Pulsed S-parameter Measurements

RF, Microwave and Millimeter-Wave Measurements for a Variety of Pulsed Conditions, using the VectorStar™ VNA.

MS4640A Series Vector Network Analyzer

Introduction

Many devices, particularly power devices, were not designed to operate continuously or with CW signals. When devices are being tested on-wafer, this becomes even truer since thermal resistance is often greatly increased (e.g., [1]). In these cases, S-parameter measurements must often be performed in a pulsed environment.

The details of the measurement are greatly dependent on the pulse properties being studied. At one extreme is the realm of high pulse repetition frequencies (PRFs) and fairly narrow pulses as is common in radar applications. At the other extreme is the communications arena where PRFs are quite low and pulse widths fairly wide (e.g., GSM [2]). These two extremes exemplify two techniques, termed bandwidth limited and triggered, that are discussed in this note. The two approaches overlap in terms of allowed parameters to a certain degree so most situations can be covered by one if not both of them. Pulse profiling of the detailed transient response is not covered here although it is briefly discussed with regard to triggered measurements elsewhere [3]. Certain rise/fall time behaviors can be studied using time domain mode [4] but that will not be discussed either. The objective is to gain an understanding of performing general S-parameter measurements with a vector network analyzer (VNA) across a range of pulsed conditions for both RF and microwave/mm-wave measurement applications.

Background on the spectra of pulse RF signals

A pulsed RF signal will have a spectrum composed of a series of spectral lines with an envelope described by a sinc function (e.g., [5]). The spacing of the lines is set by the PRF while the envelope shape is fixed by the pulse width (assuming rise and fall times are small relative to the width). The relationship is shown in Figure 1. The ‘size’ of this spectrum with respect to the IF bandwidth (IFBW) of the network analyzer determines the measurement mode.

In the case of low PRF and wide pulses, the entire spectrum can fit within an IFBW. In this case, the measurement proceeds normally without a significant reduction in dynamic range. Some additional smoothing/averaging may be needed to reduce effects of the outlying portions of the distribution in Figure 1. A requirement in this measurement is that the VNA measurement be aligned in time with the pulse, hence the term triggered.

In the case of a high PRF, the line spacing can be substantial relative to the IFBW so the analyzer can just pick off the center line (thus the term bandwidth limited). The measurement of just this line is sufficient to perform an S-parameter measurement (since it carries the magnitude and phase of the envelope at the center point) as long as a calibration is performed under those same conditions. Since only a fraction of the total signal energy is used, however, the dynamic range may be limited.

Figure 1. The spectrum of a pulsed RF signal is shown here. The center maximum is at the RF frequency, the line spacing is equal to one over the pulse period T0, and the first envelope null offset at one over the pulse width T1 (neglecting rise and fall times).
Triggered measurements

Since the spectrum fits entirely in an IFBW in this case, the dependence of the measurement on the pulse train would appear simple. In the time domain sense, however, one wants the sampling to occur during the ‘on’ period of the pulse in order to capture the desired information. This is accomplished by triggering the VNA to measure in the appropriate points in time.

The details of this process (and applications to other measurement types) are covered in greater detail elsewhere [3] but will be summarized here.

As shown in Figure 2, the idea is for the trigger pulse to arrive at the VNA sometime before the RF pulse in order to account for instrument latency, although starting later is allowed. The sampling can begin sometime after the RF pulse has settled unless that process is of interest as well. The sampling can continue for a substantial portion of the pulse but should not continue beyond the end. As a gross limit, the IFBW must be greater than 1/(pulse width) to keep sampling from overrunning the pulse. Because of pulse settling, internal filtering and some other latency issues, some safety margin is required. This will vary greatly depending on setup and may require some experimentation. If too small an IFBW is used (or with too much averaging), the trace data will become very noisy.

The pulse for the RF or the DUT control often comes from a pulse generator. The external trigger pulse can come from another channel of the same generator or it can be derived from the main pulse chain with a small delay circuit of the user’s design. An example setup is shown in Figure 3. Some power level details for the various systems are given in the appendix.

There are additional limitations on the trigger frequency that can be fed to the VNA. With lower PRFs as in GSM, for example, sampling can occur on every RF pulse. With higher PRFs, it may be necessary to sample only on some pulses which may require a more elaborate timing setup. The maximum triggering frequency is dependent on the instrument, the mode, the IFBW, the frequency range, and user-intervention (button pushing or other interrupts) among other issues. Check the appendix for some VectorStar-related limits and recommendations.
Example of GSM Amplifier Measurement
As a very simple example, the gain of an amplifier was measured non-pulsed and under GSM conditions at a pair of power levels. The IFBW was quite high in these examples (30 kHz) and only a frequency response (i.e., normalization) cal was performed. In the low power case, when the amplifier was far from compression, the pulsed and non-pulsed results agree reasonably well as shown in Figure 4. When the amplifier is in compression at the higher power level (0 dBm in), the results diverge as perhaps might be expected.

