Troubleshooting and Characterizing Wide Band RF Systems Using a Real-Time Spectrum Analyzer

Introduction

The proliferation of wireless devices and an unrelenting demand for higher data rates have placed a significant strain on the radio frequency (RF) spectrum. As bandwidth requirements for RF components and systems continue to increase, spectrum availability has become a serious challenge. System operators must use every Hertz of the RF spectrum as efficiently as possible, yet they must also take great care to avoid interference with other signals that are closer and more prevalent than ever before. Of course, all of this must be accomplished as quickly and with the lowest capital expenditure possible, resulting in a classic engineering dilemma.

These divergent requirements are driving considerable innovation in RF communications. Advances in digital signal processing, combined with strides in Analog-to-Digital (ADC) and Digital-to-Analog (DAC) technologies, have enabled new generations of remarkable networks and systems. RF spectrum distortions can now be controlled in real time using digital control loops with much higher spectrum performance and efficiency compared to analog techniques. Cost advantages and manufacturing efficiency have been gained by pushing digital circuitry as far up the RF chain as technology will allow. Yesterday's narrow band, single-carrier, triple conversion systems are being replaced with wide band, multi-carrier transmitters enabled by digital signal processing (DSP) and DACs that produce direct

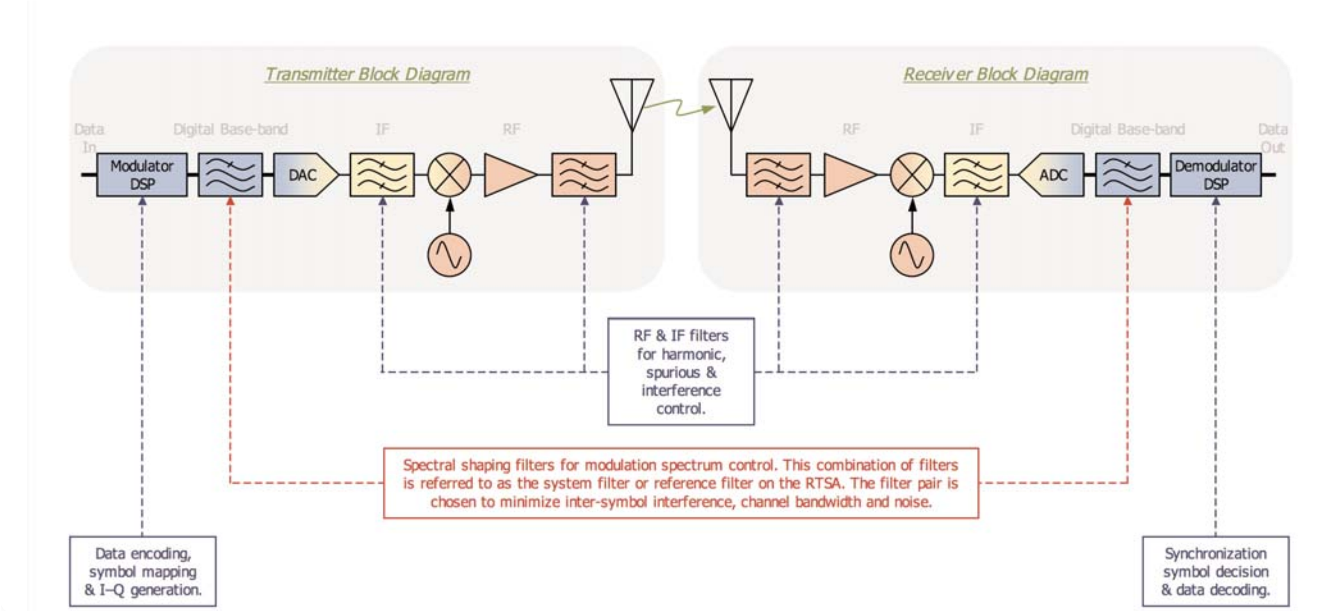

Figure 1. *The RTSA must act as the receiver in a Tx/Rx pair when measuring vector signal parameters.*

IF, or even direct RF outputs to the RF amplifier. And waveforms are now digitally pre-distorted for maximum efficiency and tight spectrum control.

Although their benefits are palpable, these innovative RF systems and techniques create new challenges for the design engineers and system operators who must troubleshoot and characterize them. Troubleshooting an RF design now requires the ability to trace a signal from a DSP-generated baseband to a wide-band digitally modulated RF output. These digitally generated RF signals create new, transient faults that previous generations of RF test equipment are unable to discover, trigger on and measure. In addition, optimizing wide band systems, especially those that use Digital Pre-Distortion (DPD) in the transmit chain, requires the creation of a pre-distorted waveform. This requirement necessitates signal analyzers that are capable of vector capture of not only the transmit bandwidth, but a high fidelity capture that is 3 to 5 times the transmit bandwidth as well.

This application note examines the characteristics of modern RF systems and demonstrates the use of Tektronix RSA6100A Series of Real-Time Spectrum Analyzers (RTSAs) in troubleshooting and characterizing them. Basic vector and spectrum measurements of transmitters, troubleshooting high-bandwidth systems and characterizing wide band DPD systems will be covered.

Digitally Modulated Signal Characterization: Common Measurements and Measurement Correlation

Vector Measurements

When a RTSA is used to measure the vector parameters of modulated signals, the test equipment acts as the receiver in a Transmit/Receive (Tx/Rx) pair. Figure 1 illustrates the components of a generic Tx/Rx chain and the role the RTSA plays in replacing the Rx function.

The receive chain begins with a low-noise RF amplifier tuned to the receive frequency. For many laboratory measurements, an amplifier is not required in the RTSA since the transmitter is connected directly to the test instrument and the signal does not pass through an air interface. In the case of off-air measurements, an internal preamplifier is available for the RSA6100A Series that provides 30 dB of gain for low level signal conditioning up to 3 GHz. In Figure 1, the receiver's mixer and ADC are replaced with the mixer chain and ADC of the RTSA. While the RTSA contains an intermediate frequency (IF) filter for spurious and interfering signal control, its bandwidth is that of the instrument's capture bandwidth, which may allow unwanted signals into the measurement.

A "system filter" or "reference filter" is the combination of spectral shaping filters in the Tx/Rx chain (see Table 1). It represents the ideal spectral shape of the entire chain, but it may be divided between the transmitter and receiver. For example, a raised-cosine system filter may be split such that a root-raised-cosine (RRC) is used in both the transmitter and receiver. This enables the transmitter to achieve the desired spectrum shape, while allowing the receiver some measure of spurious signal rejection. Use of a Nyquist filter, such as a pair of RRC filters, results in no Inter-Symbol Interference (ISI) in the system.

