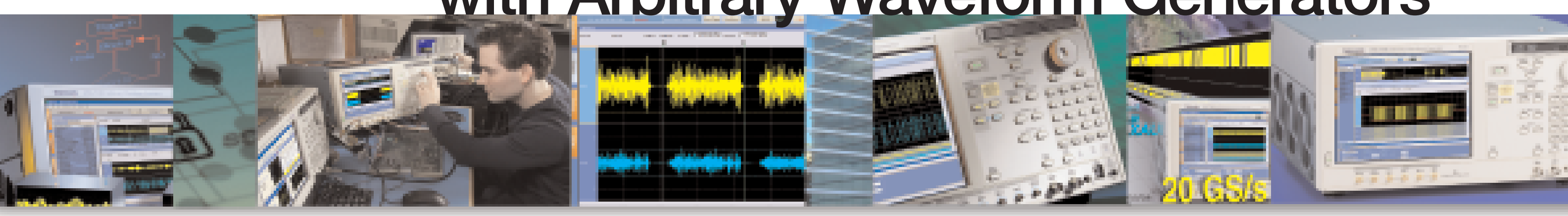
Creating Wireless Signals

with Arbitrary Waveform Generators



RF Primer

Tektronix
Enabling Innovation

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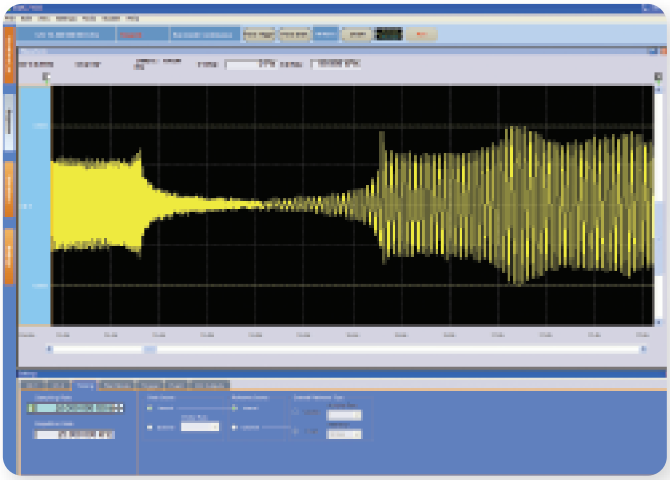
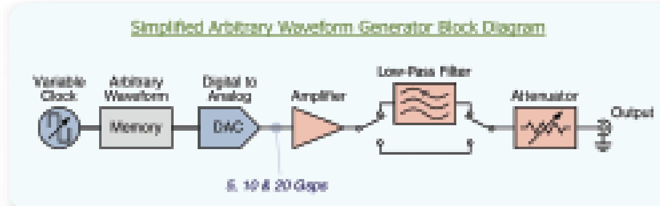




▶ **Figure 1.** *The Tektronix AWG series simplified block diagram reveals a variable clock controlling the arbitrary waveform and is available with sample rates up to 20 GS/s.*

Abstract

Arbitrary Waveform Generators (AWGs) have been commercially available and steadily improving in performance for many years. Advanced arbitrary waveform generators like the latest Tektronix AWG series are now capable of supporting many of today's most complex wireless test signals. The modern AWG can generate base-band, IF and RF frequency stimulus for efficiently testing wireless device and system performance. The 20 GS/s, 10-bit deep resolution of the AWG7000 can even accommodate extreme applications like Ultra Wide Band (UWB) radio designs. Similarly, the 14-bit deep resolution of the AWG5000 can handle high dynamic range narrow band applications. The unique value of the arbitrary waveform generator quickly becomes apparent when synthesizing complex digital wireless modulations. In this primer we look at the technology propelling the digital wireless revolution, some common AWG wireless test applications and important considerations for getting the best performance possible from the arbitrary waveform generator.

Introduction

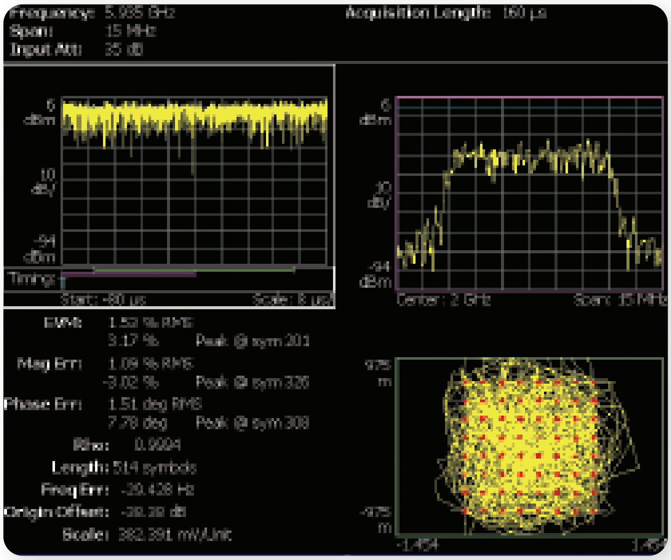
In recent years the wireless equipment industry has grown explosively and ushered in many new wireless devices. The industry growth has been made possible in large part by advances in RF semiconductors and the widespread use of digital modulation technology.