![Figure 4](image)

Figure 4. A comparison of pulsed (triggered under GSM conditions) and non-pulsed measurements of an amplifier is shown here. At low power levels, the results basically agree (no match correction accounts for small differences). When the amplifier is under compression, the results start to diverge.

In this measurement class, calibrations may be performed without pulsing although if a pulsing switch (as in Figure 3) is used, it should be present so its reflections and loss can be calibrated out. For full calibrations (other than just a normalization), any pulsing switch should precede the test coupler (or ideally, the reference coupler as well). In the MS4640A series VectorStar VNA, the external pre-amplifier loop available with options 051 or 06x allows a modulator to be inserted preceding the test coupler.

Bandwidth limited measurements
In this case, the spectrum of the pulsed RF signal is very wide with respect to an IFBW. The selected IFBW must be small enough that it does not capture significant energy from other lines than the center lobe. Clearly, this technique has the most utility for PRFs of 10 kHz or higher although lower rates are allowed if the user is willing to use smaller IFBWs than the typical few kHz. An example measurement where too wide an IFBW was used is shown in Figure 5. Here the PRF was about 30 kHz and a 30 kHz IFBW was used; although this might have worked if the IF filters had perfect stop bands, this is not true in practice. Note that narrower IFBWs also have the advantage of increased dynamic range.

![Figure 5](image)

Figure 5. A bandwidth limited measurement with a PRF of 30 kHz is shown here. The flat trace represents a measurement with an IFBW of 3 kHz and is correct. The noisy, incorrect trace is a measurement with a 30 kHz IFBW in which additional spectral lines are admitted to the IF system.
An important point about this technique is that a fair amount of the signal energy is thrown away by the IF filter. The signal reduction is given by:

\[ \text{Reduction(dB)} = 20 \cdot \log_{10} \left( \frac{\text{Period}}{\text{Pulse Width}} \right) \]

Thus the dynamic range will become limited as the duty cycle shrinks. For duty cycles of 1% or more, the reduction is in the range of 40 dB. The MS4640A series VectorStar VNA offers excellent non-pulsed Dynamic Range, so sensitivity reduction due to Pulse Duty Cycle can easily be tolerated. Narrower IFBWs will enhance dynamic range in all of these limited bandwidth cases since less integrated noise is sent to the receiver.

This measurement also requires periodicity of the pulse. The triggered measurement could be more lax in this respect as long as the VNA was triggered at the right time. The bandwidth limited measurement makes assumptions about the spectral content as discussed previously so periodicity is implied.

These assumptions about spectral content also feed into the method of generating the RF pulse. It is assumed that the on/off ratio is very high so if the switching is poor (or the DUT control is not too effective), there will be additional uncertainties. While the spectral lines will not move in frequency, some of the amplitudes may change and may require a smaller IFBW than would be obvious for a quality measurement. An on/off ratio of 50 dB or better is preferred.

**Example of 30 kHz PRF (duty cycle= 3%) Amplifier Measurement**

As a simple measurement example, consider an amplifier to be pulsed with a PRF of 30 kHz and a duty cycle of 3%. The measurements will be made with an IFBW of 1 kHz and compared to non-pulsed measurements at a pair of power levels. A one-path two-port calibration was used to correct for input match effects. Different calibrations were needed for the pulsed and non-pulsed cases since the calibration must occur under the same signal conditions for bandwidth limited measurements. The results for pulsed and non-pulsed drives are about the same when the RF level is low as shown in Figure 6. At compressive levels, however, the results diverge. This might be expected since the average signal seen by the amplifier is quite different in the two cases.

![Graph showing Pulsed and Non-Pulsed Amplifier S21, Base RF Drive= -10 dBm and Base RF Drive= 0 dBm](image)

**Figure 6.** Bandwidth limited example measurements for an amplifier are shown here. NP denotes a non-pulsed measurement while P denotes a pulsed measurement.

In this measurement type, calibrations must be performed under the same pulsed conditions. As discussed in the previous section, any pulsing switches should precede at least the test coupler for full calibrations (other than simple normalizations).

If simple normalization calibrations are all that are desired, then the pulsing switch may be after the couplers. This was done for the example measurement in Figure 7. In this case the DUT was a simple W-band waveguide high pass filter and it was measured both pulsed and non-pulsed over approximately 71 to 80 GHz. The pulsed normalization was done with the pulsing switch in place and operating at a PRF of 10 kHz with a duty cycle of 10%. The curves agree quite well, any differences are primarily due to differences in uncorrected match in the two setups.

It is important to note the dynamic range well in excess of 40 dB evidenced by this plot. Even though the pulsing reduces the dynamic range by 20 dB (per an earlier equation) and the pulsing switch in this case only has about 50 dB of on/off ratio, there is still sufficient range to make this measurement.
Should other components be used in the setup, other than the modulator? Typically no other components are needed, assuming a proper modulator is used. Today’s modulators are self-terminating, eliminating the need for an amplifier after the modulator or an isolator ahead of it, to present a constant impedance at the input and output. A High Pass Filter is also not needed after the modulator, since any Video Feedthru is absorbed by today’s modulators.

