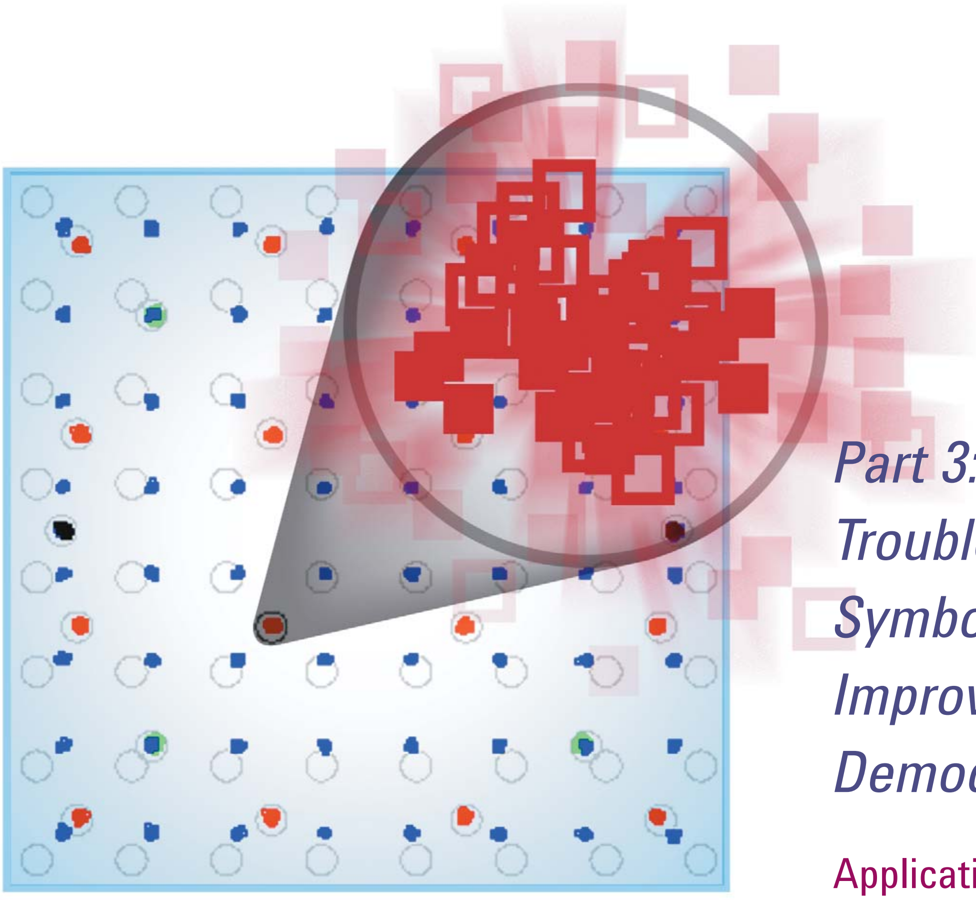
# Agilent WiMAX Signal Analysis



## *Part 3: Troubleshooting Symbols and Improving Demodulation*

Application Note

Agilent Technologies

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## Introduction

This application note is intended for engineers who are familiar with the IEEE 802.16-2004 (WiMAX) physical layer standard and wish to improve their measurement understanding and capabilities using a vector signal analyzer (VSA). This note will provide information on how to improve WiMAX signal analysis and includes measurement tips when designing and troubleshooting a new or an existing product. In order for the RF engineer to successfully test and troubleshoot a WiMAX device, a well-organized approach to the signal analysis will yield the greatest level of understanding and reliability in the measurement. This application note is one part in a series that provide the framework for the preferred measurement approach that includes frequency and time measurements, digital demodulation, and analysis of the advanced functionality within the WiMAX physical layer definition. If you are familiar with the 802.16-2004 standard but not necessarily familiar with WiMAX measurements, you may find reading all the application notes in this series very useful for expanding your knowledge of testing and troubleshooting this complex signal. For the engineer that is relatively new to the 802.16-2004 standard, a brief review of the standard will be provided which includes many technical references for those wishing to gain additional background into the IEEE standard and OFDM structure of the WiMAX physical layer.

## Reviewing the WiMAX physical layer

The IEEE 802.16-2004 [1] and 802.16a-2003 standards, often referred to as WiMAX, define the physical layer (PHY) and medium access control (MAC) protocol that define products that extend broadband wireless access (BWA) from the local area network (LAN) to the metropolitan area network (MAN). These standards contain specifications for licensed and unlicensed BWA operating between 2 and 11 GHz. Initially licensed operation will cover the frequency ranges from 2.5 to 2.69 GHz and 3.4 to 3.6 GHz and unlicensed operation will use 5.725 to 5.850 GHz. In order to address the international wireless market and regional spectrum regulations, the WiMAX standard includes varying channel bandwidths. The channel bandwidths are selectable from 1.25 to 20 MHz. The 802.16-2004 standard, sometimes referred to as 802.16d, includes minor improvements over the earlier 802.16a-2003 standard. The 802.16-2004 standard also provides system profiles that can be used for product compliance testing. These profiles include minimum performance requirements for such parameters as transmitted power level, adjacent channel rejection, dynamic range, and bit error rate (BER). This application note will review signal analysis and measurement techniques relative to the 802.16-2004 standard.

The need for inexpensive and flexible commercial deployment of this technology has driven the requirement for multiple user access under non-line-of-sight (NLOS) operation and over distances up to 30 km. The 802.16 specifications define three different PHYs optimized for different wireless operation and conditions. These include a single-carrier modulation, a 256-carrier orthogonal frequency division multiplexing (OFDM) format and a 2048-carrier OFDM format. The current industry focus [2], and the heart of this application note, is on the 256-carrier OFDM format.

### OFDM subcarriers

The WiMAX specifications for the 256-carrier OFDM PHY define three types of subcarriers; data, pilot, and null. Two hundred carriers are used for data and pilot subcarriers. Eight pilot subcarriers are permanently spaced throughout the OFDM spectrum. Data subcarriers take up the remaining 192 active carriers. The remaining 56 potential carriers are nulled and set aside for guard bands and removal of the center frequency subcarrier [3].

### Modulation types

The IEEE 802.16-2004 standard defines a set of adaptive modulation and coding rate configurations that can be used to tradeoff data rate for system robustness under various wireless propagation and interference conditions. The allowed modulation types are binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), 16-quadrature amplitude modulation (16QAM) and 64QAM [3]. Pilot subcarriers always use BPSK modulation. During RF transmission, robust modulation types, such as BPSK and QPSK, are sent first followed by less robust modulation types, such as 16 and 64QAM.

## Duplexing techniques

The IEEE 802.16-2004 standard allows for a flexible burst transmission format with an adaptive frame structure within fixed frame durations. Duplexing is provided by means of either time division duplex (TDD), frequency division duplex (FDD), or half-duplex FDD (H-FDD) [3]. In licensed bands, the duplexing method shall be either TDD or FDD. FDD subscriber stations (SS) may use a H-FDD format. Unlicensed operation is limited to using the TDD format.

## Frame structure

A WiMAX frame consists of a downlink (DL) RF subframe (subframes are generally RF bursts) and an uplink (UL) subframe. The TDD frame consists of one DL subframe followed by one or multiple UL subframes. There are currently seven supported frame durations in the IEEE 802.16-2004 standard ranging from 2.5 to 20 ms. The flexible frame structure of the TDD signal consists of an adaptive boundary between the DL and UL subframes. A short transition gap is placed between the DL and UL subframes and is called the transmit/receive transition gap (TTG). After the completion of the UL subframes, another short gap is added between this subframe and the next DL subframe. This gap is called the receiver/transmit transition gap (RTG). The time durations of the transition gaps are called out in the 802.16 standard and are a function of the channel bandwidth and the OFDM symbol time [4].

