Vector signal analysis in an oscilloscope

Arthur PiniPatrick Connally, - February 07, 2017

Digital or vector modulation can provide increased spectral efficiency, higher data security, and higher quality communications. This comes at a cost of increased system complexity and a resultant increase in test difficulty.

Adding vector signal analysis (VSA) to an oscilloscope reduces the count of necessary test instruments and simplifies the testing process by consolidating analysis within a single instrument. This article looks at vector signals and the analysis tools needed to effectively measure them.

Vector state measurements

Vector or quadrature signal generation achieves high spectral density by transmitting multiple bits with each symbol sent. Consider quadrature phase shift keying (QPSK) which encodes two digital bits with each transmitted symbol. These two bits can have any of four values, 00, 01, 10, and 11. QPSK uses phase modulation to encode these values, assigning a distinctive phase for each of the two bit digital values. The phase shifts are created by breaking the data stream into two orthogonal components called the in-phase (I) and quadrature (Q) components. These components, having a fixed 90° phase difference, can be added – using different amplitude weights – to create any possible phase. In QPSK, the weighted I and Q components are combined to produce phase shifts of 45°, 135°, 225°, and 315°. This can be visualized by cross-plotting the I and Q components in an X-Y display. An example, using the Teledyne LeCroy VectorLinQ software option is shown in **Figure 1**.

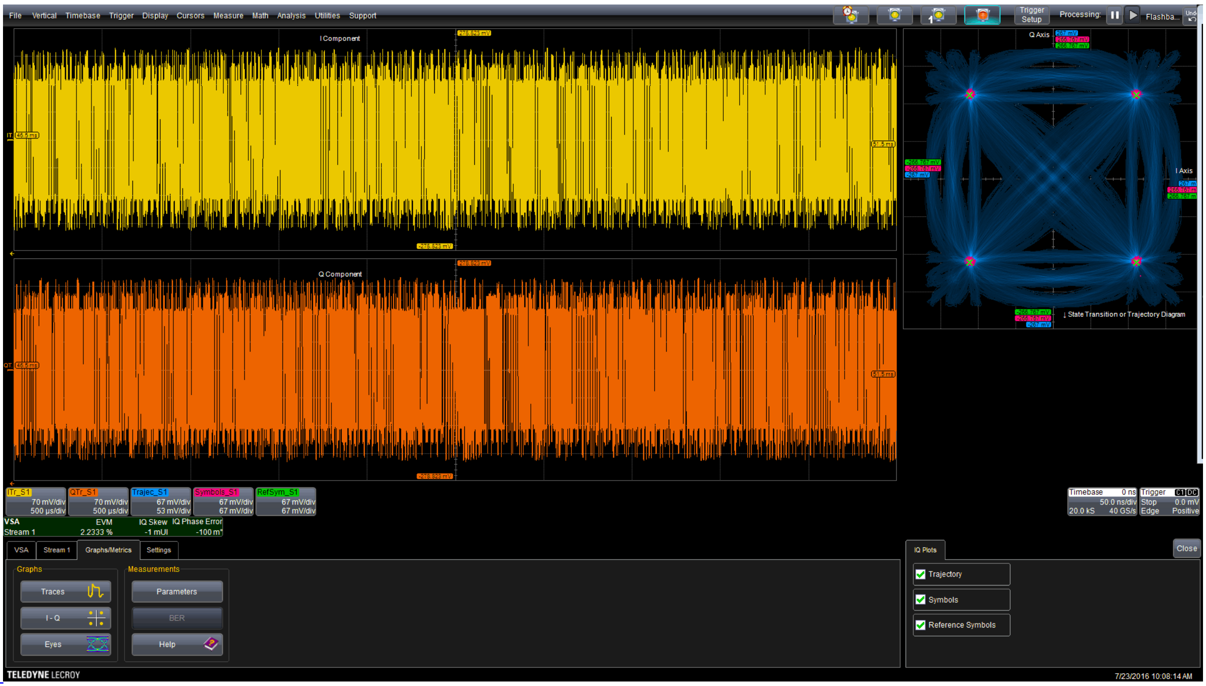

Figure 1. Cross plotting the I and Q components of a QPSK signal creates a state transition or trajectory diagram which shows the phase and magnitude of each encoded bi-pair as well as the transition paths between states. Reference (ideal) states as shown as 'x' marks and measured states are shown in red.

