IEEE 802.11 spectral measurements using vector signal analyzers

The vector signal analyzer is fast becoming the instrument of choice for RF designers working on advanced digital communications systems. They can perform many of the same measurement and characterization tasks as the spectrum analyzer, with the added ability to perform many useful digital demodulation functions.

By Jerry Archambault and Shravan Surineni

Over the past decade, many new digital communications systems have been developed that are far more bandwidth-efficient with respect to the amount of information that is packed into a given channel bandwidth. These new systems achieve this efficiency by using advanced digital modulation techniques. These advanced modulation techniques produce signals that are similar to random noise when viewed in both the time and frequency domains. The noise-like characteristics of the signal present challenges to the engineers and technicians working with them when trying to measure the actual signal parameters. The increased deployment of today's RF data communications systems using these advanced digital modulation techniques increases the likelihood that the engineer or technician will run into situations where power measurement of these digitally modulated signals will occur.

New equipment is being developed to measure and characterize the RF signals generated by these new digital communications systems. The vector signal analyzer (VSA) is a new tool that is replacing the spectrum analyzer (SA) as the tool of choice for RF designers working on these systems. The VSA is a powerful tool that can perform many of the same measurement and characterization tasks that the SA can, but it can also perform many more useful digital demodulation functions. The SA and VSA operate in different manners. These operational differences can result in measurement errors if these differences aren't properly considered while making a measurement.

One of the important measurements in RF communications is the spectral mask measurement. This article discusses the equivalent setup on a VSA to make a spectral mask measurement as traditionally performed on a SA.

Spectrum analyzer

The spectrum analyzer measures the power (or amplitude) of the signal vs. the frequency of the signal. SAs are best suited for measuring tonal signals such as continuous wave (CW) where the time-varying signal characteristics do not alter the detected power levels. Two important architectures are used in an SA: the classical superheterodyne/detector architecture and the FFT architecture.

A simplified block diagram of superhet-

One of the important measurements in RF communications is the spectral mask measurement.

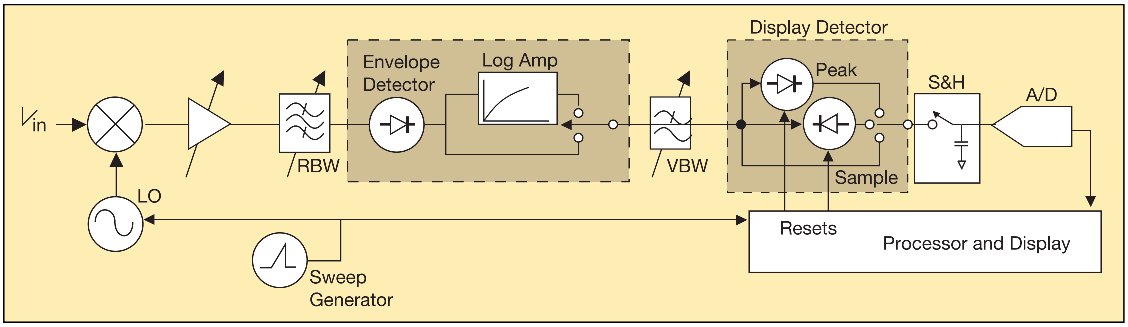

Figure 1. Simplified spectrum analyzer block diagram.

