Agilent
Equalization Techniques and OFDM Troubleshooting for Wireless LANs

Application Note 1455

Abstract

OFDM (orthogonal frequency-division multiplexing) signals used in 802.11a and 802.11g wireless LAN systems include provisions for equalization in the receiver to correct for some types of system and channel impairments. These features can be used by test engineers to find the source of system problems and to improve measurement performance. This note describes these equalization features and their use in analyzers or measuring receivers. It also describes other features of the OFDM signal and corresponding analyzer capabilities, which are useful complements to equalization.

The discussions and measurements described here apply most specifically to the Agilent 89600 Series vector signal analyzers and their wireless networking measurement software. This software provides the industry's most comprehensive and flexible set of capabilities for signal analysis and troubleshooting. Many of those capabilities will be discussed here in terms of how they can be used together to make the highest quality measurements and yield the most powerful insights into signal or system problems.

Introduction

Like many digital communications signals, the OFDM wireless LAN standards 802.11a and 802.11g include specific provisions for adaptive equalization in the receiver. This equalization improves receiver performance by correcting for linear errors or impairments such as amplitude and delay distortion. These errors can arise from phenomena such as multipath in the signal path between the transmitter and the receiver, or by frequency response problems in the transmitter circuits.

This adaptive equalization is particularly useful for broadband signals such as those used in OFDM wireless LAN standards, where the channels are nearly 20 MHz wide and the opportunity for frequency response problems is correspondingly greater than that for more narrowband signals.

The equalization features required by these standards can also be used by measuring receivers (such as Agilent's vector signal analyzers) to identify the source of transmitter problems, as the measuring receiver can be configured to calculate and perform the adaptive equalization in different ways, and to explicitly display the results of the equalizer calculations or corrections.

The discussions here apply in general terms to the use of equalizer tools for troubleshooting, but specifically to the Agilent 89600 Series vector signal analyzers, as they have the most flexible and comprehensive set of features for demodulation and other types of signal analysis.

