Using advanced signal analysis to identify sources of WLAN transmitter degradations

Design engineers can use measurements of the error vector magnitude, frequency error, phase noise, and the transmit power envelope to identify the sources of degraded WLAN transmitter performance. In particular, techniques are described to identify and troubleshoot the impacts of amplitude, phase, and group delay imbalances between the I and Q channels, phase noise, spurious signals and transient effects, and signal compression on transmitter performance.

By Christian Olgaard

The performance of an 802.11/a/b/g wireless local area network (WLAN) transmitter directly affects product quality. Given the crowded field and thin profit margins typical of today's WLAN product market, enhanced quality can differentiate a product and increase its sales, reduce product returns, and improve manufacturing yields and thus profitability. Transmitter performance, however, is sensitive to RF section design choices, circuit board layout and implementation, and component variations and changes, and is further complicated by the different modulation types and frequency bands demanded by the 802.11a/b/g standards.

Test instruments that combine spectrum analyzer, vector signal analyzer (VSA), and power meter capabilities with signal analysis software—such as LitePoint's IQview™ 802.11a/b/g WLAN Test Solution and its associated IQsignal Software Suite—provide the necessary tools to assess most WLAN transmitter issues. The spectrum analyzer and power meter capabilities allow measurement of frequency offsets, signal transients, phase noise, in-band power, adjacent channel power, and other parameters, while the VSA capability can demodulate a given signal into quadrature components and capture a complex waveform as a vector characterized by magnitude and phase or as a complete symbol constellation. Signal analysis software can then simplify the measurement process as well as derive statistical performance estimates.

With these tools, measurements can be made in the modulation, time, and frequency domains to assess and troubleshoot transmitter performance in the design process and during production. Moreover, these tools simplify analysis of the complex waveforms employed by 802.11a/b/g by allowing measurement of a single convenient figure of merit, the error vector magnitude (EVM), to reduce the many parameters that characterize a transmitted RF signal to a single parameter. In production line testing, EVM can be used as a pass-fail metric, simplifying transmitter quality assurance and increasing test throughput, while in the design process, EVM is a valuable indicator of overall signal quality.

Error vector magnitude is a direct measure of modulation accuracy and transmitter performance. Qualitatively, EVM reflects the error vector, defined as the difference between a measured signal and its ideal error-free point in the signal constellation, as shown in the complex plane in Figure 1.

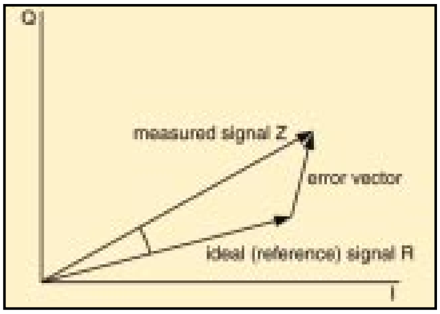

Figure 1. Modulation accuracy.

As can be seen, the measured signal differs from the ideal signal in amplitude and phase. Completely deterministic and non-varying impairments would simply shift the signal from its ideal point. In the presence of intersymbol interference and noise, however, repeated measurements will typically show the measured signal to vary randomly about the ideal signal, defining an "error cloud" around the ideal constellation point.

Quantitatively, EVM is a statistical estimate of the magnitude of the error vector normalized by the magnitude of the ideal signal. For a specific symbol, EVM is mathematically defined as:

$$\mathrm{EVM} = \sqrt{\left[\frac{\sum_{k=1}^{M}\left\|Z(k)-R(k)\right\|^{2}}{\sum_{k=1}^{M}\left\|R(k)\right\|^{2}}\right]}$$

where Z is the measured signal corrected as may be necessary for any time and frequency offsets; R is the ideal or reference signal, an ideal version of the signal being measured; M is the number of

