Using Agilent X-Series Signal Analyzers for Measuring and Troubleshooting Digitally Modulated Signals

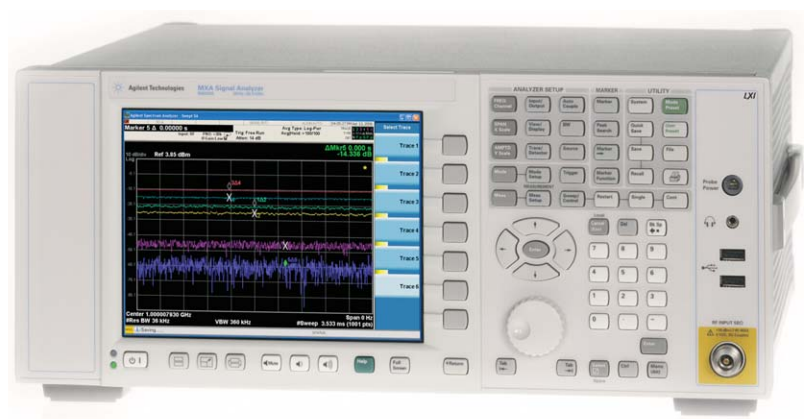
Application Note 1585

Introduction

Signal analysis in digital modulation applications takes many forms, ranging from straightforward spectrum analysis of CW oscillators to demodulation and modulation quality analysis in R&D to simple go/no-go final tests in manufacturing. The most common tools for this analysis are spectrum analyzers and vector signal analyzers (VSAs), with oscilloscopes and logic analyzers often used to view baseband I/Q signals in analog and digital form, respectively.

The Agilent X-Series signal analyzer is one tool that can support multiple types of signal analysis through its multiple measurement applications including spectrum, VSA, and standard-specific digital demodulation.

Whether they are swept spectrum, VSA, or standard-specific demodulators, the architecture of most RF signal analysis solutions is similar: A superheterodyne receiver downconverts and filters the signal to an intermediate frequency (IF) where final filtering and analysis are performed. Though their architectures are similar, spectrum analyzers and VSAs usually perform different kinds of signal analysis using different signal processing schemes and, importantly, have quite different user interfaces.



Fortunately, the trend is for spectrum and vector signal analysis to be increasingly combined in the latest signal analyzers to yield a single tool that can offer the familiar capabilities and user interface of a spectrum analyzer and still be instantly switchable to provide complete vector signal analysis and digital demodulation.

This application note describes the use of the X-Series signal analyzers and their measurement applications for digital wireless analysis in the context of an effective and efficient measurement process. The process itself is best suited to the design phase of R&D, though the discussion of measurement modes applies to tasks such as design verification and some (typically prototype) manufacturing.

X-Series Signal Analyzer Measurement Applications

The best way to achieve a simple user interface while also providing capabilities for vector and digital demodulation measurements is to embed standard-specific knowledge in a spectrum analyzer in the form of a measurement application or personality. That is the approach taken by the Agilent X-Series signal analyzer, where spectrum analysis, standard-specific measurement applications and complete vector signal analysis are all available as different user interfaces for the same hardware platform.

The X-Series takes maximum advantage of the architectural benefits of both an RF spectrum analyzer and a VSA. A high performance RF downconverter is coupled to a wideband all-digital IF to provide extensive spectrum analysis functions and complete vector signal analysis, including both flexible and standard-specific digital modulation analysis. To make the design process more efficient the analyzer can switch between the modes or applications in a fraction of a second. The analyzer's measurement applications are accessed through the [Mode] front-panel key.

