler is connected directly to the test port in order to minimize the loss of the input signal to the test port. The step generator is implemented using a tunnel diode. Since the tunnel diode is a low impedance device, it lends itself to a terminated configuration. If a protection circuit is inserted at point A in (Figure 11), the stray capacitance of the protection circuit and the impedance seen at point A will form a lowpass filter to distort the step stimulus leading to measurement errors.

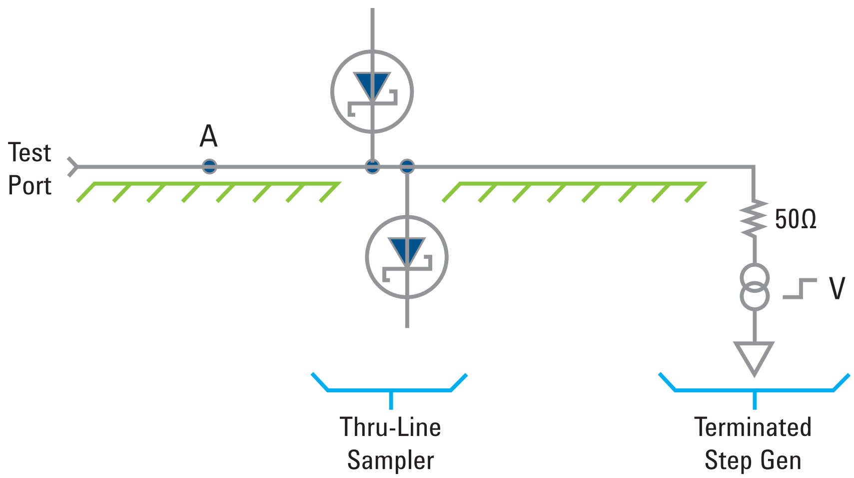

Figure 13. Block diagram of connection between the sampler and pulse generator on a TDR oscilloscope.

Protections circuits can easily be implemented on the VNA to protect against ESD. On a VNA, a sine wave stimulus is swept across frequency and the vector ratio between the input and output is calculated. Even if there is some loss associated with the protection circuit, the loss is canceled out by taking the vector ratio and thus the measurement accuracy is not affected.

Summary

Comparisons have been made on the limitations and accuracy of a VNA-based and oscilloscope-based TDR instrument. The TDR measurements performed on the VNA was shown to have correlation to measurements performed on a traditional TDR oscilloscope. In addition, the high dynamic range, better source stability, and increased robustness of the VNA-based solution were discussed. There are many benefits in choosing a VNA for TDR measurements.

Appendix:

Dynamic range comparison between a VNA and TDR Oscilloscope in the frequency domain

Note: The same assumptions and notational conventions defined under **Dynamic Range Comparison between the VNA and TDR Oscilloscope** will also be used in this section.

VNA

Since both the signal and noise is assumed to have a flat frequency response, the dynamic range is also uniform in the frequency domain and can be described by the following equation:

$$\frac{f_{IF}}{f_C}\,\frac{a^2}{b^2}$$

Since the measurement time on a single point is $1/f_{IF}$, it will take $N \times 1/f_{IF}$ for measurements on N points.

TDR Oscilloscope

Before considering the sampling oscilloscope, first consider the case of a real-time oscilloscope which has a much higher sampling frequency (f_E) than the cutoff frequency (f_C). Sampling the step stimulus across the time span T, the following discrete data is obtained, where the number of data points $2M = Tf_E$:

$$x[n] = \begin{cases} 0 & (-M \le n < 0) \\ a & (0 \le n < M) \end{cases}$$

The direct Fourier transform of x[n] will result in ripples in the frequency domain and the calculations becomes simpler if x[n] is differentiated before considering the frequency domain characteristics. The derivative of x[n] is defined as follows:

$$y[n] = \begin{cases} x[n] - x[n-1] & (-M < n < M) \\ 0 & (n = -M) \end{cases}$$

Since y[n]=aδ[n], the Fourier transform Y[k](–M ≤ 0 < M) is a constant value.

$$Y[k] = \sum_{n=-M}^{M-1} y[n] e^{-2\pi j \frac{nk}{2M}} = a$$

The frequency step of Y[k] is $\Delta f = 1/T = f_E/2M$.
The measurement data is the sum of x[n] and noise p[n]. Differentiating the measurement data will also result in differentiation of p[n]. The differentiation of p[n] is defined as:

$$q[n] = \begin{cases} p[n] - p[n-1] \; (-M < n < M) \\ 0 \; (n = -M) \end{cases}$$