Equalizer Features in the OFDM Signal

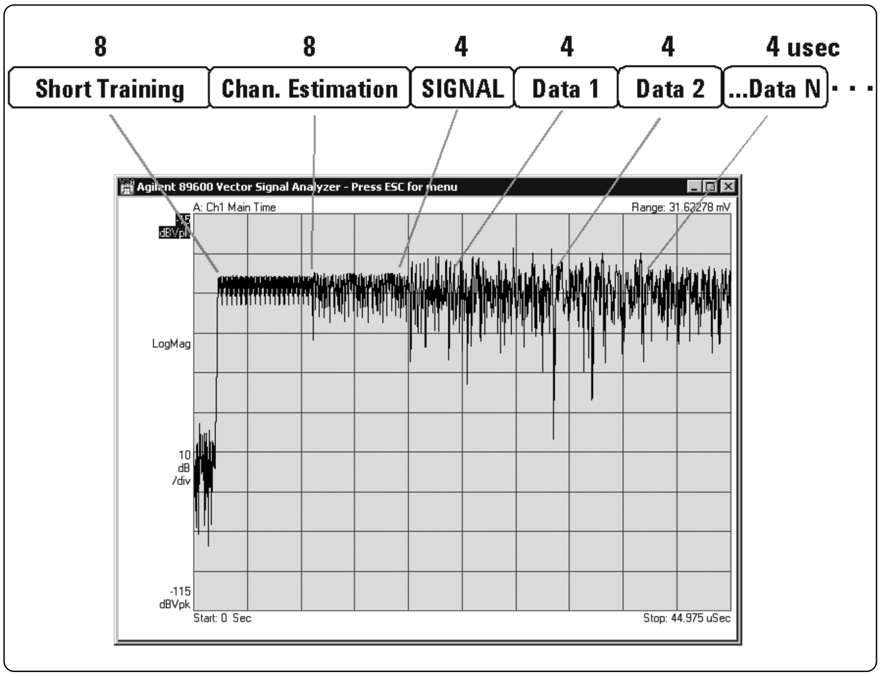

Figure 1. Structure of an OFDM burst or frame

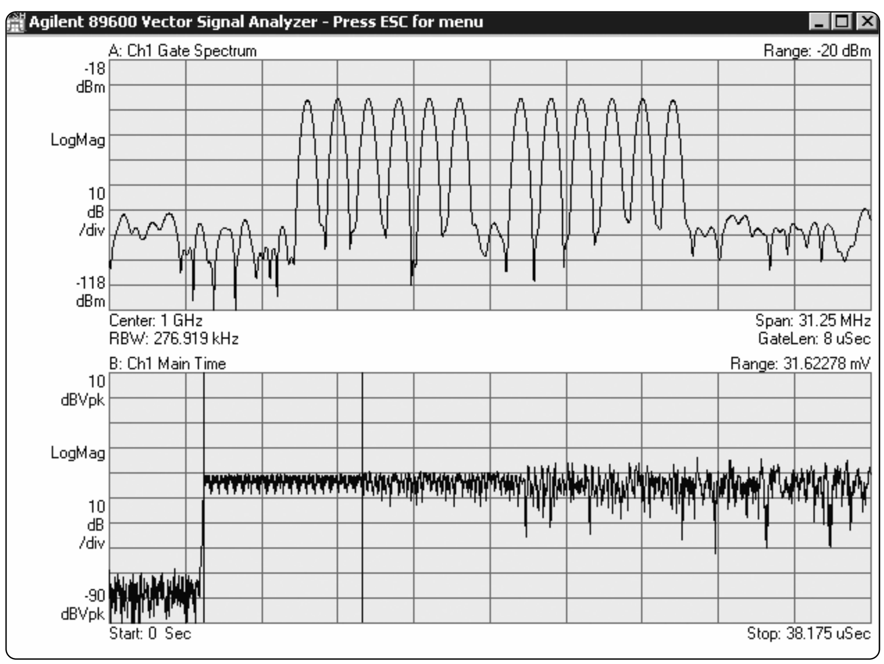

Figure 2: Gated spectrum measurement of carriers in short training sequence

As shown in Figure 1, the preamble of the typical OFDM burst is composed of two double-length (8 microseconds instead of 4) symbols followed by a 4 microsecond “signal” symbol.

The first of the two double-length symbols is called the short training sequence, and a gated spectrum measurement of this part of the signal is shown in Figure 2. For this sequence the transmitter sends only every 4th carrier—a total of 12 carriers out of the total set of 52. The carriers are transmitted with a common phase and all at the same amplitude. The simplicity of this signal makes it easier for the receiver to perform coarse signal acquisition and timing synchronization, and to adjust its gain.

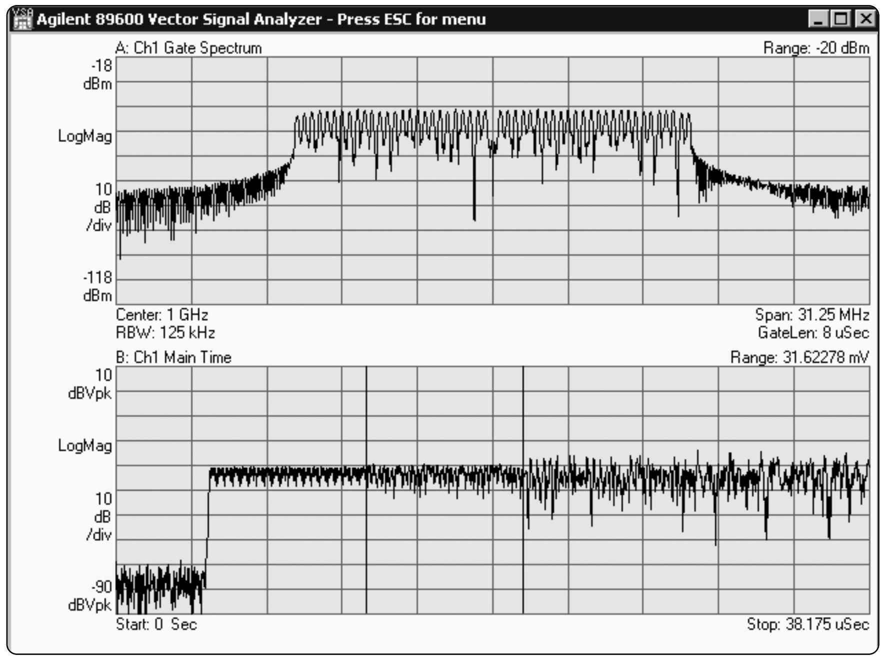

Figure 3: Gated spectrum of carriers in channel estimation sequence

The second double-length symbol is called the channel estimation sequence, and a gated spectrum measurement of this part of the signal is shown in Figure 3. For this sequence the transmitter sends all 52 carriers. Once again, the carriers are transmitted with a common phase and all at the same amplitude. This is the primary training sequence for the equalizers in OFDM receivers. It also allows the receiver to precisely track the frequency and phase of the transmitter, a task which is critical for preventing inter-carrier interference between the closely-spaced and overlapping OFDM carriers.

The gated spectrum measurement in Figure 3 represents very fine frequency resolution compared to the relatively short (8 microsecond) gate time. This measurement was produced by taking advantage of specific features of the signal and the 89600 analyzer, including the periodicity of the sequence in the gate window (set exactly at 8 microseconds), and ability of the 89600 to use a “uniform” FFT window, which is designed for self-windowing signals or those that are periodic in the selected gate time period. This combination provides the greatest possible frequency resolution for a given time record (gate) length.