Today's digital wireless signals present an array of new challenges in synthesizing test signals. As the industry has shifted to digital wireless technology, it has brought a vast increase in modulation waveform complexity. Fortunately the steadily rising AWG performance now enables flexible, efficient generation of very complex test stimuli.

The concept behind the arbitrary waveform generator is simple. A variable frequency clock steps through a pre-stored digital representation of an arbitrary waveform, which is then converted into an analog signal.

Though simple in concept, a variety of important considerations are necessary to get the best performance possible from the AWG for each test application.

To understand how to get the best performance from the AWG, we begin by reviewing the RF transmission channel and why complicated digital modulations are so attractive.



▶ **Figure 2.** *Complex modulations like this 64 QAM signal contain waveforms that can be difficult to synthesize without an arbitrary waveform generator.*

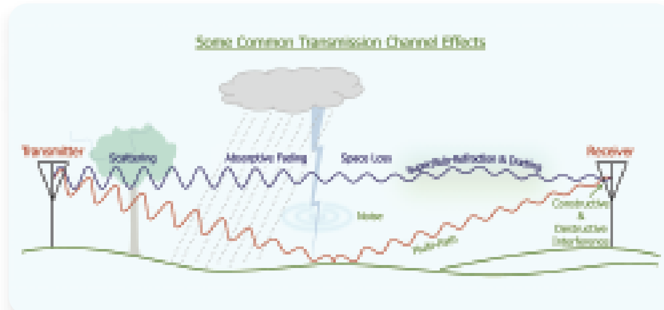
The primer then looks at some common wireless test examples, followed by important considerations in applying the AWG at base-band, IF and RF. We conclude with some thoughts on the expanding outlook of the AWG in RF testing.

Wireless Applications and Digital Modulation

Many of today's complex RF modulation waveforms are chosen because of their desirable properties for combating wireless transmission channel effects. The transmission channel medium through which the signal must pass between the transmitter and receiver is bounded by the RF channel bandwidth allocated to the signal.

The Challenges of Wireless Transmission

Transmitting and receiving electromagnetic radiation through the wireless channel can be challenging. The transmission channel usually significantly attenuates the transmitted signal, and its noise and dispersion properties can drastically distort the transmitted waveforms.



▶ **Figure 3.** *Wireless signals undergo a variety of channel effects that can severely alter the transmitted signal. To improve reception, complex digital modulations can be helpful.*

Wireless applications from radio to radar span a wide range of channel types. Wireless signal propagation is dependent on the frequency and bandwidth of the transmitted signal, as well as nearby reflective and absorptive objects. Atmospheric and ionospheric conditions can also significantly alter the transmitted signal as it travels to the receiver.

To be useful, modulated transmitter signals must be recoverable by the receiver after suffering severe path impairments. For example a 1-Watt (+30 dBm) transmit signal might be attenuated to one trillionth of its original amplitude (-90 dBm) by the time it reaches the receiver. If multi-path is present, the attenuation might not be consistent across the transmitted bandwidth. The attenuation and delays through the channel may also fluctuate with physical movement of the receiver.

In recent years, wider bandwidth signals have gained popularity for combating fluctuating channels. Techniques like Ultra Wide Band (UWB) modulations can deliver high data rates through multi-path filled, dispersive transmission channels. However, many test signal generators simply are not capable of generating the wide bandwidth that UWB signals require, creating a significant development and test hurdle.

Before exploring the UWB challenges and generation techniques in greater depth, let us review what digital modulations are and why they have become so popular.

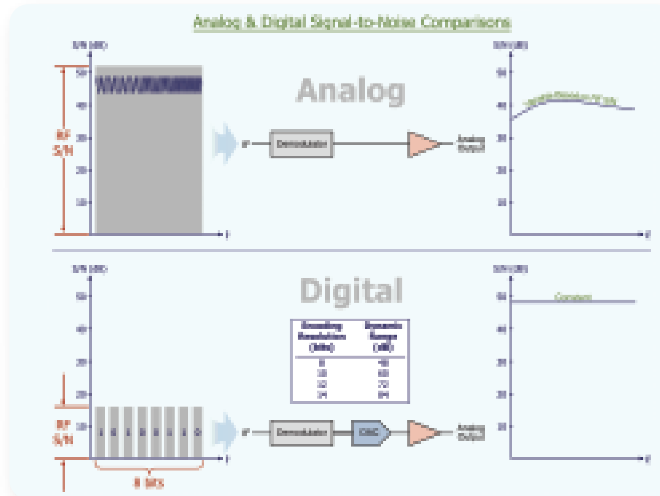
Why Digital Modulation?