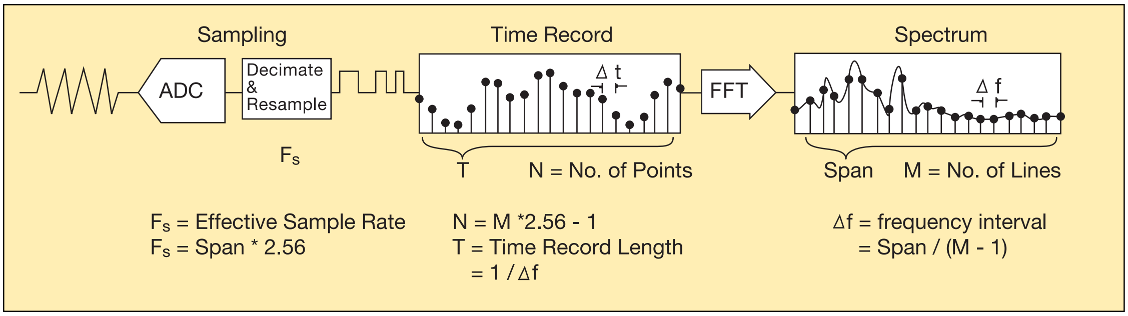

Figure 2. Simplified vector signal analyzer block diagram.

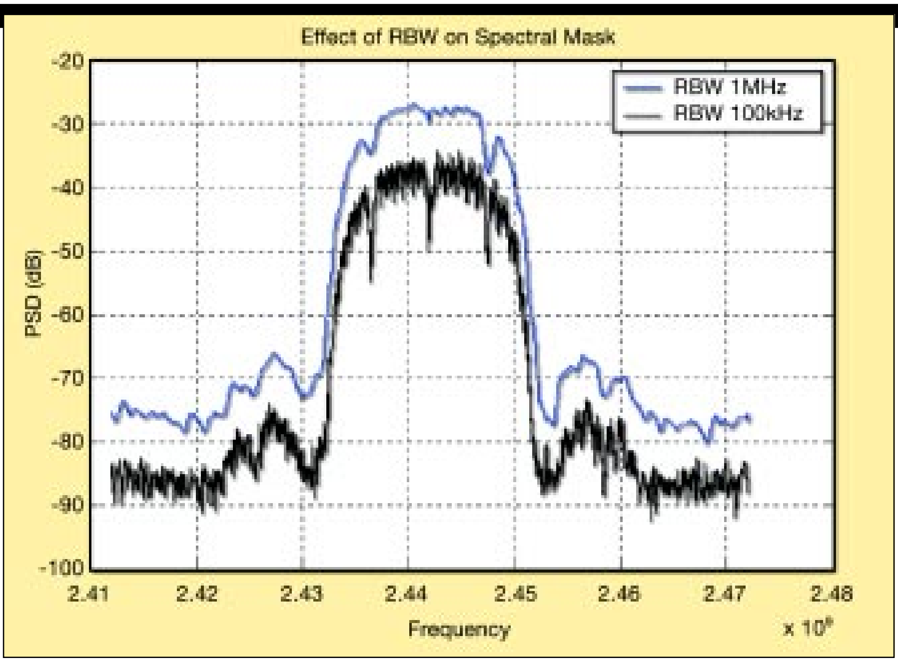

Figure 3. Effect of RBW on spectral mask measurement.

erodyne/detector SA is shown in Figure 1. The signal of interest is presented to the RF input of a wideband RF mixer where it mixes with a signal from a local oscillator (LO). The LO input of the mixer is swept over the frequency range of interest. The output of the mixer is the signal of interest downconverted to a low intermediate frequency (IF) that is typically 70 MHz. The mixer, being a non-linear device, also produces the harmonic signals and signals at the sums and differences of the original frequencies and their harmonics. The output of the mixer is fed to a switched bandpass filter, called the resolution bandwidth filter (RBW). This filter bandwidth is selectable so that the SA can display different resolution levels on the frequency axis. This allows the SA the ability to display a small signal next to a relatively large signal. If any of the mixed signals fall in the passband of the RBW filter, they are further processed and rectified by an envelope detector. This voltage is amplified by a log-amp to produce a voltage proportional to logarithm of the RF power for better dynamic range.

The log-amp output voltage is then fed to a low-pass filter to help eliminate some of the signal variations over time. This filter is selectable and called a video bandwidth filter (VBW). (The video bandwidth name results from the fact that this signal was used to deflect the electron beam in the original analog spectrum analyzer's video display.)