This measurement demonstrates one aspect of equalization. Analysis of the 52 signal peaks allows measurement of the amplitude flatness portion of the frequency response of the transmitter + channel combination. This frequency response can then be inverted and multiplied by the incoming signal to correct for these frequency response problems.

The signal symbol that follows these training sequences is a normal (4 microsecond) symbol, always transmitted as BPSK. This symbol contains information on the data rate of the burst, the modulation format, and the signal coding to be used.

The Agilent 89600 Series analyzers decode the information in this symbol and use it to automatically configure their demodulators for the correct modulation type (which may change from burst to burst) and burst length.

Training Sequence Types and Training/Adaptation Methods

In most systems the training sequences are composed of digitally modulated signal sequences at a specific time in a burst or frame, and where the bit sequence to be transmitted is already known to the receiver. Generally, the modulation type and symbol rate are the same as those of the rest of the digital transmission. These are not absolute requirements however, and system architects may make other choices for a variety of reasons. Many different types of training sequences could be used, so long as the receiver knows (or can determine) what the signal should look like, and as long as the sequence provides sufficient energy at the frequencies of interest. That is, the training signal must properly “exercise” the transmission channel.

The use of an explicit training sequence is not the only way for a receiver to compute equalizer coefficients. In some cases the transmitted data itself can be analyzed to determine the characteristics of the transmitter and the transmit channel. This technique is sometimes called “data-directed” equalization.

For some systems, data-directed equalization in a receiver provides useful advantages. In general, the quality of the calculated equalizer coefficients is better if more data is used to calculate them. Specifically, if signal variance due to noise is the primary mechanism limiting the quality of the calculations, the noise in the received signal that impairs the ability of the receiver to calculate coefficients is proportional to the square root of the number of independent samples of data in the training sequence. For example, using 25 data symbols from a burst would be significantly better than using the one double-length symbol (the channel estimation sequence in this case), as the noise variance would be 3.5 times less.

There are disadvantages to this technique, however. Two are worth note here: First, it is more difficult (more computationally intensive) to determine equalizer coefficients based on a larger block of data symbols, whose sequence is not known beforehand. This computational load may be more than a system can bear, or the return may not be worth the costs. Second, the ability of a receiver to (at least approximately) calculate equalizer coefficients in poor transmission conditions where there are many bit errors is much greater when the receiver has prior knowledge of the training sequence.

These training sequence techniques may, of course, be combined or used selectively, depending on conditions. For OFDM signals, the 89600 Vector Signal Analyzers have the ability to train on the channel estimation sequence or on the entire burst, and the benefits of this flexibility are described later in this note.

Equalizer Activity in 802.11a/g OFDM Receivers

As in all techniques of this kind, time spent transmitting the training sequences means less time is available to transmit data. The decision about what features to include in the transmitted signal presupposes (in general terms) the likely impairments of the signal and the techniques that would be employed in receivers. However while the standard constrains the characteristics of the transmitted signal relatively closely, the designer of receivers has considerable freedom in how the signal is handled and how features such as training sequences are used.

The estimate of the likely impairments in the signal includes the degree and type of impairment, and also its dynamic nature. The training sequence must be transmitted often enough to track changes in the transmit channel (changes in delay paths, for example). The training sequence must also be transmitted in close proximity (in time) to the data that is to be corrected, so that the channel characteristics do not change significantly from those valid at the time the training sequence is transmitted. In some systems the training sequence is transmitted in the middle of data bursts or frames, to correct approximately equally the data before and after the training sequence. In 802.11a and 802.11g OFDM signals, however, the bursts are short, generally less than 1 ms in length, and the transmit channel characteristics are expected to be relatively constant during this time. Therefore transmitting the training sequence approximately once per burst is adequate to correct the data of the entire burst.

In 802.11 OFDM systems it is generally assumed that the equalizer coefficients will be calculated once per frame or burst, without reference to the coefficients from prior frames. Frame-to-frame memory in the tuning of equalizer coefficients could provide more data to allow better tuning of equalizer coefficients and while it is not prohibited by the standards, it is not known to be employed at this time.

For these systems it is generally assumed that practical receivers calculate equalizer coefficients based on the channel estimation sequence, and do not use the payload data in the burst. As with burst-to-burst memory, data-directed equalizer training is not prohibited, but not known to be employed at this time.