Amplitude Modulation (AM), Frequency Modulation (FM), and Phase Modulation (PM) were all widely used analog modulations before digital modulations grew in popularity. The primary issue with analog modulations is that the signal to be transmitted is typically not encoded. The analog signal is simply modulated on to a high frequency RF carrier that will propagate through the transmission channel. For example, an analog voltage from a microphone is typically FM modulated directly onto a broadcast Radio Frequency (RF) carrier.

Since there is no encoding, the achievable analog Signal-to-Noise Ratio (S/N or SNR) after the receiver demodulates the signal is a function of the RF carrier's signal strength. Achieving static free transmissions with wide dynamic range – so the demodulated noise level is very small compared to the desired signal's amplitude – requires very high RF S/N ratios. Since the background thermal noise power spectral density of the transmission channel is usually fixed at -174 dBm/Hz, the only way to improve reception quality for the analog modulation is to transmit higher power levels, use larger and more directional antennas, or modulate over wider bandwidths. These analog modulation limitations restrict the dynamic range performance that can be achieved through the transmission channel.

Digital modulations, however, are uniquely able to deliver high dynamic ranges with low RF S/N ratios.

Digital modulations solve the S/N dynamic range problem by encoding the signal to be transmitted into a different form that requires lower RF S/N ratios for successful reception. For example, a voltage from the microphone can be digitized and encoded into an 8-bit word. Each bit can then be transmitted at a much lower RF S/N ratio with a high probability of accurately determining the correct bit,



▶ **Figure 4.** *Analog modulations require high RF S/N ratios for high S/N ratios after demodulation. Digital modulations can achieve very high S/N ratios after demodulation with low RF S/N ratios by adding bits of precision.*

using a simple binary decision. When the bits are put back together into an 8-bit word in the receiver, a 48 dB dynamic range results, even though the RF channel may have only had 25 dB of S/N ratio. Better still, the signal fidelity at the receive end is for the most part constant above the minimum S/N required for an acceptable bit error rate of the digital modulation.

These properties have allowed digital modulations to eliminate static noise and provide exceptionally reliable communications after suffering severe transmission channel impairments.

Digital modulations are also frequently credited with numerous other advantages over analog modulations. One such advantage that has allowed widespread use of digital modulations comes directly from the Digital Signal Processing (DSP) used to create the modulation. Most digital modulations are now generated with DSP techniques in some type of digital circuit, such as a Field Programmable Gate Array (FPGA) or a specialized DSP microprocessor. Digital circuits are significantly more stable with temperature variations than many of their analog counterparts. The stability, precision and reliability of digital circuits eliminate temperamental analog designs and manual circuit alignment, saving massive amounts of production labor. This keeps costs down and makes widespread deployment of the technology feasible.

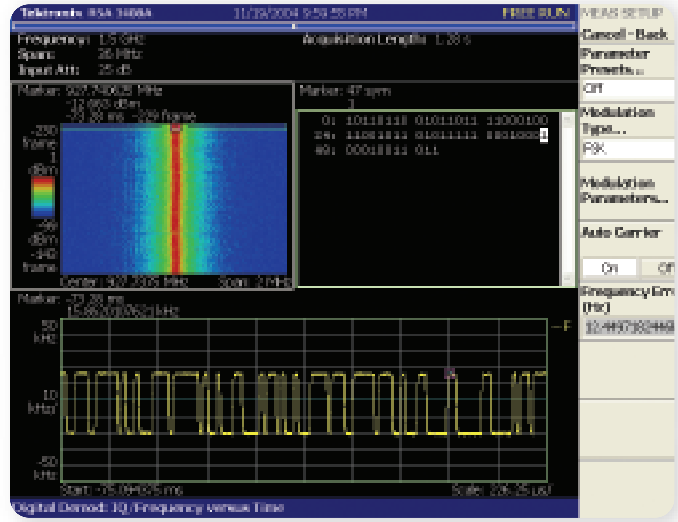
While digital modulations are often credited with significant reductions in spectral bandwidth over analog modulations, in most cases this is not exactly true. Many of the today's popular digital modulations are not substantially more bandwidth-efficient than popular analog modulations. However, since digital data can be compressed before being sent to the modulator, substantial information bandwidth reductions are often possible. Thus, the combination of digital signal compression techniques and a digital modulator routinely achieve a 3:1 reduction in the amount of RF bandwidth needed to send many types of wireless data.

To better understand the bandwidth performance of digital modulations and why the AWG is so useful for creating their challenging waveforms, let us now consider the waveforms used to send binary '1s' and '0s'…

What are Digital Modulations?

