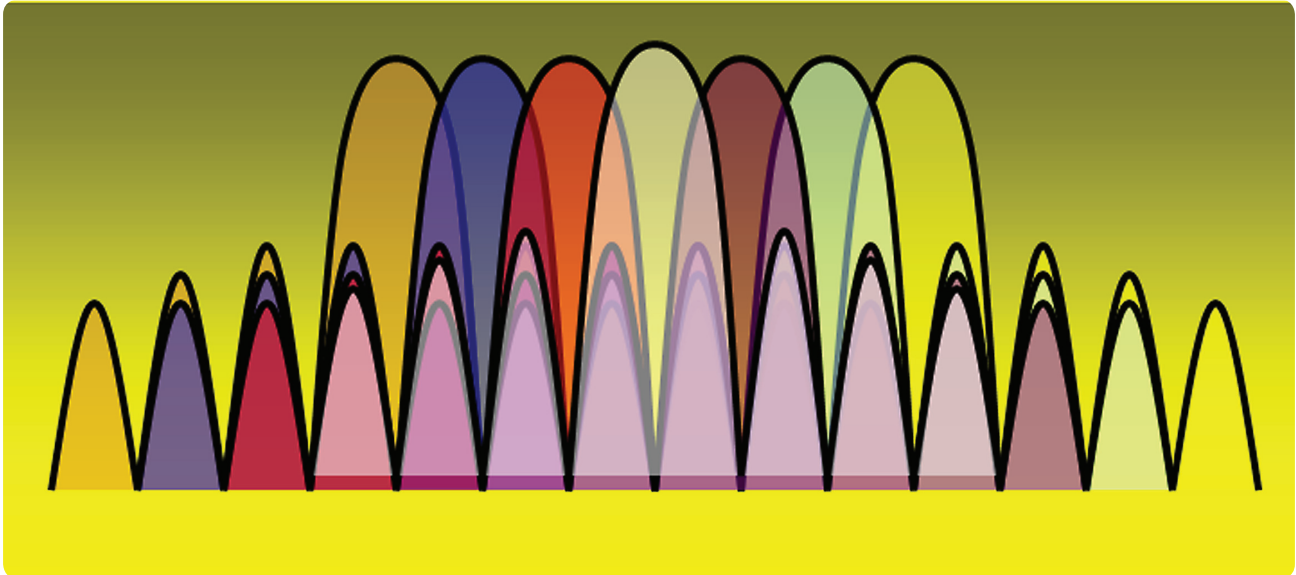


Flexible OFDM Signal Generation, Analysis and Troubleshooting

Application Note



1.0 Introduction

Algorithm design and analysis are essential steps in the development of any communications system. Some modulation schemes make accomplishing these steps more challenging than others. A prime example is the Orthogonal Frequency Division Multiplexing (OFDM) digital multicarrier modulation method. Waveforms based on this scheme are inherently complex and typically require a great deal of customization. Until now, no flexible or general-purpose solution has been available to aid in their creation and analysis.

This application note presents a flexible solution for rapid OFDM waveform generation and analysis that employs traditional signal generation and analysis using a practical commercial off-the-shelf (COTS) approach. This approach utilizes Agilent Technologies' SystemVue Electronic System Level (ESL) environment to perform system modeling and 89600 Vector Signal Analysis (VSA) software to troubleshoot and analyze the resulting waveforms. By employing

this approach, waveforms can be quickly and easily created for a wide range of purposes, including: creating typical OFDM signals compatible with new, emerging standards; exploring proprietary OFDM variations and algorithms to suit particular applications; supporting secure and military formats with minimal customization; and creating and downloading test signals into measurement equipment for hardware verification.



2.0 OFDM System Architecture Challenges

OFDM has quickly gained in popularity for wideband digital communications. Providing a combination of spectral efficiency, flexibility and robustness, it is now considered the modulation scheme of choice for many current and emerging commercial standards and is today used in such diverse applications as digital television and audio broadcasting, wireless networking, and both mobile and military communications.

When designing an OFDM signal, there are often specific design goals that must be realized. Some examples include: creating a robust waveform with minimal transmission issues and that offers a high quality of service, ensuring high throughput and resistance to interference, and compliance to standards or creation of a waveform that is unique enough (proprietary) so as to inhibit its unauthorized demodulation.

To achieve these goals, many design options at the physical layer (PHY) must be considered. For example, how many sub-carriers will be used, should encoding or interleaving be employed and what will be the mapping type. Decisions must also be made regarding what the preamble, payload OFDM symbol and pilot structure will look like. Once these decisions have been made and the waveform designed, the next step is to evaluate its system performance. Was it designed as intended and did it turn out correctly? In the initial stages of algorithm design, the answer will likely be no since there are many challenges—like fading problems and channel effects—that are associated with custom OFDM communications systems. Other challenges that may be encountered include:

- Interference issues—OFDM is vulnerable to frequency offset errors that can destroy the subcarrier orthogonality, resulting in intercarrier interference and degradation of system performance. Adjacent channel interference can also prove problematic.

- Distortion—Intermodulation distortion between OFDM subcarriers can raise the noise floor both in-channel and out-of-channel and must therefore be minimized. Phase distortion can also occur that reduces the maximum achievable data throughput rate.
- Synchronization issues—Issues like imperfect frequency synchronization can cause a loss in subcarrier orthogonality, severely degrading system performance.
- High peak-to-average-power ratio (PAPR)—OFDM signals typically have a higher PAPR than single-carrier signals. This can be very problematic for the power amplifier as it results in nonlinearities and loss of efficiency, as well as in-band and out-of-band distortions.

In each case, a range of techniques (e.g., symbol windowing, higher order modulation and adjustments to the preamble or pilot structure) can be employed to ensure the quick resolution of these issues in the waveform.

