Pulsed Signal Measurements With Vector Network Analyzers: The Basics

This article is second in a series of quarterly guest columns by Justin Panzer, manager of product marketing, Rohde & Schwarz.

Radar systems and other microwave applications transmit and receive pulsed signals, so anyone who must evaluate components and subsystems used in these systems needs to understand how to make pulsed signal measurements. The vector network analyzer (VNA) is one of the primary measurement tools used for this purpose, and in this Talkin' Test we'll look at pulsed signal measurements and some things you need to know to perform them properly.

Before looking at the various types of pulsed measurements, let's review the various kinds of pulsed signals used by radars and other applications.

Basic Pulsed Signals

- *Single Pulse:* While it's used by radars, this most basic of pulsed signals (*Figure 1*) is also widely used for on-wafer measurements to reduce the average power input to device while still measuring it at a prescribed peak signal level.

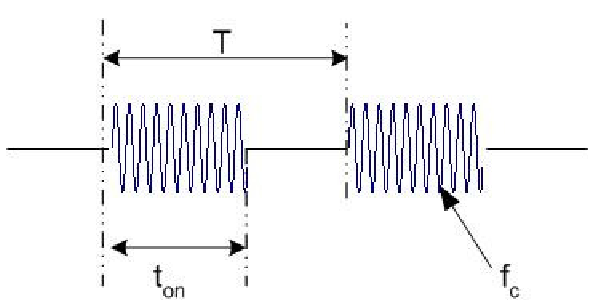

Figure 1: *The single pulse*

As seen in the May 13, 2008 edition of the RF Globalnet (www.rfglobalnet.com) newsletter.

- *Double Pulse:* Weather, target tracking, and astronomical Doppler radars use double-pulsed signals, which produce a double echo that can easily make its way through complex radar signal processing and can eliminate noise and other interferers that can degrade accuracy.

- *Pulse Trains:* These signals (*Figure 2*) combine periodic or nonperiodic pulses onto which modulation can be applied.

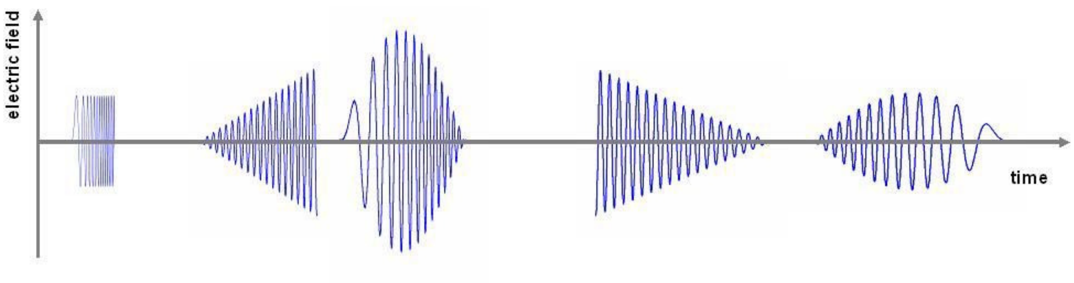

Figure 2: *A typical pulse train*

Modulated Pulses
There are three basic types of modulated pulses:

- *Chirped Pulse:* This type of pulse is frequency-modulated, and its frequency varies over time (*Figure 3*). It can be linearly or nonlinearly "chirped" depending on the specific waveform desired. (Gaussian is a good example.)

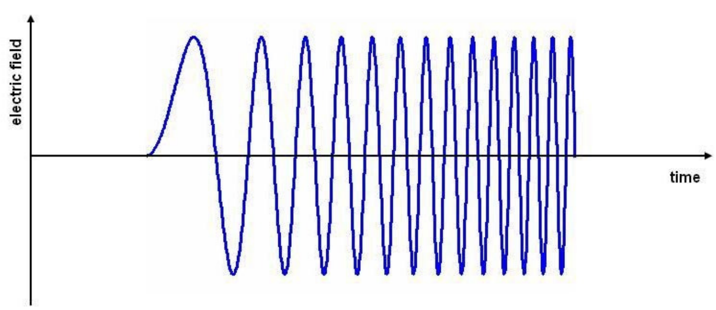

Figure 3: *A pulse with variations in frequency over time (chirped pulse)*

- *Barker Pulse:* This digitally modulated waveform (*Figure 4*) uses binary phase shift keying (BPSK). With a bit value of 1 the phase is set to π, and a bit value of 0 leaves the phase at 0. By applying an additional phase offset the constellation points can be rotated. For high distance resolution in radar systems, small pulses are normally used, which decreases the signal-to-noise ratio. To achieve wider pulses and better signal-to-noise ratio, pulse compression is often employed.