Digital modulations are similar to analog modulations, varying RF amplitude, frequency or phase, but with digital modulations the parameters being modulated take on a specific set of waveform states or symbols. Conversely, analog modulations are continuously variable over amplitude, frequency or phase.

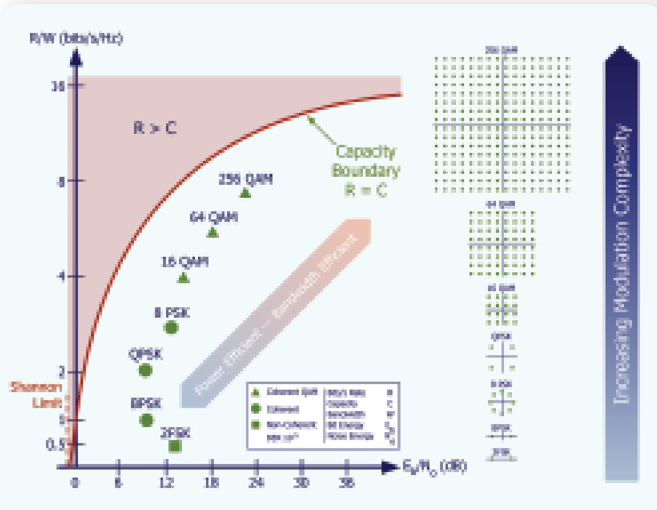
Simple digital modulations such as amplitude On-Off Keying (OOK), two-level Frequency Shift Keying (FSK), or Bi-Phase Shift Keying (BPSK) use only two states to represent the binary encoded data. With these simple two-state modulations, each encoded state or symbol represents either a binary 1 or 0.



▶ **Figure 5.** *A transmission from a cordless phone captured on an RSA3408A Real-Time Spectrum Analyzer (RTSA) shows the two frequencies the 2-level FSK signal takes on, along with the recovered symbols.*

OOK, 2 state FSK and BPSK provide good power efficiency and can be received reliably with low signal to noise ratios. However, these modulations have poor bandwidth efficiency, meaning that for a given data rate (bits/s), considerable RF transmission channel bandwidth (Hz of RF spectrum) after modulation is needed. In contrast, power efficient modulations do not achieve very high data rates in a restricted channel bandwidth.

One can easily see the power efficiency of these simple modulations when comparing them on the bandwidth efficiency plane to other modulations for a given Bit Error Rate (BER). The low required E_b/N_o or S/N ratio of 2FSK and BPSK makes them attractive where receive power is restricted.



▶ **Figure 6.** *The bandwidth efficiency plane compares the performance of different digital modulations at a given Bit Error Rate (BER). Simple power efficient modulations use low bit energy to noise ratios (Eb/No or S/N). Bandwidth efficient modulations require greater Eb/No and are more complex to generate but squeeze in higher bit rates into less RF spectrum.*

Limited spectral resources often favor bandwidth efficiency over power efficiency. The wireless radio spectrum is a carefully regulated and shared resource. Consequently, most wireless transmission channels tightly restrict the amount of available RF bandwidth for each user. This favors bandwidth efficient modulations that can get more bits through the available channel bandwidth faster.

To increase data link capacity with a fixed bandwidth allocation, higher complexity bandwidth efficient modulations, which require greater Eb/No or S/N ratio, have become popular. Thus the waveforms needed to test most modern digital data links have continually grown more complex as manufacturers try to provide the greatest data link performance for the limited RF bandwidth available.

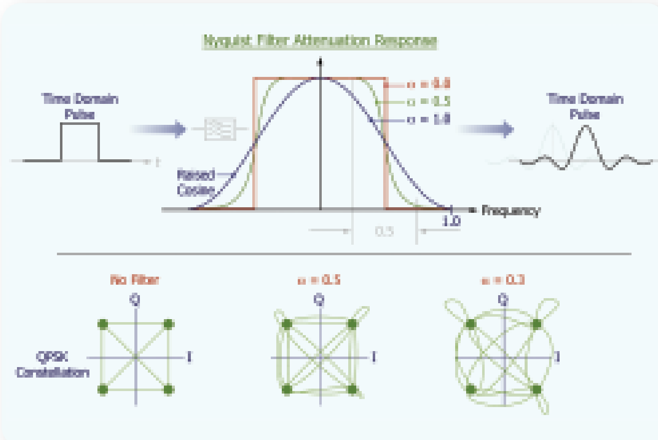
The more complex modulations generally use Quadrature Amplitude Modulation (QAM) where an In-phase (I) and Quadrature (Q, 90° out of phase) sine and cosine wave are summed together. Depending on the relative amplitude with which these signals are summed together, a phasor vector can be placed anywhere on a constellation of symbol points. As the number of symbol points increases, usually by powers of two, so too does the number of bits represented by each symbol point sent.