3.0 A Flexible Solution for OFDM Signal Generation and Analysis

Signal generation and analysis using the Agilent SystemVue open simulation and modeling environment and the 89600 VSA signal analysis software offers an effective solution for rapid waveform design and analysis. These solutions are critical to quickly and easily wade through the numerous design considerations and overcome the design challenges essential to ensuring a robust OFDM signal.

SystemVue creates the OFDM communications signals that can be used to model and test Layer 1 PHY architectures, both in simulation as well as when downloaded into test equipment (Figure 1). The VSA software then demodulates the signal and performs any associated analysis. A link between SystemVue and the VSA software allows demodulation to be quickly set up, since the actual waveform parameters can just be imported into VSA for implementation.

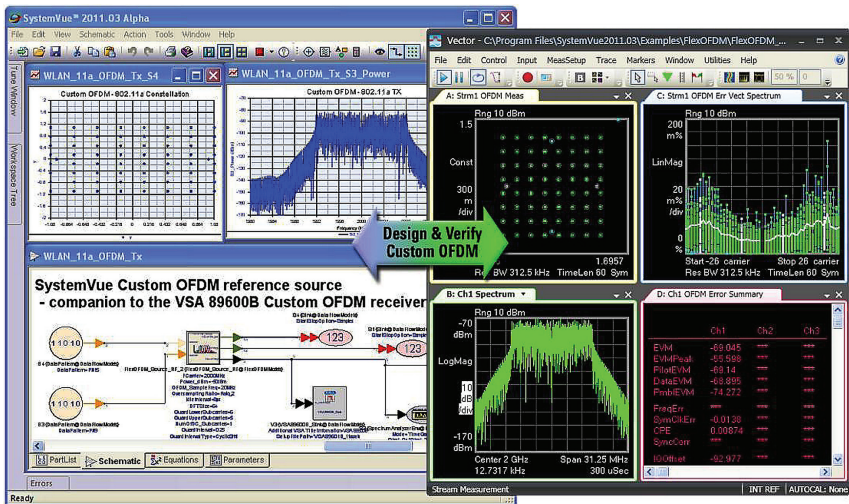


Figure 1. SystemVue creates a custom OFDM waveform that can operate in the test environment (simulation) or be downloaded into a signal generator to look at with a device under test (DUT) or analyzer to see how it performs and interoperates with any part of the block diagram.

4.0 Rapid OFDM Signal Generation

SystemVue is a system-level modeling and verification environment that provides a cross-domain PHY modeling framework for model-based design (Figure 2). It can be used to create a working PHY that integrates real-world baseband and RF using any combination of software, hardware, simulation, and measurements. This

can be especially helpful when editing an existing baseband design or tweaking an existing model to create a new proprietary waveform. Once in the SystemVue platform, the intellectual property (IP) can be used throughout the larger flow and input into other EDA tools or even used for testing and integration.

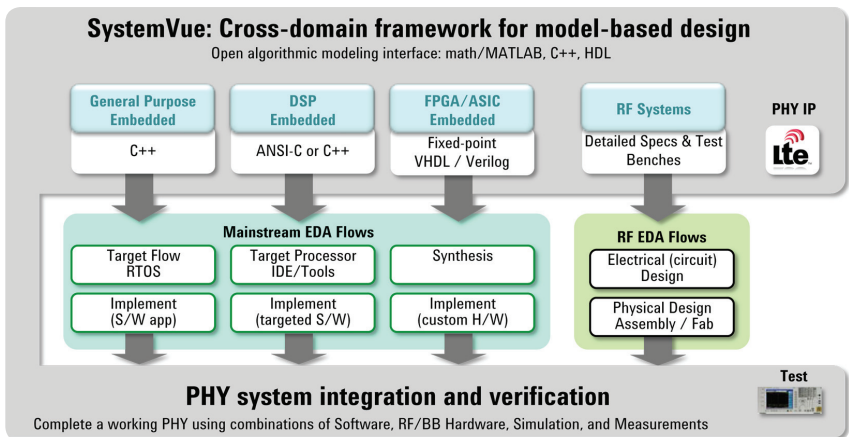


Figure 2. With SystemVue's open algorithmic modeling interface, designers can plug in IP models in a range of formats (e.g., math/MATLAB, C++ and HDL).

Using SystemVue, OFDM waveforms can be quickly and easily created. A flexible OFDM graphical user interface (GUI) simplifies the process, allowing parameter data to be entered to configure the structure of the OFDM waveform or configure their own OFDM frames from specific requirements (Figure 3). The GUI features OFDM-specific reference models that have been abstracted to a higher level (e.g., channel coding & interleaving, mapping, spectrum shaping, and IFFT), so in-depth knowledge of OFDM is not required (though usually still useful). These models can be used to explore trade-offs in OFDM system architectures. SystemVue enables scenario modeling by adding fading, noise, interferers, and the RF effects necessary for realistic system analysis and early R&D verification using connections to live test equipment.

An example of the SystemVue OFDM GUI is shown in Figure 4. All system parameters of the OFDM source are set in this GUI. The frame parameters—the switch of Preamble 1 and Preamble 2, Pilot 1 and Pilot 2, and the number of OFDM symbols of Data 1 and 2 (if available) payload—are also set. Additionally, whether or not to use symbol windowing between OFDM symbols is selected. Symbol windowing is a technique often used to help obtain a sharper roll off, although care must be taken since its use may result in a reduction in multi-path fading immunity (Figure 5). The rectangular pulse shaping resulting from symbol windowing can also introduce phase discontinuity.

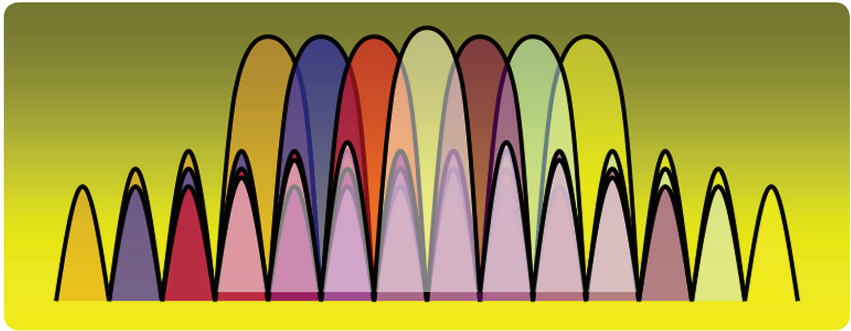


Figure 3. OFDM is a multi-carrier scheme where closely spaced carriers overlap. Nulls in each carrier's spectrum land at the center of all other carriers for zero inter-carrier interference.