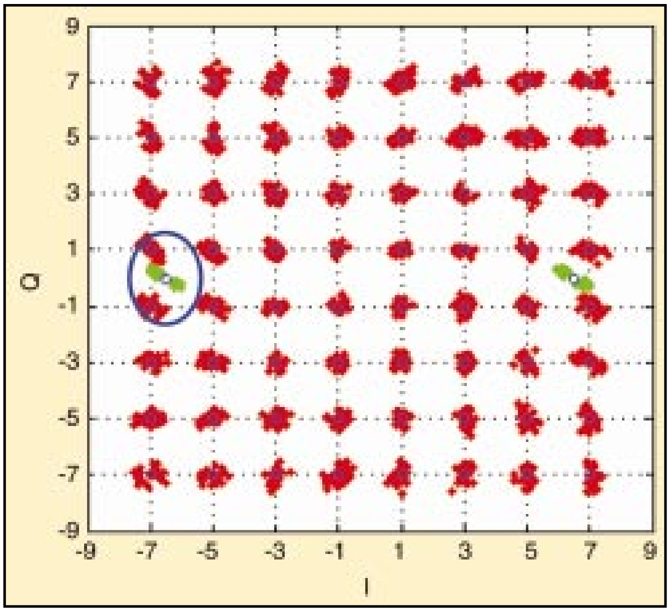

Figure 2. 802.11a/g 64-QAM OFDM constellation with 2% amplitude and 2° phase imbalances.

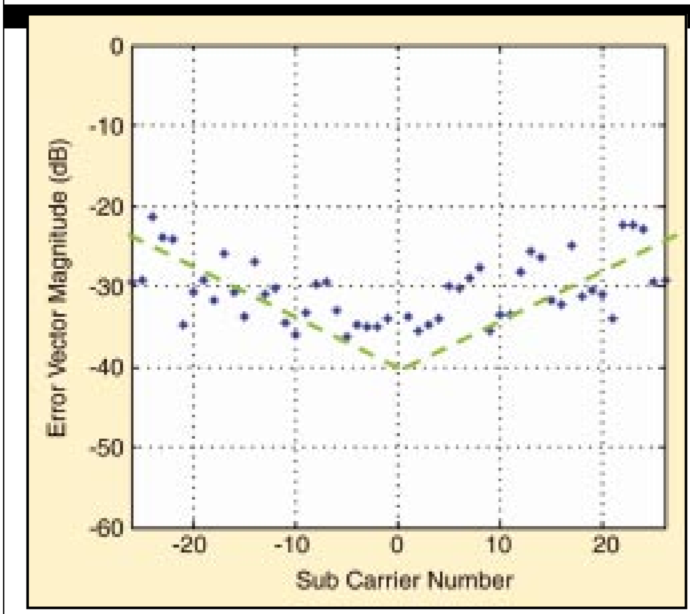

Figure 3. EVM vs. subcarrier for a 64-QPSK OFDM signal with ~1 ns group delay imbalance.

measurement samples; and k is the sample index.

The definition of EVM can then be extended to all the symbols of a given modulation scheme by averaging over a large number of sampled symbols. A single EVM value reflects the overall signal quality. By definition, EVM is always a positive number less than or equal to unity. Expressed in decibels or as a percentage, EVM is, respectively:

$$EVM_{dB} = 20 * \log_{10}(EVM)$$

and

$$EVM_{\%} = 100 * EVM$$

For example, an EVM dB value of –25 dB is equivalent to an EVM percent of approximately 5.6%. The better the signal quality, the lower the EVM value: a good transmit signal's EVM, expressed in decibels, will be a larger negative number than that of a poor signal; alternatively, a good signal's EVM, expressed as a percentage, will be a smaller percentage than that of a poor signal.

EVM is used in the 802.11/a/b/g standards to specify the overall modulation accuracy of a transmitter, with guidelines given for how EVM should be measured for the direct sequence spread spectrum signals of 802.11b and 802.11g and for the orthogonal frequency division multiplexing (OFDM) signals of 802.11a and 802.11g. For example, the 802.11a/g standards employ binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), 16-bit quadrature amplitude modulation (16-QAM), and 64-QAM OFDM signals. For those signals, EVM is defined in the standard by sampling the signal over all the OFDM data subcarriers that constitute a symbol and over all the OFDM symbols that constitute a frame (with a minimum of 16 symbols per frame), then normalizing by the average power of the signal constellation and averaging over at least 20 frames. In this way, a single EVM value can be determined for each particular 802.11a/b/g mode.

As a measure of overall modulation accuracy, EVM reflects many different signal distortions. For many modulation schemes, it can be shown that the reception of a distorted signal with a specific EVM is equivalent to the reception of a distortion-free signal in additive white Gaussian noise with an effective signal-to-noise ratio (SNR) inversely proportional to the square of the EVM value:

$$SNR_{AWGN} \propto 1/[EVM]^2$$

The proportionality depends on the particular modulation scheme, reflecting, for example, the peak-to-average power ratio or the process gain. For a particular modulation scheme, SNR_{AWGN} and the measured EVM can be related to the bit or packet error rate (BER or PER) and the overall system communications performance. By contrast, the actual measurement of the signal-to-noise power ratio does not capture the effects of signal distortions, and a measured SNR_{power} value will not necessarily be an indicator of BER or PER performance.