Figure 1 shows the acquired I and Q component waveforms in the two grids to the left, and the state-transition or trajectory for the QPSK signal in the X-Y diagram on the right. The green "×" symbols on the trajectory diagram mark the ideal or reference state locations, and can be customized by the user. The red areas show the measured state locations. The blue traces show the transition paths between states. A related X-Y plot is the constellation diagram. Getting into the subtleties a little more, the difference between a constellation and a state-transition diagram is that the constellation shows specifically the signal position at the recovered symbol clock times (the red points). The state-transition diagram shows these points as well as the trajectories (path the signal takes to get from one symbol to the next).

Ideally the measured state locations should be under the reference states. The degree to which their location differs from the ideal is measured by the error vector magnitude (EVM) parameter which is also shown to the left above the setup dialog box. The numerical value displayed as EVM is the RMS value of all the digital states' magnitude errors captured during that acquisition. Also shown is the *Phase Error* which is the phase difference between the signal vector for each state and the ideal reference vector. The value displayed as *Phase Error* is the RMS of all the states captured during that acquisition.

Modulated carrier

The I and Q components are used to phase modulate a carrier for transmission. Vector Signal Analyzers are capable of acquiring and demodulating such a signal for vector analysis as shown in **Figure 2**.

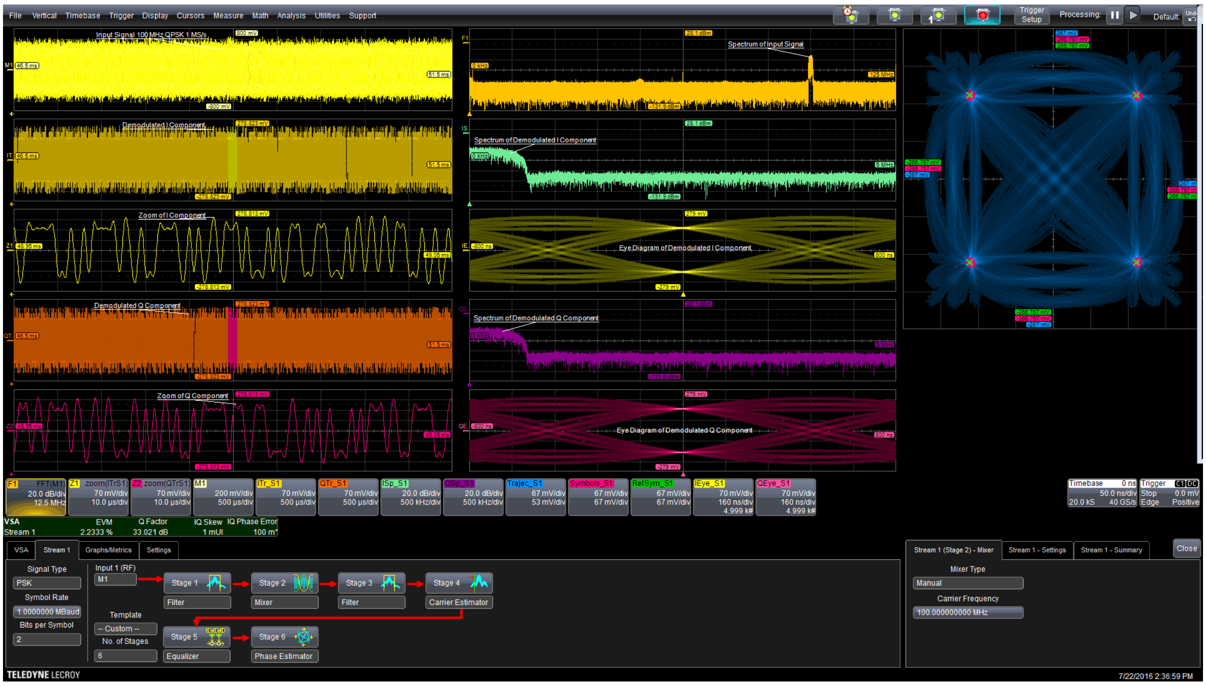

Figure 2. Demodulation and analysis of a QPSK signal on a 100 MHz carrier showing both time and spectral views of the signal as it is processed.

Figure 2 is a story board of the processing involved in analyzing the modulated RF carrier. The source, shown as trace M1 in the upper left grid, is a 100 MHz RF carrier that has been phase modulated by a QPSK signal at 1 MSymbol-per-second. The grid to the immediate right of the source is the Fast Fourier Transform (FFT) of the modulated carrier. The FFT provides a frequency domain or spectral view of the signal. It shows a spectral peak, representing the source signal centered at 100 MHz. The dialog box at the bottom of the display shows the VSA software processing flow which is controlled by a template.