## Preambles and FCH

The downlink subframe begins with two OFDM symbols used for synchronization and channel estimation at the Subscriber Station (SS). These two symbols together represent the preamble of the DL subframe and are referred to as the long preamble. The uplink subframe begins with one OFDM symbol that is used at the base station (BS) for synchronization to the individual SS. This single uplink symbol is referred to as the short preamble. The time duration of the long and short preambles are determined by the specified length of the OFDM symbol [3].

The long preamble of the DL subframe is followed by the frame control header (FCH), which contains decoded information for the SS. The FCH contains the Downlink Frame Prefix (DLFP) that specifies the modulation type and number of symbols associated with one or several downlink bursts that follow the FCH. The modulation and coding used in the first downlink burst immediately following the FCH is specified in the Rate_ID. The Rate_ID is a 4-bit code with values shown in Table 1. The Downlink Interval Usage Code (DIUC) is a 4-bit code similar to the Rate_ID and is used for identifying the profiles of the other bursts in the downlink or uplink transmission interval. The DLFP also includes an 8-bit Header Check Sequence (HCS), which is used to detect errors in the DLFP, and the Base Station ID (BSID), which tells the base station whether the associated data is registered to that system or not. The user data that follows the FCH contains one or more bursts of payload data. The burst is defined as an integer number of symbols using a particular modulation and coding rate. Figure 1 shows a measurement of a FCH using a vector signal analyzer. The lower right OFDM Subframe Info trace shows that the modulation type for the FCH is measured to be BPSK, which is also the modulation type specified in the IEEE 802.16 standard. This trace also shows that the measured BSID is 5 and the Rate_ID is 1. The Rate_ID of 1 corresponds to QPSK modulation using a 1/2 coding rate, which is used in the first data burst following the FCH.

**Table 1. OFDM Rate ID encodings**

| Rate_ID | Modulation / RS-CC Rate |
|---|---|
| 0 | BPSK1/2 |
| 1 | QPSK1/2 |
| 2 | QPSK 3/4 |
| 3 | 16QAM 1/2 |
| 4 | 16QAM 3/4 |
| 5 | 64QAM 2/3 |
| 6 | 64QAM 3/4 |
| 7-15 | reserved |

### OFDM symbol

The OFDM waveform in the frequency domain is created by the inverse Fourier transform of the OFDM symbol in time. The OFDM symbol of duration, Ts, includes the *useful* symbol time, Tb (Tb = 1 ÷ carrier spacing), and a prefix, Tg. The prefix, termed the cyclic prefix (CP), is a copy of the end of the symbol appended to the beginning. The guard interval, G, is defined as the ratio of the CP length to the useful symbol time (G = Tg / Ts). The IEEE 802.16-2004 standard specifies four ratios for the guard interval, 1/4, 1/8, 1/16, and 1/32 [4]. The guard interval is used by the receiver to collect multipath and improve system performance [1].

## Adopting the best measurement approach

It is often more useful to have a clear understanding of the signal and a reliable analysis approach than to know all the technical details of the standard. A well-organized measurement approach to WiMAX signal analysis will reduce setup and measurement errors, find problems at the earliest stages in the analysis, and provide the quickest path to complete troubleshooting of the WiMAX component or system. Measurement of the WiMAX signal is best accomplished with a vector signal analyzer (VSA) capable of measuring the RF and modulation quality of the digitally modulated signal. The measurement approach begins with basic spectrum and vector analysis using frequency and time domain measurements. Once the basic spectrum characteristics, such as center frequency, span, and amplitude have been verified, digital demodulation can be applied to the subframe of the WiMAX signal under test. Additional analysis and troubleshooting can be accomplished using digital demodulation of single OFDM subcarriers or symbols. Some of these measurement techniques take advantage of specific characteristics of the WiMAX signal, including built-in equalization and pilot tracking.

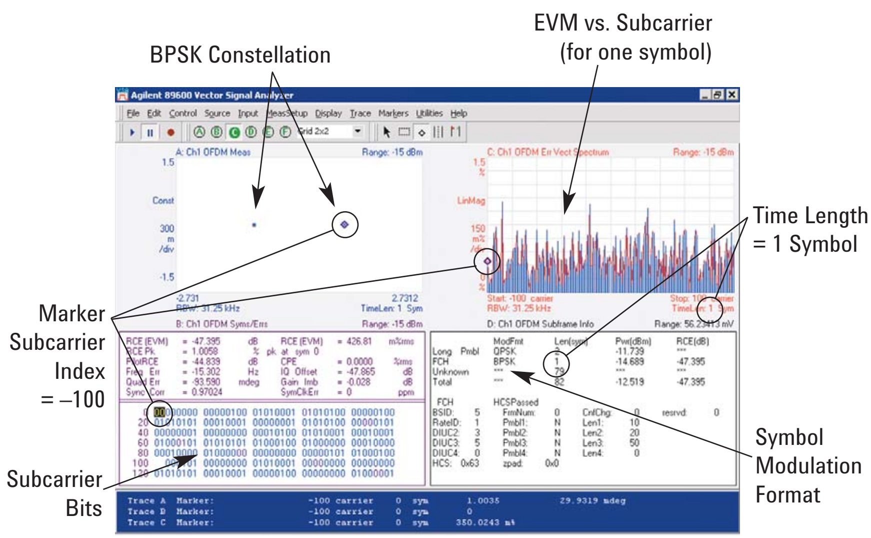


Figure 1. Time-selective demodulation of the single FCH symbol from a downlink subframe. Coupled markers placed on the frequency subcarrier with index –100 show the IQ value (upper left), demodulated bits (lower left), and EVM (upper right) for this subcarrier.

## Demodulating Specific Time and Frequency Intervals

Time and frequency (vector) analysis of a WiMAX waveform can be easily performed using a vector signal analyzer such as the Agilent 89600 VSA [5]. These analyzers are capable of demodulating the RF burst and measuring the signal quality in multiple domains including subcarrier frequency and symbol-time [6]. In addition, the VSA can be configured to demodulate specific subcarriers and symbols within the WiMAX subframe. The demodulation of specific elements within a subframe is a powerful troubleshooting tool for finding problems that may be too subtle or complex to uncover using the basic demodulation mode available in the VSA. Analysis of specific time and frequency intervals can also provide isolation of signal errors or impairments within the complex structure of the WiMAX waveform.

### Analyzing specific time intervals

Demodulation of specific time intervals within the WiMAX subframe is a powerful analysis and troubleshooting tool. This technique can be used to identify impulsive, intermittent, or periodic sources of errors. Demodulation of a specific symbol or group of symbols is accomplished by specifying two measurement parameters on the 89600 vector signal analyzer. These parameters, named the Measurement Offset and Measurement Interval, allow OFDM analysis over a specific time interval within the measurement time span. The measurement time span is called the Result Length and is defined as the total number of symbol-times included in the acquired and demodulated data [6]. The Measurement Offset, specified in symbol-times, determines the start position of the measurement analysis with respect to the first symbol following the preamble. The Measurement Offset must be equal to or less than the Result Length value minus one. The Measurement Interval specifies the time length (in symbols) that is used for the analysis. The Measurement Interval is also entered as a value in units of symbol-times.