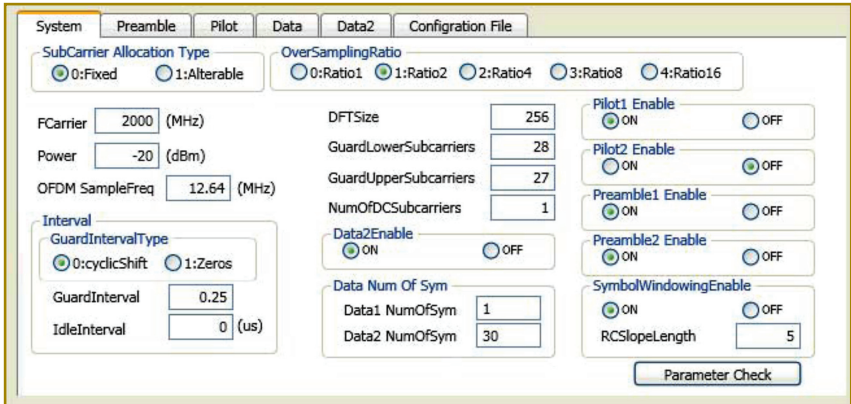


Figure 4. SystemVue's flexible OFDM System GUI allows manipulation of all waveform parameters.

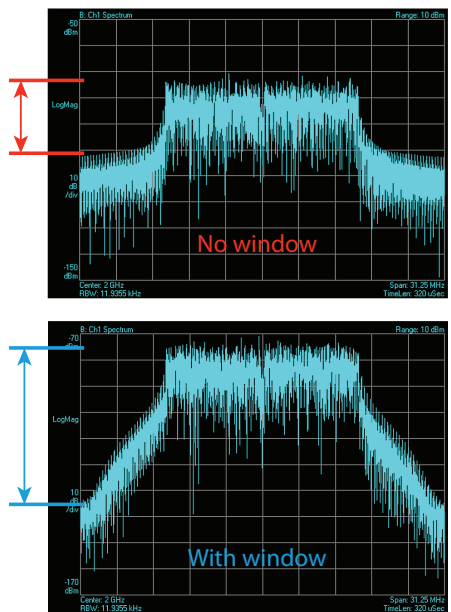


Figure 5. These images depict a waveform with and without symbol windowing.

Using the OFDM system GUI, the OFDM system parameters can be set and the waveform's I-Q structure mapped. Once this is done, the next step in developing a waveform is to structure the preamble using the OFDM preamble GUI (Figure 6). Note that the GUI will only appear if the OFDM system has a preamble (e.g., Preamble 1, Preamble 2 or both). If not, the GUI will disappear. SystemVue's custom OFDM source provides a number of parameters for configuring the preamble, including specialized indexing.

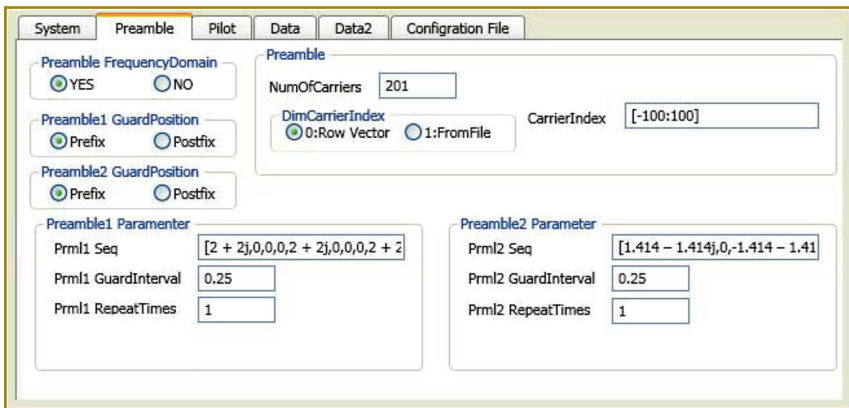


Figure 6. SystemVue's OFDM preamble construction interface shows a multi-format structure. For standards like IEEE 802.11a, a multi-format structure is generally desired.

Next, the data (payload) must be configured. There are two different options, or loads, that can be used for the OFDM design, Data and Data2. Which GUI appears depends on which option is selected (Data 1 and/or Data 2 payload), as shown in Figure 7. This GUI is also where the modulation type is specified.

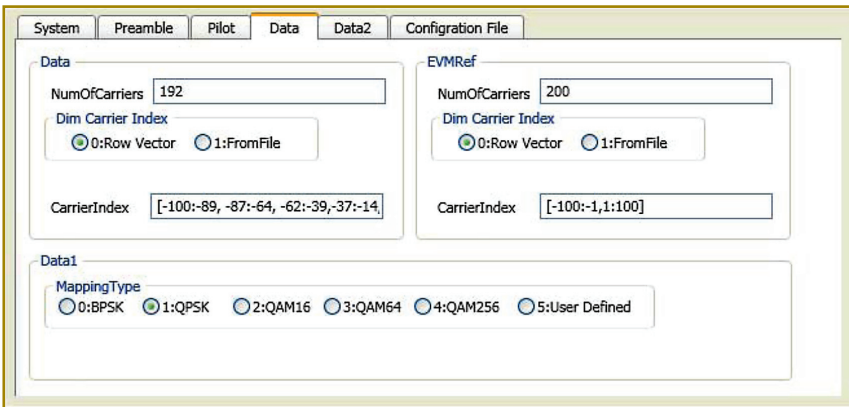


Figure 7. The data GUI shows all the parameters of the Data 1 and Data 2 (if available) payload.