What are the advantages of modulating ahead of the Reference Coupler as well as the Test Coupler? When making ratioed measurements, trace noise may slightly improve when both receivers are pulsed. Also, if amplifiers or other drift-prone components are used, any common drift would be ratioed-out. Typically, these are not serious concerns, which is why we recommend placing the modulator in the source loop, placing it only ahead of the Test Receiver. In order to also place it ahead of the Reference Receiver, a coupler needs to be placed after the modulator in the source loop, with its input-coupled port going to the Reference Input Loop.

Should the Pulse PRF match the chosen VNA IF Bandwidth Filter’s Notch? Choosing a Pulse PRF that matches the notch spacing of the VNA IF Bandwidth selected can also slightly improve the trace noise of the measurement. Figure 8 shows the Pulse Spectral lines with the PRF spacing, super-imposed with the Sync function response of the VNA’s digital IF Filtering. Check Appendix A for figuring out the notch spacing for the different VectorStar IF Bandwidth selections.
Summary

Two different techniques for pulsed S-parameter measurements have been presented along with some details on how to make successful measurements. As a summary of when each of these techniques is most appropriate, a table is provided below.

<table>
<thead>
<tr>
<th></th>
<th>Pulse width &gt;50 us</th>
<th>Duty cycle &gt;1%</th>
<th>Duty cycle &lt;1%</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRF &gt;10 kHz</td>
<td>N/A</td>
<td><em>BW limited</em></td>
<td><em>BW limited (reduced DR, harder at high frequencies)</em></td>
</tr>
<tr>
<td>PRF 1-10 kHz</td>
<td>Triggered (measure on only some pulses)</td>
<td><em>BW limited (lower IFBW)</em></td>
<td><em>BW limited (reduced DR and lower IFBW, harder at high frequencies)</em></td>
</tr>
<tr>
<td>PRF &lt;1 kHz</td>
<td>Triggered</td>
<td><em>BW limited (lower IFBW) or triggered (if duty cycle &gt;5%)</em></td>
<td><em>BW limited (reduced DR and lower IFBW) difficult</em></td>
</tr>
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</table>

The italicized entries are optimal while the other parts of the parameter space are measurable with some performance trade-offs. Note that for the BW limited applications, a narrower IFBW may be required as the PRF drops; this narrower IFBW tends to increase DR.

References


Appendix
MS4640A series VectorStar VNA-related Recommendations and Limits

External triggering:
External triggering must be enabled, either from the front panel or via GPIB. The front panel path is as follows: Sweep\Trigger\Trigger Source\External. In the same menu, please find External Trigger Setup for selecting the Rising or Falling Trigger Edge, and to add Delay Time between Trigger to Measurement.

  Trigger Level: 0 to 3.3 V input (5 V Tolerant); High Impedance Input (>100 kΩ)
  Trigger Width: 100 ns minimum
  Trigger Rate: 4.5 kHz maximum

Power levels:
The instruments have different allowed input and output power combinations. Consult your MS4640A series VNA datasheet for available source power (without added pre-amplifiers), for the compression levels of the receiver at the test ports or at the direct-access loops, and for damage levels. P_{0.1 dB} compression levels at the ports are in excess of +10 dBm, option-dependant. Damage levels are typically +27 dBm at the ports and +20 dBm at the direct-access loops.

Averaging:
Sweep-by-Sweep and Point-by-Point averaging is available on the MS4640A series VNA. Sweep-by Sweep averaging will reduce noise without interfering with measurement timing. Point-by-Point will be more effective at reducing fast noise, yet it will have some impact on timing, particularly in triggered measurements.

IF Bandwidth:
IF filtering is performed digitally and accomplished by taking more data samples for narrower IFBWs. It functions identically to averaging so one can compute an effective IFBW=labeled IFBW/(# of averages).

Calculating the first notch spacing of the selected IF BW Filter:
The ideal PRF is equal to the first notch of the filter or to multiples thereof.
For IF BW ≥ 10 kHz: First Notch = 1.54375 MHz ⋅ [IF BW/(1 MHz)]
For IF BW < 10 kHz: First Notch = 1.02917 MHz ⋅ [IF BW/(1 MHz)]

Gain Ranging:
Gain Ranging is set to ON as default. Gain Ranging can also affect measurement timing, unless turned OFF by following the path: System\Utility\Gain Ranging [on/off]. Turning Gain Ranging OFF will only affect dynamic range, reducing it by about 10 dB at the narrower IFBWs only.

For Bandwidth Limited measurements, Gain Ranging could cause slight magnitude errors if it is performed at the wrong level. If the ON and OFF amplitudes of the pulsed RF are relatively close, then Gain Ranging will work as designed for CW mode, without the need to turn it off. In cases however where the ON amplitude is large, coupled with a wide on/off modulation ratio, Gain Ranging could occur at the low OFF state, while the measurement is performed at the significantly higher amplitude ON state. The larger amplitude coupled with the wrong Gain Range would overdrive the IF ADC into compression, causing slight distortion. In these cases, Gain Ranging should be turned off. The effects of slight Dynamic Range reduction would not be noticed in this case anyway, since the ON amplitude is high.