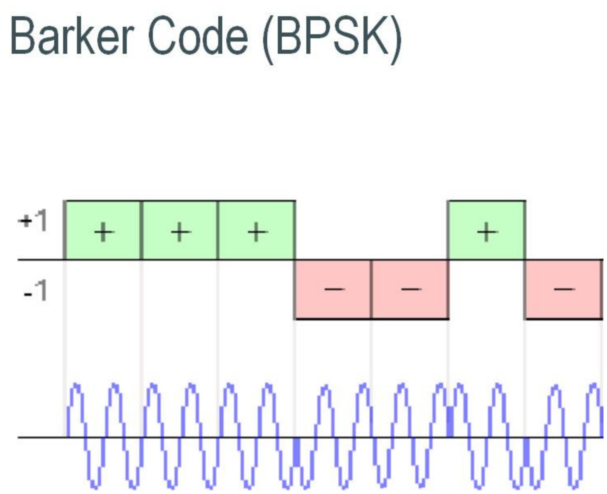

Figure 4: *7-bit Barker code*

Having covered the various types of pulsed signals, we can now look at the types of pulsed signal measurements that can be used to gain the required information needed to characterize a component or subsystem.

Point-In-Pulse Measurements

A point-in-pulse measurement (*Figure 5*) produces accurate S-parameter and power measurements by shifting the moment of data acquisition within the pulse, which eliminates the dependency of dynamic range on duty cycle. However, the measurement requires a VNA that has a wide measurement bandwidth. The pulse is monitored only during its "on" phase, so the sampling time (T_{spl}) required to acquire the raw data of a wave quantity or an S-parameter must be shorter than the pulse width, t_{on}.

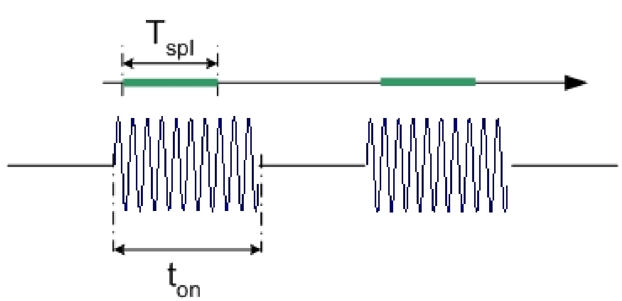

Figure 5: *Sampling time for point-in-pulse measurements*

The measurement bandwidth of the VNA's receiver will largely determine the sampling time, which along with measurement bandwidth is defined as $T_{spl} \approx 1/IFBw$. So as measurement bandwidth increases, sampling time decreases and shorter pulses can be analyzed. A typical VNA implements IF filters digitally, and measurement bandwidths can be as high as 600 kHz, so the sampling time is 1 µs or more. The R&S ZVx Series

VNAs, for example, have an IF bandwidth of at least 5 MHz, which translates into sampling times as fast as 400 ns. Since sampling should only occur during the "on" phase of the pulse, a trigger signal synchronized with the pulse is required. The VNA is used in its point trigger mode, which in practical terms means that data sampling for every measurement point begins after the trigger event has been detected.

Active devices such as amplifiers exhibit settling or ringing effects at the beginning of the pulse, but you'll probably be primarily interested in how the device behaves after it has settled. To accommodate this, you can select a suitable trigger delay so that the sampling process can begin during the amplifier's quiet pulse roof. When using the point-in-pulse method, the achievable dynamic range and sensitivity are directly related to the VNA receiver's sensitivity and measurement bandwidth, both of which are independent of the duty cycle of the RF pulse. Consequently, dynamic range depends on pulse width, and pulse width determines sampling time (and thus the required measurement bandwidth). If you apply averaging, you can increase dynamic range by maintaining the measurement bandwidth. For example, ten-times averaging in the IQ domain increases dynamic range by a factor of 10.