Finally, the pilot characteristics are set using the OFDM Pilot GUI (Figure 8). Note that there are two kinds of pilots (Pilot1 and Pilot2) supported in the Data 1 and Data 2 payloads of the flexible OFDM system. Each pilot can be turned on or off according to each OFDM system's unique pilot pattern requirements. The four major pilot patterns in current OFDM standards are: no pilot, continuous pilots, scattered pilots, and both continuous and scattered pilots. In general, most OFDM communications (e.g., IEEE 802 series) have only one kind of pilot, either continuous or scattered. An example of a no-pilot format is the G3-PLC power line communications standard. In contrast, wireless video formats like DVB-T and DVBT2 typically have two kinds of pilot, continuous and scattered.

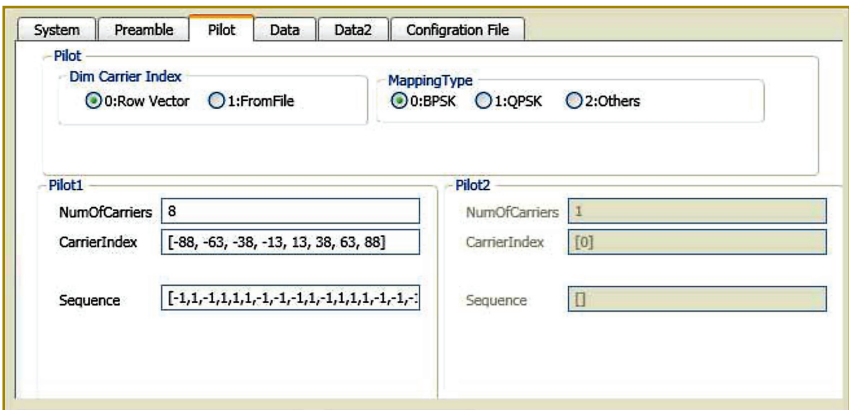


Figure 8. The OFDM Pilot GUI provides a flexible user interface for the pilot configuration. In addition to supporting the four major pilot patterns, SystemVue's custom OFDM source supports various random pilot patterns by allowing each pilot subcarrier index and its value to be input.

Once all necessary parameter data has been entered, SystemVue automatically generates the waveform. It can then be evaluated and tweaked, as necessary, to ensure the result is exactly as intended and will work for the specific application in question. SystemVue waveforms can be inserted anywhere in the block

diagram (e.g., baseband, IF, RF, analog, and digital) and used to help optimize system performance against specific requirements.

As previously mentioned, OFDM signals typically have a higher PAPR than single-carrier signals, which can be very problematic for the power

amplifier. One way to deal with this is to include specific allocated pilots to destructively add to the OFDM waveform to algorithmically reduce the PAPR. SystemVue provides a PAPR reduction algorithm that supports this capability. The algorithm features reserved carriers or peak reduction tones and is virtually distortionless.

5.0 OFDM Signal Analysis

Once the OFDM waveform is created, it can be demodulated with the 89600 VSA software. The ability to accurately demodulate the waveform provides clues to modulation quality and aids in the quick identification and resolution of any potential physical layer signal problems. It also allows system performance to be optimized against any particular design requirements.

The 89600 VSA is an advanced analysis solution that provides simultaneous views of virtually every facet of complex wireless signals, information that is critical to achieving the clarity needed to find the root cause of signal problems. The 89600 VSA software runs on a PC or inside PC-based Agilent instruments and measures over 70 signal standards and modulation types covering a range of applications (e.g., mobile communications, wireless connectivity, military communications, satellite communications, and more). Its advanced troubleshooting tools quantify spectral performance with high resolution FFT-based measurements; analyze time-domain signal quality with high quality time tools (PVT, CCDF, pulse, signal, capture/play); and characterize complex modulation down to the raw bits. The VSA works easily with spectrum analyzers, signal analyzers, oscilloscopes, logic analyzers, modular vector analyzers, and simulation software—more than 30 Agilent platforms. Because of this flexibility, signals can be evaluated anywhere in the block diagram including analog and digital baseband and IF, RF and microwave. So, VSA software operates inside a simulation, on data from an FPGA and a logic analyzer, on wideband baseband time-domain data from an oscilloscope, or on more traditional IF data from a spectrum or signal analyzer.

For convenience, SystemVue exports the configuration files needed to set up the VSA software for demodulation and analysis, both for simulated signals, as well as for hardware measurements. This is done using the SystemVue OFDM GUI Configuration File screen.

Demodulation in the VSA is done by first isolating the waveform for one symbol and synchronizing it in frequency, time and phase. Next, FFT is performed on the down converted and band-filtered signal. The FFT returns a number of vector values (subcarrier I-Q values) that are mapped onto a QAM constellation. Finally, the constellation states are converted to data bits.

During demodulation, the block of data (or time record) is used to produce a large number of individual demodulation values, one per subcar-

rier. Some are used for pilots or the preamble and therefore, are not transmitting active data. Others, like the center frequency, are not transmitting at all. Note that there is no particular requirement that the modulation scheme on any subcarrier be the same as on any other subcarrier. Pilots, for example, often use BPSK, while data carriers employ more complicated modulation schemes.

OFDM signal analysis mimics many of the same steps as demodulation, except that rather than converting the constellation states to data bits, standard constellation metrics (e.g., EVM, SNR, etc...) are computed for each subcarrier in each symbol (Figure 9). Doing so allows an EVM result to be determined that provides clues to modulation errors. Once errors are identified, there are a number of ways to troubleshoot the possible signal problems.