The total combined length of the Measurement Offset and Interval must be less than or equal to the Result Length. Figure 2a shows an illustration of the relationship between the preamble, Result Length, Measurement Interval, and Measurement Offset. As shown in the figure, the RF burst contains the entire subframe pulse consisting of the preamble and Result Length. The Measurement Offset shows the starting point for the analysis relative to the preamble and the Measurement Interval defines the segment of time that is used during the VSA analysis.

The values for Measurement Offset and Measurement Interval are entered using the Demodulation Properties dialog on the lower portion of the Time tab in Figure 2b. In this example, the offset is set to 5 symbol-times and the interval is set to 3 symbol-times. In this case, the measurement analysis will begin with the sixth symbol following the preamble and the displayed results will cover a total of three symbols. Note that the indexing for the Measurement Offset begins with zero, which specifies the first symbol following the preamble. Entering the value for Result Length is also performed on this menu. Additional details concerning the Result Length configuration can be found in the 89600 VSA help menu [8] or using the additional references listed at the end of this application note [6,7].

A unique feature of the 89600 VSA allows the user to change any of the settings on the Demodulation Properties Menu, including the Measurement Interval and Offset, without the need to acquire new measurement data. For example, when changing the time interval or offset, the analyzer re-computes the trace results using the existing measurement data. This feature will allow the user to scroll along the measured subframe in order to verify and troubleshoot each specified time segment within the measured waveform.

The flexibility of isolating specific time intervals within the subframe allows for analysis of the various modulation formats used in the FCH and data symbols. As demonstrated previously, Figure 1 shows a multi-trace display of the FCH symbol contained in a DL subframe. Knowing that the FCH is the next symbol following the preamble, the instrument is configured with a Measurement Offset equal to zero and a Measurement Interval of length one symbol. The Constellation trace (upper left) in Figure 1 shows the proper BPSK modulation as expected for a FCH. The constellation shows the response for all 200 subcarriers included in this one OFDM symbol.  Note that this constellation trace also includes the eight BPSK pilot subcarriers that are overlaid on the FCH data points. The Error Vector Spectrum trace is also shown in Figure 1 (upper right) and displays the magnitude of the vector errors across all of the 200 subcarriers contained in this one OFDM symbol. Included in this trace are the EVM values for the eight pilot subcarriers denoted by a different color on the display. If there are specific subcarriers within this symbol that require a closer inspection, markers can be placed on the individual traces and coupled together for an in-depth analysis of any single subcarrier.  Coupled markers allow coordinated movement of the markers among the various traces that use the same x-coordinate. In Figure 1, markers placed on the Constellation, Error Vector Spectrum, and Symbols/ Errors (lower left) traces will track each other as they are moved along the various OFDM subcarriers. This feature allows the user to place markers on peak errors on one trace and observe the same data point using other trace formats.

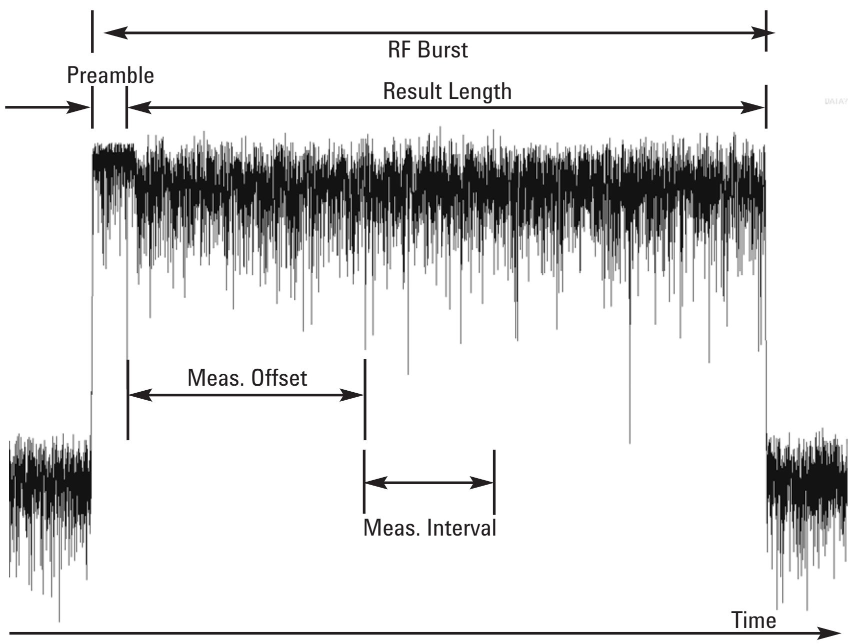


**Figure 2a. RF envelope of an OFDM subframe showing the relationship between Measurement Offset and Measurement Interval to the Preamble and Result Length.**

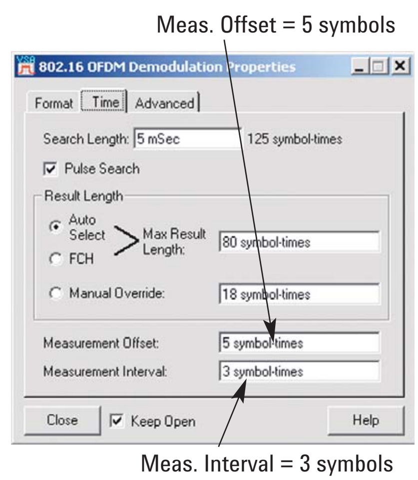


**Figure 2b. Demodulation Properties dialog on the 89600 VSA showing values entered for Measurement Offset and Measurement Interval.**

Using the 89600 VSA software, it is also possible to select a single subcarrier or only the eight pilot subcarriers for the analysis over a specific time interval. This technique allows analysis down to the smallest element within the subframe, namely an individual symbol on an individual subcarrier or an individual symbol over the eight pilot subcarriers. Selection of the subcarrier frequency or Pilot Only subcarriers is performed on the Advanced tab on the 802.16 OFDM Demodulation Properties dialog. Figure 3a shows the menu for selecting the Pilots Only subcarriers that will be used in the analysis. In this configuration, the trace data will only show measurements using the eight pilot subcarriers over the specified time interval which can be chosen as a single symbol, group of symbols, or the entire RF burst. As a measurement example, Figure 3b shows the Constellation, Error Vector Time, Error Vector Spectrum, and Symbols/Errors traces for the eight pilot subcarriers in the FCH symbol. As a WiMAX system uses these pilots to correct for time varying errors in the received signal (and thus the demodulation is performed relative to the pilots), it is important that the modulation quality of these symbols be very high. Figure 3b shows a marker placed at the peak error in the Error Vector Spectrum trace (upper right). In this case, the peak shows a 0.22 percent EVM, which is fairly good for a pilot subcarrier. The lower left trace of Figure 3b shows the Error Vector Time for this single (FCH) symbol. The eight EVM values for the eight pilot subcarriers are all displayed in a vertical column. The peak EVM value of 0.22 percent is also shown on this trace. The lower right trace shows the decoded bits for the eight pilot subcarriers. The hex values shown are the bits detected directly from the constellation diagram, without any de-interleave, decoding, or descrambling. Bit values can also be expressed in binary format.

It has been shown that the measurement flexibility in the 89600 VSA provides the means for demodulating an individual symbol as a function of subcarrier frequency. This technique allows the troubleshooting of a time-specific problem in a WiMAX subframe where the modulation type changes with time. Additionally, it is possible to troubleshoot frequency-specific problems using the same approach. This technique will be discussed in the next section of this application note.