Averaged Pulse Measurements

As mentioned before, the point-in-pulse measurement requires a VNA with a wide measurement bandwidth, which eliminates many VNAs as candidates for making this type of measurement when pulse widths are short. Fortunately, the averaged pulse measurement technique, which is also called "narrowband" or "high-PRF" measurement, can be used instead. The VNA samples and measures the averaged value of the pulse during several pulses. It requires less VNA performance, but configuring an acceptable test set up is more difficult and the measurement is dependent on pulse and VNA parameters. The pulsed signal is generated by multiplying a periodic rectangular signal that varies between 0 and 1 using a CW signal. Multiplication in the time domain is a convolution of the spectra of both signals in the frequency domain (*Figure 6*).

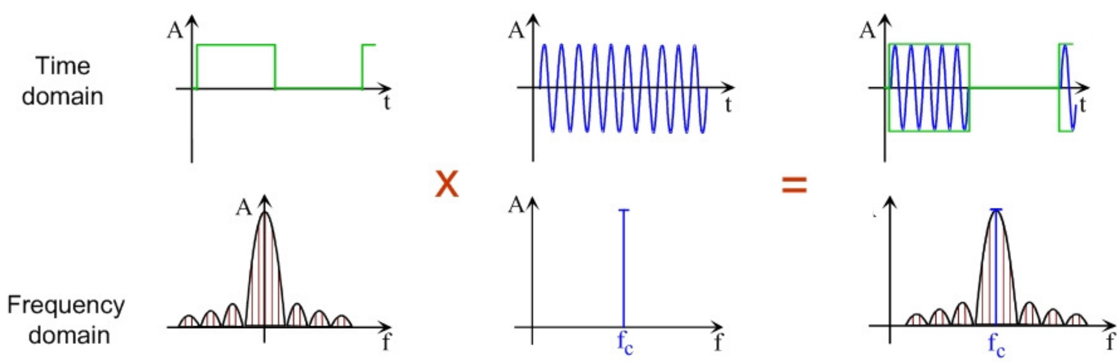

Figure 6: *Signals in the frequency and time domains*

The spectrum of the pulse envelope (NF signal) is shifted by the convolution to the frequency f_c. Since S21 equals b_2/a_1 (where a_1 is the incident wave into the device and b_2

is the wave transmitted through it), the ratio between one spectral line of a_1 and the equivalent spectral line of b_2 can be measured. This technique encompasses all S-parameters. To achieve the greatest dynamic range, select the strongest spectrum line at f_c (the main carrier):

$S21 = b_2 (f_c) / a_1 (f_c)$
$S11 = b_1 (f_c) / a_1 (f_c)$.....etc.

For averaged pulse measurements, the bandwidth must be narrow enough so it captures only the main carrier. The frequency spacing between the carriers is equal to the pulse repetition frequency (PRF = 1/T).

The lowest value of trace noise can be obtained only if the adjacent carriers are suppressed by 40 dB or more. This means you should select a measurement bandwidth that is about 10 times narrower than the carrier spacing with respect to the pulse repetition frequency. If you decrease the measurement bandwidth, the test will require more time. Only the main carrier is detected, which is the convoluted carrier of the NF signal at frequency 0 that represents the DC value of the NF pulse, which is simply the average value of the NF signal.

The shape of the VNA's digital IF filters can be problematic with this measurement technique. The VNA typically stimulates the device under test with a CW signal, but the IF filters are designed for fast settling but not for high sidelobe suppression, which is often 20 dB or less. As soon as one of the adjacent tones falls into the maximum of a sidelobe, the measurement result can be corrupted. To meet this challenge, one of two procedures can be employed. First, since some instruments use spectral nulling (*Figure 7*), you can select IF filters, depending on the period of the pulse, so that the nulls of the filter are exactly where the tones to be suppressed are expected to be. Some high-end VNAs have highly selective filters without sidelobes, so no spectral nulling is required (*Figure 8*).

