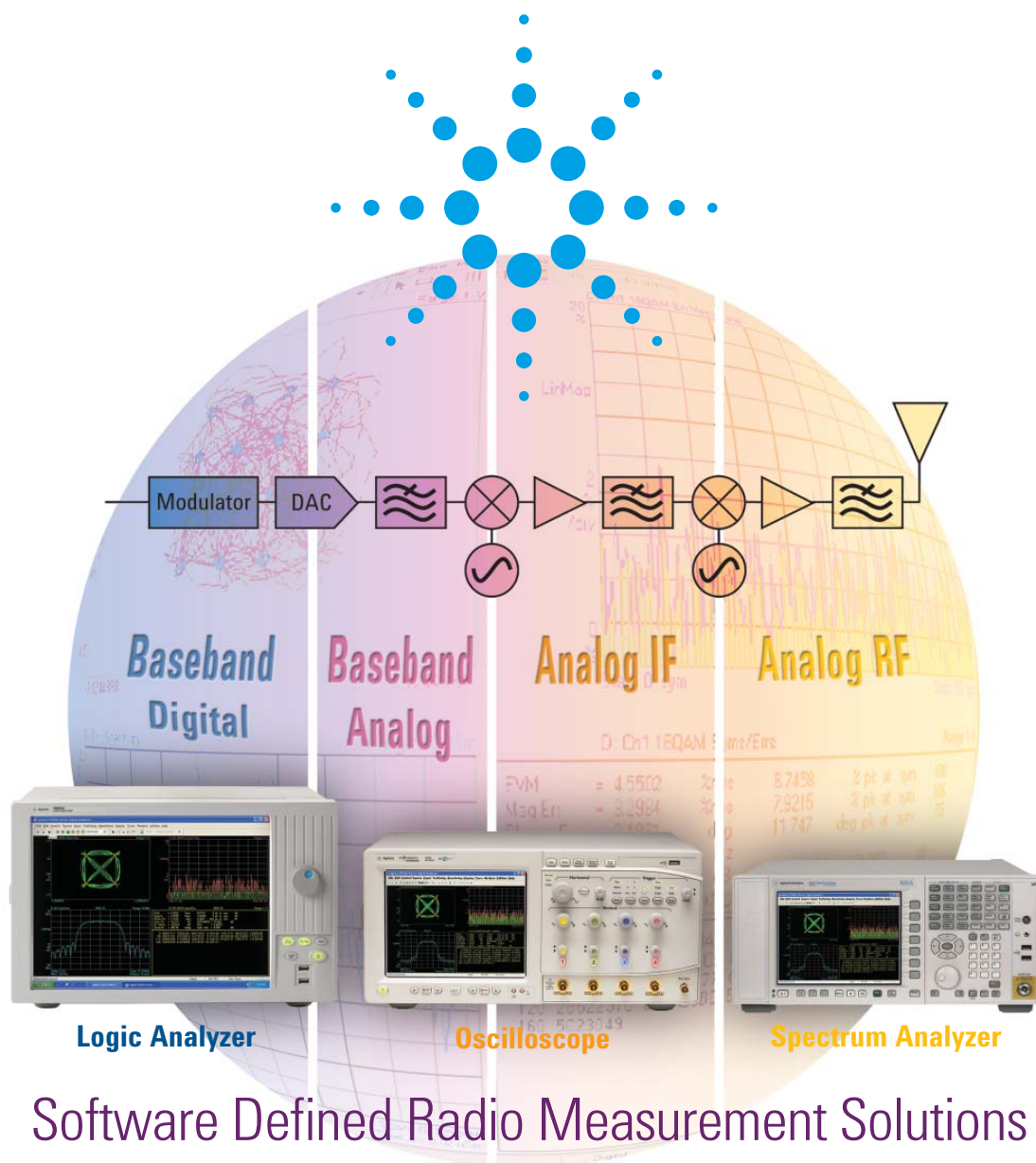




Software Defined Radio Measurement Solutions

1.0	Introduction	2
2.0	Software Radio Architectures	3
3.0	Software Radio Impairments	5
4.0	Bit Error Rate Testing	6
5.0	Multiple Domain Analysis Tools	7
6.0	Vector Signal Analysis	9
7.0	Vector Signal Analysis Across Multiple Domains	11
8.0	Digital VSA	13
9.0	Signal Generation Tools for SDR	15
10.0	Simulation Tools and Instrument Connectivity	17
11.0	References	19



Agilent Technologies

1.0 Introduction

Interoperability concerns and high costs, associated with existing communication systems, are driving the integration of software defined radio (SDR) technology into commercial and military wireless systems. On the commercial side, the mobile communications industry has seen the parallel evolution of a wide variety of incompatible radio standards throughout the world and even within specific geographies. Consumers want the ability to use the most reliable service in a given location. Developing a truly international handset is nearly impossible. Multi-mode handsets provide some relief, but with increased cost, higher power consumption and limited flexibility as standards evolve.

On the military side, yesterday's model of using independent communication systems for different tactical functions simply doesn't fit with the network-centric warfare model being pursued by virtually every modern military. Today forces are fast, mobile, tightly integrated and closely coordinated, which requires the ability to quickly and freely communicate across organizational boundaries. Additionally, maintaining today's diverse systems requires a large support footprint with its corresponding high cost. A similar situation exists for public-service organizations, such as law enforcement and fire departments, who also use a large number of non-interoperable radios at federal, state, and local levels.

In the original context, the term software defined radio (SDR) refers to a reconfigurable radio based solely on software and having the analog-to-digital conversion occurring directly at the antenna [1, 2]. While practical limitations in the current performance of analog-to-digital converters (ADC) prevent sampling wideband waveforms directly at the antenna, the development of a radio system that can change its operating frequency, modulation, operating bandwidth and network protocol without the need to change the system hardware is highly desirable.

As digital signal processing (DSP) and ADC speeds increase, more of the signal processing will be done digitally. Where a radio once processed analog signals from the RF through to baseband, newer SDR-based systems implement a digital baseband and digital IF with an evolution of moving the transition between the digital and analog domains as close to the antenna as technically possible. However more digital content in the radio leads to new measurement and troubleshooting challenges for the traditional RF designer who now has to deal with the digital signals and bus structures of reconfigurable logic. In addition, DSP and digital hardware designers are now faced with understanding and measuring signal quality in terms of high-level functional performance that includes vector diagrams and error vector magnitude (EVM) metrics.

This application note introduces the SDR architecture and types of analysis tools that are available when measuring the digital, analog and RF sections of a software radio. This note also shows how vector signal analysis tools can be applied across multiple domains when designing and troubleshooting SDR components and systems. Also discussed are vector signal generation and how software radio design has influenced the connection of this predominately RF/analog hardware into the digital domain. Lastly, this note will introduce how instruments and radio hardware can be directly integrated into advanced software simulation tools.