System (Reference Filter)	Tx Filter	Rx Filter (Measurement)
Raised-Cosine	Raised Cosine	None
(3GPP), Raised-Cosine	Root-Raised Cosine	Root-Raised-Cosine
(3GPP2), IS-95-defined	IS-95 Transmit Filter	IS-95 Receive Filter (eq.)
(GSM), Gaussian	Gaussian	None

Table 1. *Common system filters and their components. The reference filter of an RTSA is analogous to the system filter of a Tx-Rx pair, and the Measurement Filter of an RTSA is set equal to the system's Rx Filter.*

Vector measurements of digitally modulated signals require the transmission of an identical data stream, meaning the incoming signal must be compared to an ideal signal of the same modulation type. To do so, the signal analyzer needs to be aware of, and capable of reproducing, the modulation parameters of the signal, including:

– Frequency

– Symbol rate

– Modulation type

– Transmit / receive filters

– Transmitted symbol values

Measurement	Definition
Frequency Error	The frequency difference between the measured carrier frequency of the signal and the user-selected center frequency of the analyzer
Error Vector Magnitude (EVM)	The normalized RMS value of the error vector between the measured signal and the ideal reference signal over the analysis length. The EVM is generally measured on symbol or chip instants and can be reported in units of percent or dB. EVM is usually measured after best-fit estimates of the frequency error and a fixed phase offset have been removed.These estimates are made over the analysis length
Magnitude Error	The RMS magnitude difference between the measured signal and the reference signal magnitude
Phase Error	The RMS phase difference between the measured signal and the ideal reference signal
Origin Offset	The magnitude of the DC offset of the signal measured at the symbol times. It indicates the magnitude of the carrier feed-through signal
Gain Imbalance	The gain difference between the I and Q channels in the signal generation path. Constellations with gain imbalance show a pattern with a width that is different from height
Quadrature Error	The orthogonal error between the I and Q channels. The error shows the phase difference between I and Q channels away from the ideal 90 degrees expected from the perfect I/Q modulation. Constellations with quadrature error will show some leakage of I into Q and vice versa
Rho (ρ)	The normalized correlated power of the measured signal and the ideal reference signal. Like EVM, Rho is a measure of modulation quality. The value of Rho is less than 1 in all practical cases and is equal to 1 for a perfect signal measured in a perfect receiver

Table 2. *Vector Measurements Summary of Definitions.*

The signal analyzer must construct an ideal, or reference signal to which the measured signal can be compared for errors. Two methods are used in creating the reference signal. In the first, the transmitted data is known by the measurement instrument prior to the capture and demodulation of the signal. This has the advantage of not relying on the signal for any reconstructed data, but this method cannot be used when the transmitted data is not known. Since knowledge of the transmitted data is difficult to have prior to its demodulation, most analyzers use a second method by which the transmitted data is extracted from the signal to be analyzed, and the reference signal is created based on the demodulated data symbols. The advantage of the second method is that so long as the basic modulation parameters are known, signals with random or unknown data can be evaluated; the user does not need to pre-define the data. However, if the incoming signal contains extremely high distortion, the data symbols recovered and used in construction of the reference signal can become corrupted, causing errors in the symbol table and underestimates of vector errors.

Once the signal has been demodulated and the reference signal constructed, vector measurements can be performed. These measurements are defined in Table 2 and illustrated in Figure 2.

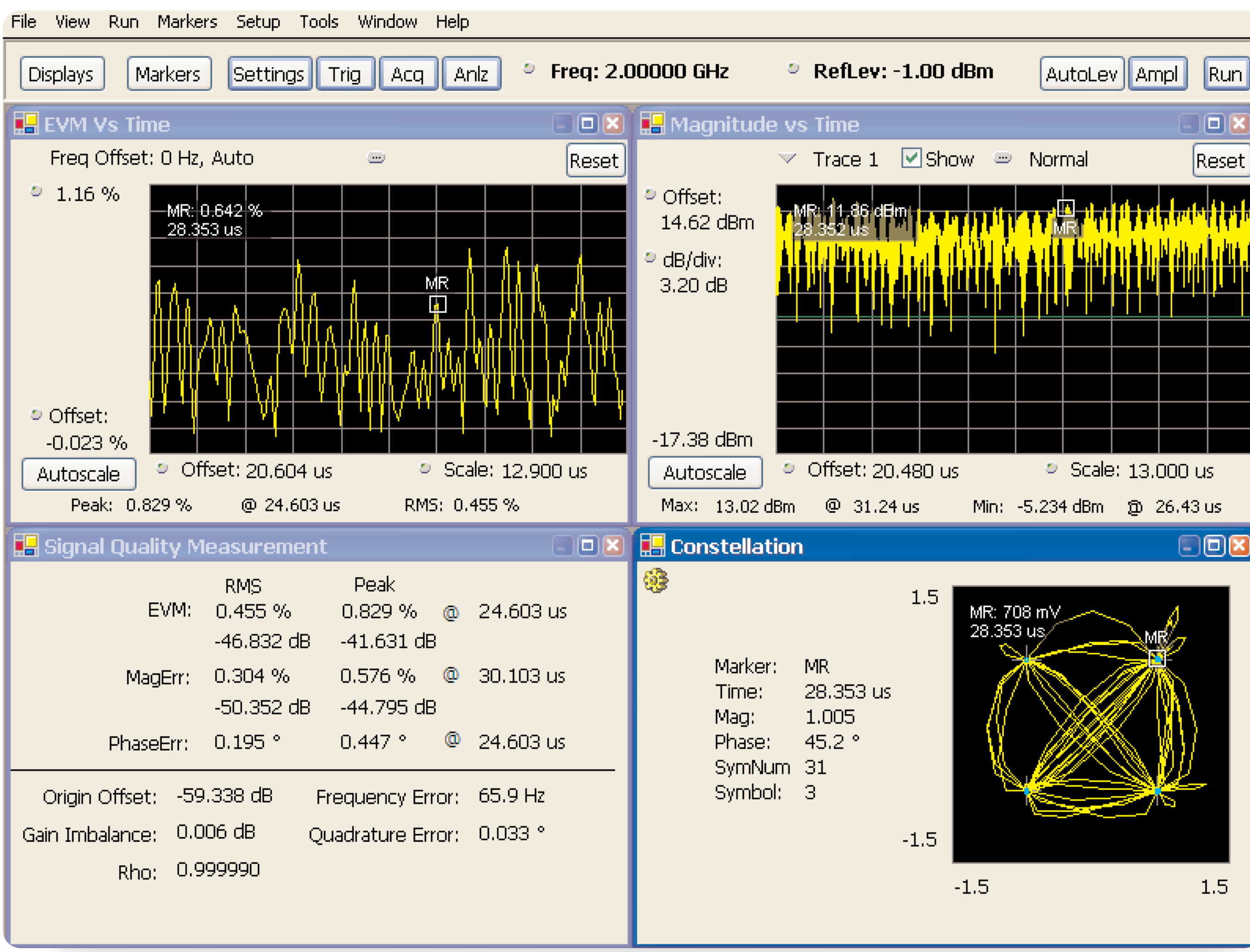

Figure 2. *Examples of vector measurements made by the RSA6100A Series, including EVM, Magnitude Error, Phase Error, Origin Offset, Gain Imbalance and rho. Other panels display magnitude vs. time, EVM vs. time and constellation display of the same time period.*

Peak-to-Average-Ratio and Complementary Cumulative Distribution Function

Modern transmitters use sophisticated techniques to limit the Peak-to-Average-Ratio (PAR) of the amplified signal in order to optimize output distortions and amplifier efficiency. However, the measurement method used can have a significant impact on the resultant measurement.