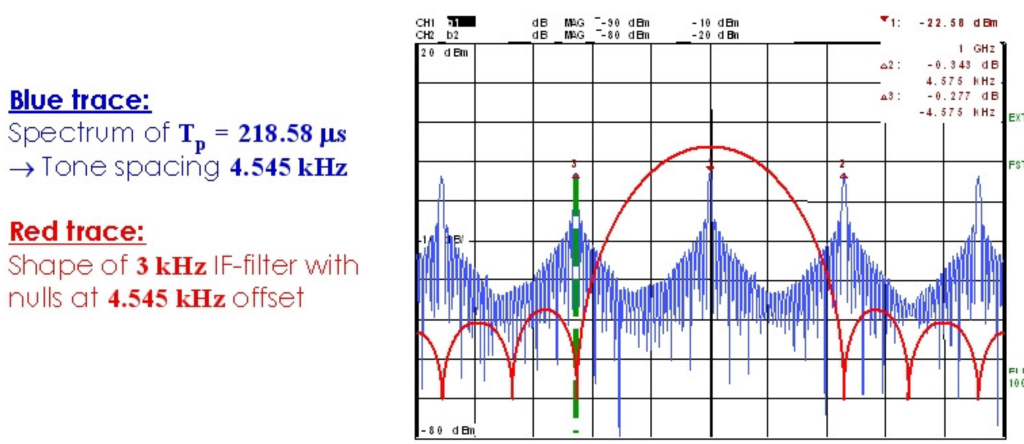

Figure 7: *Example of spectral nulling*

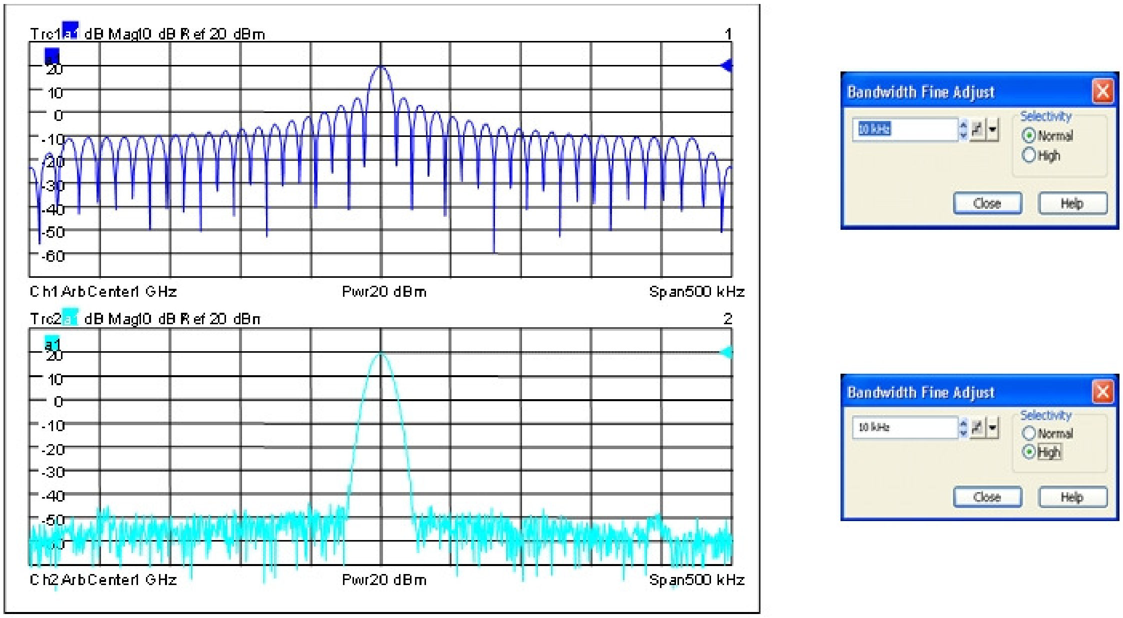

Figure 8: *Digital IF filters of a VNA and the highly selective IF filters of a high-end VNA*

Second, you can perform averaged pulse measurements in swept mode using the same setup as the one employed for point-in-pulse measurements — without the trigger. As averaged pulse measurements determine the average values of wave quantities, absolute power measurement is influenced by duty cycle. For a duty cycle of 1%, the measured power of the main carrier is 40 dB lower than the peak power, a phenomenon called pulse desensitization. When the duty cycle is very low, signal-to-noise ratio also becomes very low, which limits the dynamic range of the measurement.

Traditional Pulse Profile Measurements

To analyze the time-dependent behavior of a device during a burst, the VNA must perform a so-called pulse profile measurement. The pulse profile method can be performed with most VNAs. Its disadvantages are that analysis of non-periodic pulses, double pulses, pulse trains, or complex modulated pulsed signals cannot be performed; and that it has low dynamic range for low duty cycles, as well as low measurement speed. Calibration must also be performed with every change in duty cycle.