Spectrum analysis

By far the most common tool for the RF and microwave engineer, the spectrum analysis mode is both powerful and easy to use, especially for CW signals. This mode provides both basic and advanced measurement features including multiple traces and multiple simultaneous detector types, along with a full suite of power measurements. The utility of these features is complemented by extremely fast measurement speeds and speed-enhancing capabilities such as list sweep and multiple high-speed digital interfaces, such as 100Based-T LAN and USB 2.0. The spectrum analysis mode also includes features for measuring digitally modulated signals, with standards-based presets for quick and easy setup and is thus an ideal complement to the detailed, in-depth troubleshooting provided by the 89601A measurement application

Vector signal analysis

This measurement mode is designed for time-varying, digitally-modulated, and wideband signals and, for maximum efficiency, uses a mouse/keyboard interface rather than front-panel keys/softkeys. The VSA mode is a complete, embedded version of the 89601A vector signal analyzer software and while it can be used to perform traditional spectrum measurements is primarily designed for applications where spectrum analysis falls short, such as time-gated and transient measurements, time-selective signal statistics, and digital demodulation & modulation quality measurements of all kinds. The 89601A is the industry's leading signal analysis solution for time-varying and digitally modulated signals, and has the same user interface and capabilities whether operating standalone or inside the analyzer.

Standard-specific spectrum analysis and demodulation

The standard-specific measurement applications in the analyzer are optimized for convenience and ease-of use. They provide simpler measurement setup along with features such as limit lines, pass/fail testing, and results tables. The flexibility and analysis capabilities of the standard-specific applications are not as extensive as the 89601A VSA, but the most important spectrum, power, and demodulation measurements can be made through a customized and simplified user interface.

Standard-specific measurement applications are a good match for design verification and manufacturing applications where the goal is to measure signal quality and confirm proper operation. The standard-specific measurement applications offer SCPI programming over GPIB, LAN and USB interfaces. However, in some situations the measurement application may not provide sufficient measurement flexibility for troubleshooting, requiring the use of a full (and somewhat more complicated) VSA solution.

X-Series Signal Analyzer Measurement Applications

When measuring or troubleshooting digital wireless components and systems, modulation quality analysis is an obvious requirement. However, we have learned from wide experience that a measurement sequence that begins with spectrum analysis may yield a finished design faster. An example process that begins with basic spectrum measurements and continues with vector (combined frequency and time) measurements, before switching to digital demodulation and modulation analysis as shown in Table 1.

This application note will relate this sequence to the appropriate modern measurement tools available in the hardware and software associated with the Agilent X-Series.

The sequence of measurements is especially useful because it improves the chance that you will find important signal problems at the earliest stages of design. In particular, the spectrum and vector (time and frequency) domain measurements at the beginning of the sequence provide for the measurement and verification of many signal parameters (including many associated with the digital modulation itself) without the need to perform digital demodulation. This is an advantage in some development situations where demodulation is not yet available or is in some way questionable (results vary from one receiver to another, for example). In addition, some important measurements such as spectral occupancy and CCDF are typically not performed in a demodulation mode.

Table 1. A suggested measurement sequence for troubleshooting and performance verification.

Frequency, frequency and time	**Basic digital demod**	**Advances and specific demod**
Get basics right, find major problems	Signal quality numbers, constellation, basic error vector measurements	Find specific problems and causes

X-Series Signal Analyzer Measurement Applications

Spectrum measurements

Traditional spectrum measurements are an excellent beginning point because of their fundamental nature and the ease of operation of a spectrum analyzer. Many signals in a wireless system need spectrum measurements of power, distortion, noise (or signal/noise), phase noise sidebands, etc. Traditional spectrum measurements are also used to verify frequency conversion operations for proper frequency and amplitude. A simple spectrum measurement is shown in Figure 1.

In a zero-span mode spectrum analyzers can also be used to display the RF envelope of a signal. Zero-span measurements can be used to understand turn on/off events and other signal characteristics such burst timing and amplitude droop. In many cases, however, these time-related measurements are more conveniently and perhaps more accurately made with the X-Series signal analyzer in its VSA mode as described later in this note.