Vector signal analyzer

The VSA works in a similar manner to the SA for the first stage (see Figure 2). The signal of interest is downconverted to a low IF using an LO. The mixer output is low-pass filtered to prevent aliasing. The signal is then sampled with a high-speed, wide-dynamic-range analog-to-digital converter (ADC), (95 Msamples/s for Agilent 89600VSA).

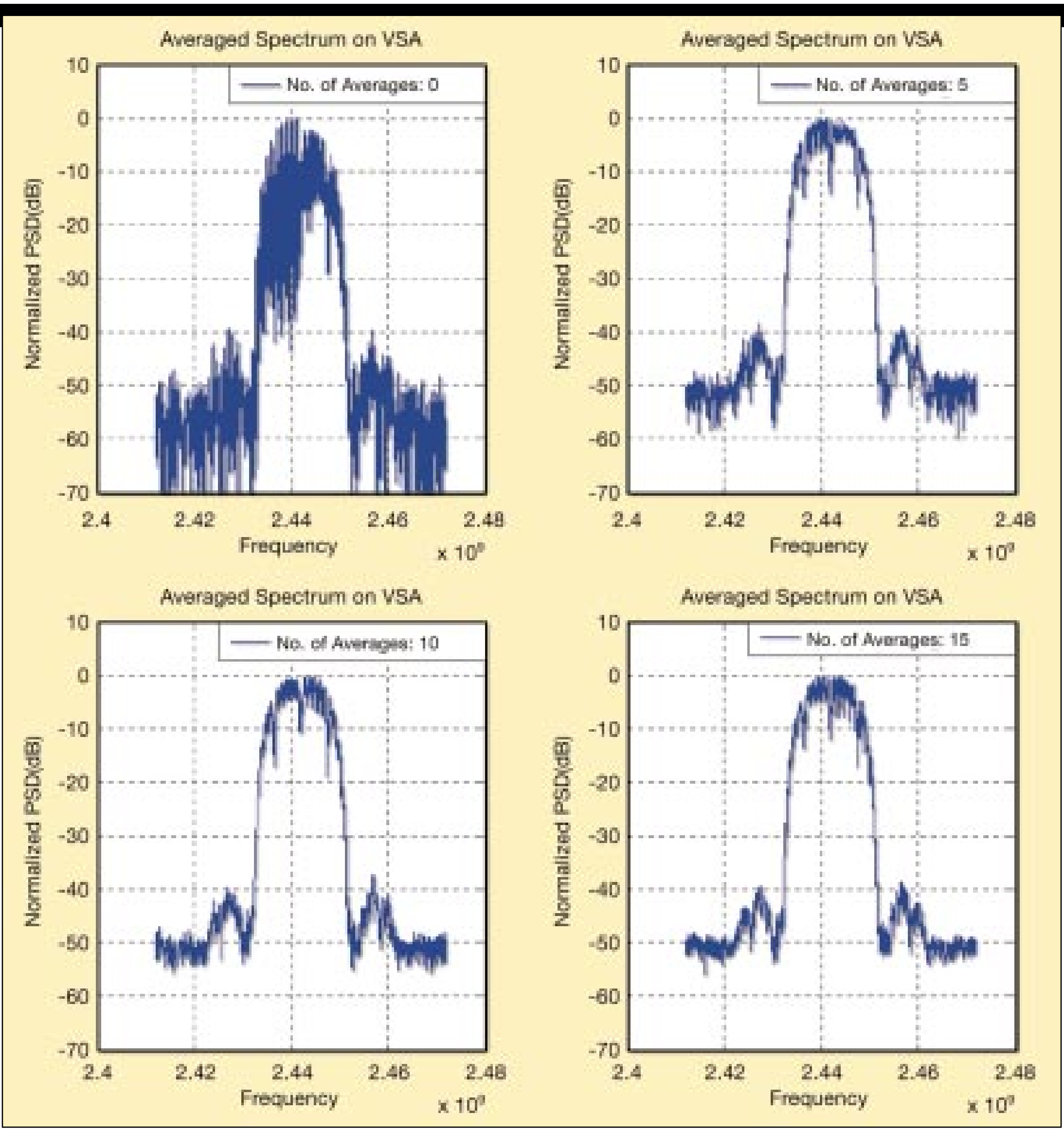

Figure 4. Effect of averaging the spectrum (on VSA).