PAR is simply the ratio of a signal's peak power compared to its average power over a defined period of time. Complementary Cumulative Distribution Function (CCDF) is a statistical characterization that plots power level on the x-axis and probability on the y-axis of a graph. Each point on the CCDF curve shows what percentage of time a signal spends at or above a given power level. The power level is expressed in dB relative to the average signal power level (see Figure 3).

The technique used in the RSA6100A Series and some other signal analyzers is to perform the PAR and CCDF measurements on a contiguous set of time domain data. This approach has the advantage of providing results that are correlated to other measurements, and is most useful for determining the effect of signal statistics on signal quality produced by the device under test (DUT).

The above method is different from that of most conventional spectrum analyzers, which utilize a sampling of the waveform while in zero span to make measurements. The measurement data is passed through the resolution bandwidth of the spectrum analyzer prior to sampling. This method is statistically valid when performed over a long enough period of time, where the sampling is able to intersect all possible values of waveform peak-to-average. It also has the advantage of being able to monitor the signal for indefinite periods of time. Since the spectrum analyzer must be in zero span while making CCDF measurements, CCDF measurements taken by these instruments do not correlate to any other measurement that may be desired.

The RTSA offers both of the above analysis methods. Figure 3 illustrates the correlated method, where a CCDF measurement is performed and a single "outlier" amplitude transient is shown. The signal exhibits this peak once in 10,000 symbols, as is seen in both time vs. amplitude and the EVM vs. time displays and correlates to the unusual peak in the CCDF chart with 0.01% probability. This transient represents the type of amplitude peak that can occur as a result of a calculation overflow in a digital system.

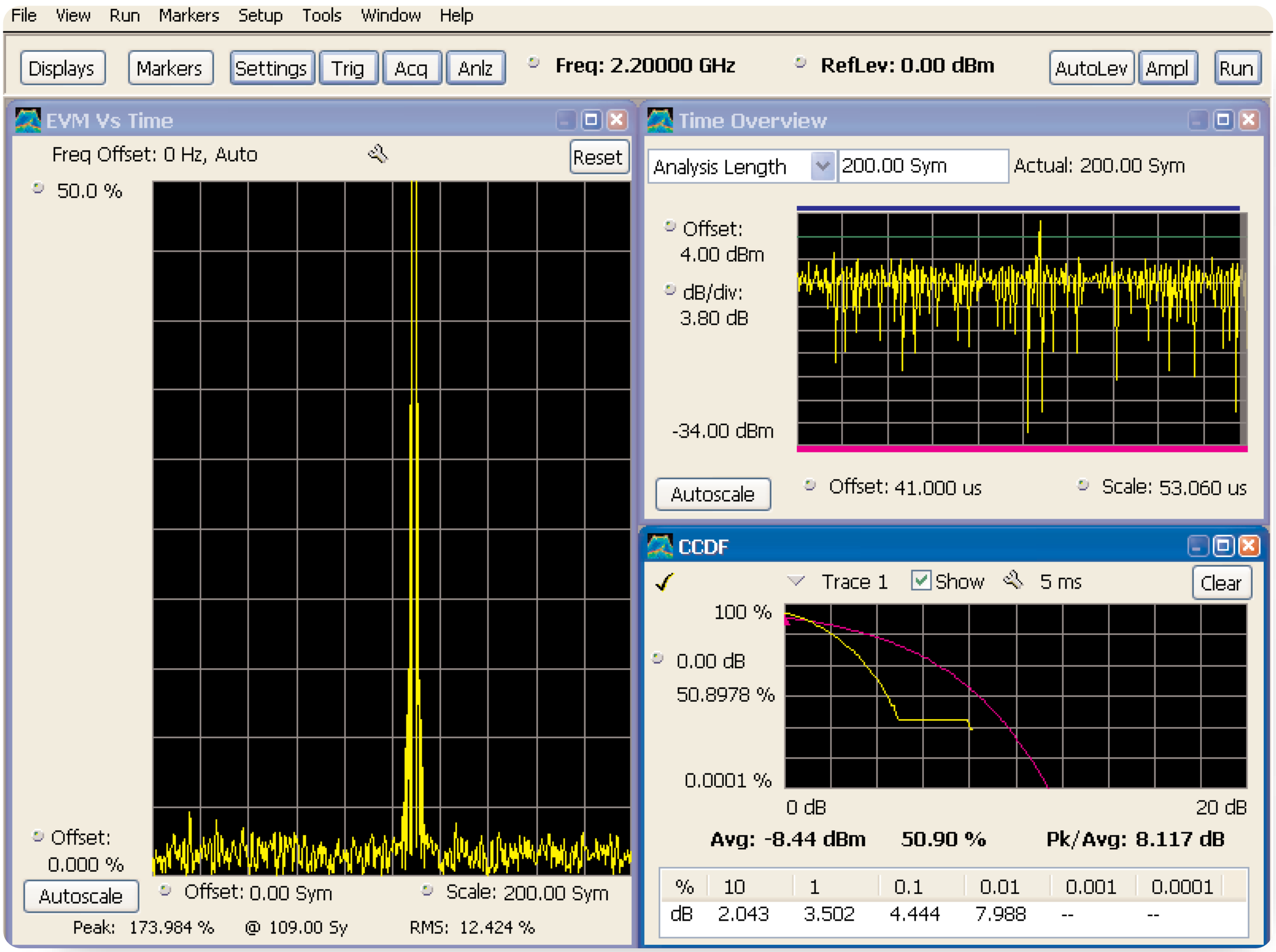

Figure 3. *Amplitude peak occurring at 0.01% probability, seen in amplitude vs. time, EVM vs. time and CCDF displays. The magenta trace on the CCDF Display (lower right) is a Gaussian reference curve: the yellow CCDF is measured from the captured waveform.*

Adjacent Channel Power and Leakage Ratios

Adjacent Channel Power Ratio (ACPR) and Adjacent Channel Leakage Ratio (ACLR) are terms that tend to be used interchangeably, and the differences between them are slight. ACPR is used to describe the power level in a channel adjacent to the transmit channel without regard for any receive filter that may be used in the communication system of interest. ACLR is a more recent term that takes into account the receiver filter used in the system of interest. The convention of ACPR is used in the 3GPP2 system, and power is integrated equally over the channel and adjacent channel bandwidths. In the 3GPP system, a RRC receive filter with α=0.22 is used to make both channel and adjacent channel power calculations. For the purposes of this application note, the convention of ACLR will be used, recognizing that the receive filter shape may be rectangular, resulting in a traditional ACPR value.