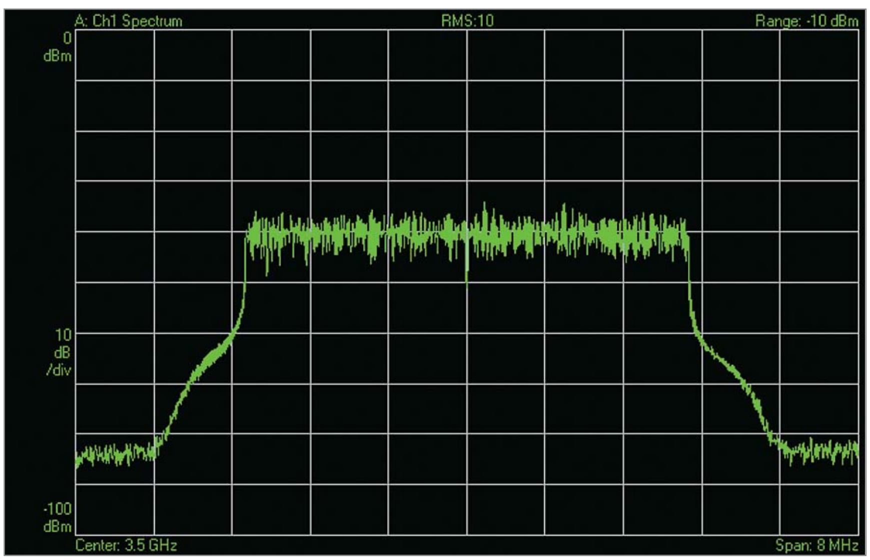


Figure 1. This basic spectrum measurement reveals much about an OFDM signal, though its untriggered averaging of a pulsed signal introduces some uncertainties. This measurement is good for determining the signal center frequency and approximate bandwidth, average power and flatness, and verifying the missing (normally untransmitted) center carrier.

X-Series Signal Analyzer Measurement Applications

Time-related and time specific measurements

Most digitally modulated signals are time-varying, including on/off RF bursts and changes in signal composition due to equalizer training and synchronization sequences. Therefore, time-specific measurements of spectrum and power are crucial. As previously noted, the X-Series signal analyzer's application may be used for these measurements in some cases, though the primary design tool will be the VSA application and (where available for design verification and manufacturing) standard-specific measurement applications. The MXA's 89601A VSA application offers important triggering capabilities and uses FFT/DSP operations to provide some important benefits for accurate measurements of this kind:

- Pulse-triggered measurements with adjustable levels, holdoff and positive/negative trigger delays to precisely select the start of the measurement interval
- Flexible time gates to select the desired portion of the signal for measurement
- Adjustable frequency resolution and RBW (window) filter shape to optimize amplitude accuracy and time vs. frequency resolution, often an essential capability for measuring closely-spaced signals such as OFDM carriers
- Gating applicable to all measurements including spectrum, power, occupied bandwidth, complementary cumulative distribution function (CCDF), power spectral density (PSD), etc.
- Time capture and replay functions for single-shot measurements, gap-free (real-time analysis for the capture) analysis, and the ability to measure the same signal with different analysis settings. The X-Series has a maximum capture memory of 32 million measurement points (complex pairs).
- Adjustable FFT time record size with the capability of very large records, up to 409,600 points for vector measurements of entire RF bursts. Some signals such as WiMAX, WLAN, and WCDMA have wide bandwidths and long burst lengths where each RF burst represents a very large amount of information. Making time-gated or other vector measurements of all or parts of these bursts is facilitated by the ability to process very long time records.