A whole set of DSP techniques can then be implemented on the sampled time data. Performing FFT on these time samples and calculating the magnitude of the FFT complex values gives a power spectral density (PSD) plot similar to a SA. Varying the sample rate, total time captured and the FFT size can allow the implementation of various FFT frequency resolutions (FFT bin size). This is analogous to the resolution bandwidth function of the SA by the VSA. The frequency span of the instrument is set by the sample rate of the ADC and is generally in the range of tens of MHz (36 MHz for Agilent 89600VSA). Higher spans are normally required in SA applications to observe the spectral side lobes and spurious emissions that may be present in bands that are far in frequency from the signal center frequency. These higher spans are made possible by a segmented or blocked sweep approach. When the required span exceeds its capability of the VSA ADC, the VSA divides the span into *N* smaller frequency spans and by changing the LO, downconverting and digitizing successive frequency spans. These segments are concatenated together to produce a continuous spectrum over the required span. The VSA does not have a detector or post-detection filter function that acts in the same manner as the SA post detection video filter (VBW filter).

Spectral mask measurements

Spectral mask measurement is a test method used by regulatory agencies (i.e., FCC, ETSI) to ensure that the RF signal produced by the transmitter provides minimal interference to other systems that are not on the same RF frequency. The spectral mask sets limits on maximum out-of-band power that the transmitting system can produce relative to its peak transmit power level. Traditionally, spectral mask measurements were done on an SA. In carrier-based systems (analog TV broadcast, AM or FM radio, etc.) the carrier contains the significant power of the RF signal. The spectral mask generally has a flat top representing the power level of the carrier, and outside the band the mask shows the limits that a transmitter should not exceed. Anyone familiar with an SA knows that for a true measurement made on CW

VBW	RBW/VBW	No. of Averages	Spectrum Analyzer			VSA (Spectrum Analyzer Application)		
			Channel Power	Peak	SA delta PSD	Channel	Peak Power	VSA delta PSD
100kHz	1	1	-7.50	-20.21	12.71	-8.06	-18.82	10.76
100kHz	1	1	-7.69	-19.42	11.73	-7.96	-19.81	11.85
30kHz	3.3	3	-8.78	-20.98	12.20	-8.00	-22.36	14.36
30kHz	3.3	3	-8.52	-22.59	14.07	-7.93	-21.4	13.47
10kHz	10	10	-9.17	-23.89	14.72	-7.97	-23.03	15.06
10kHz	10	10	-9.05	-23.48	14.43	-8.11	-23.76	15.65
1kHz	100	100	-9.79	-27.26	17.47	-8.01	-23.94	15.93
1kHz	100	100	-9.64	-27.03	17.39	-8.09	-24.35	16.26

signals, the measured power will not vary as the RBW and VBW settings are changed.

But when measuring spread-spectrum signals, frequency or amplitude-modulated tones, noise or noise-like signals with an SA, both the RBW and VBW settings will affect the locations of the SA PSD trace on the display. To address this display variation resulting from the interaction of the measured signal characteristics and the SA operation, the regulatory agencies that determine the spectral mask will specify RBW and VBW settings to ensure that all spectral mask measurements are consistent regardless of the nature (tonal or spread spectrum) of the undesired interfering signals. The measurements often specify out-of-band power relative to the peak power in the spectrum. The term *peak power* has been the cause of much confusion over time because, early on, it was not clear as to whether peak power was referring to the peak power of the time domain signal or the peak power of the PSD plot. It is now accepted that the peak power refers to the peak of the PSD plot.

