Modulated S-parameters support wideband test

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New challenges for S-parameters

Modulation bandwidths continue to grow, promising higher data rates yet imposing test difficulties. Most test technologies are still rooted in past, narrowband architectures, which are increasingly proving inadequate for emerging wireless designs. S-parameter measurements, in particular, have suffered from a lack of new measurement technology. Fortunately, you can now employ modulated S-parameter measurement techniques to characterize wideband active devices.

The S-parameter response of modulated signals varies significantly from that of sinusoidal signals, particularly for active devices such as power amplifiers. Unfortunately, few options exist for engineers wishing to accurately measure S-parameters using modulated stimulus signals. In addition, traditional test setups that do use modulated signals lack any means for fixture de-embedding and vector error correction. Clearly, there must be a better way for obtaining the S-parameter data that designers and test engineers need for wideband designs.

Nonconstant envelope signals

Most modulated signals result in peak to average ratios defined in Table 1 (Ref 1). Gaussian minimum shift keying (GMSK) modulation results in inherently constant power (that is, 0 dB peak to average), but subsequent filtering and power-control stages result in a nonunity peak-to-average ratio. Peak-to-average ratio is not a new concept, but determining its implications for S-parameter measurements is.

Figure 1. Unlike an unmodulated sinusoidal signal, the power of a CDMA signal varies as much as w12 dB with time.
To date, S-parameter measurements have relied on using sinusoidal signals to stimulate an amplifier under test (AUT). This methodology was adequate for constant-envelope modulations such as FM, but sinusoidal signals result in different modes of operation in the AUT than digitally modulated signals do. **Figure 1** illustrates the power-varying behavior of a code-division multiple-access (CDMA) signal and a sinusoidal signal vs. time.

Of particular interest with a CDMA or other nonconstant-envelope power signal is the effect of the power peaks on the AUT. Most vector network analyzers (VNAs) include a ramped power sweep capability that provides insight into a device’s performance under differing drive levels. Such VNAs, however, fail to capture the rapidly varying behavior present in most modulation formats. In fact, it is the short-duration power peaks that cause the greatest strain on the amplifier and contribute the most to the appearance of intermodulation products (Ref. 2).

These peaks also result in changes in input match. Although most amplifier manufacturers have data showing input match as a function of power level, this data is generally obtained using fixed power steps or slow power ramps. What happens when the power varies rapidly with time, as is the case with complex modulation? Very simply, complex modulation causes the sinusoidal behavior to deviate from the modulated performance. The input matching network that worked so flawlessly with sinusoidal signals no longer performs ideally.

**S-parameters describe power ratios**

Developed nearly 35 years ago, S-parameters are essential tools of the RF/microwave designer. S-parameters have worked well (see "New challenges for S-parameters," p. 26), but sinusoidal S-parameter data cannot completely describe devices subjected to signals having complex wideband modulations.

S-parameters are essentially various ratios of incident, reflected, and transmitted power. Although S-parameters can be traced back to their definitions in terms of voltage or current, the difficulty in measuring voltage and current at high frequencies suggests that you can most easily determine S-parameters from power ratios, which you can measure with great accuracy even at microwave frequencies. **Figure 2** depicts the typical two-port device model, which provides an intuitive understanding of S-parameter definitions.

![Figure 2](image)

**Figure 2.** S-parameters describe power relationships in microwave circuits. The equations in this figure show S-parameter definitions for the general two-port microwave network shown.

Strictly speaking, S-parameters describe small-signal, linear networks. In the case of transistors, S-parameters correspond to a certain quiescent (Q) point and a given input power and frequency. Class A devices, due to their reasonable linearity, do not pose a challenge for traditional S-
parameter definitions. Class AB and higher devices do necessitate that you adopt a less rigorous definition of S-parameters. Most power amplifiers, be it from 1 W to multiple kilowatts, operate in the class AB or C regions to improve efficiency. In the case of cellular phones and wireless data devices, designers face the challenge of delivering class A spectral performance with class AB type efficiencies. As S-parameters are the generally accepted figure of merit for high-frequency devices, they have been used universally to specify device performance for amplifiers, no matter what mode of operation.