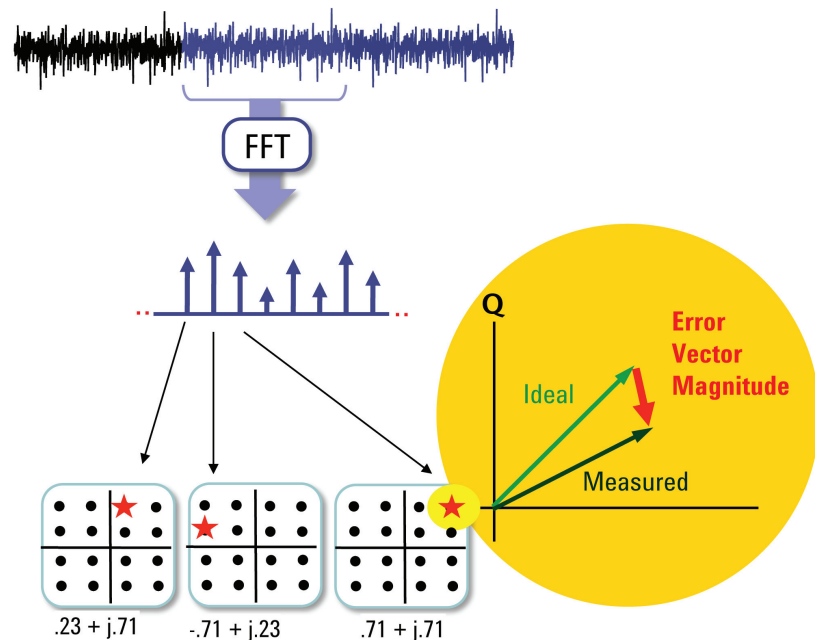


Figure 9. Shown here are the basic steps in OFDM signal analysis.

Troubleshooting signal problems first requires that the signal data errors be displayed. For an OFDM signal, that involves displaying the signal in the time or frequency domain. This pair of displays can be used to quickly understand the effects of different time and frequency interference.

Examples of time and frequency domain displays are shown in Figure 10. In the upper most time-domain display, the X axis represents the symbol number (or time), while the Y axis represents the amount of error. In other words, the display shows error versus time. The EVM numbers or values of each individual subcarrier are denoted by red dots. The RMS average is denoted by the heavy blue line. This display not only provides information about the kinds of errors in the signal, but also shows what the error spread looks like. For example, if an impulsive error was affecting a large number of subcarriers at a very narrow instant in time, the display would show one or two symbols as high in terms of error, whereas the rest of the symbols would be fairly low.

In the bottom most frequency-domain display, the X axis represents the subcarrier number or frequency, while the Y axis represents the EVM of each subcarrier. The red dots denote individual symbols in time. As an example, in the case of spurious or narrowband interference, the interference would be clearly visible on the display at a particular subcarrier(s) for all time.

The display in Figure 11 can also be used to depict OFDM signals for troubleshooting purposes. The upper left image is a composite constel-

lation showing both pilots and data subcarriers. The lower left image shows the time domain of error, while the upper right shows the frequency domain of error. The lower right image displays decoded data, along with a summary of errors (e.g., frequency and magnitude errors, and EVM), and automatically detects things like the modulation format. This array of information, coupled with engineering expertise of possible system impairments, is very helpful in identifying the waveform's potential problems and gauging their seriousness.

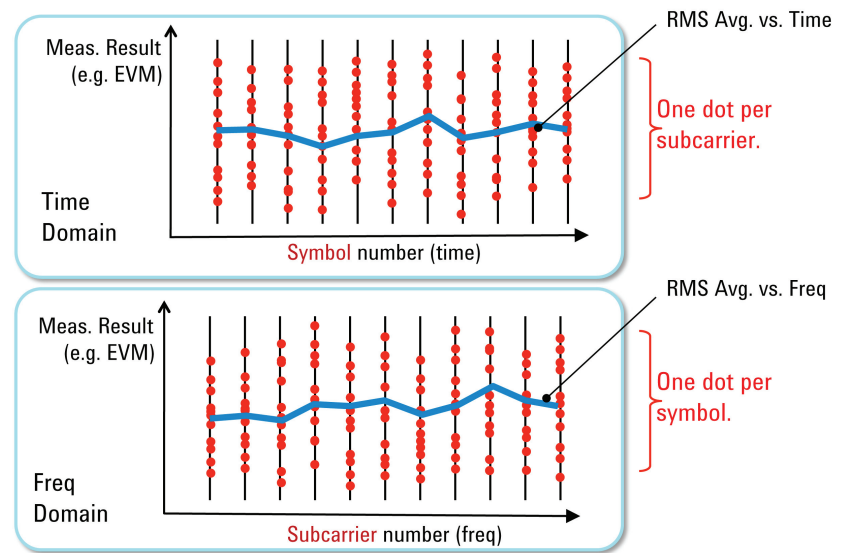


Figure 10. OFDM signals can be displayed in either the time domain (upper most graph) or frequency domain (bottom graph).

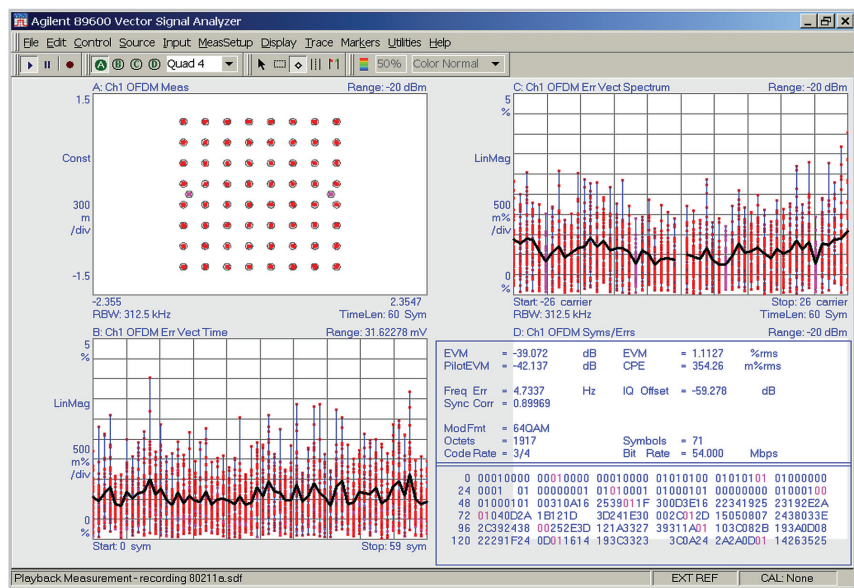


Figure 11. This display can be used to measure a waveform's modulation quality. Shown here is an example of an 802.11a waveform.