Real-Time ACLR

The RSA6100A Series ACLR measurement method differs from swept techniques. Up to the limits of the maximum 110 MHz capture bandwidth, the measurement is performed on a contiguous set of time domain data containing all of the channels to be measured. Resolution bandwidths, channel bandwidths and receiver filtering are performed mathematically after the signal is digitized. The ACLR measurement in the RTSA is no different from measurements in other domains; it is merely another mathematical calculation performed on the captured signal.

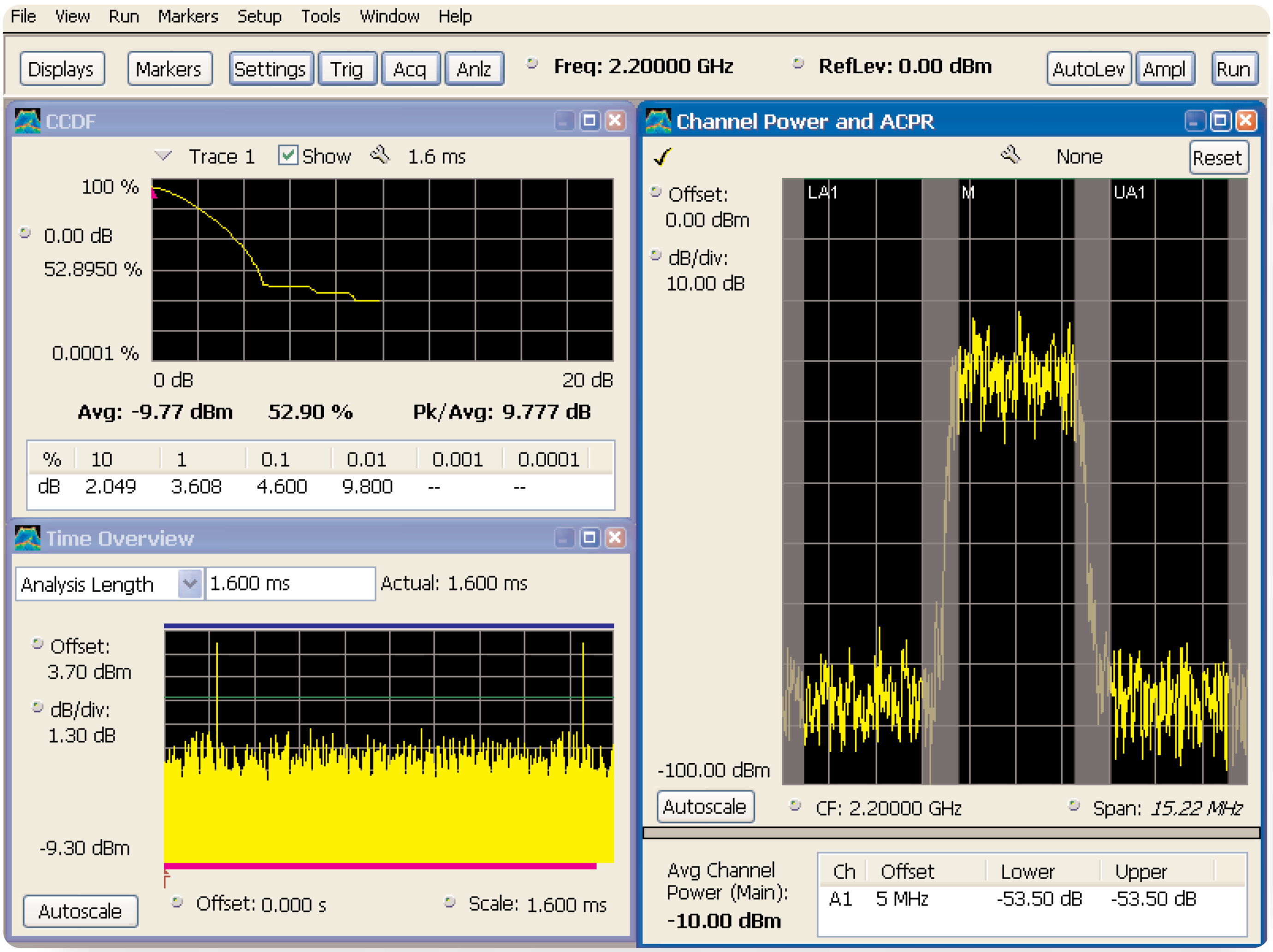

Figure 4. *CCDF, ACLR and Time Domain Correlation.*

ACLR Measurement and Correlation to Other Domains

The RTSA's ACLR measurement is correlated to other domains and measurements. This allows direct comparison of ACLR to other measurements, such as CCDF or peak-to-average ratio. Traditional techniques for performing these measurements required data to be gathered in separate or multiple acquisitions, resulting in imprecise comparisons.

Figure 4 shows an example of multi-domain analysis using a RTSA. The CCDF and PAR of the signal is calculated using the same data as the ACLR measurement, with the analysis period shown in the time overview. In this example, the amplitude spike seen in the time overview created the low-probability, high PAR seen on the CCDF chart, and is responsible for the small frequency domain transient, seen in the ACLR measurement.