The simplest QAM modulation is QPSK, which has double the bandwidth efficiency of BPSK. QPSK is very popular since its power efficiency is also very good. With four symbol points, each QPSK symbol point sent represents two bits of data, compared to BPSK's single bit for each symbol sent.

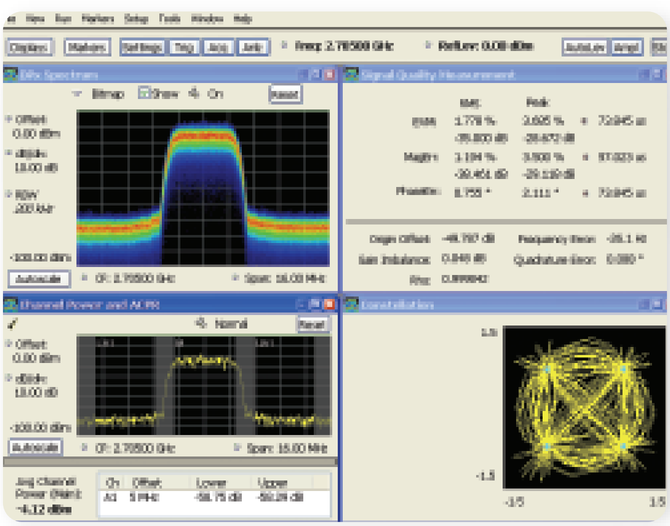
Digital modulations such as QPSK require careful base-band filtering of the time domain pulses that are sent to the modulator. Once the bits of data are encoded into symbols, the rectangular pulses must be filtered to minimize the required RF spectrum of the modulated signal.

Filtering the base-band symbol pulses is usually done with a special class of filter shapes. The most popular is the raised Cosine filter, which resembles a Cosine wave raised up above the zero Y-axis. The raised cosine family of filters has the unique property of periodic nulls or zero amplitude crossings in their time domain pulse response. Carefully chosen timing allows these nulls to prevent subsequent pulses from having their energy spread into the adjacent pulse at the symbol sampling time. This eliminates Inter Symbol Interference (ISI).

Usually implemented in digital hardware with a DSP algorithm, the raised cosine filter shape can be adjusted to alter the amount of RF spectrum that is filtered away. The shape of the raised cosine filter is based on the parameter alpha. The lower the alpha, the steeper the roll-off of the filter skirt. As alpha is decreased, the RF spectrum is reduced. However as alpha is decreased, the trajectory of the modulating vector between symbol points also begins

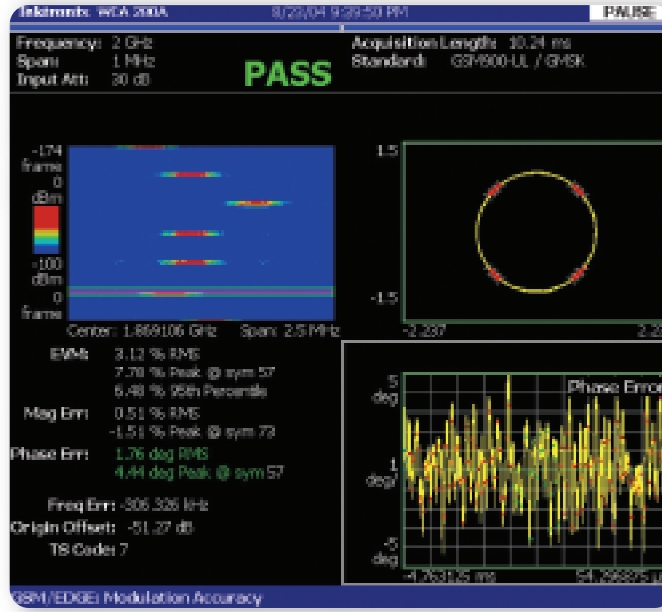


▶ **Figure 7.** *To limit the RF bandwidth of time domain symbol pulses, the raised cosine filter has a desirable response containing periodic zero amplitude crossings that avoid inter-symbol interference. However, as the a shape factor of the filter is changed, the vector trajectories on the constellation also change.*



▶ **Figure 8.** *Channel power and constellation overshoot of a QPSK signal generated on a Tektronix AWG are easily measured with the RSA6114A.*

to overshoot the bounds of the symbol constellation by greater and greater amounts. This tradeoff between RF bandwidth and constellation overshoot is an important engineering consideration as it can affect the size of the transmitter power amplifier and antennas.