Typical parameters required to characterize the time-dependent behavior include rise time, overshoot, and droop. A representative pulse waveform is shown in *Figure 9*. For this measurement, the VNA must have time resolution that is significantly greater than the pulse duration. A typical VNA's time resolution ranges from 3 to 20 µs for measurements in the frequency or time domain, which is not great enough to analyze behavior versus time with sufficient resolution. The VNA's measurement bandwidth is the limiting factor for high time resolution of pulse widths of 1 µs or below.

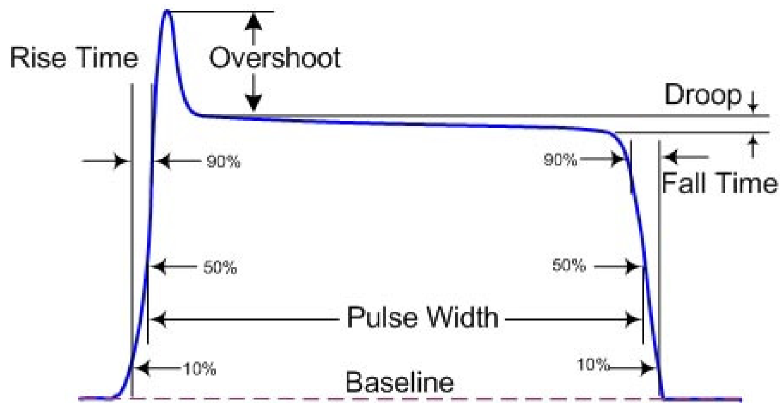

Figure 9: *A pulse waveform with various characteristics identified*

To achieve resolution of better than 1 μs, additional external hardware and software can be used to "chop up" the pulsed signal into slices with different timing positions within the pulse (*Figure 10*). The magnitude of these sliced-up pulses with regard to a specific delay is calculated based on the averaged pulse method. The delay is then increased and the next slices are measured until a desired portion of the pulse is analyzed. This chopping can occur in either the receiver paths at the RF frequency or in the instrument's IF path. If the IF is chopped, losses incurred by the required external switches must be minimized.

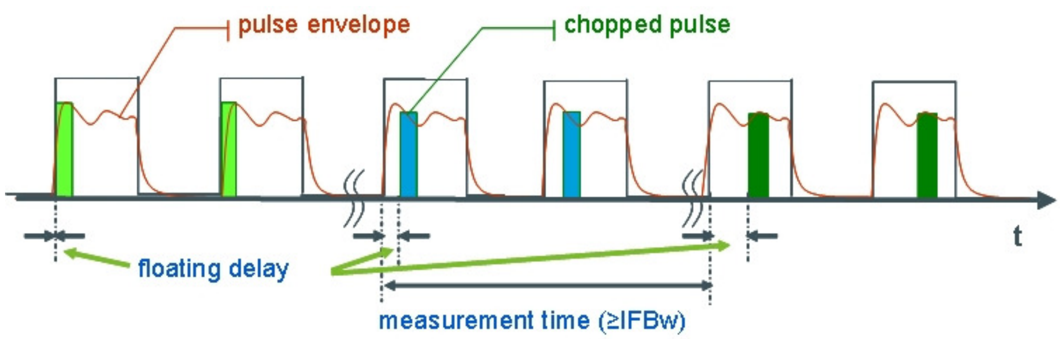

Figure 10: *An example of pulse chopping*

Enhanced Pulse Profile Measurements

A new technique developed at Rohde & Schwarz employs wideband detection and fast data recording that greatly improves pulse profile measurements. To understand the benefits achieved by the new technique, it helps to contrast it with the traditional method.

Pulse profile analysis of pulsed signals or S-parameters with pulsed stimulus is limited by the sampling rate of the analog-to-digital converter (ADC), the processing time between two data points, and the available bandwidth. Sampling rate and data processing time between two data points limit the time resolution, while measurement bandwidth determines the minimum rise and fall time of the pulse that can be analyzed.

The bandwidth-limiting factors are the analog bandwidth of the VNA's receivers and the capabilities of the digital signal processors (DSPs) used for digital filtering. A typical high-end VNA has an analog bandwidth of 15 MHz (with some performance degradation to 30 MHz), but the DSP's IF filters offer adequate performance only for normal CW or time sweeps with a 5 MHz bandwidth. The VNA samples downconverted IF signals at a sampling rate of 80 MHz, which results in time resolution of 12.5 ns. In addition to the sampling time, there is data processing time between two measurement points, which is a bottleneck for achieving high-resolution measurements in the time domain. The limitations are the IF filtering by the DSPs and the data processing time, limiting the time resolution to 1.5 μs plus sampling time.