2.0 Software Radio Architectures

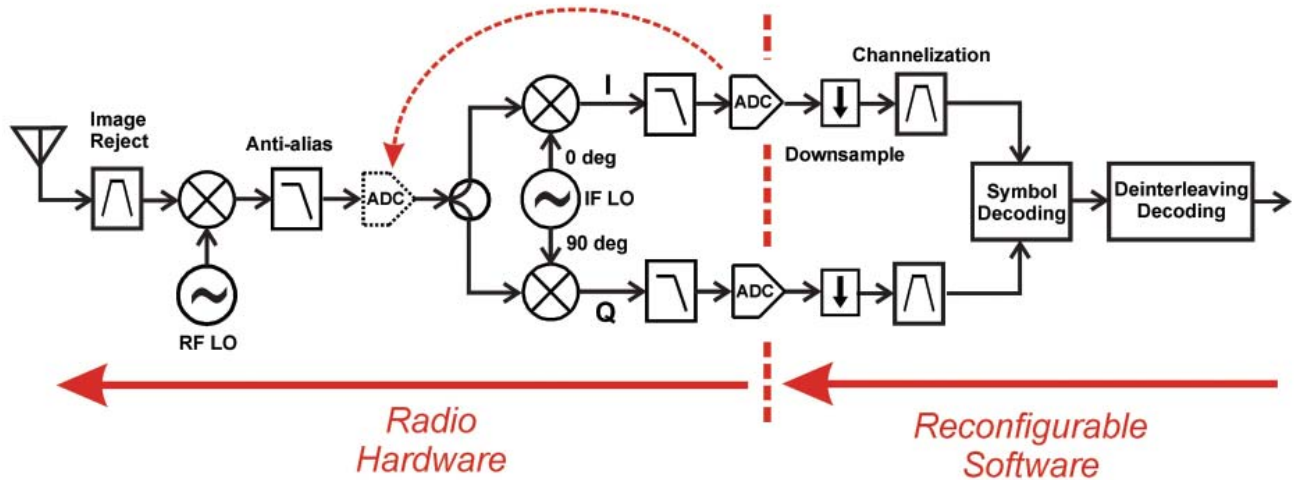


Figure 1. Simplified block diagram of a typical SDR receiver

The ideal SDR radio architecture would allow digitization of the full bandwidth covering all the radio channels to be supported by the terminal. The speeds of today's ADCs limit the operating bandwidth of the digital front-end; therefore most radios require an RF to IF conversion. The ADC's performance (i.e. bit resolution, sampling rate) and the architecture for the RF to IF conversion require a tradeoff between performance, power consumption and cost. An example of a practical SDR receiver using IF sampling is shown in figure 1. The figure shows two possible locations for the ADC within the downconversion path. In one case, the ADC is placed after the IQ demodulator. This configuration requires more analog circuitry and two ADC channels at the baseband or low-frequency IF. As ADC speeds improved, the ADC may also be placed before the IQ demodulator. In this case, the IQ demodulation occurs completely in the digital domain. This second approach removes much of the analog circuitry and the architecture begins to approach that of an ideal SDR as the transition point to digital occurs much closer to the antenna. Alternate receiver architectures use a direct-conversion of the RF signal to baseband in one

step. In this case the first local oscillator (LO1), as shown in figure 1, is eliminated and the second oscillator (LO2) is tuned to the RF carrier frequency. The direct-conversion receiver eliminates the need for an IF and an image filter at the RF front-end; however, they require good LO rejection and two ADCs: one for the I channel and one for the Q channel.

After digitization of the IF or baseband, the digitized waveforms enter the DSP domain where channelization and signal processing are performed. If digitization occurs before the IQ demodulator, the demodulator is fully digital and uses a digital LO, digital mixers, and decimation filters. The IQ demodulator converts the input signal into a complex, I and Q, baseband representation. These signals are then digitally filtered to pass the desired channel. The last step involves symbol demodulation into bits, de-interleaving and decoding. In comparison to more traditional receiver architectures, the SDR performs channelization in the digital domain and therefore can be reconfigured as required without the need to change the radio hardware.

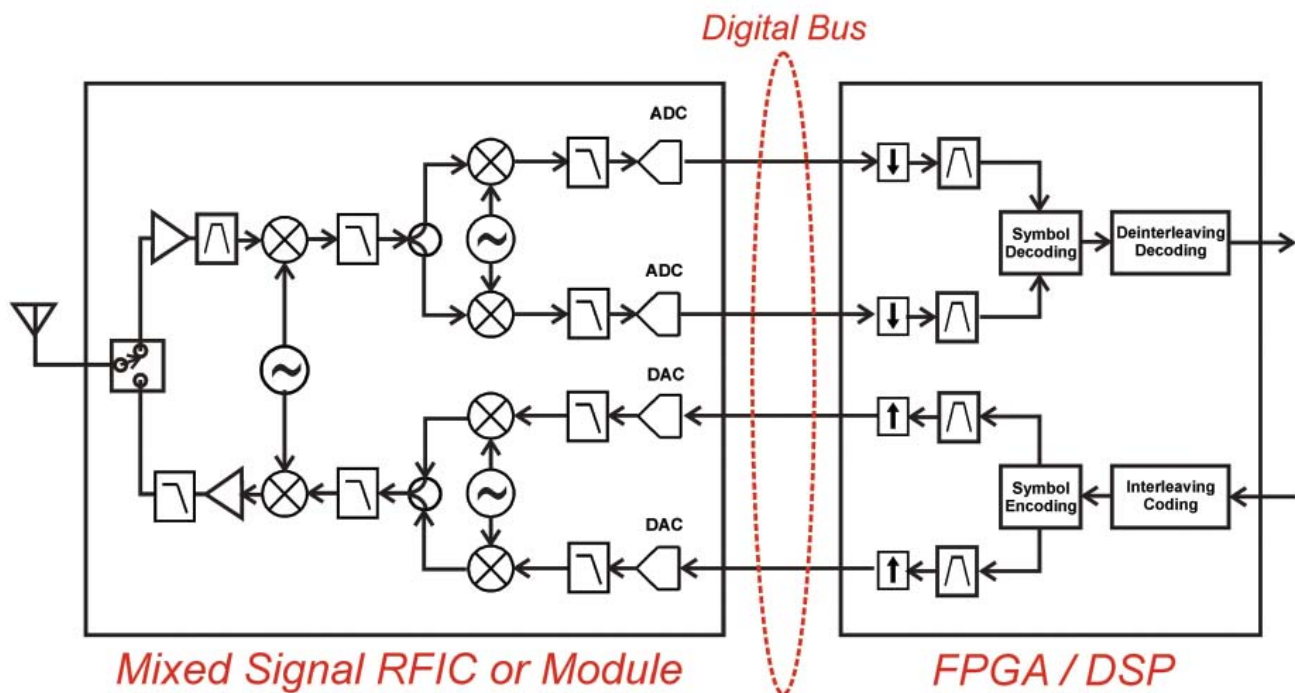


Figure 2. SDR chipset with digital interface

The radio designer must decide the appropriate architecture for the target performance and cost. Because of different requirements between the RF and digital sections, a complete radio may be constructed from two or more modules or ICs. Figure 2 shows how the transceiver of a software radio can be partitioned into a mixed signal RFIC or module and a baseband circuit. The baseband circuit will contain the DSP algorithms for data recovery using the specified network protocol. It's the use of adaptable software algorithms, as typically found in field programmable gate arrays (FPGA) and/or DSP chips, that makes the SDR reconfigurable "on the fly".

With the current trend to place the ADCs into the mixed-signal RF front-end, communication between the front-end and baseband occurs over a digital bus. Communication over this bus can be serial or parallel depending on the application. One example of a commercial digital interface is the DigRF standard [3], which was created by a consortium of chipset manufacturers that defined a standard for serial communication in 2.5G and 3G cellular chipsets. Whether standards-based or a proprietary implementation, a digital interface between the front-end and baseband requires special signal analysis and signal generation tools to properly characterize this interface. By combining Agilent's signal analysis tools and signal generation products, designers can comprehensively characterize the behavior of their SDR system from baseband to antenna.

3.0 Software Radio Impairments

A practical software radio system can suffer from a number of impairments that can give rise to error generation and degradation in overall system performance. Typical RF impairments can be created by LO phase noise, amplifier compression, spurious signals, filter tilt, filter ripple, channel fading and co-channel interference. Analog impairments at the IF can have many of the same issues as RF signals but also include modulator and demodulator imbalances between the I and Q channels. These RF and analog impairments are not confined to SDR systems but may be found in any digital radio system. The fact that the SDR uses such a large portion of digital logic and DSP introduces additional impairment concerns that may not be found in a traditional radio design. For example, the performance of a software radio is largely a function of the ADC and DAC used to transition signals between the analog and digital domains. The bit resolution and operating bandwidth of the ADC may be the limiting factor when determining the dynamic range of the SDR receiver. The performance of the ADC is also tied to the RF or analog signals driving it. A high-power blocking signal operating in an adjacent channel will limit the dynamic range of the ADC, as this interfering signal could be more than 80 dB above the desired signal. Including the fact that the ADC creates its own internally generated spurious signals due to quantization effects; the system performance is largely limited by the ADC performance under these dynamic conditions.

There are numerous other RF, analog and digital impairments that can degrade system performance. Table 1 provides a list of some of the more common problems that may exist in a practical SDR design.