6.0 OFDM Signal Troubleshooting Examples

When it comes to troubleshooting, there are a number of things that can be done fairly quickly and easily to resolve OFDM signal problems. Many of these things have been previously available for established standards, but can also now be used for more flexible OFDM schemes.

As an example, consider the issue of amplitude and phase drift. This might occur when either the channel or transmitters are not perfectly stable and often results in problems like amplitude droop or unwanted time-domain effects.

A display of an OFDM signal with amplitude and phase drift is shown in Figure 12. Note that the error vector time is displayed in the lower left graph and error spectrum or frequency-domain error in the upper right graph. A composite constellation is shown in the upper left. The constellation clearly indicates some changes since the red dots appear to be moving or spiraling.

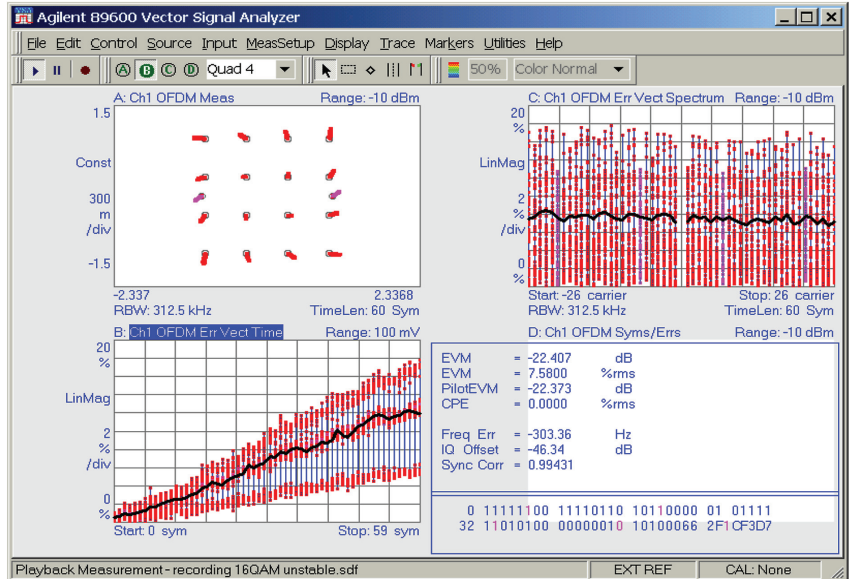


Figure 12. This display shows the case of a waveform experiencing amplitude and phase drift.

A selectable tracking feature whereby amplitude, phase and timing tracking are all selectively switched on is available in the analyzer (Figure 13). It is used for diagnostic purposes and to measure the effects of different impairments. In this case, the capability

can be used to deal with the amplitude and phase drift in Figure 12. In the upper display of Figure 13, the only tracking enabled is timing. In the center display, track phase is also turned on. As a result, the phase error that was progressing through the burst in Figure 12 is now tracked out or corrected, but there is still some amplitude error. To correct this error, amplitude tracking is enabled, as shown in the lower right display.

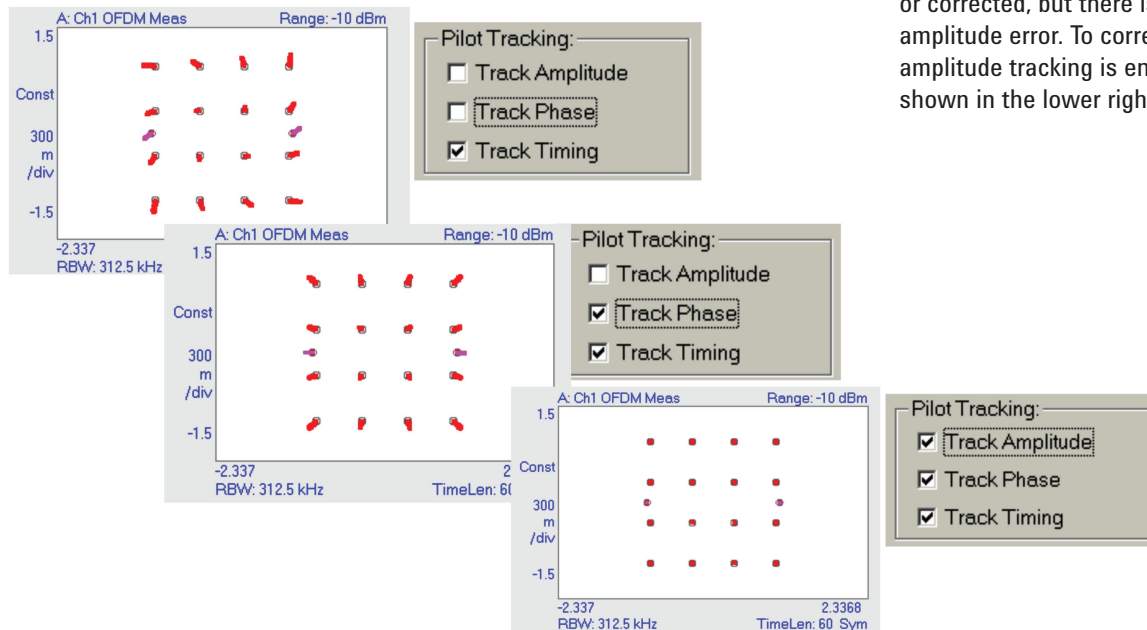


Figure 13. Selectable tracking allows a better understanding and ability to correct for the effects of individual impairments or defects.