The new technique enhances pulse profile measurement resolution by sampling the raw data and storing it directly without filtering. Instead of the DSP, the instrument's software performs digital downconversion and digital filtering after recording. The ADC continuously digitizes the data with a sampling rate of 80 MHz and writes it into high-speed RAM. This eliminates any delay that would normally occur between the samples of individual measurement points as shown in *Figure 11*.

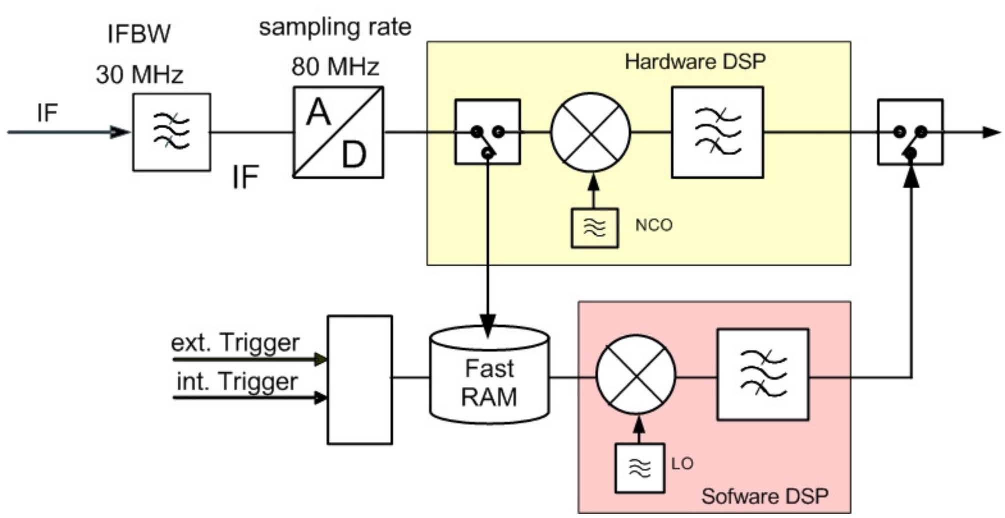

Figure 11: *Fast data recording employed in the improved high-performance pulse profile technique*

The high sampling rate allows a measurement point to be output every 12.5 ns with corresponding time resolution of 12.5 ns. The trigger signal derived from the rising edge of the pulse determines the zero point in time. Consequently, the time relationship between trigger detection and the incoming RF pulse can be measured. This relationship is especially important for determining the correct trigger delay in point-in-pulse measurements versus frequency or level.

In this scenario, the VNA can perform extremely fast pulsed measurements. With more than 10 sweeps/s over 1001 test points, devices can easily be adjusted during the measurement. The technique handles periodic single pulsed signals as well as double pulses and user-defined pulse trains. Devices stimulated with chirped pulses that are modulated in frequency and magnitude can also be analyzed.

The technique also improves S-parameter measurement of devices that have group delays about the same as the pulse width. This has been difficult or even impossible before, since the stimulated RF signal may no longer be present at the device's input by the time the VNA receives the transmitted RF signal from the output. Consequently, a correct S21 measurement can only be obtained with signal overlapping. The new technique solves this problem by applying a time offset to the wave quantities, mathematically shifting them by the amount of the device's group delay before calculating the S-parameters. A specific time delay can be assigned to each wave quantity depending on the measurement direction, so the VNA correctly displays gain (S21) versus the entire pulse duration.

Summary

Like all measurements made with a VNA, the knowledge required to effectively evaluate components and subsystems designed for pulsed signal service is most often gained by hands-on experience. Nevertheless, while the fundamentals described in this article are by no means the last word on the subject, I hope that they help save you time and increase the accuracy of your results.

Acknowledgement

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About The Author

Justin Panzer is manager of product marketing for Rohde & Schwarz in North America. His background includes more than 14 years of test and measurement and mobile communications marketing experience. He has been with Rohde & Schwarz since 2003, with previous responsibility for mobile communications test products serving 2G and 3G technology markets. Panzer holds a B.S. in marketing from Drexel University and an MBA from Auburn University.