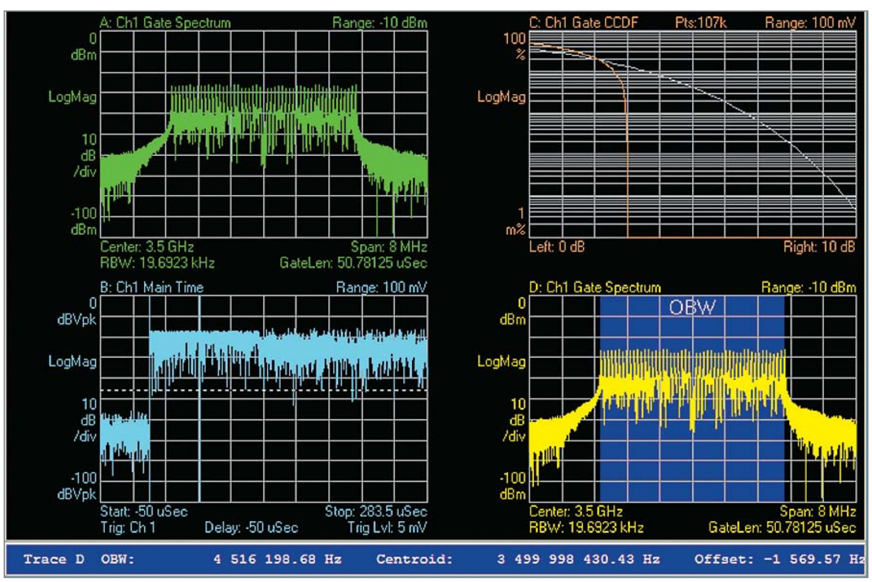


Figure 2. Time-gated measurements of a portion of the preamble of a wireless LAN signal. The spectrum, OBW & CCDF measurements illustrate VSA measurement capabilities including burst triggering, holdoff, trigger delay, selectable gate interval and RBW shape optimized for maximum frequency resolution (to resolve the closely-spaced OFDM carriers).

Basic Digital Demodulation

The previously-described spectrum and time domain measurements make it easier to achieve the goal of basic digital demodulation: correctly detected symbol states, a locked receiver symbol clock, and valid modulation analysis results such as EVM (error vector magnitude), RCE (relative constellation error), I/Q error parameters, etc.

If the analyzer is not set up correctly (center frequency & span, symbol rate, pulse search parameters, and measurement time interval) or if the test signal has these parameters wrong, demodulation will likely fail without providing good clues about the problem. Thus, the need to understand these characteristics before attempting demodulation, which is the next step in the measurement sequence described in Table 1.

Basic digital demodulation produces a number useful measurement results. Some are overall numeric measures of modulation quality such as EVM, RCE, or MER (modulation error ratio), along with direct I/Q error measures such as I/Q offset, quadrature error, and gain imbalance. Frequency and amplitude stability can be evaluated by examining parameters such as amplitude error and phase error, along with general frequency error parameters derived during demodulation.

The X-Series' standard-specific measurement applications are an excellent choice for basic digital demodulation. With its built-in knowledge of the standard, the application can speed and simplify measurement setup and reduce setup errors. The application is pre-programmed with the most useful and most common tabular and graphic displays, and provides customized features such as limit lines and pass/fail testing. An example of tabular and graphic displays is shown in Figures 3 and 4.

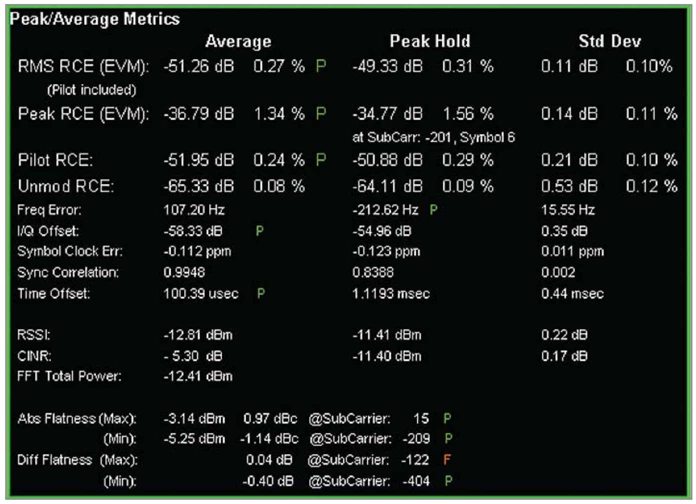


Figure 3. An X-Series standard-specific measurement application automatically generates a table of appropriate measurement results and provides pass/fail indication.