There are two default templates: one for baseband I and Q processing, and another for RF processing as shown here. The process starts with a band-limiting Gaussian filter centered at 100 MHz. This is followed by a quadrature mixer where the signal is mixed with a 100 MHz local oscillator and down-converted to baseband. The output of the mixer is lowpass filtered to retain only the baseband signal components. The filter is actually matched with an identical filter on the transmitter side in order to reduce inter-symbol interference (ISI). Note how the eye diagrams “pinch together” exactly at the clocking point (eye center). This is indicative of matched Nyquist filtering. Of course, having such a filter on the transmitter also helps to reduce occupied channel bandwidth.

The next stage in the process is the *Carrier Estimator*. This algorithm estimates and compensates for the residual frequency offset in the carrier. This is followed by an equalizer which corrects any frequency-dependent distortion in the signal. Finally a *Phase Estimator* measures the phase difference between carrier source and the local oscillator. The resultant output consists of the baseband I and Q signals.

The I component is shown in the second grid from the top on the left side. Below it is a zoomed view of the I component. The Q signal component is fourth from the top on the left. A zoomed view of it is in the bottom grid on the left.

Immediately to the right of the I and Q components is the spectral view of those signals. Note that the spectra of these demodulated signals have been shifted in frequency to baseband, beginning at 0 Hz.

The demodulated I and Q components are non-return-to-zero (NRZ) signals which carry the digital information. Immediately to the right of the I and Q zoom traces are eye diagrams of each component. The eye diagrams help to verify the integrity of these signals.

The X-Y display provides the visual analysis of the I and Q components as well as the measured parameters we discussed previously. There are fourteen distinct parameters available.

There are a total of six processing function blocks available for signal operations. These processing tools allow this software to process baseband or RF carriers using PSK, QAM, Circular QAM, ASK, or FSK modulation. There is also a custom MATLAB process which allows users to script their own custom processing functions using MATLAB.

Quadrature Amplitude Modulation

Quadrature Amplitude Modulation

Increasing the spectral efficiency of a data communications system requires increasing the number of bits per transmitted symbol. One way of accomplishing this is to encode the digital data by modulating both carrier phase and amplitude. This is quadrature amplitude modulation, or QAM. The most common format is 16QAM, where four bits per symbol are encoded as sixteen different combinations of amplitude and phase. Moving from QPSK to 16QAM doubles the data rate without increasing required bandwidth; the fact it does so by introducing lower amplitude symbol states means that the SNR margins in such a design become tighter.

The VectorLinQ view of an RF modulated 16 QAM signal is shown in **Figure 3**.