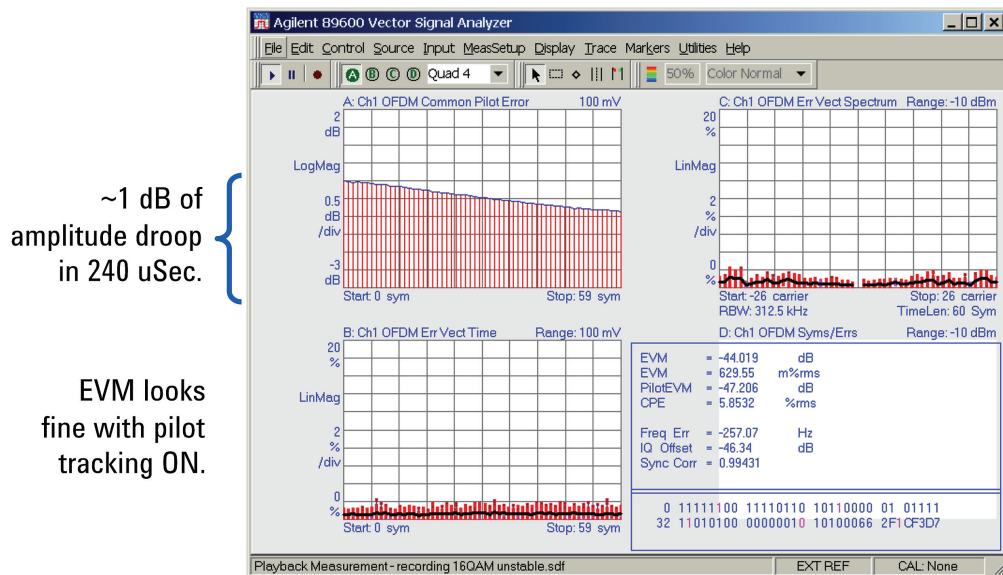


Figure 14. The CPE display is possible because the pilots are demodulated separately from the rest of the signal.

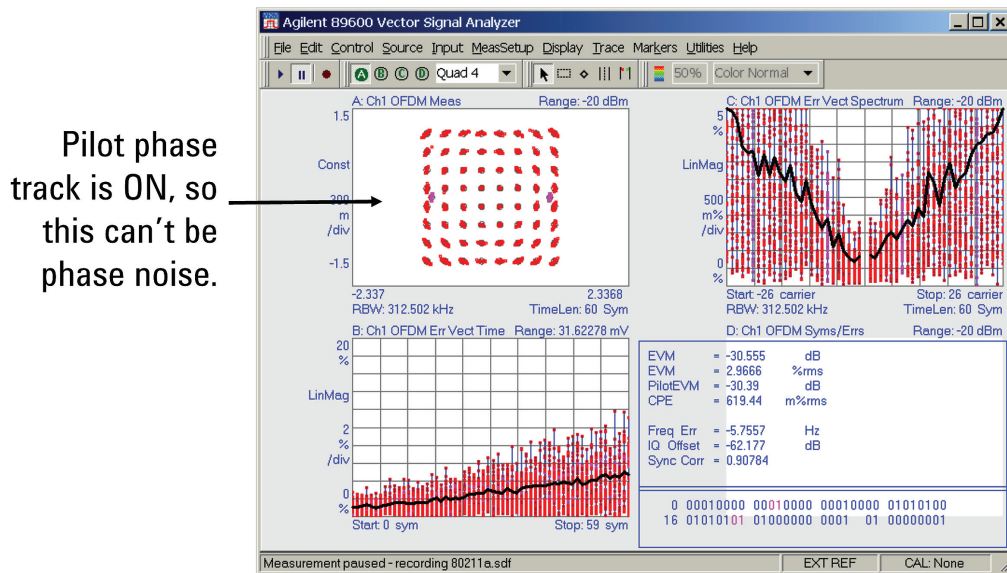


Figure 15. The V-shaped EVM plot suggests some sort of error in the OFDM signal.

The common pilot error (CPE) display in Figure 14 shows that the signal defect has now been removed. This type of display shows errors that are common to all of the pilots, which in this case is the amplitude drop. It is just one of a fairly large number of distinctive displays in OFDM analysis that are now available for flexible or custom OFDM configurations.

Another OFDM troubleshooting example relates to timing errors. Consider the display in Figure 15, which shows a V-shaped EVM plot that is V-shaped in spectrum. By

looking at the graph in the lower left it is possible to discern that the signal gets worse over time. Note that there also appears to be some kind of phase error. Next, look at the upper left display, the composite constellation. Because pilot phase tracking has been turned on in demodulation, the error can't be phase noise.

Recall that each dot in the composite constellation is a stacked set of constellations for all symbol time. It can be restricted if desired, but in this case it's the complete burst.

Consequently, each dot corresponds to a point in time and frequency. Looking back at the V-shaped plot then, notice that the errors get larger as we move away from the center frequency. This suggests a couple of possible causes for the error, either an I-Q time offset or an error in the subcarrier spacing (symbol clock error). In the latter case, as you get farther and farther away from the center subcarrier (typically untransmitted), errors get larger and the result is a larger offset in terms of frequency or phase from that center carrier.