Figure 4. The standard-specific measurement application also provides graphical results paired with limit lines and pass/fail testing.

Basic Digital Demodulation

Some demodulation results are best expressed graphically. The most fundamental are the constellation and vector (constellation with symbol transitions shown) diagrams. These diagrams provide the clearest indication of whether the demodulation is successful or locked (to the transmitter symbol clock) and whether the modulation is the desired type.

The graphical error vector measurement results are especially useful for troubleshooting, beginning with errors vs. time. The demodulation applications in the X-Series generate a perfectly modulated reference signal matching the received symbol sequence. Error vector calculations (vector subtraction of the reference signal from the measured one) are made for each symbol instant and for times in between, producing a time-based vector quantity that can be displayed according to seconds or symbol times. It is especially useful to understand that the error vector measurement represents the difference between the measured signal and an ideal signal, and can be interpreted (in any domain desired) as the residual after the desired modulation has been removed.

Evaluating errors in the time domain (error vector time) can reveal problems associated with turn on/off events, impulsive interference, operation of automatic gain control circuits, and fast fading phenomena. Examining errors vs. time can also be useful for signals such as WiMAX™ (both fixed and mobile) where modulation schemes are changed during RF bursts.

Since the measured error is a vector quantity it can be transformed (via FFT) into the frequency domain, producing an error vector spectrum measurement. Some errors may be relatively constant with respect to time but isolated to specific frequencies or bands. Common examples would be adjacent channel interference (where errors would be higher near the edge of the channel) and spurious interference (where errors would be high at a specific frequency).

Basic Digital Demodulation

A simple but often-overlooked technique for making sense of the different error measurements is marker coupling, a function available in the X-Series and 89601A VSA measurement applications. Linking the markers on multiple (as many as as 4-6) simultaneous measurement traces allows a specific demodulation result (typically an error peak) to be understood in the time, frequency, and I/Q domains. For example, an error peak found in an error vector time trace can be examined in the I/Q constellation or vector display to determine if the peak is associated with an amplitude excursion (error from compression) or a particular symbol transition. The peak error can also be examined in the symbol table to determine if it is associated with a particular symbol value or sequence, indicating possible DSP errors. Finally the peak can be examined in amplitude error or phase error traces or (particularly for OFDM modulation schemes) the peak can be associated with a specific carrier number or frequency to isolate interference from other transmitters or spurs. An example of coupled markers on multiple measurement traces in the X-Series' VSA measurement application is shown in Figure 5 below.

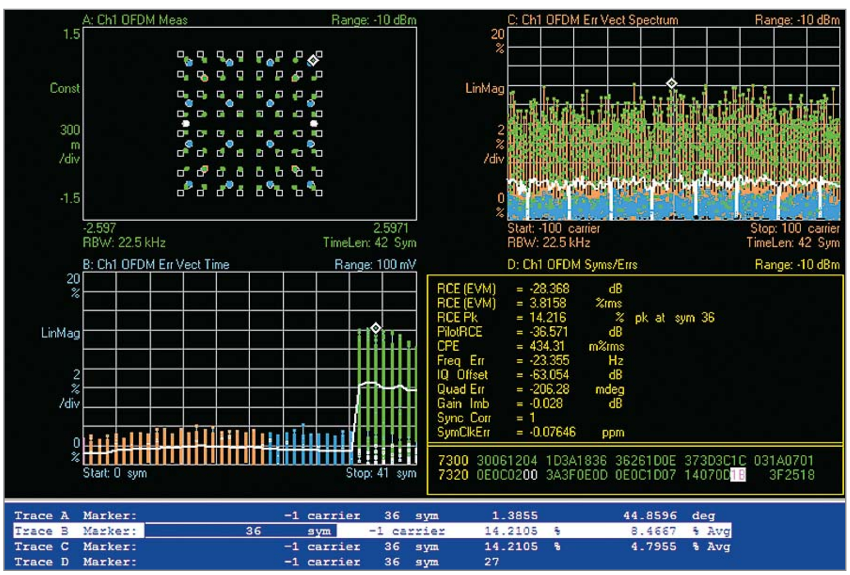


Figure 5. A basic digital demodulation result from the 89601A VSA measurement application including a constellation diagram and a composite table of error parameters and measured symbols, along with the two main error vector displays of error vs. time (lower left) and symbol and error vs. frequency (upper right). Marker coupling is used to correlate a peak in the error vector time trace across several displays and measurement domains.