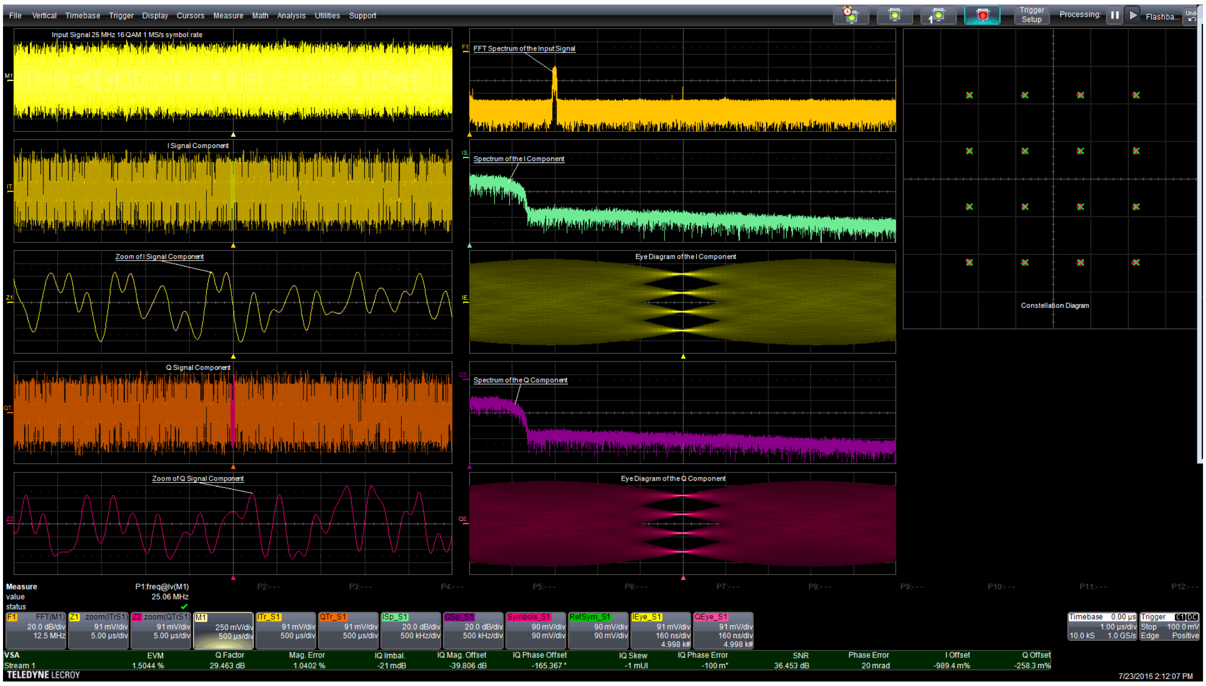

Figure 3. The analysis of a 16QAM signal including the constellation diagram and parameters

The same processing has been applied with the carrier frequency adjusted to match the 25 MHz carrier used in this example. In this case the trajectory paths are not shown, only the measured state positions and the reference states; this is a constellation diagram. As can be seen there are sixteen states representing all possible values of four bits. The eye diagram now has four levels and three intermediate eye openings. Note also that thirteen vector-related measurement parameters are shown on the bottom of the display.

The VSA software supports up to eight simultaneous processing streams. This enables operations such as comparing the results of different processing scenarios.

Consider the dual-stream processing shown in **Figure 4**.