Impairment	Domain	Digital	Analog	RF
Incorrect Symbol Rate	●			
Wrong Filter Coeff.	●			
Wrong Interpolation	●			
DAC/DSP Error	●			
ADC Error	●			
IQ Imbalance	●	●		
Burst Shaping Error	●	●	●	
Spurious Signal	●	●	●	
Filter Tilt/Ripple	●	●	●	
LO Stability		●	●	
Interfering Signal		●	●	
Compression			●	
AM-PM Conversion			●	
Fading			●	

Table 1. Typical Radio Impairments

4.0 Bit Error Rate Testing

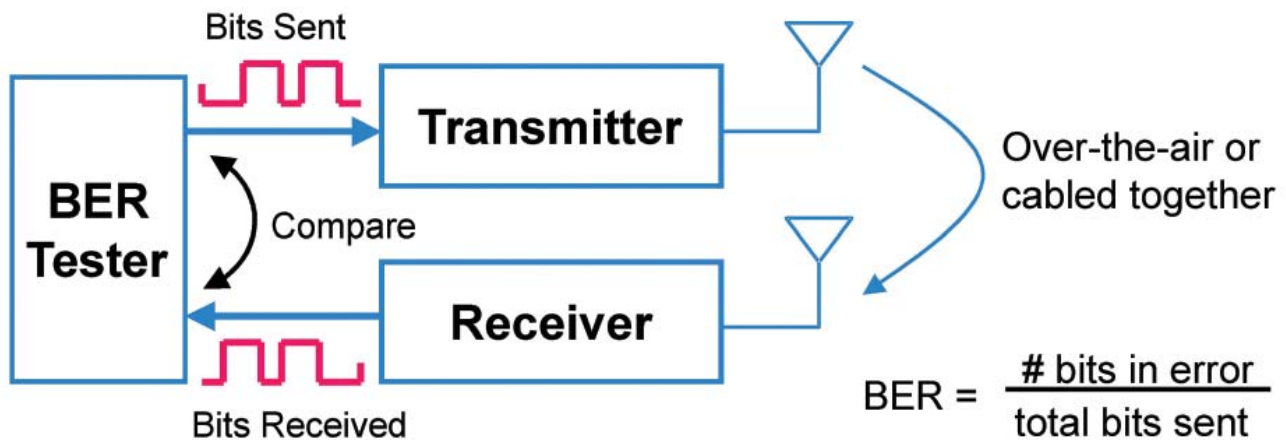


Figure 3 Bit Error Rate (BER) test configuration

A popular technique for evaluating the overall performance of a digital radio system is a loop-back Bit Error Rate (BER) test. BER testing is typically considered the ‘acid test’ when evaluating the performance of a data link. It measures how well the data bits are transported through the transmitter, across the channel and out of the receiver. Bit error rate testers (BERTs) input a known data stream into the transmitter and compare the data emerging out of the receiver to find the ratio of errors to the total bits sent (see figure 3). There are many different BERTs available for various data rates and digital data formats. Some instruments, such as the Agilent ESG signal generator, have an optional built-in BER tester. These flexible signal generators can inject modulated signals at various points in the system and measure the BER using the recovered data stream. Other BER test configurations use recorded waveforms that can be played into the receiver under a variety of conditions. The use of recorded waveforms provides a good platform for interoperability testing among the various equipment vendors. Several techniques for capturing and creating these waveforms will be provided later in this application note.

Unfortunately the diagnostic capabilities of loop-back BER testing are very limited. This system-level measurement of end-to-end performance cannot pinpoint the root causes of impairments in the system. For example, a poor BER performance may result from compression of the power amplifier in the transmitter or incorrect symbol timing in the DSP logic of the receiver’s demodulator. In either case, a BER measurement does not link the degradation in performance to the cause of the impairment.

The limitations found in loop-back BER testing really come from the nature of the signal impairments. Some signal impairments are additive in nature and are spread across the wireless system. Complicating matters further, many signal impairments add in different ways. Linearity distortion and group-delay impairments are deterministic and add arithmetically, while phase-noise impairments are probabilistic and add geometrically. Many loop-back tests remove impairments during the data recovery process and that can inadvertently lead to false measurement results. For example, a direct digital modulator to demodulator loop-back test might result in a reasonable error rate. Next, an IF loop-back test is performed and presents excessive errors, possibly indicating a problem within the IF. However, to assume so could be a false conclusion, as smaller impairments at the IF and at the modulator may have summed up to an out of specification (i.e., bit error) condition.

The only way to correctly ensure consistent error rate performance is to use system budgets that allocate a maximum amount of permissible modulation impairment from each element in the wireless chain. To do this, we must use more sophisticated measurements than loop-back BER tests. This is why design engineers customarily use more advanced measurements than simple BER tests to effectively characterize the complex effects of signal impairments. The next several sections in this application note discuss the various types of instruments and signal analysis tools that can be used to measure and characterize the performance at different domains within the software radio.

5.0 Multiple Domain Analysis Tools

Having a wide variety of signal types with the emphasis on signals operating in the digital domain make it necessary to have a set of flexible diagnostic tools for examining the quality of the signal as it moves across each of the three domains: digital, analog and RF. Typically instruments are specifically designed to measure a signal with a certain format. For example, the data bus of the digital hardware is typically probed using a logic analyzer. The logic analyzer displays the binary encoding of the numerous signal lines that digitally represent the signal to be transmitted. Figure 4 shows a block diagram of an SDR transmitter with a logic analyzer measurement taken at the input to the I-channel DAC. Since the logic analyzer can support multiple bus

measurements at one time, it is possible to simultaneously measure both the digital I and Q channels data busses by attaching multiple measurement pods to probe the device under test. Agilent has several application notes that explain the basics of logic analysis and probing [4, 5].

Another signal format consideration usually encountered with SDR designs is analog I and Q baseband signals that require two independent analog measurements. Wide-band multi-channel oscilloscopes are ideal for measuring analog I and Q waveforms. Figure 4 also shows a measurement of the analog I and Q waveforms after the DAC using an Agilent Infiniium oscilloscope.

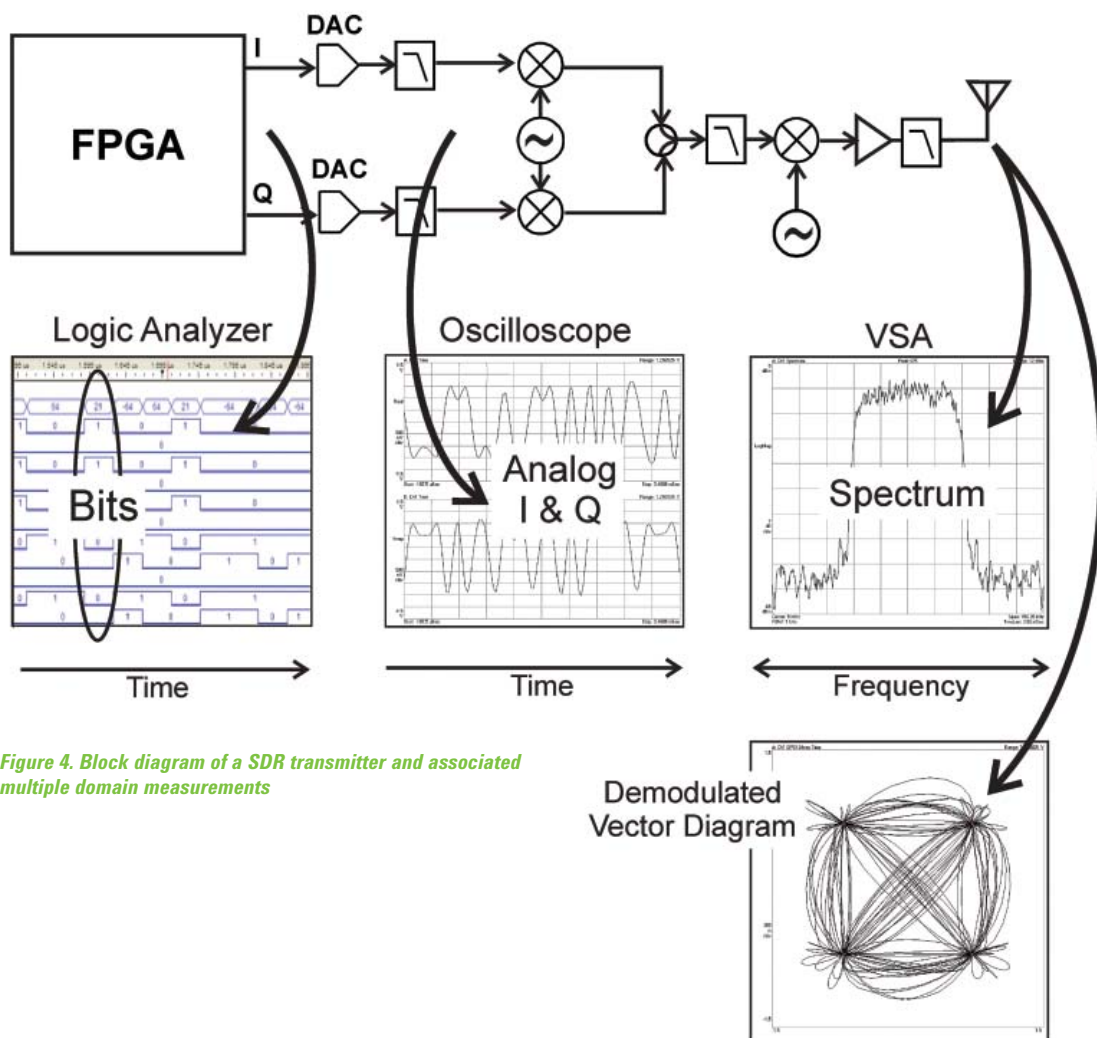


Figure 4. Block diagram of a SDR transmitter and associated multiple domain measurements