Advanced Digital Demodulation

The last step in the measurement and troubleshooting sequence (see Table 1) is the most powerful one for finding complicated problems, those with subtle causes, or problems with especially complicated modulation and multiplexing schemes such as WiMAX-OFDMA. Generally speaking, advanced demodulation techniques include demodulation of specific portions of signals in time and frequency, and/or use of more advanced demodulation operations such as adaptive equalization and configurable pilot tracking (primarily for OFDM modulation schemes).

In the X-Series, these advanced demodulation techniques are available in the 89601A VSA measurement application, whether that application is running inside the signal analyzer itself or on a separate PC attached through one of the digital interfaces such as LAN, USB, or GPIB.

Adaptive equalization

One of the most broadly applicable advanced demodulation techniques is adaptive equalization. Equalization of some type is used in most digitally-modulated systems, and thus it is useful to understand signal quality both with and without equalization. The performance of practical receivers may correspond most closely to post-equalization measurements (where linear errors have been removed) while evaluation of system components (such as modulators, filters, and frequency converters) may be done without equalization to optimize distortion and noise, whatever its cause and nature.

Through its 89601A VSA measurement application, the X-Series signal analyzer implements both a general adaptive equalization feature (available for almost all single-carrier modulation types, with no need for a training sequence) and standard-specific equalization for systems such as WiMAX-OFDMA, which require it for proper demodulation.

Following are some common adaptive equalization measurements:

- Pre- and post-equalization error measurements, with comparisons to separate linear and nonlinear sources of error
- Analysis of the equalizer coefficients, displayed in terms of both frequency response (magnitude and phase or group delay) and impulse (time domain) response
- Adjustment of equalizer filter length (in time or symbols) to evaluate equalizer effectiveness vs. typical multipath delays

The equalization results are available in several formats including frequency domain (frequency response) and time domain (impulse response). The frequency domain parameters indicate the frequency response of the channel itself, while the time domain parameters refer to the demodulator's equalizer filter itself. In some specific demodulation types such as WiMAX-OFDMA the frequency response parameters derived from the equalizer filter are expressed as the relative frequency response of the OFDM carriers and labeled "channel frequency response adjacent difference."

In the 89601A VSA measurement application, equalization can be further customized when demodulating OFDM formats by selecting the training method for the adaptive equalizer. The equalizer can be trained exclusively by the preamble sequence or by all the data in the measurement subframe. The two training approaches reflect different measurement uses and priorities. Training the demodulator only on the preamble will provide modulation quality results (and channel frequency response, etc.) which more closely indicate the performance of a radio receiver. Training the demodulator on the entire subframe, including the preamble and the data, will generally provide a more accurate equalizer response and lower error. This approach is useful for the most accurate measurements of signal quality and for measurements of components or subsystems.

Advanced Digital Demodulation

Pilot tracking

Most OFDM modulation schemes include multiple “pilot” carriers which are used as a continuous demodulation reference during an RF burst. Receivers know the data and modulation used for the pilots, along with their frequency position (thus the pilots carry no useful data) and perform their demodulation relative to the pilots. Since the pilots are affected by the same signal and channel impairments as the data carriers, demodulating the received signal relative to them allows some errors to be “tracked out.” Impairments can then be isolated and the resulting insight is very useful for troubleshooting. In the VSA measurement application tracking, in the form of amplitude, phase, and symbol timing, can be selectively enabled to isolate the cause of problems, and the error common to all the pilots (CPE or common pilot error) is available as a measurement trace for further examination.