The term peak power *has been the cause of much confusion over time because, early on, it was not clear as to whether peak power was referring to the peak power of the time domain signal or the peak power of the PSD plot.*

The IEEE 802.11 standard sets the spectral mask limitations on the transmit spectrum, for 802.11a/b/g devices. The SA should be set to the proper RBW and VBW settings as specified in the standard and a trace of transmit spectrum is taken. The mask is overlaid on the SA trace such that the in-band flat top is at the peak power of the signal PSD plot. The passing criterion is that the trace observed on SA must be below the spectral mask over the entire mask frequency range.

Resolution bandwidth (RBW)

The resolution bandwidth function is provided with both SA and VSA. It determines the analyzer’s frequency resolution. In swept SA, the RBW is defined as the 3 dB bandwidth. The RBW in a VSA is the “equivalent noise bandwidth (ENBW),” which is the bandwidth of a brick-wall filter that passes the same noise power with white noise input. In standard swept analyzers, the RBW is a function of the last filter in a series of analog IF filters prior to the envelope detector. In the VSA, a digital IF achieves the equivalent RBW functionality by using DSP techniques. The RBW function also determines how fast the analyzer can make a measurement, with narrower RBW settings requiring longer sample collection times. In most digital modulation techniques, the carrier doesn't carry any information and is suppressed. The signal energy is spread over the wide frequency band.

The energy spreading over the frequency band results in a signal that tends to have noise-like statistical characteristics. As a result, the exact PSD shape varies from scan to scan and the resulting peak power is not directly related to the total signal power. As in noise power measurements, the RBW and VBW settings will have an effect on the measurement made on an SA. As long as the signal bandwidth is greater than the RBW filter, decreasing the RBW reduces the average height of the SA trace by an amount

Pdrop = 10* LOG (RBW1/RBW2)

where RBW1 is the first resolution bandwidth and RBW2 is the second resolution bandwidth. Reducing the RBW from 1 MHz to 100 kHz reduces the average height of the signal PSD curve by 10 dB as shown in Figure 3.

Noisiness, variance and averaging

When noise-like signals are measured on the spectrum analyzer, the resulting power measurements will also be noisy. In most digital modulation techniques, the instantaneous signal power during transmission in any frequency bin smaller than the signal bandwidth can vary by up to 30 dB. This results in a hashy PSD plot that is not repeatable from scan to scan. This noisiness can be reduced in three ways.

1) Increase averaging in each measurement bin by reducing video bandwidth (VBW).

2) Increase the number of measurement bins used for a measurement.

3) Average a number of computed results (scan to scan averaging).

The variance of a result is the square of its standard deviation, symbolically s^2. Variance is inversely proportional to the number of independent results averaged. When *N* independent results are averaged, then the measurement variance is s^2/N.

Video bandwidth

The effect of noise in spectral measurements on digital modulation signals may be reduced by smoothing or averaging the display. The video filter of the SA is a low-pass filter following the detector and determines the bandwidth of the video circuits that drive the vertical deflection system of the display. This video filtering can be used to achieve the desired averaging, as long as the signal is present over the entire averaging interval.

In digital modulation, because the signal spectrum has noise-like statistical properties, the variation of the signal PSD will vary significantly if the impulse response time of the VBW filter is less than the digital modulation symbol time. Reducing the VBW (increasing the impulse response time) will result in more symbols being integrated to produce the video output that is displayed on screen. Averaging over more symbols generally results in less variation (noisiness or hash) in the resulting PSD display on the SA screen. This effect can be seen both from display point to display point and from scan to scan. In effect, the VBW filter exponentially averages the PSD display.

As video bandwidth is reduced while keeping the RBW constant, the peak-to-peak variations of the PSD is reduced. As the video filter cutoff frequency is decreased to be less than the RBW filter width, the video system can no longer follow the rapid variations of the signal passing through the IF filters. The result is averaging or smoothing of the PSD waveform. The ratio of VBW and RBW determines the degree of averaging performed. The IEEE 802.11 standard specifies the RBW and VBW settings to be used when making spectral mask measurement. In the case of a VSA, a RBW setting is available, but there is no VBW setting. Thus, to perform spectral mask measurements using VSA, while following the specifications given in the standard, a way to emulate the VBW function is required.