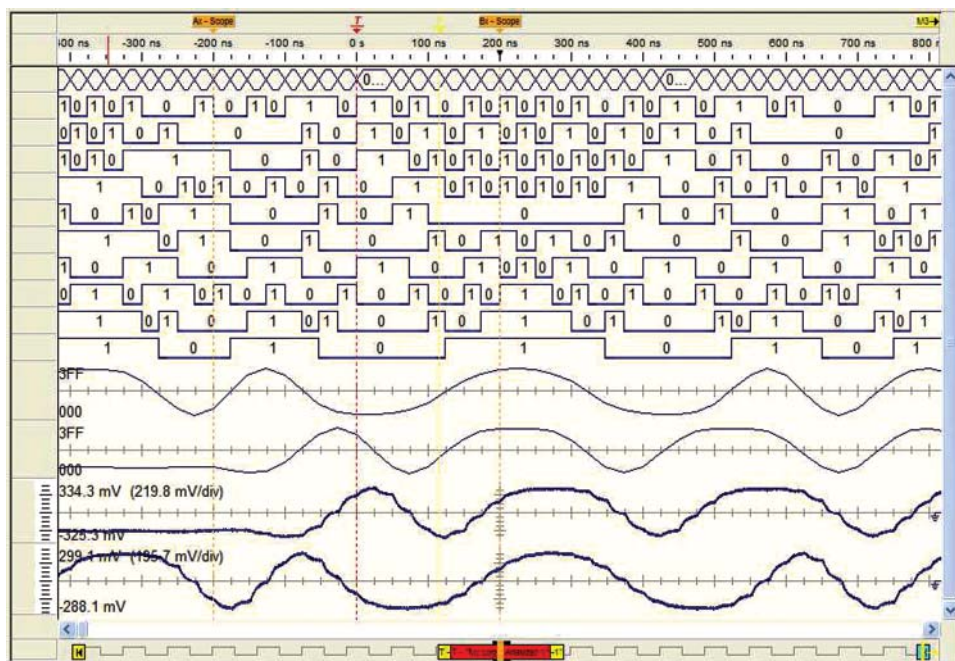


Figure 5. Logic analyzer display showing imported oscilloscope measurements

A very useful feature supported by some logic analyzers, such as the Agilent 16900, is the ability to import an analog waveform from an oscilloscope. The analog waveform is transferred from the scope to the logic analyzer through a LAN connection between the two instruments. Integration of these two measurement systems can be helpful when triggering on analog events and precisely correlating them to DSP-related activities. Figure 5 shows an example using the logic analyzer with the scope for time-correlated measurements. The figure shows the logic analyzer measurement for the digital bus associated with the DAC inputs. The figure also shows the analog representation of this signal based on the digital information measured by the logic analyzer. The lower two curves are the time correlated oscilloscope measurements from the output of the two DACs. This technique provides a comparative analysis of the two digital IQ signals with the two analog IQ waveforms. Synchronized markers provide precise timing measurements between the digital and analog waveforms. Note that the logic analyzer measurements shown in figure 5 are actually analog representations created from the measurements of the digital signals. The logic analyzer creates these representations from the bus measurements once the user associates the multiple data bus lines with a single measurement channel.

The third signal format is the RF waveform that contains the information modulated as symbols onto the RF carrier. Typical measurements relating to this signal type are spectrum measurements including RF center frequency, bandwidth, harmonics, spurious and adjacent channel power to name a few. A spectrum analyzer or vector signal analyzer (VSA) is an ideal instrument for measuring the signal amplitude over frequency. Figure 4 also shows a typical spectrum measurement using the Agilent 89600 VSA. The VSA is also a powerful analysis tool in that measurements can be displayed in combinations of time, frequency, amplitude and modulation. A vector signal analyzer, such as the Agilent 89600 VSA, has many similarities to a SDR since the VSA software can be configured to provide demodulation analysis over a wide range of digital signaling formats covering most of today's wireless standards including WiMAX, Mobile WiMAX, 802.11a/b/g, Bluetooth, TETRA, W-CDMA/HSDPA, GSM/EDGE, 1xEV-DO, cdma2000/1xEV-DV, TD-SCDMA, PHP, Digital Video, UWB and RFID.

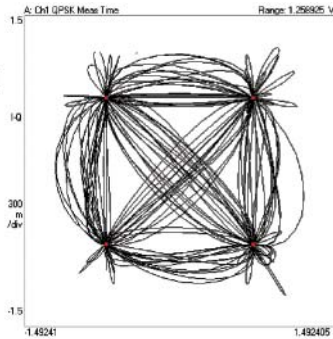
6.0 Vector Signal Analysis

The power in VSA measurements comes from its large array of demodulators, filters, displays, and analysis tools that make it ideally suited for evaluating and troubleshooting modulated signals within the SDR system. The VSA uses a popular measurement called the error vector magnitude (EVM) to characterize the quality of the modulated signal. EVM is the difference between a reference vector and the actual received signal vector. EVM allows the engineer to compare the modulation with a known “good” modulation generated in the test equipment. Because EVM provides an aggregate summary of many types of modulation impairments, it is ideal for detecting issues with a modulated signal. EVM provides a convenient metric to quickly compare signal degradation between points in the block diagram. Modulation imperfections can be identified and traced back to their fundamental mechanism by careful examination of EVM measurements. EVM can pinpoint where signals are degraded with much greater accuracy than top-level loop-back BER testing. To measure EVM, vector signal analyzers must generate a reference signal for the desired modulation. The reference signal is created by demodulating the incoming waveform and generating an ideal signal to be used to compare with the incoming signal. Subtracting the measured signal from the ideal signal provides the error vector.

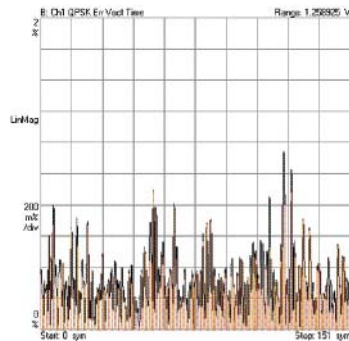
Agilent’s VSAs offer EVM measurements and other quality metrics for a wide variety of modulation types and other variations such as filtering and symbol rates. This includes many popular modulation formats such as AM, FM, PM, QPSK, QAM and OFDM.

Figure 6 shows a set of typical VSA measurements for a demodulated QPSK signal. The display in the upper left shows the vector diagram of the complex recovered signal at all moments in time. The vector diagram can be used to quickly observe if the signal has been properly modulated. The display in the lower left shows the EVM as a function of time. For the purposes of accurately recovering transmitted data from a signal, the error only matters to a receiver at the symbol times, and that is how some EVM specifications are written. However an R&D or test engineer may be very interested in the error between signals, as it may indicate the source of the impairment such as the case where improper baseband filtering is applied in the digital portion of the SDR transmitter. The display in the upper right of figure 6 shows error vector spectrum. This spectrum is calculated by taking the FFT of the error vector time trace. This spectrum display can reveal the spectral content of the unwanted signals that drive the modulated carrier apart from its ideal path. If those error components are deterministic, they will show up in the error vector spectrum as discrete line spectra.