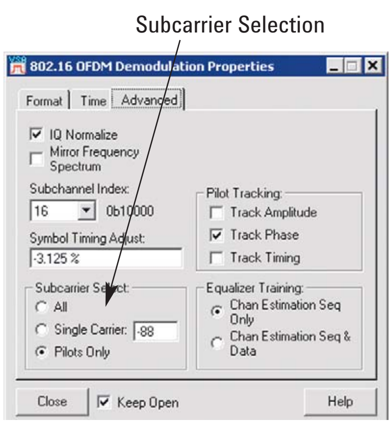


**Figure 3a. Demodulation Properties dialog on the 89600 VSA showing selection of the Pilots Only subcarrier.**

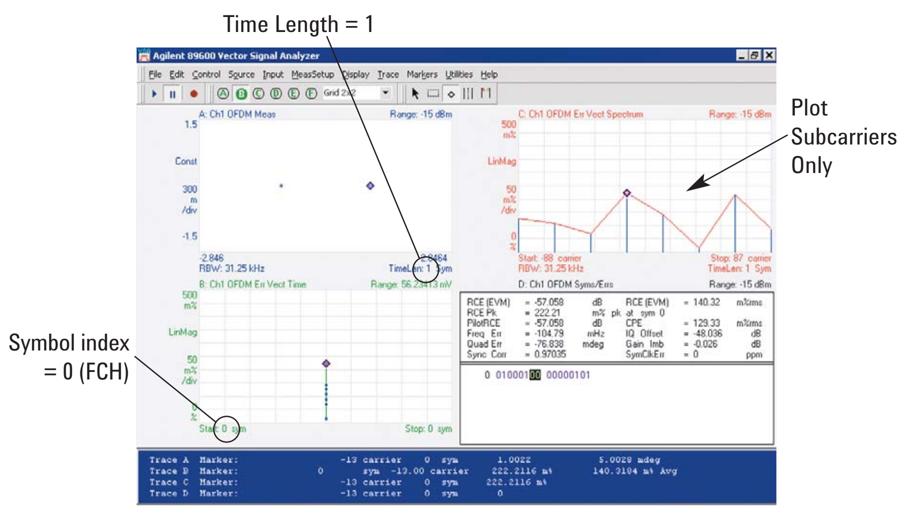


**Figure 3b. Measurement of a single WiMAX symbol (FCH) with the digital demodulation analysis covering only the pilot frequency subcarriers.**

## Analyzing specific frequency intervals

Demodulation of specific frequency intervals within the WiMAX subframe is another powerful analytic and troubleshooting tool. This feature provides the isolation of errors down to the individual subcarrier as a function of symbol time and can be used to identify such problems as interference, spurious, and DSP errors. Demodulation of any specific subcarrier or the group of eight pilot subcarriers is accomplished by selecting the appropriate option on the Demodulation Properties Menu as shown in Figure 3a. When selecting the option for a specific subcarrier, it is also necessary to enter the subcarrier index from among the 200 possible subcarriers used in the WiMAX subframe. The subcarrier indexing begins at –100 and ends at 100. The index equal to zero is not used as this value represents the RF carrier of the signal and contains only a leakage term.

Demodulating the individual subcarriers allows for the comparison of data subcarriers with pilot subcarriers. This technique is very useful when troubleshooting DSP problems. As a measurement example, Figure 4 shows the Error Vector Time and Error Vector Spectrum for a single subcarrier from an UL subframe. The upper two traces show the errors for a single pilot subcarrier with index = –88. Here, the Error Vector Time trace (upper left) shows a maximum EVM value of 2.7 percent. Also note that the EVM as a function of symbol- time does not change significantly over the complete subframe. As a comparison, the lower two traces show the errors for the data subcarrier with index = 10. The Error Vector Time trace (lower left) for this data subcarrier has a large EVM peak error of approximately 12 percent. Also note that this trace shows a large jump in the EVM for the symbols at the end of the subframe. This figure confirms that errors are occurring in the selected data sub carrier and not the pilot subcarrier. It can also be determined using the analyzer's modulation specific color-coding scheme, that the large errors are confined to the 64QAM symbols at the end of the subframe. It was later discovered that these errors are related to scaling problems in the DSP [6]. This technique is also a very useful tool when troubleshooting WiMAX signals when problems arise as a result of time-variant effects such as turn on/off settling, thermal, and power supply related problems.

It has been shown that troubleshooting a WiMAX signal for subtle defects that may occur at a specific subcarrier or at a specific time can be easily accomplished using the measurement flexibility available in the 89600 VSA. With the huge number of possible combinations available when analyzing specific time intervals and specific frequency intervals, it is easy to see that this feature provides a powerful measurement tool when analyzing the complex structure of a WiMAX signal.

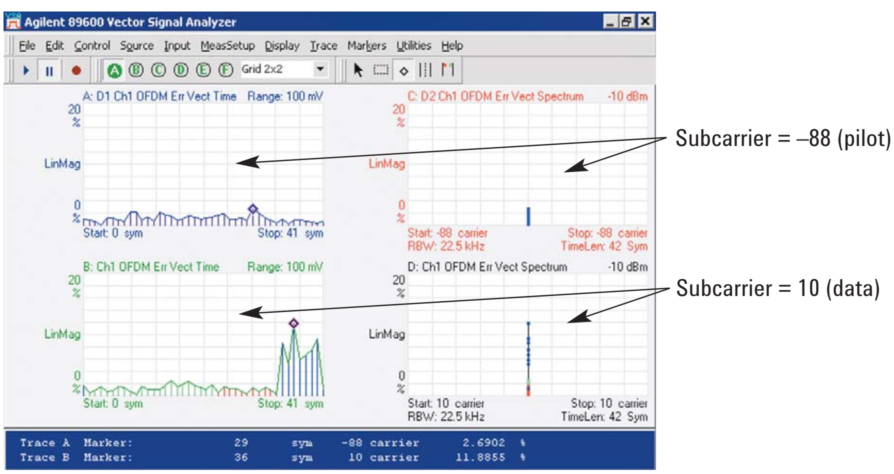


**Figure 4. Error Vector Time and Error Vector Spectrum traces using a single WiMAX frequency subcarrier. The upper pair of traces shows the results for the pilot subcarrier at index = –88. The lower pair shows the results for a data subcarrier at index = 10.**

## Digesting the Subframe Info Table

When demodulating a signal with a complex structure such as a WiMAX waveform it is often useful to provide a summary of the various components that make up a complete subframe. The 89600 VSA includes a unique measurement display called the OFDM Subframe Info trace. This display provides a large amount of tabular information that bridges the gap between the vector and demodulation modes on the VSA. The Subframe Info trace summarizes the entire WiMAX physical (PHY) layer subframe for modulation type, power level, number of symbols, and modulation quality. As the WiMAX subframe contains multiple data bursts of OFDM symbols, and with each burst possibly using a unique modulation type, it is very useful to have a table that summarizes all of the various modulation formats contained within the subframe. Modulation quality is displayed as a value for Relative Constellation Error (RCE), which is another term for EVM, as defined in the IEEE 802.16 standard. The RCE is reported as a value in dB with smaller values (larger negative numbers) related to improved modulation quality. When examining the composition of a DL subframe, details about the FCH are also included in the Summary Info table. As a measurement example, Figure 5 shows the Subframe Info table for a DL subframe containing 83 OFDM symbols.

The Subframe Info table provides detailed information about the preamble including the preamble symbol length, power level, and type. The various preamble types as specified in the 802.16 standard are Long, Short, Space Time Coding (STC), Adaptive Antenna System (AAS), and Subchannel. As shown in Figure 5, the preamble in this example is measured as having two QPSK-modulated symbols and determined to be of type *Long* verifying that this is a downlink subframe. The power level for this preamble is measured as –11.7 dBm. This power level is approximately 3dB higher than the FCH and data bursts. As the preamble is used for initial synchronization and channel estimation in the WiMAX receiver, the preamble is transmitted with 3dB more power for improved signal to noise [3].