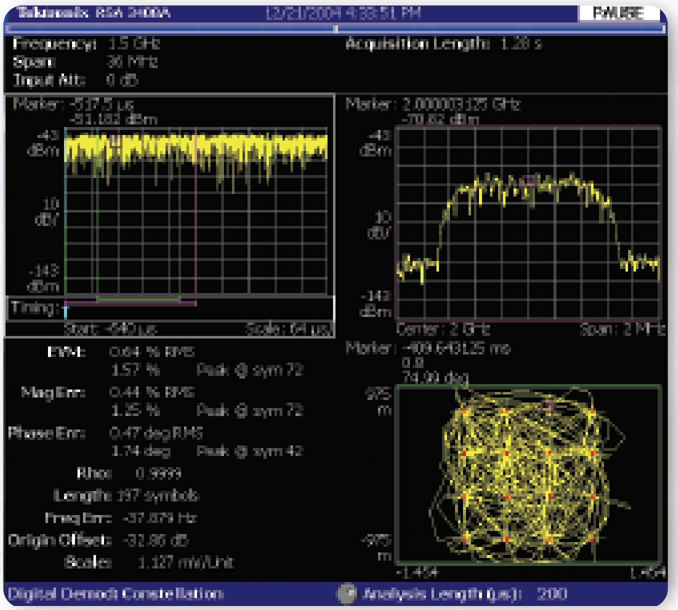
▶ **Figure 9.** *The GSM cellular signal measured here with the RSA3408A real-time spectrum analyzer is a GMSK modulation with constant signal amplitude. Unlike QPSK's precisely defined four symbol points, GMSK's Gaussian filtering causes some ISI.*

When generating digital modulations with an AWG, both the correct filter alpha and sufficient generator dynamic range are needed to accurately produce the digital modulation.

Some modulations such as GMSK do not use a raised cosine filter, but instead use a Gaussian filter shape and minimum constellation phasor movements to achieve a constant modulation amplitude envelope. The Gaussian filter does permit some inter symbol interference, leading to a row of symbol points in each quadrant.

Again, when generating a digital modulation, it is important to compile the waveforms with the appropriate base-band filter.

To further improve the bandwidth efficiency, more symbol points can be added to the QAM constellation. Moving beyond QPSK's 4 symbol points, 8PSK (3 bits/symbol), 16QAM (4 bits/symbol), 32QAM (5 bits/symbol), 64QAM (6 bits/symbol), 128QAM (7 bits/symbol) and 256QAM (8 bits/symbol) are all popular.



▶ **Figure 10.** *A correctly generated 16QAM signal has the appropriate amount of RF spectrum roll-off and constellation overshoot.*

Modulation Type	S/N	Bandwidth
2FSK	13.4	B[1]
4FSK	23.1	B/2
BPSK	10.5	B
QPSK	13.5	B/2
8PSK	18.8	B/3
16QAM	20.5	B/4
64QAM	26.5	B/6
128QAM	29.5	B/7
256QAM	32.6	B/8
9QPR	16.5	B/2
25QPR	20.5	B/3
49QPR	23.5	B/4
16TCM-2D	14.3	B/3
64TCM-2D	21.9	B/5.5

1— B = bit rate.

▶ **Table 1.** *Different digital modulations can be chosen to provide a variety of theoretical signal to noise ratios and bandwidth requirements for a 10-6 BER.*

As modulation complexity increases, the challenges of correctly generating the digital symbol constellation become more and more difficult. Increasing S/N ratios, phase noise, Digital to Analog Converter (DAC) precision, amplifier linearity and other factors conspire to make higher and higher order modulations less practical to use. For this reason, 512QAM and 1024QAM are rarely used in production systems.

Some approaches have been devised to reduce the S/N ratio requirement and filtering tradeoffs for complex QAM modulations. For example, Quadrature Partial Response uses controlled ISI to allow more efficient filtering of the modulated signal.

Trellis Coded Modulation (TCM) effectively improves Euclidian distance between symbol points on the constellation by coding the symbol points so that certain adjacent symbols are avoided during the next symbol state. Similarly, Block Coded Modulation (BCM) and Multi-Level Code Modulations (MLCM) use coding of the symbol patterns to improve the effective distance between QAM constellation points. Symbol coding makes the modulations less sensitive to geometry errors in the constellation.

Adding coding to the symbols in the constellation further adds complexity to generating a test signal. Not only does the QAM constellation have to be correctly mapped out, certain symbols are not allowed at certain times.

Modern DSP processor hardware has pushed modulation one step further by now making multi-carrier techniques like Orthogonal Frequency Division Multiplexing (OFDM) practical. OFDM uses one or more of the previously discussed single carrier digital modulations on multiple, closely spaced carriers, all combined into a single signal. Correctly spaced in frequency, symbols on each carrier are orthogonal and prevent ISI. Since the individual carrier symbol rate is slowed down with multiple symbols being sent simultaneously, relative to a single carrier modulation, OFDM is very good at combating channel multi-path effects.