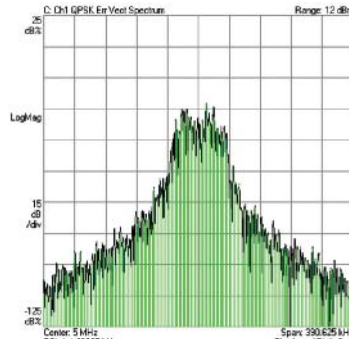
Vector Diagram



EVM Time



EVM Spectrum



Summary Table

D: Ch1 QPSK Synch/Errs				Range: 1.256825 V			
EVM	= 390.50	mVrms	885.41	m%pk at sym	55		
Mag Err	= 294.94	mVrms	-0.75.00	m%pk at sym	122		
Phase Err	= 145.23	mdeg	455.14	mdeg pk at sym	55		
Freq Err	= 12.601	mHz		SNR(MER)	= 48.062	dB	
IQ Offset	= -01.601	dB		Ratio	= 0.99029		
Quad Err	= 120.73	mdeg	Gain Imb	= -0.004	dB		
<pre> 0 00101011 00110000 01010001 00000111 01101001 10001010 46 00000011 01111011 10011000 00101011 01011101 10001001 36 00011110 11000110 01111111 11011111 01001101 01100010 144 10110110 01001110 10100001 00000001 10110100 01000100 192 10011001 10000000 00110101 11101000 00110010 00100000 240 11001111 11110100 00101000 01101110 11010110 288 11011010 10011011 </pre>							

Figure 6. Typical VSA demodulation measurement

Measuring these spectra can give added insight into the nature and origin of the signal impairments. The lower right display shows a summary table of the demodulated signal. This table can be the most powerful of the digital demodulation tools. Here, demodulated bits can be seen along with error statistics for all of the demodulated symbols. Modulation accuracy can be quickly assessed by reviewing the RMS value of the EVM. The display at the lower right shows both the demodulated symbol table and a table of calculated error parameters. Note that EVM and

magnitude/phase error are calculated in terms of peak and RMS values for the measured burst. The peak error value includes the symbol where the error occurred, potentially a very helpful result for finding the source of signal impairments. Other composite error parameters are also derived and shown, including frequency offset, quadrature error and IQ offset. Agilent supplies additional application notes that will be helpful to engineers looking to develop a further understanding of the measurement capability found in the VSA [6, 7,10].

7.0 Vector Signal Analysis Across Multiple Domains

While basic digital logic and analog analysis is very useful for troubleshooting bit level and timing anomalies in the baseband, it does not provide any insight into how the quality of this signal will ultimately affect the signal transmitted from the radio. By combining VSA software tools with logic analyzer and oscilloscope measurements, it now becomes possible to perform the full range of vector signal analysis using data captured across the full range of high-performance instrumentation.

Continuing from the previous SDR transmitter example as shown in figure 4, the VSA software is now integrated into all three types of test instrumentation and a comparative analysis is preformed at the digital, analog and RF domains. Figure 7 shows the vector diagrams at all three domains using the same vector signal analysis tool. Also shown is the measured RMS value of the EVM for each signal. Higher quality signals result in lower EVM values. The figure shows how the EVM changes as the signal transitions across the various domains in the SDR transmitter. It is observed in this example that the EVM is approximately

0.4% and 0.5% in the digital and analog domains respectively but takes a large jump to 5.0% in the RF domain when measured after the power amplifier. This large degradation in EVM would alert the engineer that a problem exists somewhere between the measured analog section and the power amplifier output. For this example, it was determined that the EVM was 1% before the power amplifier and further analysis showed that the amplifier was going into compression. After a re-design in the output amplifier, the EVM dropped below 1.4%. It is expected that some degradation in EVM will occur as the signal is transitioned between domains but this unexpected large increase allowed the engineer to pinpoint the exact problem area using the VSA tools. One important fact to note is that using a common VSA tool would yield the best comparative analysis across domains because a common algorithm is used to determine the reference signal from the measured signals. Uncertainty in the results may be introduced when measurements are made on different types of vector analysis equipment, which may use different software algorithms.

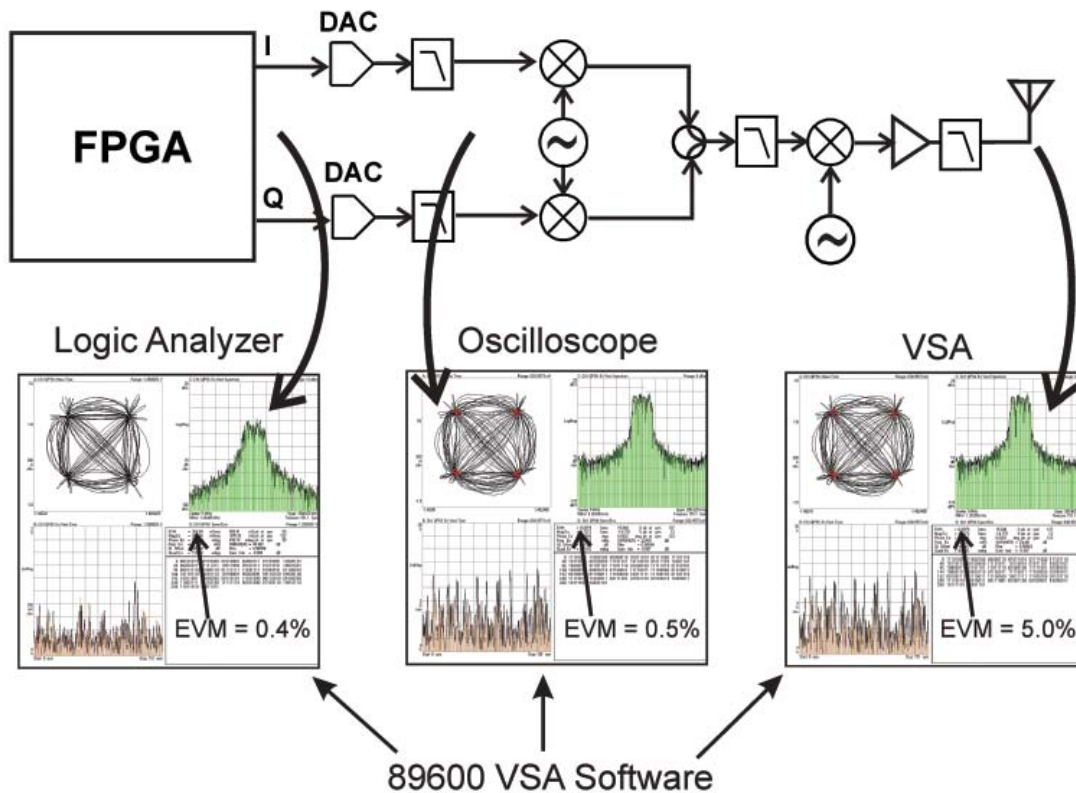


Figure 7. Block Diagram of a SDR transmitter and VSA measurements across multiple domains

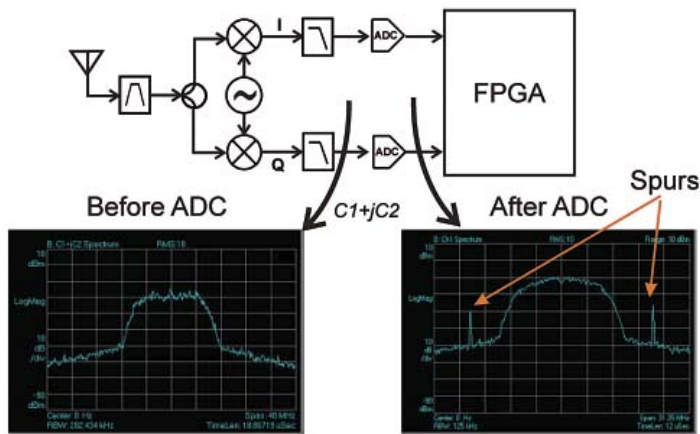


Figure 8. Block diagram of SDR receiver and VSA spectrum measurements before and after the ADC

Another example of using the VSA as a comparative and troubleshooting tool across signal domains is shown in figure 8. This figure shows the connections between the test equipment and the I and Q channels directly before and after the ADC. On the analog side of the ADC, the VSA software is configured to vectorially add the two independent oscilloscope measurements into a complex form using the $C1+jC2$ function available in the Agilent 89600 VSA software. By mathematically combining these two waveforms, the VSA operates as an ideal software modulator that reassembles the I and Q waveforms into a modulated signal. The reassembled signal can now be examined using all the available VSA tools. Figure 8 shows a measurement of the modulated spectrum at the input to the ADC. The spectrum looks correct and is free of any close-in spurious responses. The next step is to measure the output spectrum from the two ADCs. In this case a logic analyzer, such as the Agilent 16800, is used to probe the digital bus lines leaving the ADCs. Once again, these separate I and Q channel measurements are reassembled into a modulated spectrum. Figure 8 shows the measured spectrum taken from the output of the ADCs. This time the VSA displays strong clock spurs near the desired spectrum. These clock spurs could introduce errors in the bit recovery process if not properly filtered in the digital domain. Without advanced cross format diagnostic techniques, such an impairment would be very difficult to identify with such clear certainty.