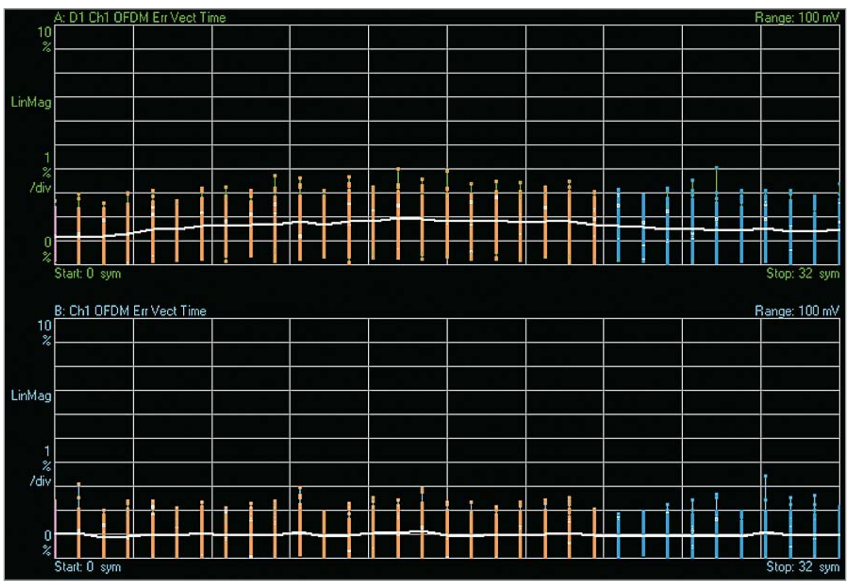


Figure 6. The magnitude portion of the error vector signal reveals the effect of pilot tracking. In the bottom trace amplitude tracking has been used, removing the amplitude drift which is evident in the top trace. Amplitude tracking improved the RCE (EVM) by about 5 dB.

Modulation Troubleshooting

As a complement to the organized measurement sequence described previously, Figure 7 summarizes a troubleshooting tree or sequence for using error vector measurements and associated displays such as constellation diagrams and equalizer or channel frequency response.