The advent of direct-sequence spread-spectrum (DSSS) communication systems has resulted in a continual expansion of channel bandwidths. Users keep clamoring for higher data rates and faster Internet service, both mobile and fixed. Although many pieces of test equipment have been modified or created to fill the needs created by these market and technical drivers, one important piece of test equipment—the VNA—has been left in the dustbowl of design, with manufacturers of power amplifiers asking, "How can a wideband design be adequately tested with an instrument using a bandwidth that is orders of magnitude less than the bandwidth of the intended device?"

**Modulated S-parameters**

If S-parameters are viewed as ratios of incident, reflected, and transmitted power, then you can reasonably take the view that S-parameters may also be used for various modes of device operation at various power levels. With this view, it's plausible that S-parameter measurements should be performed under the signal conditions in which the DUT will operate (Figure 3). Active devices, in particular power amplifiers, exhibit different performance under different modulation formats due to the peak-to-average behavior of the modulated signals and the resultant self-heating and other nonlinear effects. These effects are extremely difficult, if not impossible, to accurately model, so engineers have had to employ myriad design rules of thumb and theories based upon empirical evidence and experience. Modulated S-parameters employ the same device model as is used for sinusoidal S-parameters. In addition, all the ratios defined in the equations of Figure 2 still hold. The only difference, but an important one, is the use of real-world, complex modulated signals.

![Figure 3. The two-port device model of Figure 2 can accommodate modulated, as well as sinusoidal, stimulus.](image)

The ramifications for active devices are large. For the design engineer, tools are now available to observe the effects of modulation-specific behavior in their device, and the test engineer can verify that the device will truly perform as advertised in the customer's end-use application.

**System considerations**

Modulated vector network analysis presents new difficulties for the measurement systems used to obtain test data. Traditionally, narrowband (tens of kilohertz) receivers were used to measure the stimulus and response signals. With modulation bandwidths that are orders of magnitude greater than those of narrowband receivers, wide-bandwidth receivers are required to capture channel data.

S-parameter measurement systems generally employ three to four receivers for the instantaneous capture of the incident, transmitted, and reflected signals. To economize on hardware, many
manufacturers of semiconductor test systems don't use this approach. Instead, they frequently rely on a single receiver channel, which is switched between the incident and reflected ports. This approach is acceptable for traditional sinusoidal S-parameters, in which the phase of the source may be considered invariant for the brief moment of switching, but it is not acceptable for complex modulated signals, which have rapidly varying phase.

The wide receiver bandwidths necessary for capturing ever-increasing channel bandwidths also necessitate receivers that have much higher sample rates. A 30-MHz sample rate is the theoretical minimum for capturing a 15-MHz bandwidth. But physical filter synthesis requires that an even higher sample rate be employed because of the difficulties in building a brick-wall filter. In addition, filters with a very steep magnitude response generally exhibit phase distortion that will greatly impair the performance of the measurement system.

Of course, with higher sample rates come higher data rates. Preserving measurement speed requires a distributed digital signal processing (DSP) scheme. The data rate will easily be in the hundreds of megabytes per second, so a fast decimation system is required, followed by a fast processor dedicated to performing fast Fourier transforms (FFTs) and other mathematical routines. If the host controller were burdened by these data streams, measurement speed would suffer dramatically due to bandwidth limitations of the bus and due to processing overload for the host.

Finally, the system must provide windowing to handle wideband signals. Windowing controls the spectral leakage that occurs when the sample clock and the stimulus are off in phase. Although phase-coherent sampling allows sinusoidal signals to be captured and processed accurately without windowing, wideband modulated signals do not afford this simplification.