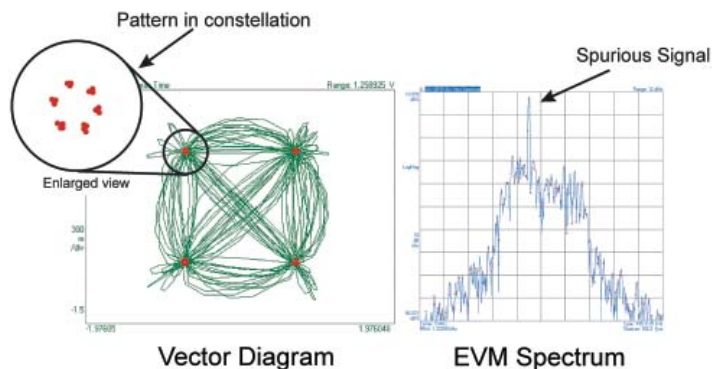


Figure 9. Vector diagram (left) and EVM spectrum (right) of a QPSK modulated signal corrupted by an in-band spurious signal

In some cases, it is hard to determine the quality of a signal just by looking at a spectrum response. For example, the spectrum plot on the left of figure 8 shows a clean response free of any significant in-band and out-of-band spurious signals. After demodulating this signal using a VSA, such as the Agilent 89600, it was found to have an unexpectedly high EVM value of 3.6%. For the system being tested, the EVM should fall below 1%, therefore, additional demodulation analysis was required. Examining the vector diagram, it was observed that the distribution of constellation points followed a doughnut shaped pattern as shown on the left in figure 9. This type of distribution is indicative of a spurious interference. If the only interference were additive noise, the constellation points would follow a random distribution. Continuing the analysis using an EVM spectrum, as shown on the right of figure 9, it was found that a spurious signal, offset 11kHz from the carrier, was the cause for the high EVM value. In-channel spurious, such as this, combines with the modulated signal, and is rarely high enough to be detected in the frequency domain (as shown on the left plot in figure 8). Using the variety of measurement tools available on the VSA, such as the vector diagram and EVM spectrum, engineers can troubleshoot and uncover numerous impairments found across the digital, analog and RF domains.

8.0 Digital VSA

With the trend in the wireless industry to implement more of the software radio's functionality in the digital domain, the ADC and DAC are moving closer to the antenna. As a result, more of the testing and troubleshooting are performed using a logic analyzer. Bridging the signal formats from analog to digital also requires the ability to correctly interpret the signal value from a digital bus. Some signals use a two's complement encoding and others use an offset binary encoding, each requiring a different interpretation. Correctly decoding the format of the signal is also important when applying VSA analysis tools directly to logic analyzer measurements [8]. Fortunately, modern VSA tools, such as the Agilent 89600 series, can directly interface with the logic analyzer system software to easily set the encoding format assignments.

Another signal format consideration usually encountered with SDR designs is that I and Q baseband signals require two independent measurement ports, one for each channel. Logic analyzers can support multiple bus measurements by using multiple measurement pods to probe the device under test. Increasing the number of bus measurements increases the number of Input and Output (I/O) pins that must be probed resulting in an increase in board size and cost. More importantly, probing is often complicated when using FPGAs, as many of the desired test points may not

be readily accessible outside of the chip. Since I/O pins on the FPGA are typically an expensive resource, there are a relatively small number available for debug. This limits internal visibility as, historically, one pin has been required for each internal signal to be probed. To access different internal signals, the FPGA design must be modified and recompiled in order to route these signals to the available external pins. This is a time-consuming process and could also affect the timing of the FPGA design. Fortunately, it is possible to multiplex internal test points onto a shared external bus using a dynamic probe assignment tool. This multiplexing tool is part of the additional design core, such as the Agilent Trace Core 2 (ATC2), that is compiled into the FPGA design [9, 10].

The ATC2 design core is embedded in the FPGA design and offers access to as many as 128 test points per external pin without altering the internal timing of the design. The test points can be arranged in banks to facilitate rapid switching between different I and Q test points. The probe banks are automatically configured and multiplexed from the logic analyzer's display. Combining the ATC2 design core, the logic analyzer and the VSA analysis software, it becomes possible to compare the modulation and spectral properties of the SDR's digital baseband at all points within the FPGA design.

An example of using the ATC2 core inside an FPGA to measure performance of an IQ modulator is shown in figure 10. Here the IQ modulator has been completely designed in the digital domain using a 25 MHz digital LO. Modulation begins as the input data stream enters the FPGA and is mapped into I and Q waveforms using a symbol encoder. In this example, the input data has already been randomized, encoded and interleaved into the desired bit-stream format. The encoder maps the appropriate signal levels for each symbol onto the I and Q channels as determined for the selected modulation type. In this case, a 16-QAM modulator was developed using 12-bit digitization. The I and Q waveforms are then up-sampled and filtered. Up-sampling increases the sample rate which allows more effective filtering and a reduction in signal aliasing. The baseband filtering is used for “pulse-shaping” the waveforms. Figure 11 shows the measured pre-filtered and post-filtered vector diagram and spectrum plots using the digital VSA. At each stage in the modulation and filtering process, the I and Q signals are examined using the ATC2 core, which multiplexes the I and Q bus lines onto a common connection to the logic analyzer. The multiplexing selection is software controlled through a JTAG connection [9]. The 16-QAM-

modulation process continues when the filtered I and Q waveforms are modulated onto the 25 MHz digital LO and combined. Figure 11 also shows the final output from 16-QAM modulator operating at an IF frequency of 25 MHz. In a complete software radio design, this waveform would be passed to the DAC for conversion into the analog domain.