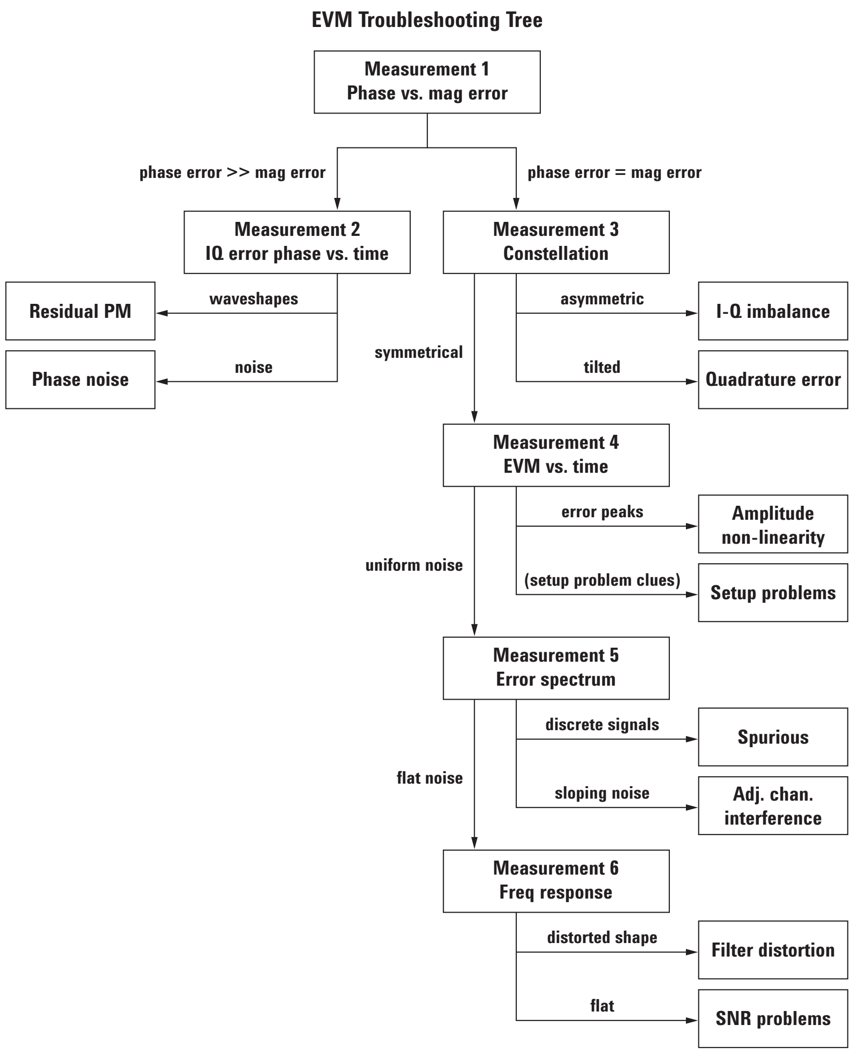


Figure 7. Error vector measurements are most effective for finding problems when used in an organized manner. This tree describes a sequence of measurements and evaluations that will focus troubleshooting efforts. More branches could be added to this tree for use on specific modulation schemes such as OFDM and CDMA.

Modulation Troubleshooting

In the X-Series, many of the measurements in Figure 7 are available in the standard-specific measurement applications, while the full complement of them (and many others) are provided in the 89601A VSA measurement application. Accordingly, the VSA measurement application is the primary tool for comprehensive modulation troubleshooting.

Note that the initial step is to separate the error vector into its magnitude and phase components, providing a way to isolate larger phase errors and any forms of discrete phase modulation. These errors, along with large frequency errors which are removed early in demodulation and displayed in the error summary table, can mask other error sources and make other modulation quality measurements less reliable.

Other error mechanisms such as distortion, noise, and I/Q impairments typically produce magnitude and phase errors which are comparable in size. A natural next step is to examine the measured constellation for obvious distortion, along with numeric parameters such as I/Q offset, gain imbalance and quadrature error.

Once the I/Q modulator is better understood it can be very useful to examine the error vector in the time and frequency domains, as described previously. In many cases error mechanisms which are quite obscure in one domain will be obvious in another.

For example, time-specific impairments such as significant amplitude droop will affect all frequencies equally but will be clearly revealed in time. On the other hand frequency-specific impairments such as adjacent channel interference will affect all symbols equally but will create a characteristic tilted or sloped error vector spectrum.

Finally, the displayed results of the analyzer's adaptive equalizer coefficients will describe the linear distortion in the signal. As noted previously, these coefficients can be examined in the time or frequency domain, providing specific information about the origin and amount of the distortion.

Conclusion

Signal analyzers such as the Agilent X-Series now offer a convenient combination of spectrum analysis, vector signal analysis, and standard-specific measurement applications. Spectrum analysis offers high performance and simplicity of operation, while vector signal analysis (including digital demodulation) provides a comprehensive set of measurement and troubleshooting tools for digitally modulated signals. Where available, standard-specific measurement applications can be the best solution for design verification and some manufacturing environments due to their speed, simplicity of operation, and customized measurement displays. Fast and convenient switching between these measurement modes or applications allows engineers to take advantage of the best combination of measurements and user interface features for their situation.

After choosing the best measurement tool or application, a fast and reliable path to design success is to follow a well-organized measurement approach, progressing from straightforward spectrum analysis through time-specific vector measurements and on to whatever demodulation and troubleshooting operations are required to find problems and achieve design goals. The organized approach can help find problems faster, and at the earliest stage of design, reducing design time and potentially reducing design cycles as well.

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