The preamble is followed by the FCH and multiple data bursts. The FCH is measured as having one BPSK-modulated symbol. This is consistent with the 802.16 specifications for the FCH. The power level and RCE is measured as –14.7 dBm and –48 dB respectively. The first data burst following the FCH is measured to have 10 OFDM symbols using a QPSK modulation. The power level and RCE for this first data burst are also measured as –14.7 dBm and –48 dB respectively. The following two data bursts use 16QAM and 64QAM formats with comparable power levels and modulation quality. The number of symbols contained in the second and third bursts are measured to be 20 and 50 respectively. The total number of symbols in this DL subframe is shown to be 83 (80 data symbols, one FCH symbol and two preamble symbols). The total power level, which includes the power in the preamble, FCH, and all data bursts, is measured as –14.6 dBm. The modulation quality for the composite of FCH and data bursts is measured as –47.9 dB. This is the value that is also reported as RCE (EVM) on the Symbol/Errors display. A word of caution, if the Result Length is configured with a value less than the total number of FCH/data symbols in the subframe, then the information on the Subframe Info trace will only include a portion of the entire subframe. If the user wishes to include all the subframe data in the measurement, then the Result Length value should be set high enough to include the entire subframe. Alternately the user can increase the Result Length value while observing the total reported symbol length on the Subframe Info trace. When the total symbol length does not increase with an increase in Result Length, then the appropriate Result Length value has been selected.

If the measured subframe contains a FCH, additional information concerning the FCH is provided on the lower portion of the Subframe Info trace as shown in Figure 5. If the subframe does not contain a FCH, such as in a UL subframe, then the table will display *None* next to the FCH listing. If the FCH is detected, then the VSA will check for errors in the DLFP and report a pass or fail condition for the HCS. Figure 5 shows that the HCS has passed for the measured DLFP in this example. The BSID is also reported on this table and shown to have a value of 5 for this measurement. The FCH also contains the Rate_ID, which is related to the first information burst following the FCH. For the example, in Figure 5, the Rate_ID is 1, which corresponds to a QPSK modulation format using a 1/2 coding rate. This detected modulation format is also summarized on the upper part of Figure 5, which shows that the QPSK modulation is used for the first data burst following the FCH. Modulation formats and rates from the second data burst up through the fourth burst are also shown on the table using numeric values for DIUC2, DIUC3, and DIUC4. These values can be converted to the appropriate formats using Table 1 from page five. For example, Figure 5 shows that the DIUC for the second and third data bursts are 3 and 5 respectively. Using Table 1, this corresponds to the formats and rates for the second and third data burst as 16QAM-1/2 and 64QAM-2/3 respectively. For this example, there is no fourth data burst and therefore the DIUC4 and length (Len4) values are set to 0.

Two other important values are provided on the Subframe Info trace that relate to the Frame Number (FrmNum) and Configuration Change Count (CnfChg). The FrmNum is used to determine the frame that contains the Downlink Channel Descriptor (DCD) information [1]. The DCD is part of a broadcast message that is transmitted by the BS at periodic intervals to define the characteristics of the downlink physical channel. The CnfChg is used to detect changes that may have occurred in the DCD. For the example in Figure 5, both values are zero, which implies that the first frame contains the DCD information and that there are no changes to the DCD encoding.

The Subframe Info trace is a very informative summary table that provides an enormous amount of data relating to the structure and quality of the measured subframe. This display can be very useful for quickly finding several types of malformed signals, including signals with missing or incorrect preamble types and lengths, missing or extra midambles, power and scaling errors, missing or incorrect FCHs, and checksum mismatches.

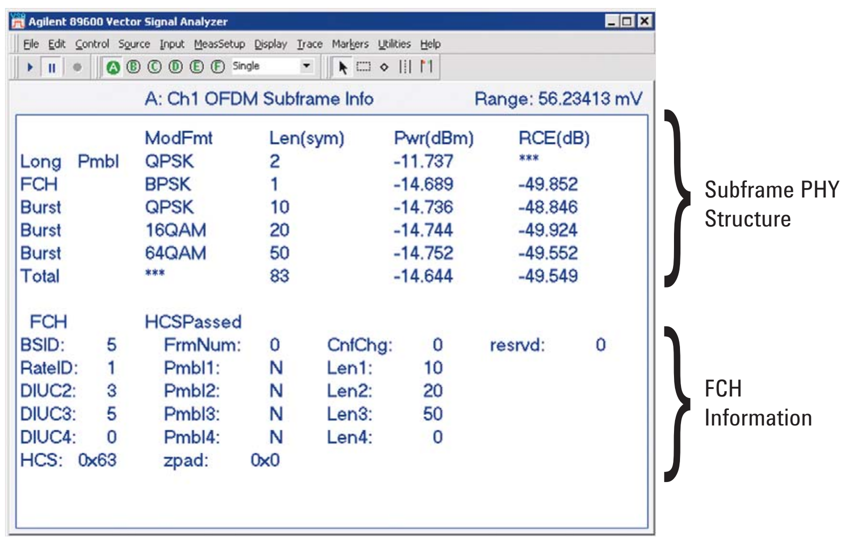


**Figure 5. Subframe Info table for a WiMAX downlink subframe containing the preamble, FCH, and three data bursts.**

## Correcting Signal Imperfections

As in many OFDM-based communications systems, the IEEE 802.16 standard includes specific provisions for *adaptive equalization* and *pilot tracking* within the receiver. These provisions improve receiver performance by correcting for linear errors; impairments such as amplitude and delay distortion. These errors can arise from phenomena such as multipath that may occur in the wireless channel between the transmitter and the receiver, or by frequency response problems in the transmitter or receiver circuitry. Adaptive equalization is initially used during the demodulation process to correct for frequency dependent errors contained in the received signal. Conversely, pilot tracking continuously corrects for time-varying errors that occur over the length of the OFDM subframe. Adaptive equalization and pilot tracking are particularly useful for broadband WiMAX signals where the nominal bandwidth can be as large as 28 MHz and the opportunity for frequency response problems is correspondingly greater than that for more narrowband signals.

Adaptive equalization and pilot tracking 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 VSA, providing important signal information and troubleshooting tools as shown in the following examples.

### Training the equalizer

In the WiMAX system, a training sequence composed of predetermined values is modulated onto the OFDM subcarriers at a specific time in the subframe often called the "channel estimation". The receiver can improve the quality of the demodulated data by adaptively adjusting coefficients in the equalizer based on the prior knowledge of the transmitted signal. The coefficients correct for linear amplitude and phase errors that occur as a result of multipath in the wireless channel or problems that may occur in the transmitter or receiver circuitry.

Equalization on the DL subframe usually occurs during the second symbol of the long preamble. This OFDM symbol is comprised of 100 subcarriers placed at every even index value. The UL subframe also uses 100 subcarriers placed at even indexes and is transmitted as a single OFDM symbol in the short preamble. Midambles may also be present and useful for updating the equalizer coefficients during the subframe.

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 channel and transmitter. This technique is sometimes called *data-directed* equalization. For some systems, data-directed equalization in a receiver provides many 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 subframe would be significantly better than using the one channel estimation sequence of a DL subframe, as the noise variance would be 3.5 times smaller [9]. Note that the DL channel estimation sequence actually consists of two repetitions of a waveform in time [1], therefore the noise variation falls by the square root of the ratio 25/2.