Equalization vs. Pilot Tracking

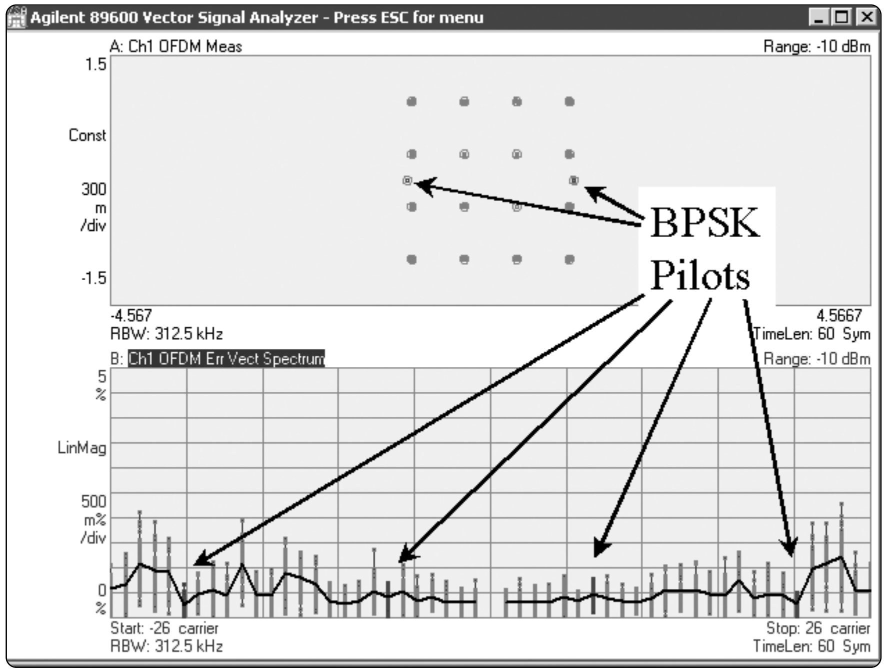

Figure 4. Location of the 4 BPSK pilots

For effective troubleshooting it is important to distinguish between the intended role of equalization and that of pilots in the transmitted signal along with the corresponding pilot tracking in receivers. The pilots are composed of four of the 52 OFDM carriers and are always transmitted with BPSK modulation. These pilots are used, in part, to create a continuous series of amplitude and phase references throughout the data frame. Demodulation is then performed relative to these pilot carriers and this allows some kinds of signal impairments to be corrected continuously throughout the burst. This use of pilots in demodulation is called pilot tracking, and errors or impairments common to all pilots are collectively called Common Pilot Error or CPE.

As with equalization, some of the theoretical capacity of the system is displaced by information used to improve the transmission of the data itself. Four carriers which might otherwise be used to carry payload data are used as an aid to demodulation in adverse conditions.

In contrast to equalization, which primarily corrects for frequency-dependent errors, pilot tracking primarily corrects for time-varying errors. For example, once the frequency reference of the receiver is set by the signals in the preamble, pilot tracking algorithms can continuously adjust the receiver phase reference to “track out” phase noise. The same is true for amplitude errors, where the receiver ALC is set during the preamble and time-dependent amplitude changes due to thermal effects or droop are tracked out during the rest of the burst.

Pilot tracking and adaptive equalization are designed to work together in the receiver, and to be complimentary, enabling the use of denser constellations and thus yielding higher data rates. These features also work together in analyzers such as the 89600 Series, providing important signal information and troubleshooting options as described below.

More information on equalization and pilot tracking is contained in the references at the end of this note.

Signal Analysis and Troubleshooting Using Equalization

In the design, troubleshooting, and evaluation of systems such as these, it is important to understand at the outset the goal of the measurements. This goal will determine which kinds of analysis are performed, which analyzer settings are used, and how trade-offs will be made. Some examples of measurement goals include:

- Emulate a receiver and interpret signal quality in the same way that the receiver would
- Get a system working and/or find broken parts or undesirable interactions
- Identify the cause of problems and use the information to improve system performance
- Evaluate the distortion performance of individual system elements such as amplifiers, oscillators and modulators

The role of signal analyzers

In general terms, signal analyzers such as the 89600 Series vector signal analyzers are intended to measure signal quality and to help find problems. In complex systems, there are many different types of analysis they can do, and different ways they can process the signal. It might be assumed that they should measure signal quality as accurately (with as much resolution and smallest error added) as possible, or that they would emulate real receivers, or that they would interpret signal characteristics in the way that would most clearly reveal the source of problems. They can, in fact, perform all of these functions, but the techniques used and setup configurations will be somewhat different, depending on the assumptions.

Important analyzer features for these measurements

Several features of vector signal analyzers such as the 89600 Series are important for equalization-related measurements and troubleshooting.