For the lower order modulation types employed by 802.11b, a relatively large EVM value is allowed by the standard, while for the higher order modulation types employed by 802.11a/g, more stringent (lower) EVM values are specified. The calculation of EVM is also specified differently by the standards for different modulation techniques—for the relatively low data rate direct sequence spread spectrum signals of 802.11b/g, EVM is calculated as a peak value, while for the high data rate OFDM signals of 802.11a/g, EVM is averaged over multiple carriers and multiple symbols. Intuitively, the transmit EVM must be small enough so that the distorted signal does not near the symbol constellation's decision boundaries, especially in the presence of additive noise and other channel and receiver effects. The highest 802.11a/g data rates employ high-order modulation techniques and are more susceptible to the effects of transmit signal impairments—a given EVM value will affect a 16-QAM or 64-QAM signal more than a QPSK or complementary code keying (CCK) signal because of the smaller decision regions.

Representative transmitter impairments

In most 802.11a/b/g implementations, the WLAN baseband processor modulates the signal and, after on- or off-chip digital-to-analog conversion, provides I (in-phase) and Q (quadrature) analog outputs at baseband that are then upconverted by the RF section. Operation of the WLAN baseband processor is generally not the source of transmit signal impairments; rather, impairments typically result from analog variations in the signal path through the printed circuit board (PCB) implementation and the RF circuitry. Component variations, imperfect PCB trace layout, crystal oscillator and frequency synthesizer instability, power amplifier distortions, and the presence of spurious signals can all contribute to a degraded transmit signal. By definition, EVM captures the effects of many different signal distortions. A poor EVM measurement by itself indicates a problem that, especially when combined with measurement of other parameters, can help identify such transmit signal impairments as:

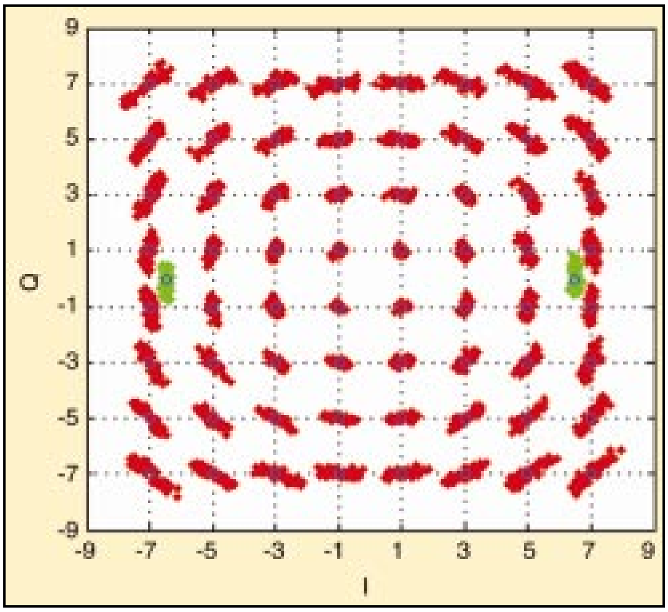

Figure 4. 802.11a/g 64-QAM OFDM constellation with 3° rms phase noise.

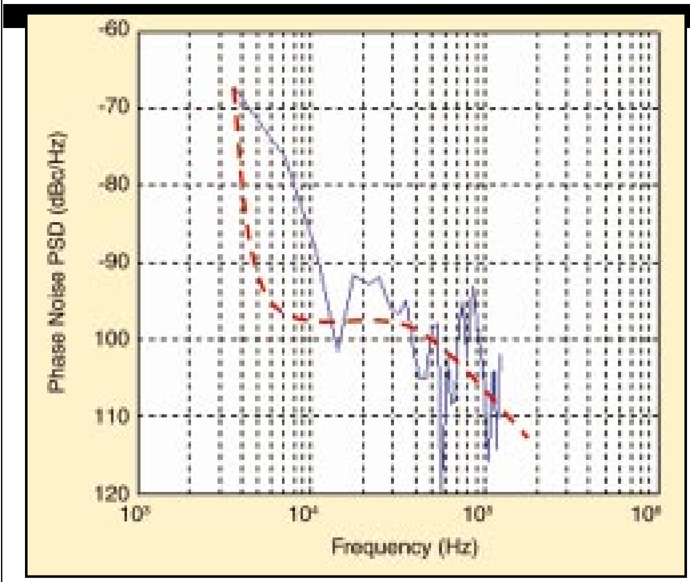

Figure 5. Phase noise PSD of a 64-QAM OFDM signal mixed by a degraded LO signal.