The 89600 vector signal analyzer supports two different ways to initialize, or "train," the instrument's equalizer. One is based on the Channel Estimation Sequence Only and the other is based on using both the Channel Estimation Sequence and the Data. Switching between the two training types can help isolate problems contributing to increased RCE (EVM). For example, the measured RCE of a signal with a malformed preamble would be much larger when only the preamble was used to train the 89600's equalizer. User selection for the type of equalizer training is performed on the Advanced tab from the 802.16 OFDM Demodulation Properties dialog (see Figure 6). The default setting is for Chan Estimation Seq Only.

The Chan Estimation Seq Only option on the 89600 VSA results in training the equalizer coefficients on the channel estimation sequence in the preamble and holds the coefficients constant while demodulating the rest of the subframe. This option models how a typical WiMAX receiver would train its coefficients. In this case, the measured RCE (EVM) more accurately reflects the signal quality seen by a typical OFDM receiver. This method also complies with the IEEE 802.16 standard for testing the transmitter constellation error. The disadvantage of this method is that the measured RCE (EVM) value may be higher for signals whose impairments change during the burst.

The second option for training the equalizer coefficients on the 89600 VSA is the Chan Estimation Seq & Data. For this option the equalizer is trained by analyzing the entire subframe, which includes the channel estimation sequence (contained in the preamble) and all the data symbols. This type of training generally results in a more accurate estimate of the true frequency response of the transmission channel. In addition, the RCE (EVM) is typically lower because noise and other forms of distortion, such as turn-on transients, have less of an impact when calculating the filter coefficients in the equalizer. The disadvantage of this method is that it is less likely to accurately reflect the performance of a typical OFDM receiver.

In addition to removing linear errors in the received signal by dynamically creating and applying a FIR (feedforward) compensating filter, it is also possible to examine the equalizer's impulse and frequency response. The Equalizer (Eq) Impulse Response can be used to measure the time delay profile of the linear distortion. The Ch Frequency Response trace shows the frequency response created from linear distortion in the channel. Linear distortion can be created by the filters in a transmitter or receiver's IF, or from the presence of multiple paths in the transmission path. These types of problems appear as group-delay ripple, tilt in the magnitude response, and frequency selective signal fading. Ch Frequency Response is computed as the inverse of the equalization filter's frequency response. The frequency response data is complex and is normally displayed in units of magnitude, phase, or group delay.

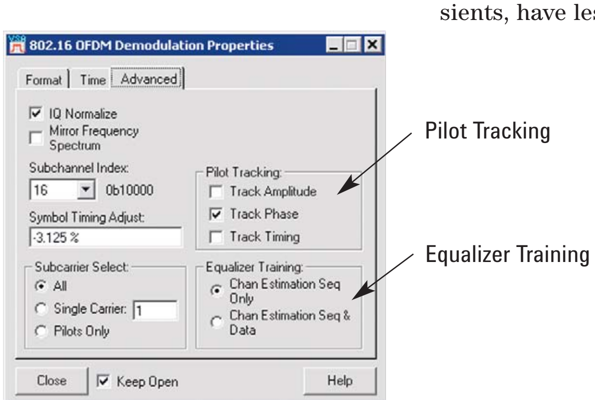


**Figure 6. Agilent 89600 VSA Advanced options for the OFDM Demodulation menu including Equalizer Training and Pilot Tracking.**

As a measurement example, Figure 7 shows the impulse and frequency response for an undistorted channel with a high signal to noise (left side) and for a non-line-of-sight (NLOS) channel with numerous multipath signals (right side). The upper left trace shows the equalizer impulse response for the undistorted signal. This channel does not have any significant filter or multipath distortion. As expected, the impulse response shows a single peak centered at zero seconds. The lower left curve is the frequency response for this channel, which shows a flat magnitude response across the measured frequency span. The frequency response is calculated from the Fourier transform of the equalizer coefficients which were developed from analysis of the preamble (or the preamble plus the data symbols if so selected). The frequency response is plotted as a function of the subcarrier index number. In contrast, for a WiMAX signal passing through a non-line-of-sight channel with numerous multipath delays, there is a spreading in the impulse response as signals are received over a larger span in time. As shown on the upper right trace in Figure 7, the path delays with the largest amplitudes occur between 0 and 1.6 μs. The complex interaction between the multipath signals result in frequency selective fading across the measured bandwidth. This fading effect can be observed using the frequency response measurement shown on the lower right trace in Figure 7. Here, the signal amplitude varies over 20 dB across the measured frequency range. This type of signal variation is expected for a NLOS wireless channel and often reduces system performance by creating inter-symbol interference (ISI) and fading in the received waveform. Conventional single-carrier systems often require complex equalization techniques in order to overcome multipath-induced ISI and signal fading. The OFDM multicarrier-based system uses a cyclic prefix and long symbol times relative to the channel impulse response in order to overcome multipath effects. In addition, frequency selective fading in the wireless channel is typically localized to a subset of carriers (each of which experiences essentially flat fading) that are relatively easy to equalize in comparison to a single-carrier modulated system.

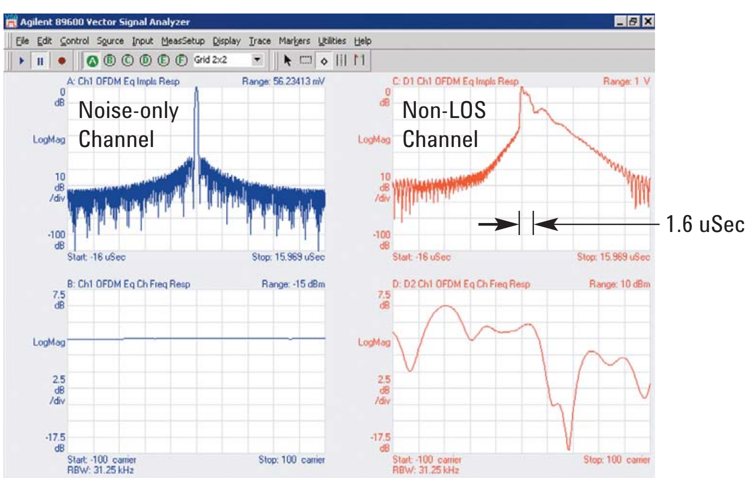


**Figure 7. Equalizer impulse response and channel frequency response for a noise-only channel (left two traces) and a non-line-of-sight (NLOS) wireless channel (right two traces).**

To observe the overall effects on training the equalizer using the preamble only and the preamble with data, the RCE (EVM) can be measured using the Symbol/Errors trace on the 89600 VSA. Table 2 shows the RCE for the two channels measured in Figure 7. In both cases, the RCE improved when training the equalizer using the Chan Estimation Seq & Data. The most noticeable improvement occurs for the non-line-of-sight channel where the equalizer does a better job of estimating the linear distortion by using the larger data set.

**Table 2. Relative Constellation Error using various equalizer training techniques**

| Channel Type | Chan.Est. Seq | Chan.Est. Seq & Data |
|---|---|---|
| Noise | 1.3 % | 0.9 % |
| NLOS with Multipath | 4.2 % | 0.9 % |

Once calculated, the equalizer coefficients remain fixed for the duration of the subframe. For signal variations within the subframe, the 802.16 standard provides a method of tracking these variations using the pilot subcarriers. Pilots are present in each OFDM symbol including the FCH and all data bursts. The next section will show the performance improvements that can be achieved using pilot tracking.