- Highly adjustable demodulation and equalization parameters — The different results obtained through changes in analysis techniques and setup parameters can provide important clues to the nature and source of problems.
- Time capture and replay capability — When analysis techniques and setups are changed it is vital to be able to assume that the change in measurement results (if any) is due to the analysis changes and not to a signal whose characteristics have changed between measurements. Time capture and replay for post-processing enable a signal to be consistently presented to the analysis routines and techniques as they are changed. This capability is especially important for pulsed or bursted signals, and where there may be variations in signal characteristics from burst to burst or from frame to frame, especially if such variations are not expected or desired.

- Setup changes without taking new data — For many demodulation setup parameters, the 89600 Series allows changes and immediately recalculates results based on the new setup. If multiple changes are to be made to the analyzer setup during analysis, this reduces overall analysis time significantly. There is no need to perform new signal capture operations or to restart signal playback for post-processing. Examples include changes in equalization training, synchronization references, pilot tracking type (amplitude, phase, timing), measurement interval, etc.
- Flexible equalization training — As described above, there are different approaches for training equalizers in receivers. Described below are techniques for employing these different approaches to provide better quality measurements (ones that better match user needs and goals) or measurements which more specifically identify the source of problems.

Using the vector signal analyzer for analysis and troubleshooting

In all digital demodulation measurements it is important to begin by verifying the basic characteristics of the signal in terms of frequency, power, and timing. See the resources at the end of this note for information on verifying the signal's frequency and burst structure, and troubleshooting using this information. Many problems with digitally modulated signals are identified without using digital demodulation.

Consider using the analyzer's time capture capability wherever possible, to capture a burst or bursts for further analysis. A specific sub-segment of captured data can be identified for repeated post-processing, ensuring comparability of results between changes in demodulation parameters. The analyzer's channel amplitude (magnitude) triggering, pre-trigger delay, and trigger holdoff can be used to make sure that the beginning of the burst (and any signals that precede it) are available for analysis. After time capture, the playback trigger function can perform similar functions on the captured signal.

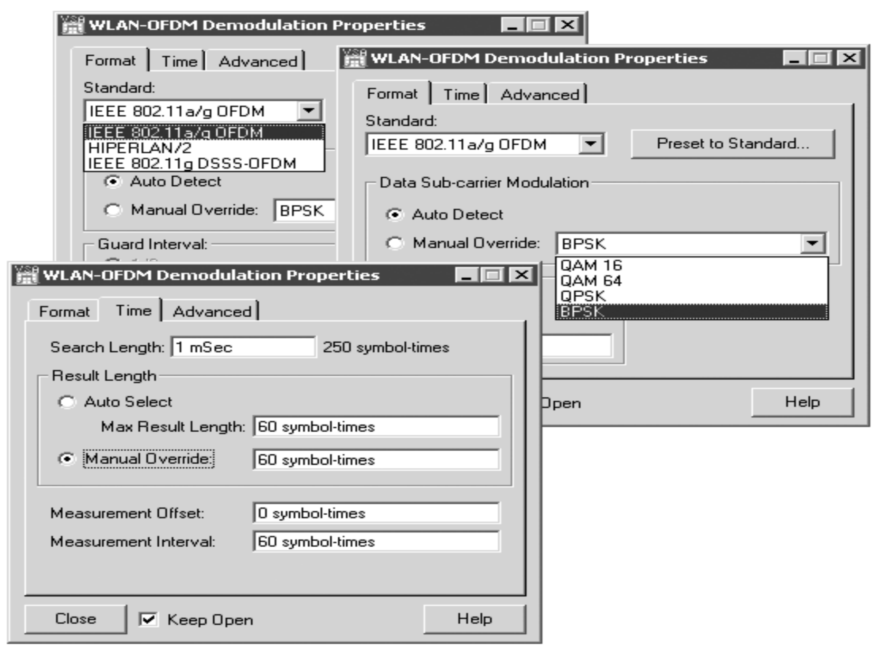

Figure 5. Selecting standard setups, modulation types, and measurement interval

Take advantage of the automatic demodulation setups in the analyzer by selecting “Meas Setup” and “Demod Properties...” See the examples in Figure 5. Note that the data sub-carrier modulation type can be set manually, but is usually set automatically by the 89600 from the information in the signal symbol described above. Similarly, the measurement interval (under the “Time” tab) is also set automatically and can be specifically identified if desired.
In the same demodulation properties dialog box, select the Advanced tab, and in the Equalization Training box choose “Chan Estimation Seq Only.” This will direct the analyzer to compute equalizer coefficients using only the channel estimation sequence, much as an actual OFDM receiver would do.

Examine various measurement results by selecting the appropriate Trace Data and Data Format settings. In particular, note the EVM in the Symbol/Errors table and the Channel Frequency Response (typically displayed with a format of Log Magnitude or Unwrapped Phase) as shown in Figure 6.