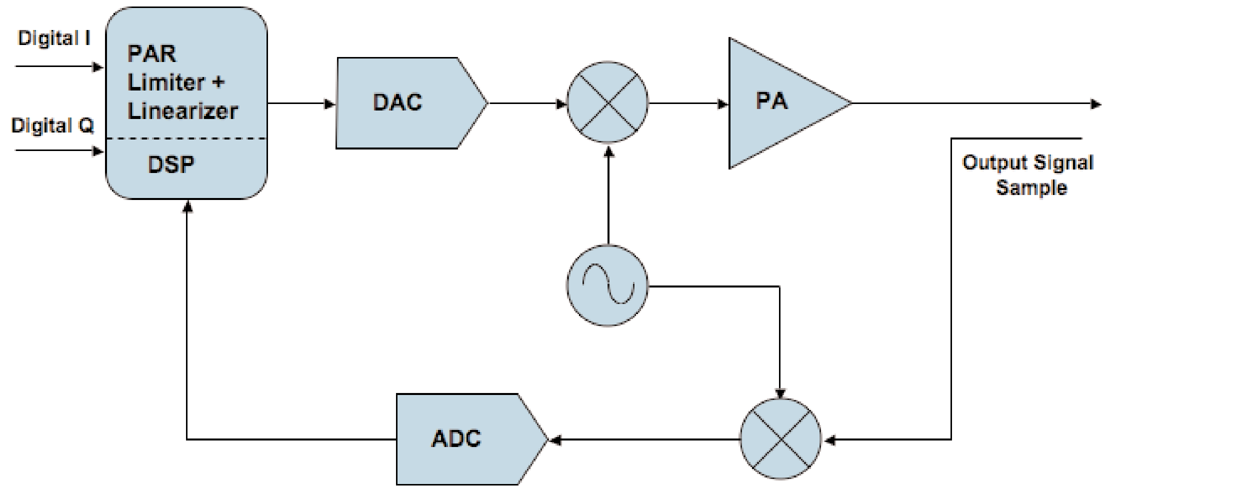

Figure 5. *Representative transmitter with digital pre-distortion.*

Digital Pre-Distortion Characterization

Modern Transmitter Block Diagram

Whether it is a high-power satellite ground station, a multi-carrier cellular base station or even a low-power mobile system, modern transmitters employ a variety of pre-distortion techniques to reduce out-of-channel interference and optimize operating efficiency. The most popular of these distortion reduction methods is Adaptive Digital Pre-Distortion. This approach uses a sample of the transmitter's output to calculate error vectors and generate correction coefficients, which are then used to pre-distort the incoming signal. To reduce analog-circuitry distortions, the signal in the chain is kept in digital format for as long as possible.

Figure 5 shows an amplifier with a low-level signal coupled from its output, down-converted and digitzed. This digitized sample is used to feed the digital signal processing circuitry, which performs analysis of the non-linearities present in the signal. These non-linear coefficients are used to alter the incoming in-phase (I) and quadrature (Q) signals in the transmit chain. This signal, now pre-distorted and with PAR reduction applied, is fed to the amplifier after being converted back to analog by the DAC, seen in the transmit chain. The resultant output signal exhibits reduced spectral distortion and lower ACLR than the signal without pre-distortion techniques.

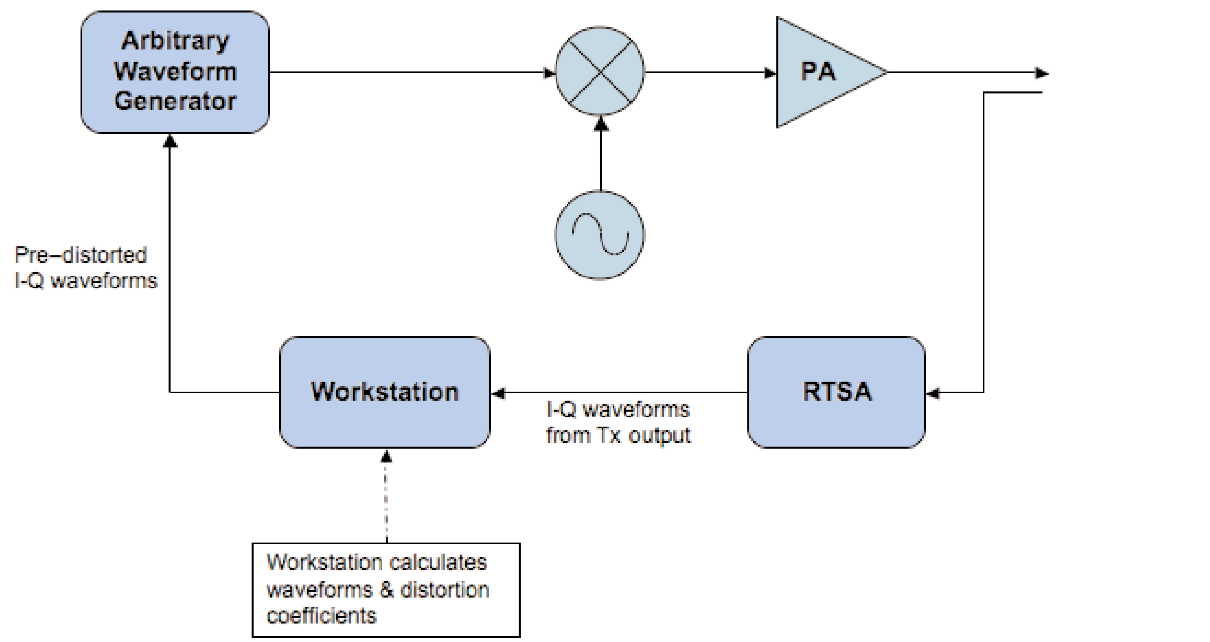

Figure 6. *Digital Pre-Distortion Development System.*

Troubleshooting and Characterization Challenges

The aforementioned scenario creates a wide variety of troubleshooting challenges not seen in traditional analog systems. Digital artifacts may be introduced into the transmit chain by the ADC and DAC, or by the DSP performed on the signal prior to analog conversion in the transmit path. These artifacts are frequently transient in nature and are difficult or impossible to capture using conventional spectrum analyzers. They may only occur rarely and can cause frequency domain effects in the adjacent and alternate channels. Effective troubleshooting of transient frequency domain signals requires not only discovery of the problem, but also the ability to trigger on it for analysis.

Characterizing these systems presents new challenges as well. In the development stage, a variety of pre-distortion and PAR reduction methods may be tested and optimized prior to the availability of the entire transmit chain. The signals in the feedback path must often be captured using test equipment, and calculation of the new non-linear distortion coefficients is performed in offline software prior to the availability of completed hardware (ASICs or FPGAs). These coefficients are then applied to the initial I and Q signals and the result is loaded into arbitrary waveform generators (AWGs) to test their performance.

Figure 6 shows a common configuration of this type of development system. An AWG is used in place of the I and Q signals and DAC, and the correction loop down-converter and ADC have been replaced with an RTSA. The I and Q vectors from the RTSA are then sent to an offline processor where pre-distortion and PAR reduction techniques are applied.