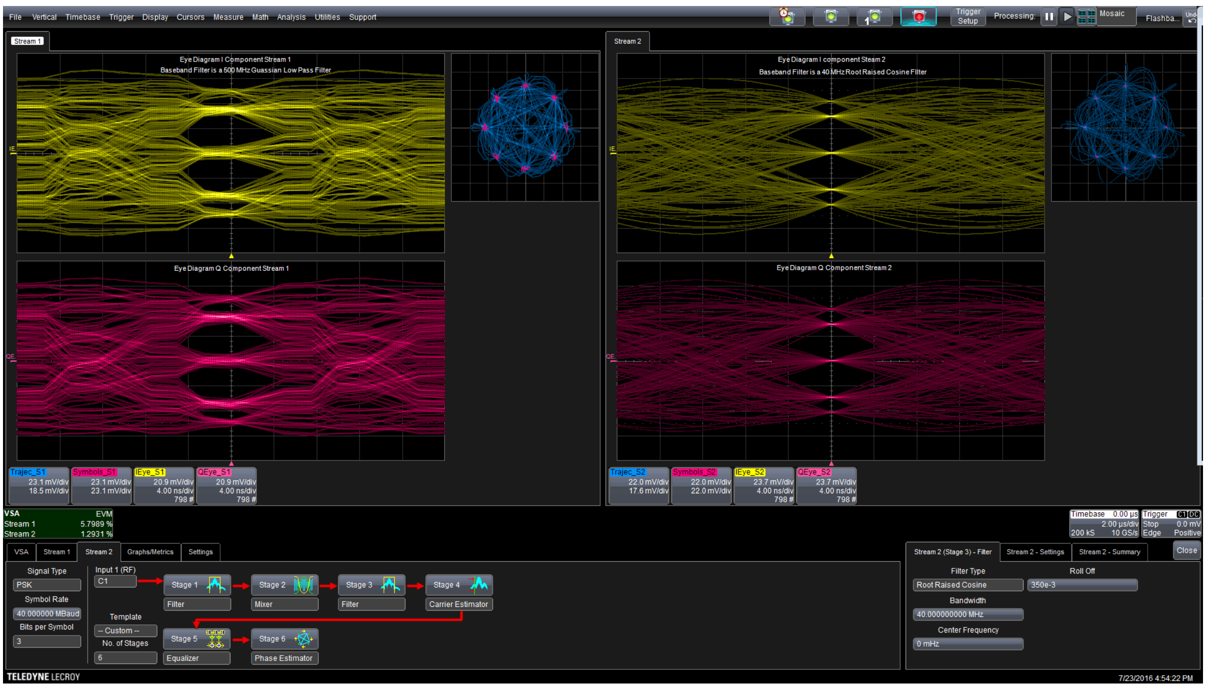

Figure 4. Using two of eight processing streams to compare the effects of different baseband filters

on demodulator performance.

In this example, a 1GHz 8-PSK signal is RF-down-converted and demodulated using two different processing setups – one in each of the two streams. The processes are identical except for the baseband filter used after the down conversion. Stream 1 (left side in Figure 4) applies a 500 MHz Gaussian filter, while stream 2 (right side in the figure) uses a 40 MHz root-raised-cosine filter. Side-by-side displays of the eye diagram and state transition diagrams permit easy visual analysis, while measurement parameters provide quantitative data.

Comparing the dispersion of state vectors in the state-transition diagrams shows that the filter in stream 2 produces a tighter grouping. And comparing the EVM parameter measurements, stream 1 has an EVM of 5.8% while stream 2 has a much better EVM of 1.3%. The eye diagrams also show a wider opening for the stream 2 filter configuration.

Conclusions

The ability to process, display, measure, and analyze vector-modulated signals on an oscilloscope makes for a powerful tool. The key features to consider when working with vector-modulated signals are: constellation and state-transition diagrams to determine the accuracy of the signal vector magnitude, phase & spectral views to verify the frequency content, and eye diagrams to confirm signal integrity. These tools are complemented by the ability to demodulate RF carriers and extract the underlying I and Q signal components.

Also see:

- Oscilloscope articles by Arthur Pini
- Oscilloscope software: spectrum analysis or vector signal analysis?
- Measure vector and area with an oscilloscope X-Y display
- Review: Signal Hound VSG25A vector signal generator

—Art Pini is an independent consultant, technical support specialist, and electrical engineer with over 50 years experience in T&M, and Patrick Connally is a Technical Marketing Engineer for high bandwidth scopes at Teledyne LeCroy.