## Tracking pilot subcarriers

When demodulating an OFDM burst, the equalizer response computed from the preamble is used to correct many flaws in the received OFDM signal. Because the equalizer response is not perfect and because some signal impairments are not correctable through equalization, pilot tracking is used to correct for imperfections in the equalizer response and for imperfections that change over the length of the burst. These pilots are used, in part, to create a continuous series of amplitude and phase references throughout the subframe. Demodulation is then performed relative to these pilot subcarriers and allows a variety of signal impairments to be corrected continuously throughout the RF burst. 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 close-in 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.

In each WiMAX OFDM symbol, eight subcarriers are dedicated to pilot signals in order to make the coherent detection robust against frequency offsets and symbol timing variations or phase noise. These pilots occupy subcarrier indexes of –88, –63, –38, –13, 13, 38, 63, and 88 and always use BPSK modulation. Pilot subcarriers are transmitted with a known data sequence. This information is used to determine the difference, or error, between an ideal signal and the actual received signal. Because the data is complex, the VSA can calculate the phase, amplitude, and timing errors in the received data and then use this information to correct both pilot and data imperfections.

The error vector magnitude of the eight pilot subcarriers is reported as the Pilot Relative Constellation Error (RCE) on the Symbol/Errors trace using the 89600 software. The IEEE 802.16 standard uses the term RCE instead of EVM, but the computed values are exactly the same. The PilotRCE is calculated as the RMS value of the EVM (in dB) of the eight pilot subcarriers for all symbols over the entire burst. The value reported for PilotRCE is determined after equalization and pilot tracking have been applied. For example, the upper trace in Figure 8 shows the OFDM Symbol/Errors table for an UL subframe using both equalization and pilot tracking. In this case, the measured PilotRCE is shown as approximately –41 dB. This value is achieved using equalization over the channel estimation sequence and pilot tracking of both the amplitude and phase. Using this equalization and pilot tracking, the RCE (EVM) for the entire subframe is measured as 2.39 percent. If the pilot tracking is disabled, then the subframe RCE (EVM) increases to the very poor value of 21 percent. As expected, pilot tracking can often greatly improve the quality of the demodulated signal. Selection of pilot tracking is made using the Advanced Tab on the 802.16 OFDM Demodulation Properties Dialog as shown in Figure 6. The 89600 VSA provides the unique capability to select the tracking type using the amplitude, phase, and timing or any combination of the three.

As discussed previously, the PilotRCE shows the resulting EVM after equalization and tracking is applied to the demodulated pilot signals. Alternatively, the actual errors or impairments that result from tracking the pilot subcarriers are collectively called Common Pilot Error (CPE). The CPE is expressed as a function of symbol-time showing how the amplitude and phase error of the pilots can change over the OFDM burst. Ideally, the CPE trace data has a magnitude of one and phase of zero. The CPE trace data is measured at each symbol-time over all eight pilot subcarriers. The errors from ideal are averaged together producing a single complex value at each symbol-time. As a measurement example, the two lower traces in Figure 8 show the CPE trace data as a function of symbol-time for the amplitude and phase respectively. The measured data for the CPE phase response varies randomly across the subframe. Phase errors such as these may be caused by phase noise of the transmitter's frequency oscillator. Fortunately, close-in phase noise can be tracked out of the signal using the pilot tracking function. The amplitude response of the CPE shows an increase in the pilot error during the early part of this subframe. This rapid increase in the pilot amplitude error is the result of amplitude droop occurring over the subframe. Possible causes for this error could be the result of thermal or power supply related problems in the RF amplifier of the WiMAX transmitter. A marker placed on the amplitude response shows that the maximum CPE occurs at symbol 29 with a value of 0.35 dB. A marker placed on the peak phase response shows a value of 0.4 degrees at symbol 19 showing that peak errors are not necessarily coincident between the various responses.

An RMS value of the CPE is also reported on the Symbol/Errors trace adjacent to the PilotRCE value. This CPE value is calculated as an RMS value minus 1, in percentage terms, using all the CPE trace data across the subframe. The CPE using pilot tracking of both the amplitude and phase for the waveform measured in Figure 8 is shown as 3.3 percent. Note that the CPE value on the Symbol/Errs trace is only valid when at least one type of pilot tracking is selected. Otherwise, the CPE is reported as zero on the Symbol/Errors trace.

In addition to selecting amplitude and phase tracking of the pilots, it is also possible to track the timing. Timing errors may be caused by both analog and digital sources. For example, oscillator frequency errors or DSP errors such as an improper number of samples in the guard interval or improper sample rate may create large timing errors, which often require pilot tracking to correct. When Track Timing is selected the analyzer applies timing error correction (frequency offset correction) to the pilot and data subcarriers. For the measured waveform in Figure 8, it was found that tracking the timing of the pilots did not improve the demodulation quality as observed using the RCE (EVM) or PilotRCE values in the Symbol/Errors trace. In this case, only amplitude and phase tracking provided the greatest improvement to the demodulated signal.

The 89600 VSA provides one additional timing adjustment at the point of demodulation in the OFDM symbol. The OFDM symbol time consists of a guard interval plus an *FFT length*. The Symbol Time Adjust parameter allows the user to move the FFT length's starting position within the full OFDM symbol. No specific time position is called out in the IEEE 802.16 standard, and different timing settings may affect the measured demodulation quality. In particular, if ISI or multipath signals affect the guard interval, certain offsets in symbol timing may result in improved signal demodulation. Using the 89600 VSA, the Symbol Timing Adjust parameter is expressed as a percentage of the FFT length. This parameter makes the point of demodulation within the symbol time back up into the symbol and guard interval. The minimum value in percentage is equal to –(Guard Interval value) x 100 and the maximum value is zero. The default value is –3.125 percent if the guard interval is 1/16 or greater and –(Guard Interval value) x 100 ÷ 2 if less. The Symbol Time Adjust parameter can be changed using the Advanced Tab on the 802.16 OFDM Demodulation Properties Dialog as shown in Figure 6.  Always verify that the start of the FFT period does not include corrupt data from the transition time at the beginning of the subframe.

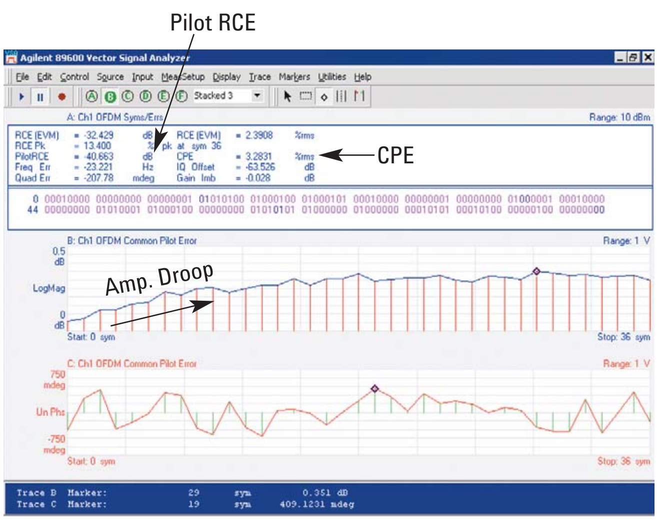


**Figure 8 PilotRCE and CPE for an UL subframe. Center trace shows the amplitude response of the CPE with amplitude pilot tracking enabled. Lower trace shows the phase response of the CPE with phase pilot tracking enabled.**

## Uncovering IQ Errors

Digitally modulated systems that use IQ vector modulators to impress the information onto an RF carrier will all experience some level of signal distortion due to imperfections in the IQ modulator and associated components. Impairments such as IQ gain imbalance, IQ quadrature skew and IQ channel mismatch will all lead to distortion in the received signal that may reduce the overall system performance. It is important to note that the observed effects resulting from IQ impairments will often look different for single-carrier modulated signals when compared to OFDM modulated signals [10].  The 89600 VSA provides measurement and analysis information for many IQ impairments such as IQ Offset, IQ gain imbalance (Gain Imb), and IQ Quadrature error (Quad Err). A measurement example of this analysis was previously shown on the Symbols/Errors trace in Figure 8 (upper trace). Additional details concerning these IQ measurements are discussed in subsequent paragraphs.