System Type	Single Carrier	# of Carriers, Channel BW Spacing	Multi-Carrier Transmit BW	3rd-OrderDPD Characterization BW	5th-order DPD Characterization BW
3GPP2 cdma2000	1.2288 MHz	12, 1.25 MHz	15 MHz	45	75 MHz
3GPP W-CDMA	3.84 MHz	4, 5 MHz	20 MHz	60 MHz	100 MHz
Wide-band Satellite	85 MHz	1, N/A	85 MHz	255 MHz	420 MHz
Proposed 4G Systems	98-105 MHz	1, N/A	Up to 105 MHz	305 MHz	Up to 525 MHz

Table 3. *Wideband system types and characteristics.*

The AWG employed must be of sufficient resolution, bandwidth and memory depth to replace the digital system used in the transmit chain. Tektronix produces a variety of AWGs that meet a range of these requirements.

The RTSA employed must have sufficient frequency range, capture bandwidth, capture-fidelity and memory depth for the application. The capture bandwidth must be able to digitize a minimum of 3 times the transmit bandwidth to assure the third-order distortion products are digitized. Many systems now use 5th-order distortion products in the calculation of the pre-distortion coefficients; if this is the case, the RTSA's capture bandwidth must be sufficient to acquire these products. Table 3 outlines the bandwidth requirements for selected systems.

When capturing distortion products, the test instrument's signal fidelity in both amplitude and phase domains are vital. The amplitude-phase linearity and distortion characteristics of all Tektronix Real-Time Spectrum Analyzers can be found in their respective datasheets for comparisons to your requirements.

The signals captured during development may contain very long sequences of specialized data, which are intended to exercise the limits of the amplifier by creating the worst-case operating scenario. These sequences may be 1 second in length or more, depending upon the design requirements. The RSA6100A Series has the ability to capture up to 1.7 seconds of I and Q data at its maximum capture bandwidth of 110 MHz. Longer captures are possible at reduced capture bandwidth.

Capturing long record lengths allows the user to examine the performance of devices in response to real-world signals. The ability to capture many packets of data is very useful, especially as it relates to changes in PAR, including changing modulation type, changing number of active code channels and adaptively changing power levels.

Once the data is captured, it must be moved from the RTSA to the computer used for analysis and correction. The RSA6100A Series employ a 1 Gb/s Ethernet connection for this transfer, and GPIB commands may be sent directly over the Ethernet connection. Alternatively, the user can store data on the internal DVD±RW on the RSA6100A Series for archiving and “sneakernet” data transfer. Data is exported in a comma-separated variable (CSV) format for easy import into offline analysis packages, such as Matlab™ and Excel™.

Troubleshooting

The process for finding faults consists of three steps:

1. Discovery of the problem
2. Trigger on and capture the fault
3. Trace the problem to the source

One example is a time-domain transient in the waveform (simulated with an AWG) that causes spectral splatter in the RF output. This can occur as a result of a fault in any of the digital circuit blocks, whether they are part of the feedback digitizer, the DSP code, the ADC in the upconversion circuit or signal delay and heating effects seen in the RF circuitry. Such transients can be infrequent and seemingly asynchronous to any clock in the system.

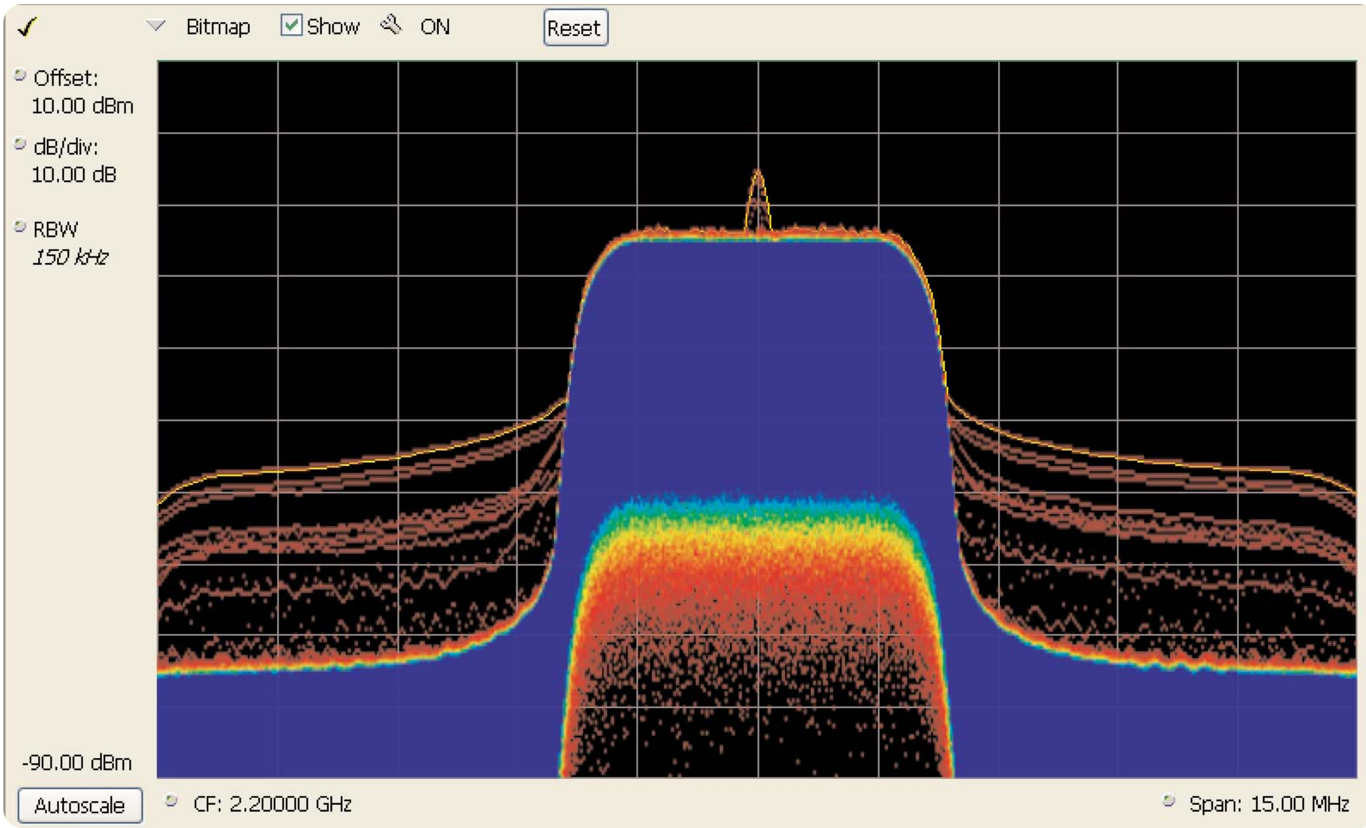

Figure 7. *DPX™ spectrum display of a QPSK signal at 3.84 MSymbols/s with a repeating fault twice per second. Data gathered over a 5 second period.*

Discovery

Detecting the problem can be a difficult challenge. The RSA6100A Series is uniquely suited to this task by virtue of its DPX™ spectrum processing engine. This window into the spectral domain will analyze any signal of duration as short as 24 μs with 100 percent probability of capture, ensuring that transient signals are analyzed on screen. Conventional spectrum analyzers that rely on swept techniques have minimum signal duration requirements 1000 times greater than the DPX spectrum processing engine, making fault identification either impossible or very time consuming.