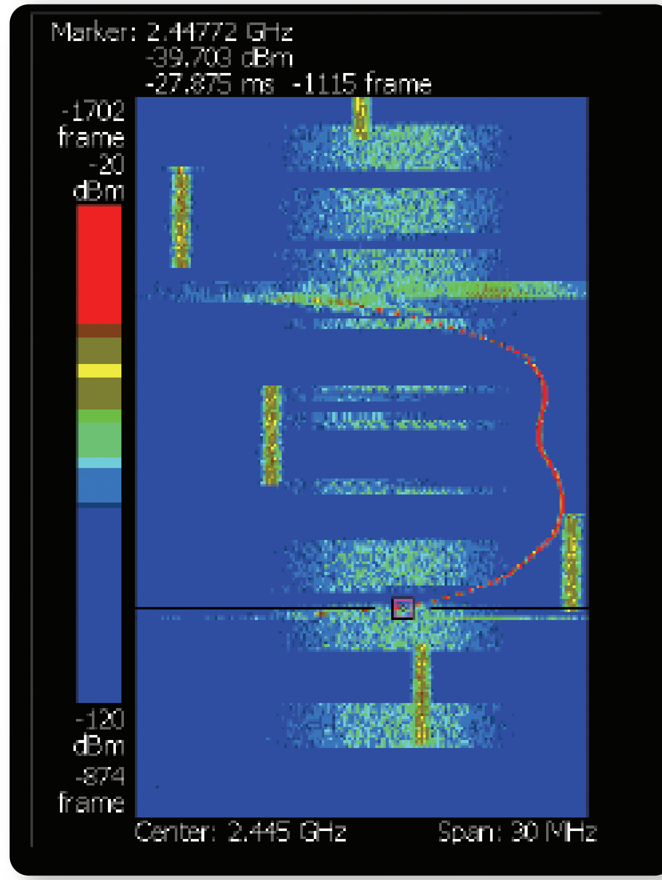
Many wireless data links further optimize transmission rates by dynamically changing modulations to best fit the prevailing channel conditions. For example, Wireless Local Area Network (WLAN) modems can dynamically change the modulation type and data rate to suit the available channel characteristics. If sufficient receiver S/N ratio is available for 64QAM, then that modulation is used. As S/N levels drop, a different modulation like QPSK that requires a lower S/N ratio can be selected.

Generating modulations that change dynamically can be challenging. The arbitrary waveform generator's ability to store complex waveforms containing several modulations is particularly valuable for testing modems that can change modulation formats.

Another popular trend in modulations is the use of spread spectrum signals with wider bandwidths than the modulation requires. Spreading the spectrum intentionally produces a variety of desirable properties, including good multi-path performance, the ability to use code division multiplexing to share the same frequency band with multiple signals, and increased resistance to interference.

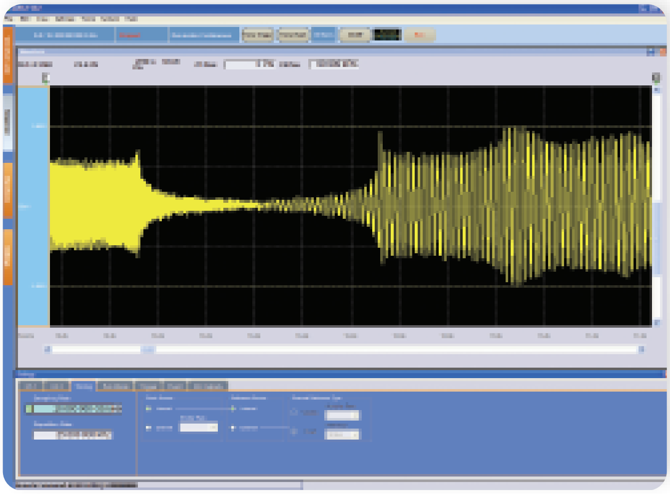
Frequency Hop Spread Spectrum (FHSS) increases the modulated signal's complexity by hopping the signal over a set of predetermined frequencies. There are two types of frequency hoppers: slow hoppers that send many symbols per hop, and fast hoppers that hop many times during each symbol. Both types of FHSS systems usually employ a QAM modulation, often QPSK, spread by a Pseudo-random Number (PN) sequence.

Direct Sequence Spread Spectrum (DSSS) is another popular technique for spreading a modulated signal. DSSS uses a PN sequence to phase modulate the modulated signal (often QPSK) spreading the spectrum. Each pseudo-random number used to spread the modulated signal represents a spreading chip. DSSS chip rates can be very high, thus spreading the spectrum over large bandwidths.



▶ **Figure 11.** *This spectrogram reveals two common spread spectrum signals. The yellow hopping signal is a Bluetooth FHSS transmission, while the constant center frequency aqua signal is a WLAN DSSS transmission. The red line is caused by a microwave oven leaking RF radiation.*

Like FHSS, DSSS can require wide bandwidth signal sources to create the signals needed to test receiver performance.