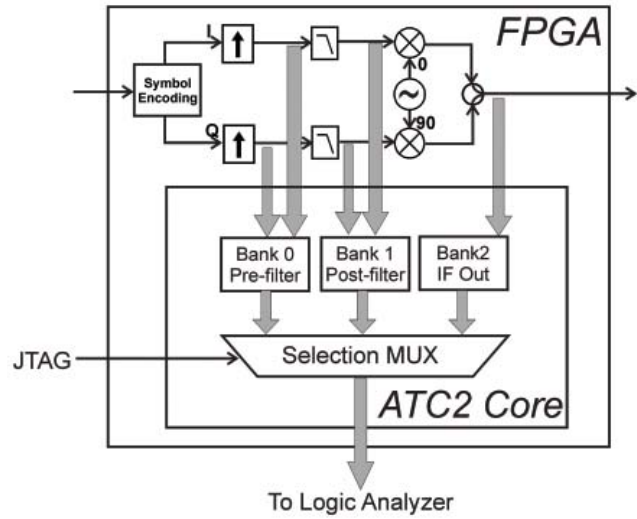


Figure 10. ATC2 core embedded as part of the FPGA digital IQ modulator design

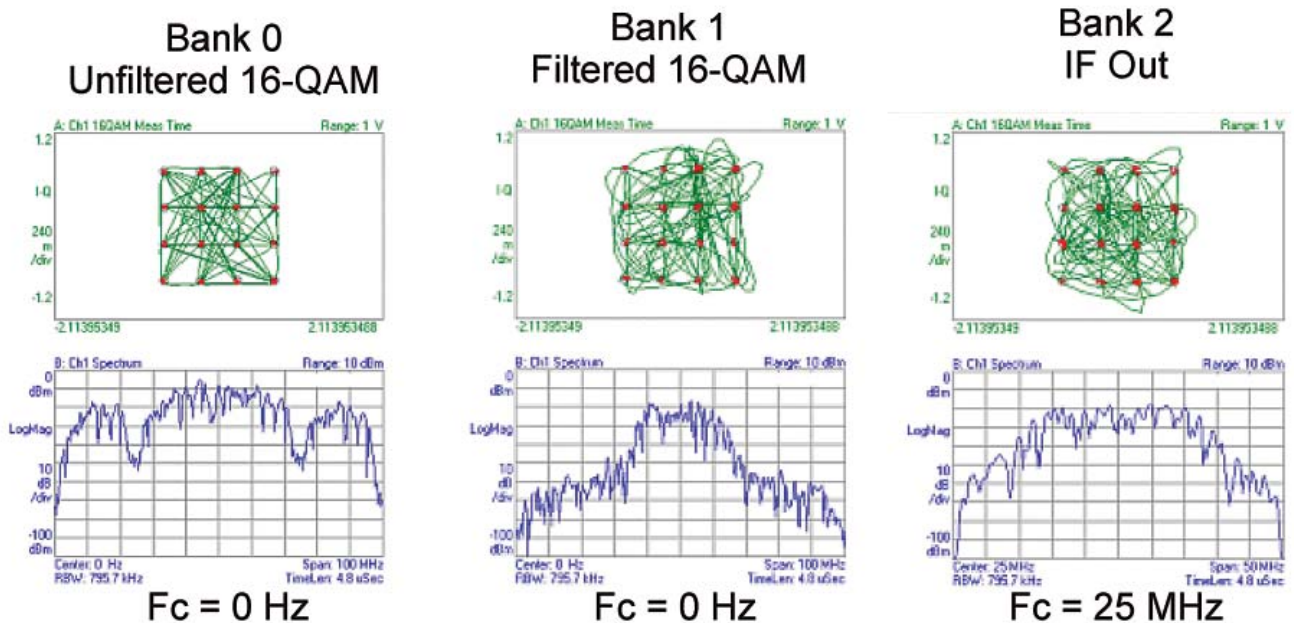


Figure 11. Measured Vector Diagram and Spectrum for digital IQ modulator

9.0 Signal Generation Tools for SDR

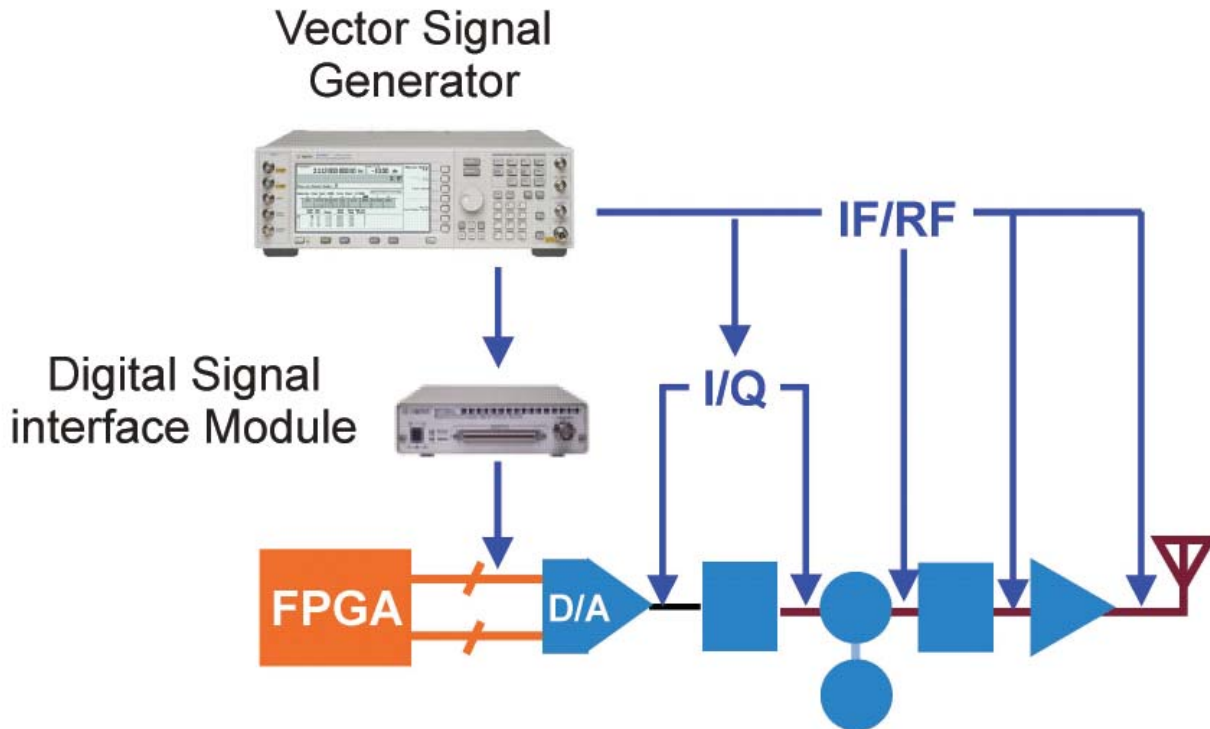


Figure 12. Vector signal generator and digital signal interface module connection to a SDR transmitter

Digital radio and more specifically SDR have been driving the evolution of signal generation test equipment. With the introduction of digital radio communications over a decade ago, signal generators, such as Agilent's ESG, PSG and MXG series generators, have become capable of creating custom and standards-based digitally-modulated signals. These basic vector signal generators are used to create RF and IF modulated waveforms that can be applied at various points within the transmitter and receiver channels of a digital radio system. Vector signal generators use either an internal baseband waveform generator or Arbitrary Waveform Generator (AWG) to create test signals that are applied to the built-in IQ modulator. When using an AWG for waveform creation, sampled I and Q waveforms are

typically created and downloaded into the AWG's memory. The baseband waveforms can be created directly from the generator's front panel or by using a software design tool such as Agilent's Signal Studio, Agilent's Advanced Design System (ADS) or Mathwork's MATLAB®. The baseband analog I and Q waveforms are typically made available from the signal generator in order to directly drive the I and Q ports of an external modulator or drive the ADCs in a receiver subsystem. The versatility of modern generators allows the analysis and troubleshooting of component and subsystems within the digital radio. Figure 12 shows several RF and analog connections between a vector signal generator and a digital radio transmitter. Figure 13 shows similar connections to a digital radio receiver.

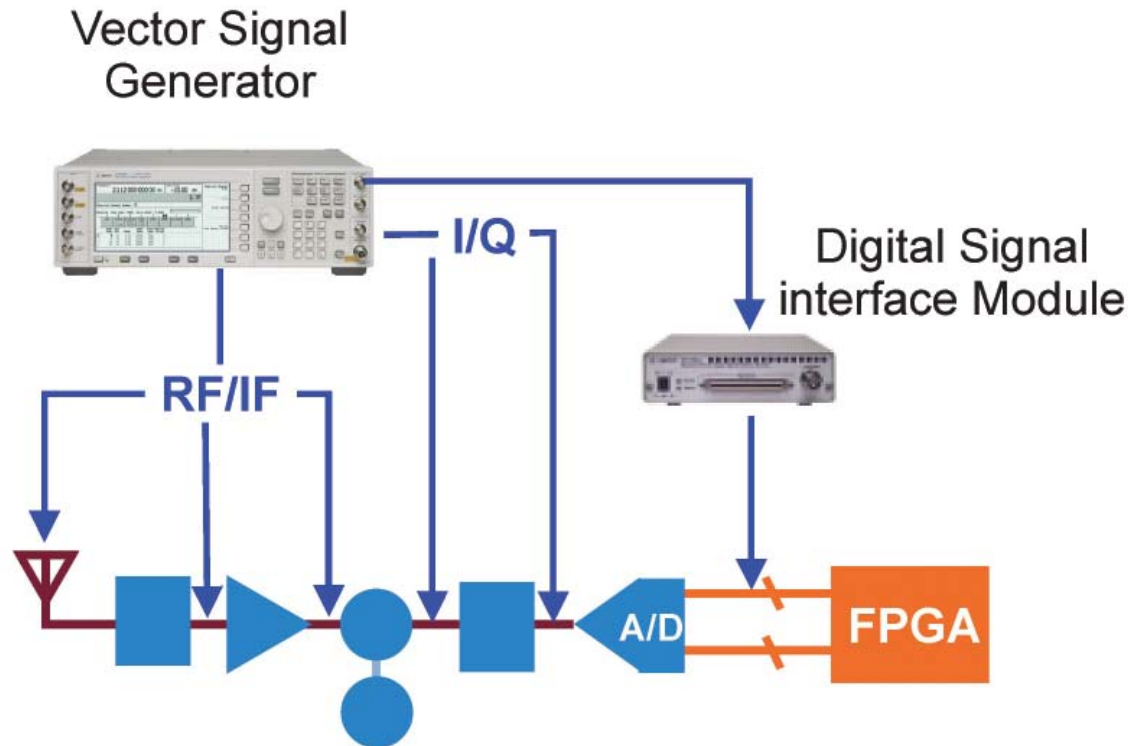


Figure 13. Vector signal generator and digital signal interface module connection to a SDR receiver

When measuring the performance of software defined radios, it is important that the signal generator be capable of applying test signals to the digital subsystem and ideally operate using the same baseband waveforms that are used at the RF and IF domains. For these newer SDR applications, test equipment manufacturers have added additional tools to expand the capability of vector signal generators. For example, when testing the digital signal interface to a DAC, an interface module, such as the Agilent N5102A [11], is connected between the vector signal generator and the DAC input (see figure 12). The interface module can be used as the source to drive the DAC. This technique allows analysis of other radio components prior to the development of the actual FGPA and DSP subsystems. The interface

module can also capture the digital output from the transmitter's FPGA and transfer this data to a vector signal generator for up-conversion to the RF or IF frequency. This procedure allows digital baseband subsystem testing without the need for the IF and RF sections of the transmitter to be designed. In this case the transmitter is realized by using the vector signal generator's fully calibrated RF path as a substitute for the actual SDR transmitter's front-end. A similar approach can be used to measure the receiver's digital subsystem performance by applying ideal test signals directly to the receiver's FPGA inputs. In this application, the digital interface module is used to create test patterns for simulating real digitized signals under controlled conditions (see figure 13).