Video averaging

Video averaging function is normally provided by the VSA (and with some SA that have digital display modes). The video averaging function averages the display trace points in each display pixel after the log amplifier. In this way the averaging is performed on a point-to-point basis over two or more sweeps. With video averaging, at each display point the new value is averaged in with the previously averaged data.

$A_{avg} = [(n-1)/n]\, A_{prior\ avg} + (1/n)\, A_n$

where A_{avg} = new average value

$A_{prior\ avg}$ = average from prior sweep

A_n = measured value on current sweep, and

N = number of current sweep

Thus, the display gradually converges to an average over a number of sweeps (assuming the signal is present for every sweep). The number of sweeps selects the degree of averaging or smoothing. The important factor to consider is that both video filtering and video averaging take about the same time to reach a given averaging or smoothing level. If the signals are noise or noise-like, both video filtering and video averaging have the same effect, with video filtering performing averaging in real time and video averaging requiring multiple sweeps to achieve the full degree of averaging. In video filtering, each point is averaged only once for a time of about 1/VBW on each sweep. Display averaging at each point takes place over the full time period needed to complete the multiple sweeps in video averaging.

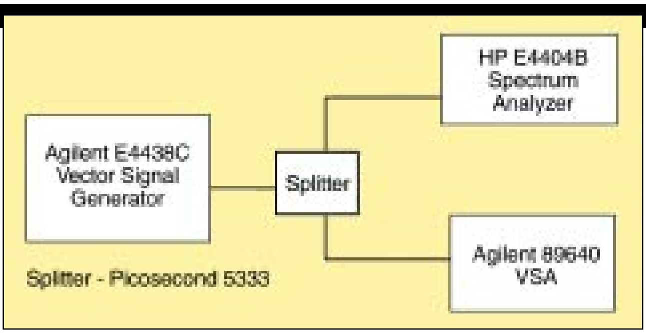

Figure 5. Setup used for spectral measurements.

Effect of VBW on spectral mask measurements

For a single frequency CW signal (like the carrier for an AM signal), changing the VBW has little effect on the measured signal's PSD peak with the SA. Thus, the lack of a VBW function does not affect the placement of the flat-top portion of the spectral mask relative to the total signal power.

For carrierless digital communications, changing the VBW does affect the signal PSD curve. The VBW filter will tend to average out the fluctuations, if set to a bandwidth narrow enough so that the filter's impulse response spans many symbols. This provides a smoother display. For the spectral mask, measurements on digital modulation signals the smoothing of the PSD (or lack of it) as the VBW setting changes will alter the placement of the spectral mask relative to the actual average signal power. Thus, it is important that the VBW setting specified in the spectral mask setup be followed or communications systems will be incorrectly measured against the regulatory agency's mask.

The VBW filter acts as a signal-averaging function on the displayed signal's PSD. This suggests that the smoothing of the scan-to-scan averaging function of the VSA could be used to emulate the video bandwidth filtering of the SA. Because the ratio of the RBW to the VBW determines the amount of smoothing on the SA display, it is reasonable to assume that the number of scans to average *N*, be given by

$$N = RBW / VBW \qquad (2)$$

Experimental results

As an experiment to test this conjecture, the SA, a VSA and a signal generator were set as shown in the test setup (Figure 4). The SA is set to 100 kHz RBW and various