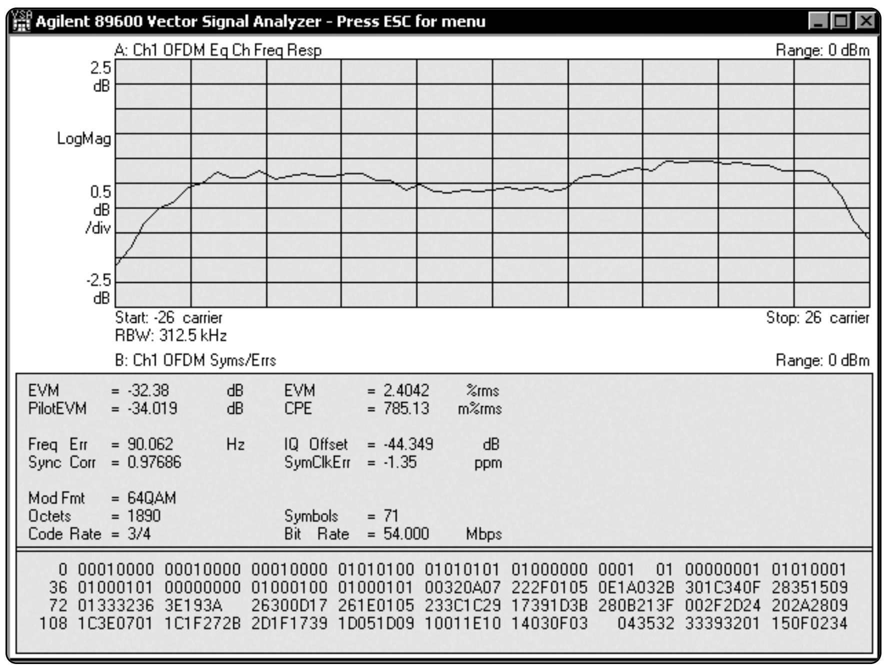

Figure 6. Channel frequency response from equalizer (top) and symbol/errors table (bottom), including EVM. Equalizer was trained using the channel estimation sequence only.

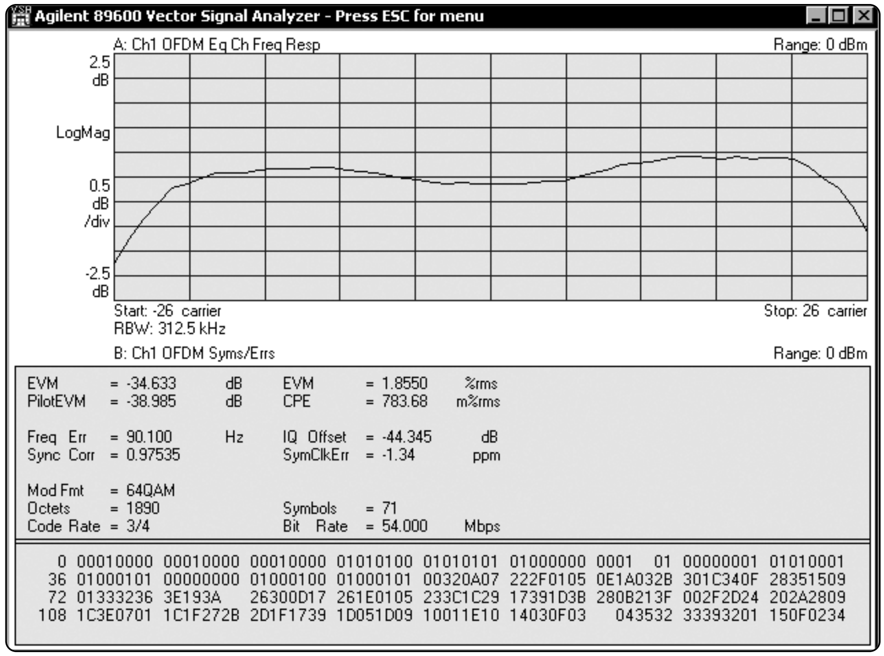

Figure 7. Channel frequency response (top) calculated by training equalizer on both channel estimation sequence and burst data

It is often instructive to make continuous measurements of parameters such as Equalized Channel Frequency Response while changing the Equalizer Training to Channel Estimation Sequence & Data and back to Channel Estimation Sequence Only. The effect of noise in the signal will make the equalizer coefficients (represented by the EQ Channel Frequency Response) similarly noisy, and this response will vary more on a burst-to-burst basis when only the channel estimation sequence is used. You may also want to compare the EVM using the two different techniques.