10.0 Simulation Tools and Instrument Connectivity

The very nature of the software-defined radio is changing the design process as hardware development shifts to software development. Rapid design and validation using powerful simulation tools can save valuable time and money. Simulation tools, such as Agilent's Advanced Design System (ADS) and Mathwork's Simulink, contain extensive libraries of circuit and system-level models ranging from digital and RF components to communication and signal processing blocks and numerous channel models.

Advances in these simulation tools have also bridged the gap between hardware and software by providing direct connection between test equipment and software simulation tools. Agilent calls this bridge a "Connected Solution" [13], and it is the integration of test instrumentation into the ADS simulation tool that allows the sharing of signals, measurements, algorithms, and data in both directions between the two domains. Connected solutions can be used to create simulation models from measurements of existing components and can be used to determine whether or not a component or sub-system will work within a system without having to build the whole system

in hardware. These solutions can also be used to create signals for device testing that include actual signal impairments that will be present when the system is deployed.

An example of a connected solution is shown in figure 14. This figure shows an ADS model for a SDR transmitter design where the input source driving the model comes from actual baseband waveforms. The waveforms can be captured from a logic analyzer, oscilloscope or VSA. Alternatively, the ADS tool can co-simulate the HDL code that created the FPGA-based waveforms without the need to capture the waveform on an instrument. ADS also allows connection to MATLAB® models and tools using the bi-directional co-simulation capability within the ADS environment. On the analysis side, ADS supports connections to the 89600 VSA as an embedded measurement tool. This link allows high-level modulation analysis within the ADS simulation. The 89600 VSA software, whether embedded in the software simulation or running within one of many instrument platforms, can provide consistent analysis across the design and troubleshooting lifecycle of an SDR system.

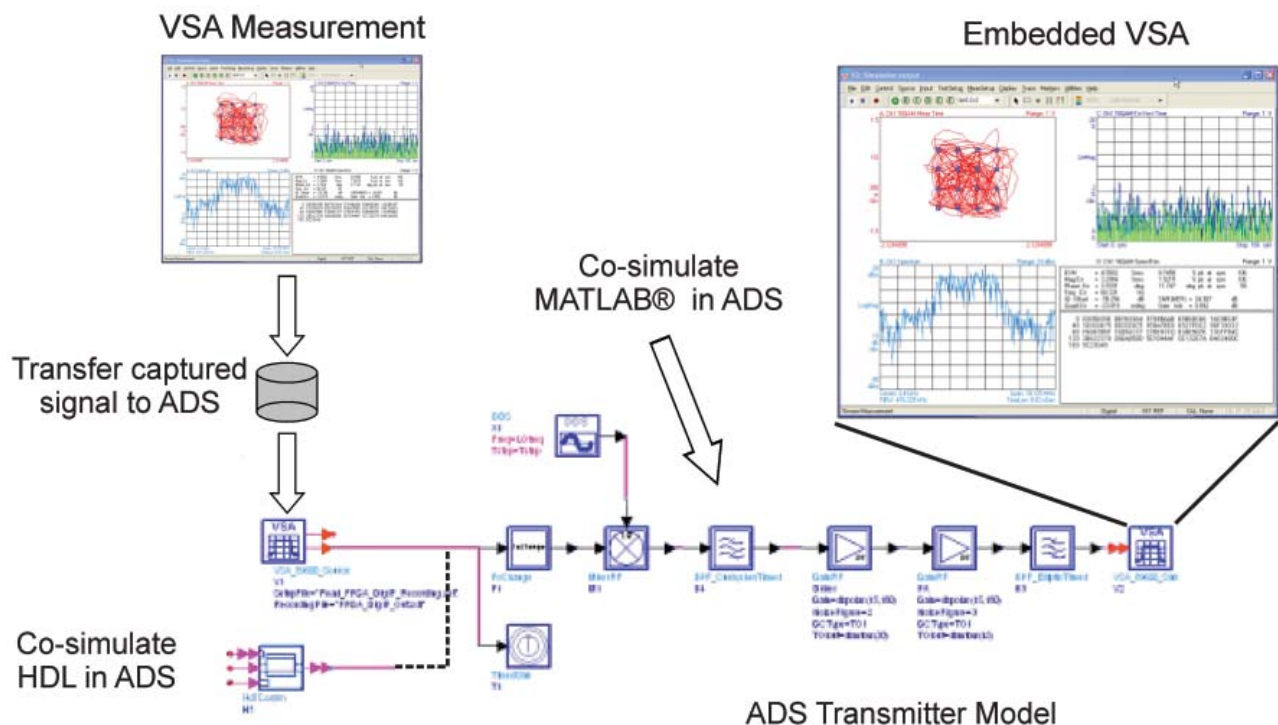


Figure 14. ADS transmitter model showing a "Connected Solution" to the VSA application and the embedded VSA software. Also shown are co-simulation capabilities for running MATLAB® and HDL within ADS.

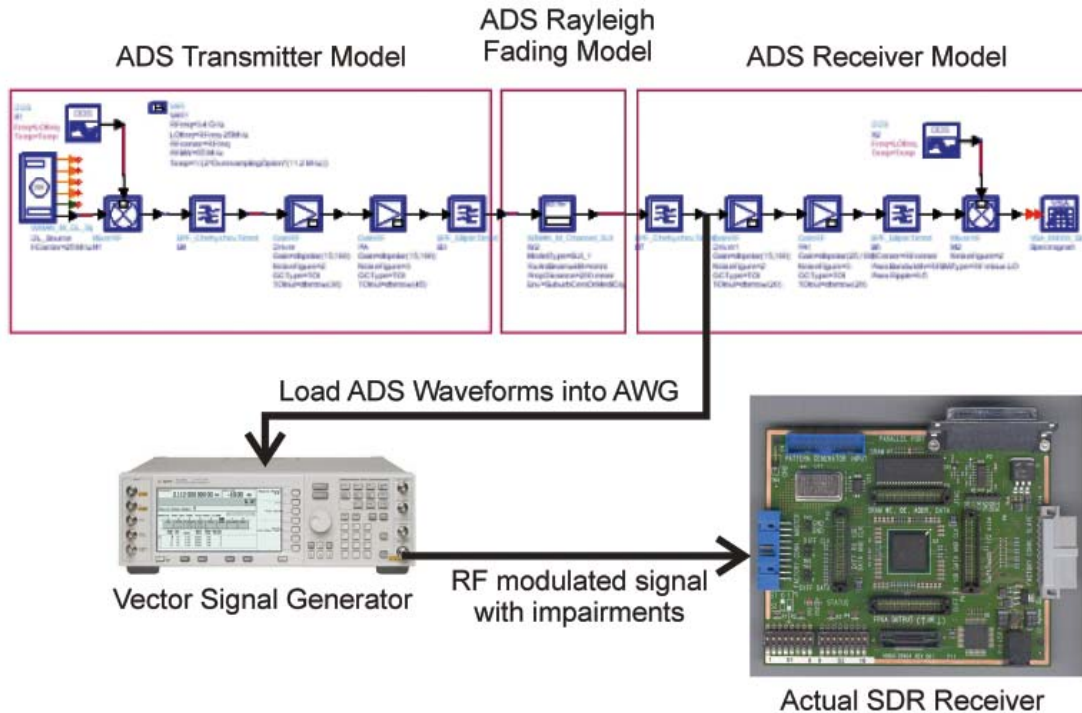


Figure 15. ADS Connected Solution to a vector signal generator for the creation of an RF waveform impaired by Rayleigh fading. The waveform is applied to a SDR receiver for performance testing.

Connected solutions also exist between software simulators and vector signal generators. Figure 15 shows an example of using ADS to create a modulated waveform from a SDR transmitter that is passed through a Rayleigh faded channel. This simulated waveform of the faded signal is then downloaded into an arbitrary waveform generator, such as the internal AWG found in Agilent's ESG vector signal generator. The faded signal is now physically created by the signal generator and applied to the actual receiver hardware. This same technique can be applied for generating baseband waveforms using Agilent's N5102 Baseband Module.

Linking the software simulation tools to the SDR design process allows software developers and hardware engineers to share signals, measurements, algorithms, and data in both directions in order to rapidly diagnose problems and optimize SDR system performance.

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