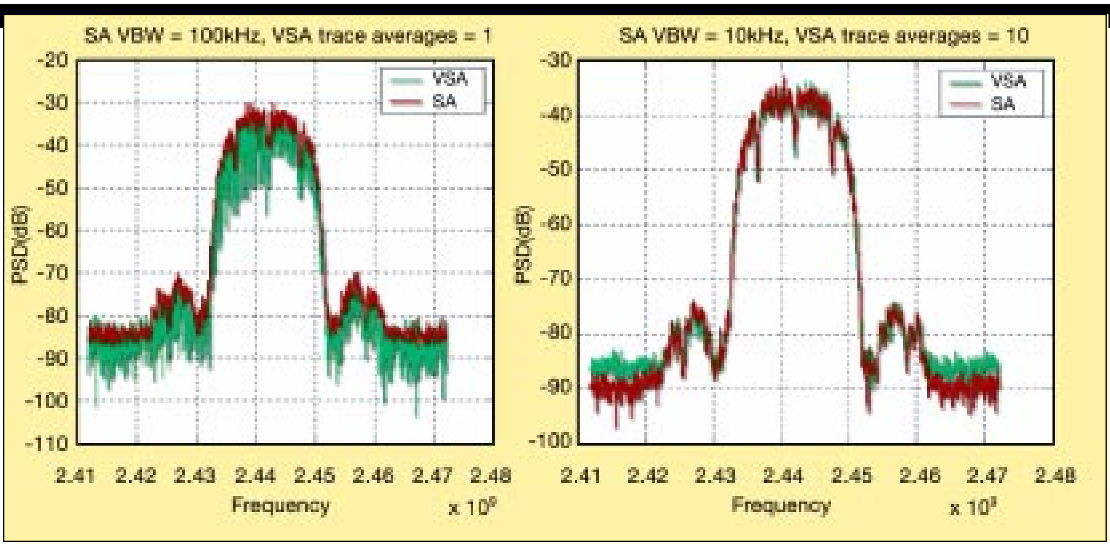

Figure 6. Comparison of spectral mask on SA and VSA.

VBW settings. A nearly continuous 802.11b signal (>98% duty cycle) was input to both the SA and VSA using a power splitter. The peak of the PSD plot and the average integrated channel power for each VBW setting is noted with the SA in sample detect mode. The same signal was then measured by the VSA with a RBW of 100 kHz with video averaging enabled and the number of averages set using the above equation. Again, the peak of the PSD plot and the average integrated channel power in the channel was measured for each value of *N*. The ratio of the PSD peak in signal band to the signal average channel power is taken for both instruments.

The measurement accuracy of the SA is ~1.0 dB. The VSA accuracy is similar. Thus these results show close agreement in the peak-to-average measurement values on an IEEE 802.11b signal between the SA and the VSA when the number of trace averages *N* is set by Equation 2. Thus, we can conclude that the VSA can be used to measure spectral masks for 802.11 signals as long as the scan-to-scan trace averaging function is used to emulate the video bandwidth filtering of the SA and the number of traces averaged is set according to Equation 2 above.

Measuring the spectral properties of burst signals

Spectral measurements are generally performed while the device is transmitting modulated data in continuous transmit mode. Most WLAN devices do not have a continuous transmit mode, and all measurements are to be made during their normal operation. To accurately measure spectral properties of these burst signals, time-gated spectral measurements should be used.

Time-gated measurements enable analyzing that specific portion of signal that is of interest. Averaging can be performed externally on spectral data corresponding to these burst signals, and this would decrease the variance in the measurement. In this case, as the measured power is the summation of many identically distributed bin values, the distribution of measurement approaches a Gaussian distribution. FFT-based vector signal analyzers offer both time and frequency domain measurements at the same time, enabling time-gated measurements to be done on the input signal. RFD

ABOUT THE AUTHORS

Jerry Archambault is RF systems architect at Engim, based in Acton, Mass. He holds a BSEE degree from Oakland University (Rochester, Mich.) and an MSEE degree from Syracuse University. He can be reached at jerry@engim.com.

Shravan Surineni is a staff member of the Research and Development division of the University of New Hampshire's Wireless Consortium, InterOperability Lab in Durham, N.H. He hold a B.Tech (EE) degree from Jawaharlal Nehru University (Hyderabad, India) and a MSEE from the University of New Hampshire in Durham, N.H. He can be reached at shravans@iol.unh.edu.