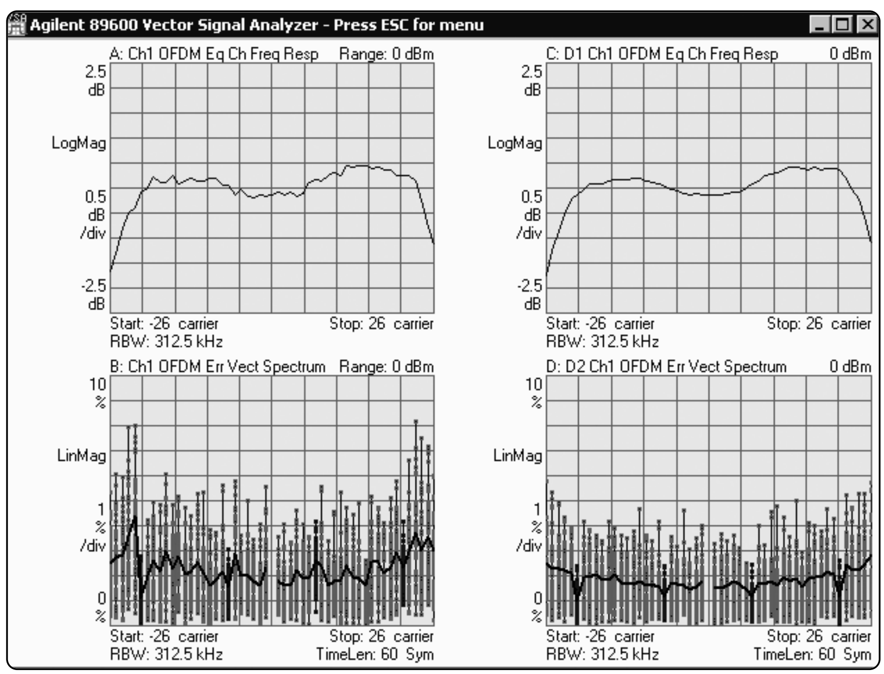

Figure 8. Channel frequency response (from equalizer) and EVM vs. frequency, with the equalizer trained on the channel estimation sequence (left) and on the channel estimation sequence + data (right)

Measurements such as these will give you insight into signal quality as a receiver would see it, and the role of noise in the quality of the equalization. In Figure 8 these effects, though slight (the signal is a very clean one) are apparent. The use of a greater amount of data (channel estimation sequence and all frame data) to train the equalizer provides a smoother frequency response for the channel and for EVM, and the EVM itself is lower.

If the equalization coefficients are well behaved and the channel frequency response is stable from burst to burst, the choice at this point is simply between which equalization training sequence better serves the goal of the measurement. Using the channel estimation sequence better predicts real receiver performance, while using the entire OFDM frame produces a measurement with lower error. However if problems are found in the signal and the equalization is suspect, other tools in the 89600 OFDM demodulation software should be used. Here are some examples:

- Error Vector Spectrum — Spurious interference can interfere with calculation of equalization coefficients, and error vector spectrum measurements offer great sensitivity to low-level spurious within the channel. Error vector measurements are essentially residual measurements, where the desired signal is removed, clearly revealing distortion and noise.
- Error Vector Time — Some signal impairments are impulsive, transient or otherwise time-related. Examining the error vector signal vs. time in terms of amplitude or phase can help reveal disturbances that can cause poor equalizer function, including large variations from burst-to-burst.

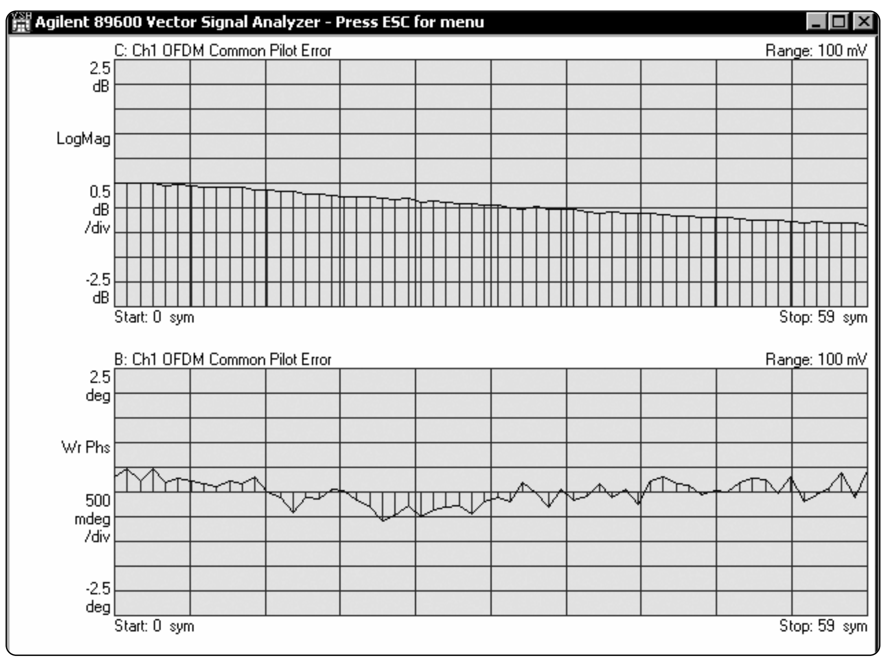

Figure 9: Common pilot error (CPE) measurements of amplitude (top) and phase (bottom) error vs. time or symbol