- I/Q imbalances (amplitude, phase, group delay);
- phase noise;
- spurious signals and transient effects; and
- effects of signal compression.

I/Q imbalances

Imbalances or mismatches between the I and Q signal paths will directly affect modulation accuracy. Differences in the parasitic capacitances and inductances along the PCB traces for the I and Q signal paths can cause such I/Q imbalances, as can component variations and even design variations in the baseband and RF ICs. Figure 2 illustrates an 802.11a/g 64-QAM OFDM constellation in the presence of a combined 2% amplitude and 2° phase mismatch between the I and Q channels. In the figure, each point of the 64-QAM signal constellation is displayed as a cloud of red measurements taken from each of the 48 OFDM data subcarriers and over many symbols. Because of the amplitude and phase imbalances, the constellation appears to be distorted and smeared rather than composed of sharply defined points. In this example, the effect of the I/Q imbalances results in an EVM value of approximately -30 dB, where this value would be approximately the same for each of the subcarriers if measured separately.

Note the two green constellation points in the figure, representing the four BPSK-modulated pilot tones stipulated by the 802.11a/g standard. Because there is a fixed relationship between the data that modulates the pilot tones, their constellation points appear relatively clean compared to data constellation points, and they provide an easy way to qualitatively assess the impacts of I/Q imbalances. An I/Q amplitude mismatch results in the pilot tones separating mostly along the I axis, while an I/Q phase mismatch results in the pilot tones separating mostly along the Q axis. In Figure 2, the pilot tones are separated along a line that is tilted with respect to the I and Q axes, indicating the presence of both amplitude and phase imbalances.

Besides amplitude or phase imbalances, a constant differential group delay between the I and Q signals can also adversely affect modulation accuracy. Such an imbalance is usually related to the PCB layout and different trace lengths for the baseband I and Q signals. The constellation will again appear distorted, but the effects of the differential group delay are dependent on frequency and will affect each OFDM subcarrier differently. Signal analysis software such as that provided by IQview can compute the EVM for each of the different subcarriers. The green line in Figure 3 shows how the EVM values plotted as a function of the subcarrier index reveal a clear correlation to frequency, indicating the effect of a differential group delay of approximately 1 ns.

Phase noise

Phase noise can be introduced into a signal when it is mixed with a local oscillator (LO) signal to frequency translate it from baseband to RF. The LO phase noise contribution reflects the frequency stability of the reference crystal oscillator used by the frequency synthesizer, the frequency stability of the free-running voltage-controlled oscillator (VCO) used by the synthesizer's phase-locked loop (PLL), and the loop bandwidth of the PLL used in the frequency synthesizer. The PLL acts as a low-pass filter with respect to the crystal oscillator and as a high-pass filter with respect to the free-running VCO. Depending on the PLL loop bandwidth, the ideal result is that the synthesizer's output phase noise spectral density is dominated by the generally