7.0 Analyzing Proprietary OFDM Signals

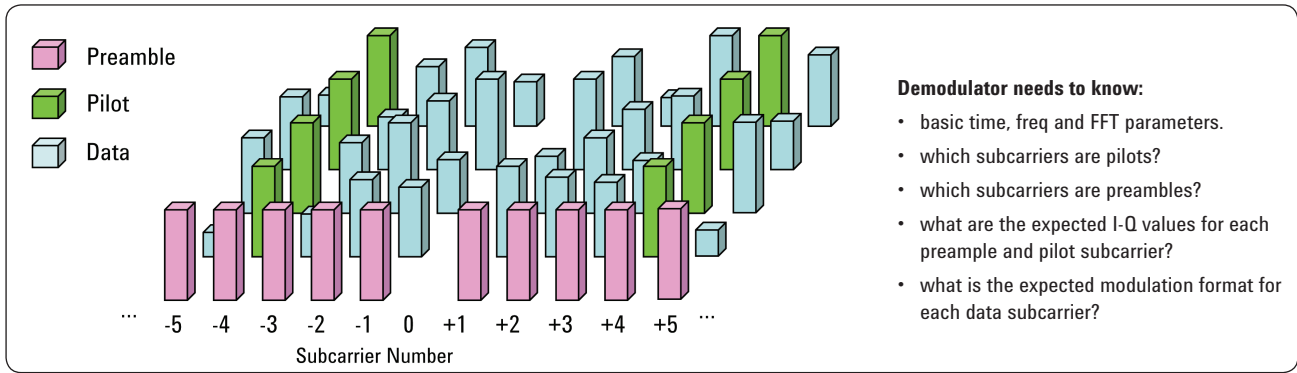


Figure 16. In order to demodulate custom or proprietary signals, the analyzer needs to know a range of information such as that listed above. The designer provides some of the information and the analyzer then figures out the rest on its own.

The same techniques used to analyze standard OFDM signals can also be used on custom or proprietary signals. One simply provides the analyzer with the basic parameters needed to perform demodulation and it then performs automatic detection and synchronization to figure out the rest (e.g., modulation types on pilots and data subcarriers, and so on). Most analyzers are very good at detecting characteristics, so the key to analyzing proprietary OFDM signals lies in getting the basics of the signal right (Figure 16).

In OFDM systems with hundreds of subcarriers, a preamble and various pilots, there can be a large number of parameters to tell the analyzer. If the waveform was generated in SystemVue, the configuration files with the necessary parameter information can simply be exported into the VSA for demodulation, thus eliminating the need to manually enter the data.

When data must be entered into the VSA software manually, it is done using the custom OFDM configuration window (Figure 17). Here, users can enter a range of information (e.g., the type of guard interval being used, and the pilot I-Q and preamble I-Q values) in much the same way they would fill out a spreadsheet.

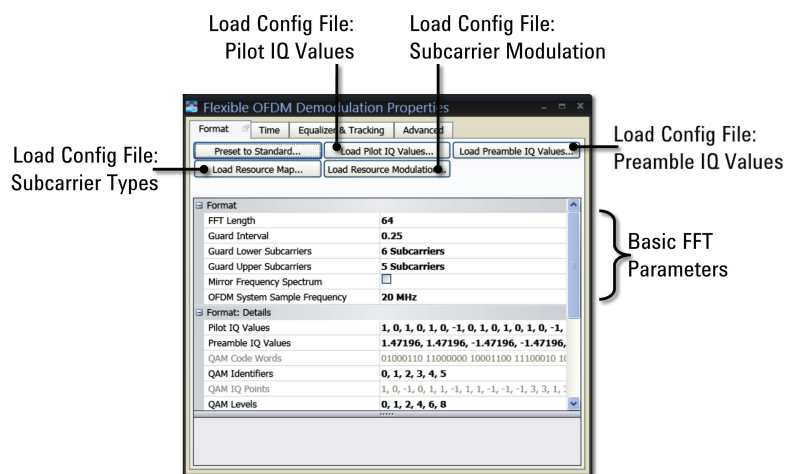


Figure 17. In this custom OFDM configuration window, files loaded into the analyzer are listed at the top of the screen (e.g., subcarrier types and preamble IQ values). The remaining fields are then populated in the window with basic FFT parameter information.

An example of a configuration file, the ResourceMap, is shown in Figure 18. The function of this file is to describe how each subcarrier is defined for every symbol during a burst. On the vertical axis, there are symbols numbered 0 through 5, while on the X-axis there are the individual subcarriers identified for each symbol

as data, pilot, preamble and as an untransmitted subcarrier (null). With this ResourceMap, the modulation type for any subcarrier for any symbol can be chosen as a way to allocate the spectrum space in a manner that will provide the kind of robustness needed to get data transmitted in a suboptimal environment.

4434443444344434443444344434444444434444434443444344434444344	Symbol #0
4434443444344434443444344434444444434444434443444344434444344	Symbol #1
333333333333333333333333333433333333333333333333333333333333333	Symbol #2
333333333333333333333333333433333333333333333333333333333333333	Symbol #3
000001000000000000001000000400000010000000000000000100000	Symbol #4
000001000000000000001000000400000010000000000000000100000	Symbol #5

Subcarrier type: 0 = data 1 = pilot 3 = preamble 4 = null

← repeat

Figure 18. The ResourceMap configuration file describes the function of each subcarrier and every symbol.

8.0 Conclusion

Some of the features available in the VSA to help simplify configuration include:

- Auto-detect pilot I-Q;
- Auto-detect data subcarrier modulation format (for any individual subcarrier or all of them at once);
- A loop mode for continuously looping through last N symbols, enabling shorter configuration files; and
- An indexed modulation format table to allow fairly high flexibility in terms of modulation format and how that modulation format changes during the burst. The table can modify all data subcarrier modulation formats simultaneously, by changing one value in the table.

Once all configuration files have been imported into the VSA, basic FFT parameters have been entered, and all remaining information automatically detected, the next step is troubleshooting. To do this, one might start by analyzing just the preamble and symbols one at a time, optimizing them until they are right. Then, this information can be used to verify that what is intended to be transmitted is actually being transmitted so that it is possible to make good quality modulation measurements throughout the rest of the system.

Generating and analyzing typical and custom or proprietary OFDM signals for modern communications systems can be a difficult task, in large part due to OFDM's inherent complexity. A practical COTS approach that utilizes the SystemVue system modeling tool and 89600 VSA signal analysis software now provides an ideal solution to this dilemma.



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