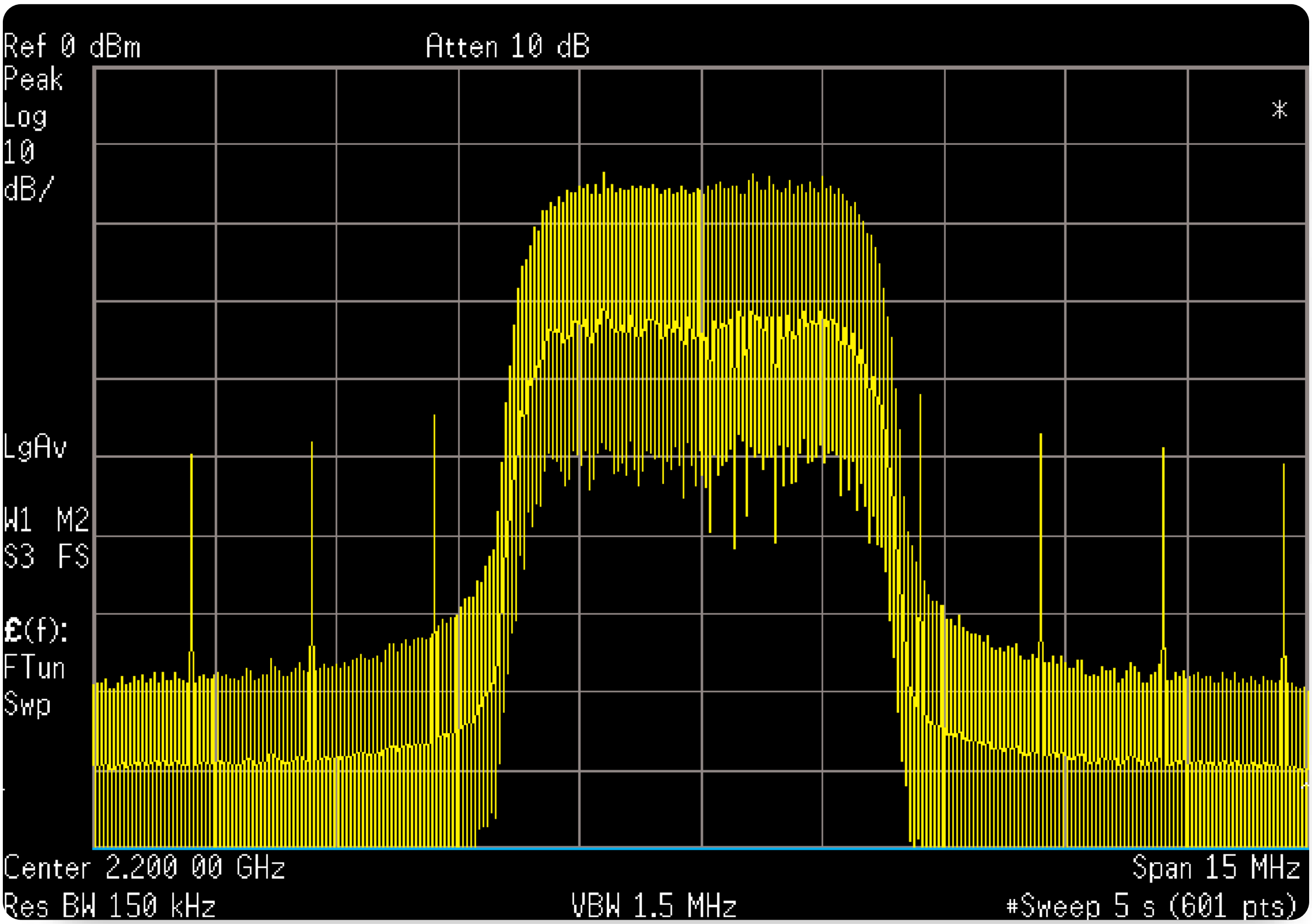

Figure 8. *Swept spectrum analyzer, optimized for best probability of intercept, after 5 seconds of signal analysis.*

Figures 7 and 8 highlight the difference between DPX spectrum processing and conventional swept spectrum analysis. Here, a fault with a duration of 30 us appears in the output waveform, occurring twice every second. On the DPX™ display, this is easily identifiable and displayed on every occurrence over a 5 second duration. In comparison, the swept analyzer (Fig 8) sweep speed has been optimized to create the highest probability of intercept. Max-hold was used to keep the signal intercepts on screen, and the instrument was allowed to sweep for 5 seconds. It is difficult to determine whether the signal is a side band or a single transient. The use of the DPX™ spectral display (Fig 7) has allowed us to see every instance of the signal.