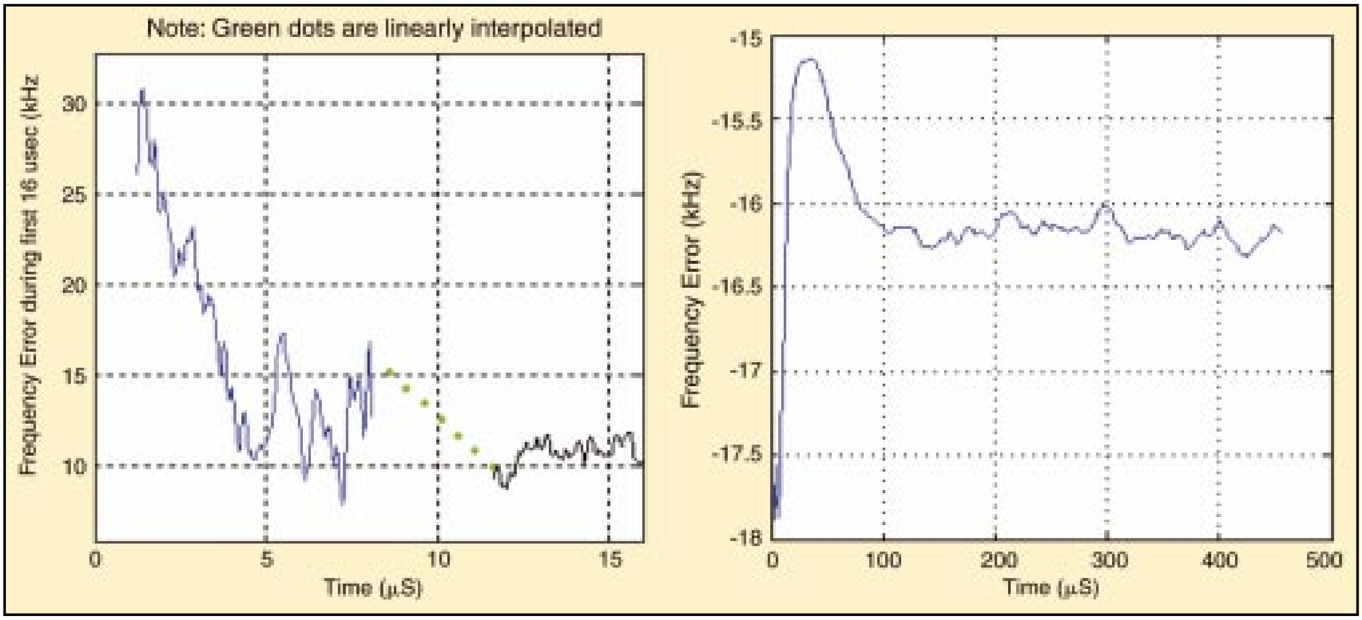

Figure 6 (L) Fast-settling frequency error caused by frequency pushing of the VCO; (R) slow-settling frequency error caused by frequency pushing of the crystal oscillator.

good long-term stability of the crystal oscillator at low frequency offsets and by the generally good short-term stability of the VCO at high frequency offsets, with the in-band noise floor established by the phase detector and frequency dividers of the PLL itself.

Phase noise affects modulation accuracy and, like other impairments, contributes to EVM. In the display of a signal constellation, the impact of phase noise is evident as a circular distortion of the signal points about the center of the constellation, as shown in Figure 4. In this example, the resultant EVM is approximately –25 dB. At low data rates, integration over the symbol time removes the worst effects of short-term frequency instability, leaving only the residual contribution of the crystal oscillator's long-term instability. With the OFDM signals employed by 802.11a/g at the highest data rates, the effects of phase noise are somewhat mitigated by using the pilot tones at the receiver to track phase variations of the signal. As long as the phase variations are relatively slow with respect to the symbol rate, they can be tracked and compensated.

Excessive phase noise must be eliminated, however, and may be symptomatic of various implementation problems such as a noisy crystal oscillator, spurious signals due to noisy power supplies or insufficiently shielded activity on the circuit board, incorrect signal levels of the reference crystal oscillator into the frequency synthesizer or at the mixer, or other design or manufacturing issues. Inspection of the phase noise power spectral density (PSD) is the best way to identify excess phase noise as the source of poor EVM. Certain single-instrument testers with VSA capabilities such as LitePoint's IQview can perform phase noise analysis of the modulated WLAN signal. For example, Figure 5 shows the phase noise power spectral density for a signal corrupted by leakage of low-frequency noise into the synthesizer's reference signal, where the red line indicates the spectral density that would normally be expected.

Spurious signals and transient effects

Before an 802.11a/b/g design is fit for volume production, the implementation must be free of spurious signals and transients that adversely affect the transmitter performance. As discussed previously, the reference crystal oscillator and frequency synthesizer VCO are particularly sensitive to noisy power supplies, direct current to direct current (dc-dc) converter switching noise, or unshielded signals. Coupling between such spurious signals and the crystal or VCO can introduce phase noise, degrading the transmitted signal.

Transient effects that degrade transmitter performance can be especially difficult to isolate and identify. For example, the RF power amplifier is generally switched on and off with each burst of WLAN communications in order to minimize power consumption. When the power amplifier is enabled before a burst, the amplifier will start drawing significant current and may cause a drop in the power supply voltage or induce a ground current. Unless these effects have been fully decoupled from the rest of the board, they can affect the crystal oscillator or frequency synthesizer, introducing transient frequency errors and phase noise that momentarily degrade the transmitted signal. Such frequency pushing caused by power amplifier turn on and the oscillators' sensitivity to supply voltage can have different impacts depending on its duration. As shown in Figure 6, frequency pushing of the synthesizer's VCO will generally settle quickly, recovering within microseconds, while frequency pushing of the crystal will settle slowly, recovering within tens of microseconds.