- Common Pilot Error—Since the demodulation of the signal is relative to the pilots and the demodulator is designed to “track out” certain types of errors, examination of the various CPE parameters can isolate specific problems during the burst. This error is shown vs. time or symbol, and can show amplitude, phase, and frequency errors anywhere in the burst.

- Preamble error—Preamble error and preamble frequency error can provide detailed visibility of signal quality and stability during this critical portion of the OFDM frame, as shown in Figure 10. These measurements are unusual, in that they measure a portion of the signal outside of the digital demodulation interval, while digital demodulation is performed only within that interval.

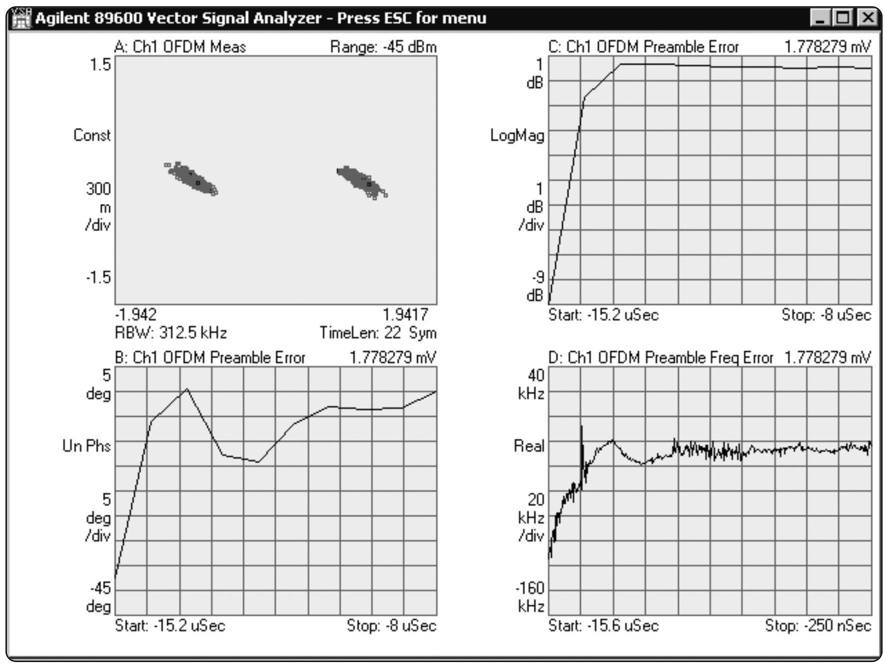

Figure 10: Preamble error measurements of the short training sequence, including phase error (lower left), magnitude error (upper right) and frequency setting (lower right)

Which Equalizer Training Technique is the "Right" One?

While there is no single "right" answer for all situations, an understanding of the measurement goal will usually point to the best technique. See "Summary of the Benefits of the Different Equalizer Training Techniques" for an overview. In general, the main choice is between a technique designed to reflect the performance of real receivers (using the channel estimation sequence), and a technique which provides the least residual error and most consistent results (using the entire OFDM frame).

Summary of the benefits of the different equalizer training techniques

Using the channel estimation sequence

- Provides measurements which are better indicators of signal quality as a receiver would see it
- Limited length and specific location of the training sequence can help isolate problems such as transients or settling problems during the preamble
- Complies with the description in the "Transmit Modulation Accuracy Test" (Section 17.3.9.7 of the 802.11a standard)

Using the entire burst (including data symbols)

- The EVM is typically lower because the equalizer is less impacted by noise and some other forms of distortion. (EVM represents the error due to noise, non-linear distortion, spurious, and residual linear distortion.). This lower residual error can provide better sensitivity in measuring low-distortion signals such as when evaluating incremental error in power amplifiers.
- The equalizer coefficients typically reflect the linear channel impairment with greater accuracy, as the data set used to train the equalizer is larger and is less affected by turn-on transient effects in the burst.
- EVM measurements are often more stable burst-to-burst, due to the averaging effects of the larger training data set.

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Useful URLs

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