![Figure 4. The unwindowed spectra of a wideband p/4 DQPSK modulated waveform exhibit spectral leakage in the form of sidelobes that render measurements all but useless.](image)
Figure 5. Application of a four-term Blackman-Harris window to the π/4 DQPSK modulated waveform of Figure 4 suppresses measurement-hindering sidelobes.

Figure 6. A power amplifier characterized here shows significantly different levels of gain (|s21|) when driven by a modulated, instead of sinusoidal, signal.

Figure 7. Measuring $\angle s_{21}$ for an amplifier driven by modulated stimulus yields information useful for implementing phase-correction methods for linearization.

Figures 4 and 5 demonstrate the effects of a π/4 DQPSK modulated waveform that is processed with and without a window. In Figure 4, the spectra aren’t windowed, and the resultant spectral leakage is evident. The sidelobes due to the FFT process all but render the resulting data useless. In Figure 5, a four-term Blackman-Harris window (Ref. 3) was applied, and the sidelobes are well suppressed.

**Modulated vs. sinusoidal performance**

Modulated and sinusoidal stimuli have a dramatic effect on the behavior of active devices. To demonstrate these effects, we characterized a handset power amplifier with both modulated and sinusoidal (CW) stimulus. For this experiment, we operated the amplifier slightly below its P1dB (output power at 1-dB gain compression) point—near the limits of its amplification capability, where power peaks can send the device into strong compression and possibly even cause clipping. This is not an atypical operating point for a power amplifier, which must operate near these regions to achieve reasonable efficiency. Behavior at the P1dB point could never be captured using traditional VNAs, as their sinusoidal-only capabilities would not have uncovered this time variant behavior. Figure 6 illustrates the resulting gain ($|s_{21}|$) of the device.

Measuring $\angle s_{21}$ yields even more information about the behavior of this amplifier under modulated stimulus. This additional information is particularly useful for designs that employ phase correction methods for linearization. Researchers have performed much work in obtaining accurate AM/PM transfer characteristics and translating them into efficient predistortion algorithms for DSP-based linearization applications, but they have experienced difficulty obtaining these characteristics accurately using traditional test equipment. Traditional network analyzers do a nice job of obtaining AM/PM characteristics with sinusoidal signals, but they offer no help with modulated signals. Figure 7 illustrates the differing phase response for both modulated and sinusoidal cases.
The results between the modulated and sinusoidal stimulus vary by as much as 5°. This difference could easily mean the difference between a design passing its specifications or failing them. Combine the difference in results with the fact that a few degree changes in phase can result in degradation in intermodulation levels of 10 dB or more (Ref. 2), and the gravity of the problem becomes obvious.

The trend toward using wide information bandwidths will continue in order to satisfy the millions of data hungry wireless users. Testing with complex modulated signals while employing vector error correction ensures that both device designers and test engineers will have the tools they need to meet the design challenges while hitting the cost of test targets that allow aggressive pricing of wireless devices.

Table 1. Peak-to-average ratios for common modulation formats

<table>
<thead>
<tr>
<th>SIGNAL TYPE</th>
<th>MODULATION METHOD</th>
<th>PEAK-TO-AVERAGE RATIO</th>
</tr>
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<tbody>
<tr>
<td>Analog</td>
<td>FM</td>
<td>0</td>
</tr>
<tr>
<td>GSM</td>
<td>GMSK</td>
<td>1.5 dB</td>
</tr>
<tr>
<td>TDMA</td>
<td>p/4 DQPSK</td>
<td>3.5 dB</td>
</tr>
<tr>
<td>CDMA</td>
<td>QPSK, DSSS</td>
<td>10 to 12 dB</td>
</tr>
<tr>
<td>TD/CDMA</td>
<td>QPSK, GMSK, DSSS</td>
<td>TBD</td>
</tr>
<tr>
<td>W-CDMA</td>
<td>QPSK, DSSS</td>
<td>8 to 9 dB</td>
</tr>
<tr>
<td>Other wideband</td>
<td>QPSK</td>
<td>8 to 9 dB</td>
</tr>
</tbody>
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References