Analog IQ modulators always have some degree of imbalance of the amplitude and phase between the I and Q channels. Gain mismatch or gain imbalance will result in the amplitude of one channel being smaller that the other. The Gain Imb measurement on the 89600 compares the gain of the I signal with the gain of the Q signal and calculates a value using the equation 20Log (I Gain/Q Gain). Gain imbalance will alter the constellation for an OFDM modulated signal much differently from that of a single-carrier modulated signal. In a single-carrier modulated signal, the gain imbalance results in a visible distortion in the constellation, as a square constellation would become rectangular. In an OFDM modulated signal, the imbalance will result in a spreading of the constellation points similar to a signal experiencing noisy conditions. An imbalance in an OFDM modulator produces two error terms in the transmitted signal. The first error occurs at one subcarrier frequency (+kth index) and the second error occurs at the frequency mirror-image subcarrier (– kth index) [10]. As the data is generally uncorrelated on these subcarriers and the constellation points for OFDM signals is a function of subcarrier frequency rather than time, the randomness in the error terms results in a spreading of the constellation states in a noise-like fashion.

As a measurement example showing the effects of IQ imbalance, Figure 9 shows constellation plots for a single-carrier modulated waveform (upper trace) and an OFDM modulated waveform (lower trace). Both waveforms use 64QAM data modulation. As shown, the single-carrier modulated signal shows a distortion in the constellation, as the values along the Q-axis become larger than values along the I-axis resulting in a rectangular-shaped constellation. Alternately, the constellation points for the OFDM –modulated signal show a more noise like distribution. Also shown on the lower trace are the pilot subcarriers that are present in all OFDM symbols. It is shown that the distribution of constellation points for the pilot subcarriers follow a linear pattern along the I-axis when there exists an IQ imbalance [10]. As the pilot subcarriers use BPSK modulation and do not contain an imaginary term, the imbalance errors introduce a linear spreading along the I-axis as shown in Figure 9.

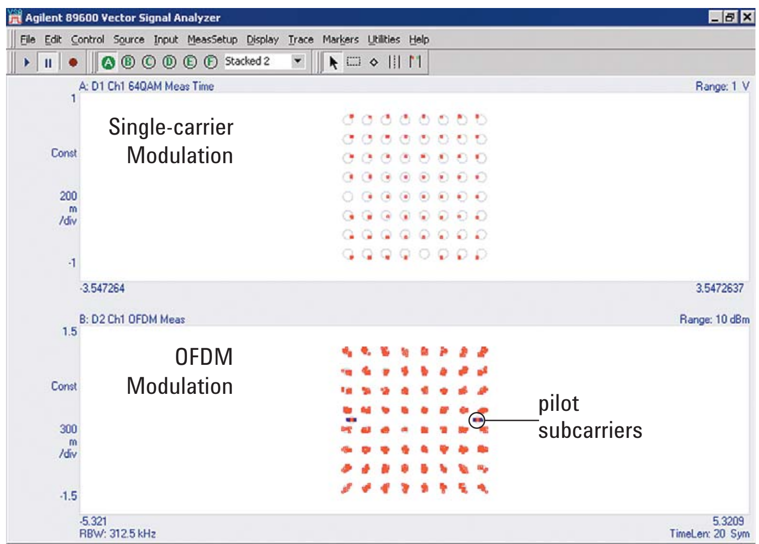


**Figure 9. Constellation traces for single-carrier (upper trace) and OFDM (lower traces) modulated signals with IQ gain imbalance.**

Quadrature Skew Error (Quad Err) is another IQ modulator impairment that indicates the orthogonal error between the I and Q signals. Ideally, I and Q channels should be exactly orthogonal (90 degrees apart). For small angular errors, it can be shown that the resulting error is orthogonal to the data. As with gain imbalance, the error generates energy at the subcarrier and its mirror image and the resulting constellation for data subcarriers again appears to have a noise-like distribution. For the BPSK pilots, the error again produces a linear distribution but this time in the orthogonal axis or Q-axis.

IQ Offset, also called I/Q origin offset or carrier leakage, indicates the magnitude of the carrier feedthrough and is measured during the channel estimation sequence portion of the preamble. IQ Offset can be observed as an offset in the constellation or shown as a single value in dB on the Symbols/Err trace. When there is no carrier feedthrough, IQ offset is zero (-infinity dB). As an example, Figure 8 shows that the IQ offset for this WiMAX subframe is –63 dB.

Additional IQ modulator impairments can be analyzed by examining their effects on the constellation trace using the 89600 VSA. Table 3 shows a variety of impairments and the anticipated effect on the measurement trace. The table includes waveforms using OFDM and single-carrier modulation, noting that error in the constellation may appear different for each modulation type.

**Table 3. Signal impairments and their effect on the displayed constellation**

| Impairment | OFDM | Single-carrier modulation |
|---|---|---|
| IQ gain balance | State spreading (uniform/carrier) | Distortion of constellation |
| IQ quadrature skew | State spreading (uniform/carrier) | Distortion of constellation |
| IQ channel mismatch | State spreading (nonuniform/carrier) | State spreading |
| Uncompensated frequency error | State spreading | Spinning constellation |
| Phase noise | State spreading (uniform/carrier) | Constellation phase arcing |
| Nonlinear distortion | State spreading | State spreading (may be more pronounced on outer states) |
| Linear distortion | Usually no effect (equalized) | State spreading if not equalized |
| Carrier leakage | Offset constellation for center carrier only (if used) | Offset constellation |
| Frequency error | State spreading | Constellation phase arcing |
| Amplifier droop | Radial constellation distortion | Radial constellation distortion |
| Spurious | State spreading or shifting of affected subcarrier | State spreading, generally circular |

## Glossary

OFDM - orthogonal frequency division multiplexing
OFDMA - orthogonal frequency division multiple access
MAC - medium access control
TDMA - time division multiple access
TDM - time division multiplexing
TDD - time division duplex
FDD - frequency division duplex
H-FDD - half-duplex frequency division duplex
BPSK - binary phase shift keying
QPSK - quadrature phase shift keying
QAM - quadrature amplitude modulation
IEEE - Institute of Electrical and Electronics Engineers
BS - base station
SS - subscriber station
TTG - transmit/receive transition gap
RTG - receive/transmit transition gap
BWA - broadband wireless access
MCM - multi-carrier modulation
PHY - physical layer
FEC - forward error correction
LAN - local area network
MAN - metropolitan area network
NLOS - non-line-of-sight
LOS - line-of-sight
RS - Reed-Solomon block code
CP - cyclic prefix
DL - downlink (base station to subscriber transmission)
UL - uplink (subscriber to base station transmission)
FCH - frame control header
BER - bit error rate
PMP - point-to-multipoint
RCE - relative constellation error
EVM - error vector magnitude
CPE - common pilot error
DLFP - downlink frame prefix
HCS - header check sequence
DIUC - downlink interval usage code
DCD - downlink channel descriptor
STC - space-time coding
AAS - adaptive antenna system
ISI - inter-symbol interference

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Printed in USA, July 26, 2005
5989-3039EN


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