The 802.11b/g standard requires initial transmission of either a

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short or long preamble, with the short preamble being 72 µs in duration and the long preamble being 144 µs. The 802.11a/g standard, by contrast, requires initial transmission of first 10 repetitions of a short training sequence totaling 8 µs followed by two repetitions of a long training sequence totaling another 8 µs. Slow-settling transient frequency errors can disrupt 802.11a/g signals and can adversely affect even the low data rates supported by 802.11b/g. But even fast-settling transmit frequency errors can affect performance if a particular receiver design bases its estimate of the transmit frequency on the first few microseconds of the received preamble.

Realizing that such transients are occurring, however, can be difficult, and one may not happen to inspect the signal's frequency error vs. time at all stages of the design process. Some test instruments such as, for example, IQview, allow the calculation of EVM for OFDM signals to be based upon frequency estimation of either the short training sequence, the long training sequence or the full packet—if the resultant EVM values vary significantly, then it is a clue that the transmit frequency may be subject to transient errors.

Effects of signal compression

To minimize power consumption and operate at the highest efficiency, an RF power amplifier is ideally operated close to its saturation point. Unless the average output power of the power amplifier is reduced (backed off), however, different modulation types can push the amplifier into its saturation region, compressing the signal. The non-linearity associated with amplifier saturation can then lead to harmonic distortion, intermodulation distortion and spectral regrowth, cross modulation, SNR degradation, and modulation inaccuracy. The degree to which the signal can be compressed reflects a trade off between power consumption and signal quality that directly affects product cost and quality. With too much compression, the transmit signal quality will be degraded; with too little compression, a more expensive RF power amplifier will likely be required in order to achieve the desired average output power.

The single-carrier M-ary phase-shift-keying (M-ary PSK) signals employed by 802.11b/g can typically be operated in compression up until spectral regrowth introduces adjacent channel interference or violates the required spectral mask. Measurement of the RF output spectrum with a spectrum analyzer can quickly reveal such effects. For such signals, compression generally does not affect the measured EVM to the point where it exceeds the value specified by the standard or significantly affects BER performance. The multicarrier OFDM signals employed by 802.11a/g, however, generally require a greater degree of amplifier back off because of their high peak-to-average power ratio (PAPR). The operating point of the power amplifier must be reduced so that the OFDM signal's input voltage excursions do not bring the amplifier into saturation and induce intermodulation and spectral regrowth effects that adversely affect the OFDM signal's 52 subcarriers.

The degree of compression can be most readily assessed using signal analysis software such as provided by IQview to calculate the complementary cumulative distribution function (CCDF) of the transmit output power. After statistical processing of the measured signal, a CCDF curve provides an estimate of the probability of the signal being at or above a given power level, expressed in dB relative to the average power.

To optimize power consumption, however, some degree of compression is desired. Assuming that all other sources of modulation inaccuracy have been moderated, transmit power levels can be calibrated so that the measured EVM value is within a desired tolerance. This step is typically the last production-line calibration to be performed. A single-instrument test device like IQview that can quickly measure EVM for all 802.11a/b/g signals is extremely useful, especially when employed as part of a PC-controlled manufacturing test suite that can automatically set the appropriate controls and levels in the baseband chipset and RF section to calibrate the output power to its optimum value.

Conclusion

The capabilities of a VSA, spectrum analyzer, and power meter in combination with advanced signal analysis software can simplify the optimization of 802.11a/b/g WLAN transmitters. Whether employed as part of the design process or on the manufacturing floor, the ability to rapidly assess EVM and other measurements in the time, frequency, and modulation domains can shorten design cycles, improve manufacturing yields, and directly contribute to overall product quality and profitability. RFD

ABOUT THE AUTHOR

Christian Olgaard is vice president of engineering and a co-founder of LitePoint Corporation, in San Jose, Calif., creators of advanced wireless test solutions. Dr. Olgaard has extensive design experience using CMOS and BiCMOS technologies for RF ICs and mixed-mode systems. He received his Ph.D degree in Electrical Engineering from the Technical University of Denmark, holds six patents related to wireless systems and circuits, and has applied for nine more wireless system patents.

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