The Fourier transform of q[n] is:

$$Q[k] = \sum_{n=-M}^{M-1} q[n] e^{-2\pi j \frac{nk}{2M}} = \sum_{n=-M+1}^{M-1} p[n] e^{-2\pi j \frac{nk}{2M}} - \sum_{n=-M+1}^{M-1} p[n-1] e^{-2\pi j \frac{nk}{2M}}$$

$$\cong P[k] - e^{-2\pi j \frac{k}{2M}} P[k] = 2j e^{-\pi j \frac{k}{2M}} \sin\left(\pi \frac{k}{2M}\right) P[k]$$

Since p[n] is random, the following relationship was assumed for the case of sufficiently large M.

$$\sum_{n=-M+1}^{M-1} p[n] e^{-2\pi j \frac{nk}{2M}} \cong \sum_{n=-M}^{M-1} p[n] e^{-2\pi j \frac{nk}{2M}} \equiv P[k]$$

Comparing Y[k] and Q[k] will result in the frequency characteristics of the dynamic range. First consider the magnitude of P[k].

$$\frac{1}{2M} \sum_{n=-M}^{M-1} p[n]^2 = b^2$$

From Fourier theory, the following relationship between P[k] and p[n] is defined.

$$\sum_{k=-M}^{M-1} P[k]^2 = 2M \sum_{n=-M}^{M-1} p[n]^2$$

Since it is assumed that the noise is flat across frequency up to f_C and does not exist at frequencies above f_C,

$$P[k]^2 = \begin{cases} 2M \dfrac{f_E}{f_C} b^2 \left(0 < |k| \leq \dfrac{f_C}{f_E} M\right) \\ 0 \left(\dfrac{f_C}{f_E} < |k| \leq M\right) \end{cases}$$

Assuming $f_E >> f_C$, f_C for $k(=f/\Delta f)$ corresponding to frequencies $f < f_C$, $k/2M << 1$.
In this case, the following approximation can be made: $\sin(\pi k/2M) \cong \pi k/2M$ Therefore, in the region $0 < k \leq f_C/f_E\, M$

$$Q[k] = je^{-\pi j \frac{k}{2M}} \frac{\pi k}{M} P[k]$$

In other words, Q[k] increases proportionally to frequency (k).

The dynamic range in the range $0 < k \leq f_C/f_E\, M$ can be described by the following equation.

$$\frac{|Q[k]|^2}{|Y[k]|^2} = \frac{2\pi^2 k^2}{M} \frac{f_E}{f_C} \frac{b^2}{a^2}$$

Now consider the Fourier transform of same time domain waveform on a sampling oscilloscope and the resulting dynamic range and measurement time.
The measurement time for a sampling oscilloscope is determined by the ratio between the physical sampling frequency f_P and equivalent sampling frequency f_E and is $T \times f_E/f_P$.

Since the time domain waveform obtained with the real-time oscilloscope and the sampling oscilloscope are equal, the resulting Fourier transform is also equal. On the other hand, the noise with frequency components above half the physical sampling frequency cannot be correctly recreated as defined by the Nyquist Theory. This is because the noise component of frequency f cannot be distinguished from noise with frequency components $f+n \times f_P/2$ (n is integer). In other words, high frequency noise which does not physically exist will appear in the measurement results. As a result, taking the Fourier transform of the noise obtained with a sampling oscilloscope will result in the noise diluted across the entire frequency span.

$$P[k]^2 = 2\,Mb^2$$

Consequently, the dynamic range for the range DC < f < fc can be described by the following equation.

$$\frac{|Q[k]|^2}{|Y[k]|^2} = \frac{2\pi^2 k^2}{M} \frac{b^2}{a^2}$$

Comparing the dynamic range between a VNA and sampling oscilloscope under the same measurement conditions

Now consider the dynamic range of the VNA and sampling oscilloscope under the same frequency step and measurement time. For measurement of N points on the VNA, the required measurement time is N/f_{IF}. For the same measurement on a sampling oscilloscope, the required measurement time is $T \times f_E/f_P = 2M/f_P$.

Therefore, the oscilloscope can measure $Nf_P/2Mf_{IF}$ times during a single measurement on the VNA. Averaging the measurement will result in the reduction in noise magnitude of $\sqrt{(2Mf_{IF}/Nf_P)}$ and the dynamic range will improve by $2Mf_{IF}/Nf_P$.

The resulting dynamic range on the sampling oscilloscope will be:

$$\frac{4\pi^2 f_{IF}}{f_P} \frac{k^2}{N} \frac{b^2}{a^2}$$

Taking the ratio with the VNA dynamic range results in the following relationship:

$$\frac{4\pi^2}{1} \frac{f_C}{f_P} \frac{k^2}{N}$$

The ratio of the dynamic range is determined by the ratio of cutoff frequency to the sampling frequency of the oscilloscope.

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Published in USA, July 31, 2014
5990-5446EN
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