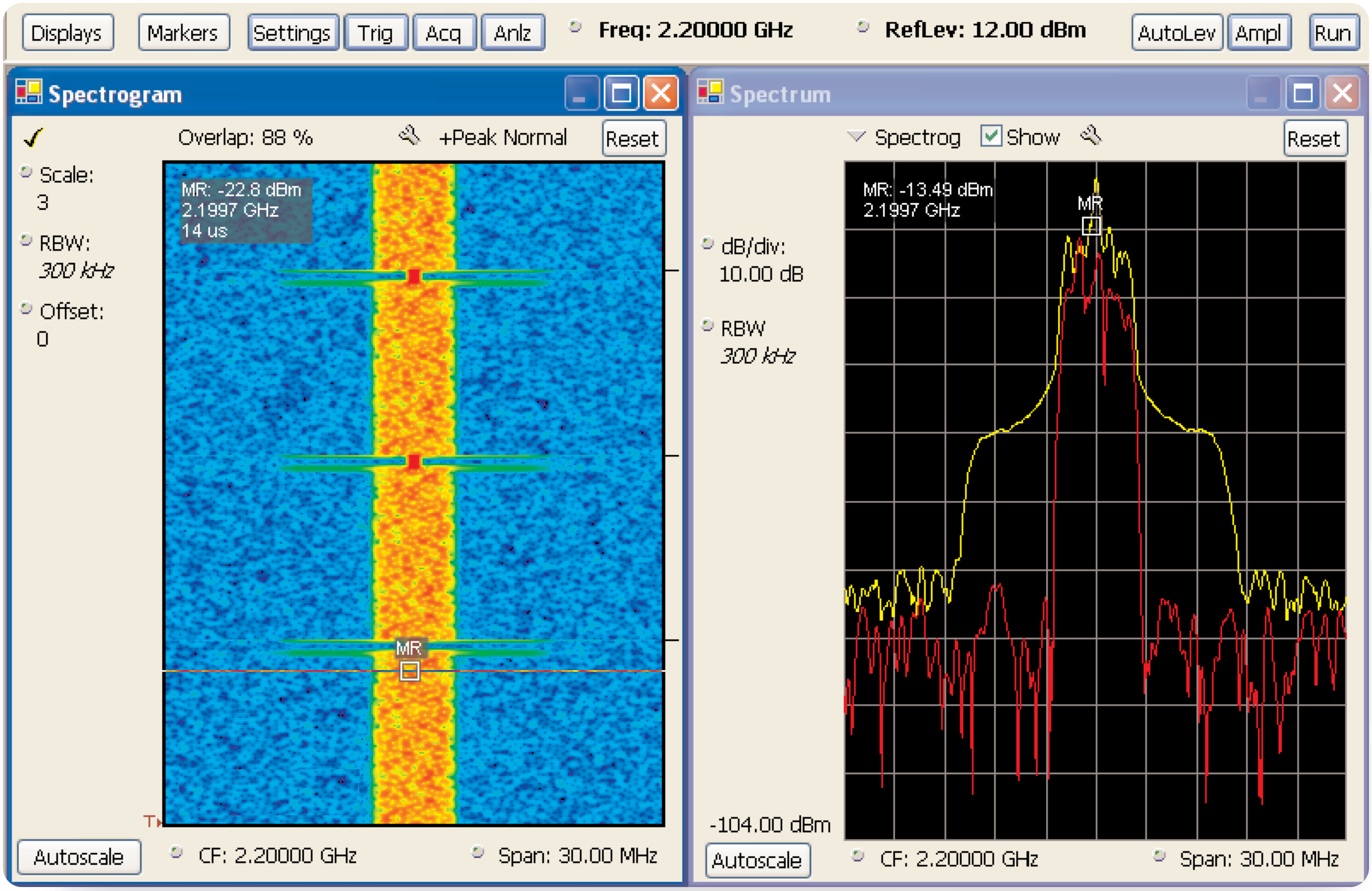

Figure 9. *Frequency Mask Trigger captures each instance of the fault. Three triggered captures are shown in spectrogram view on the left panel. In the right hand panel, the peak-detected spectrum of the entire event is shown. The red spectrum is the spectral energy during the normally-modulated portion of the capture. The yellow spectrum is the peak-detected result over one entire capture, including the transient that caused the spectrum splatter.*

Trigger and Capture

Once the problem has been identified and its characteristics understood, the user can set up a frequency mask trigger (FMT) to capture the signal for complete analysis. This is easily accomplished by referring to the DPX™ display, determining where the desired signal exists and drawing a mask to trigger on any signal outside of this area. An example of the signal first seen in Figure 7, now captured using frequency mask triggering, is shown in Figure 9.

When setting the FMT, the user is able to choose how much time domain information to collect around the fault and determine the trigger location within the time domain memory. The number of triggers is also user-definable. In this example, the FMT is set to trigger on five instances of the fault and capture 1 ms of data on each occurrence, placing the trigger near the beginning of each collected waveform.

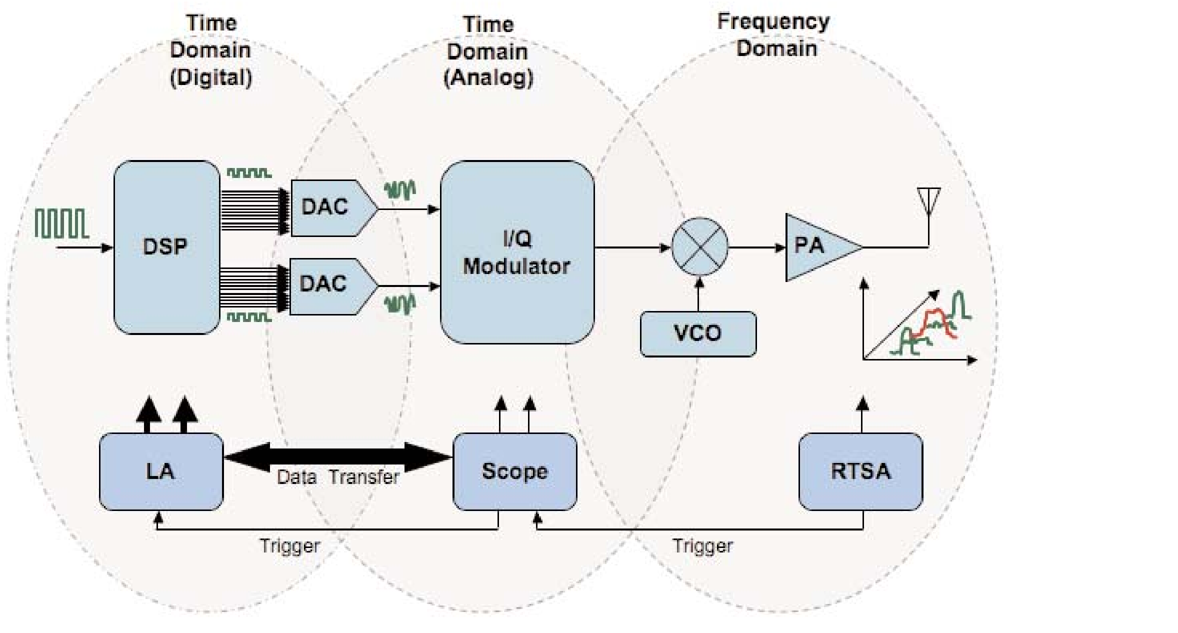

Figure 10. *Oscilloscope, logic analyzer and RTSA used in a signal path to troubleshoot faults.*

Trace the Problem

Now that the problem has been identified at the RF output, logic analyzers and oscilloscopes can be put to use in the baseband and IF portions of the circuit to track the problem to its source. The trigger output of the FMT can be used to trigger any other test equipment to help localize the problem. More complete explanations of these mixed-signal troubleshooting techniques are available in other Tektronix application notes.

Conclusions

Due to its wide capture bandwidth, deep memory and inherently correlated measurements, the RTSA is an ideal tool for the analysis and troubleshooting of wide bandwidth RF communications systems. Spectrum and vector measurements can be performed over bandwidths up to 110 MHz with high dynamic range and low residual EVM. All measurement domains are correlated, greatly improving troubleshooting capability. A new signal processing architecture, DPX™, allows for transients as short as 24 μs to be immediately analyzed in the frequency domain, improving discovery of transient spectral phenomena. And the frequency mask trigger can be used to reliably trigger on frequency transients, reducing troubleshooting time.

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