▶ **Figure 12.** *The AWG7000 shown here has sufficient bandwidth for generating most UWB signals like this UWB radar pulse.*

Ultra Wide Bandwidth (UWB) technology also demands extreme test signal bandwidths.

UWB transceivers use such wide spectrums that they are virtually immune to multi-path, making them attractive for challenging indoor environments filled with reflective objects. UWB wireless links can support high data rates using a series of narrow pulses spread across a wide spectral range. Some UWB transceivers can often eliminate significant amounts of RF frequency conversion hardware because their enormous base-band signal bandwidths reach well into the RF frequencies. The Tektronix AWG7000 series has models with high enough sample rates to effectively support the demanding bandwidths of most UWB test applications.

Similarly, compressed radar pulses used to improve target resolution often require great bandwidth. Pulse compression uses RF pulse modulation to separate overlapping radar return echoes. (An introductory discussion can be found in the Tektronix application note: "Radar Pulse Measurements with the Real-time Spectrum Analyzer.") Common pulse compression modulations are frequency chirps, FHSS and DSSS signals.

Frequency chirping, FHSS and BPSK DSSS modulations are all popular approaches to compressing pulses for improved spatial resolution between targets. There is a direct relationship between the bandwidth a compressed pulse is modulated over and the achievable spatial resolution possible. Without the convenience of a wide bandwidth AWG, often the only other means to create these challenging signals and their impaired echo returns was an expensive custom-built RF test set.

The digital modulation revolution thus not only benefits wireless communications devices but compressed pulse radars as well.

Digital Modulation Applications

Spurred on by low cost digital signal processing hardware and Software Defined Radio (SDR) implementations, the advantages of digital modulations have quickly made them ubiquitous in wireless telemetry, communications and radar systems. Only the simplest systems or legacy radio applications still use analog modulations.

One of the key test challenges for digital wireless systems has thus become the generation of test signals. As we have seen, digital wireless modulations have grown in complexity and some require extreme amounts of bandwidth. Next, let's look at how the AWG is used to test wireless systems and devices.

Digital Wireless Test

Digital wireless data links generally require a variety of modulated waveforms for developmental evaluation and production checkout. Modulated signals are frequently the best test stimulus to evaluate component and system performance.

The wide variety of test signals needed to effectively examine today's wireless designs makes the flexible arbitrary waveform generator the premier tool for the task.

Popular Modulations	
Cellular	
GSM, GPRS, EDGE	GMSK
W-CDMA	DSSS HPSK, QPSK, 16QAM
HSDPA, HSUPA	DSSS HPSK, QPSK, 16QAM
TDSCMA	DSSS QPSK
TD-CDMA	DSSS QPSK, 16QAM
IS-95	DSSS OQPSK, QPSK
cdma2000	DSSS QPSK, HPSK
1xEV-DO & DV	DSSS QPSK, HPSK, 8PSK, 16QAM
iDEN	QPSK, M16QAM
WiDEN	QPSK, M16QAM, M64QAM
TETRA	π/4-DQPSK
Point-to-Point Radio	
Short Haul	DSSS, 4FSK, 16QAM, 64QAM, 64TCM, 49QPR
Long Haul	128QAM, 128TCM, 256TCM
Radar	
	Chirps, BPSK, FHSS
Satellite	
	QPSK, 8PSK, 16QAM
HD Television	
ATSC	8-VSB, 16-VSB
DVB-T	QPSK, 16QAM, 64QAM on COFDM
ISDB-T	BST-COFDM DQPSK, QPSK, 16QAM, 64QAM
Wireless Networks	
Bluetooth™	FHSS, GPSK, π/4-DQPSK
WLAN	DSSS CCK D8PSK, DQPSK, 52 OFDM 64QAM
WiMax	OFDM BPSK, QPSK, 16QAM, 64QAM
ZigBee	BPSK, OQPSK

▶ **Table 2.** *A quick look at some of today's popular applications reveals a complex array of digital signals needed for device testing. Generating these signals and their common impairments would be difficult without an arbitrary waveform generator.*

The AWG can generate both ideal signals to test basic circuit functionality and impaired signals to test performance under adverse transmission channel conditions.

Maximum Capabilities	AWG5000	AWG7000	Units
Channels	2	2	—
Sample Rate	1.2	20	GS/s
Bandwidth	0.379	5.8	GHz
Memory Depth	32 M	64 M	Samples
Vertical Resolution	14	10	Bits
Output Amplitude*	4.5	2	Volts p-p
Marker Outputs Per Channel	2	2	—
Parallel Digital Outputs**	28	—	—

* 50 Ohm Load, ** Optional on 2-Channel Models

▶ **Table 3.** *Tektronix AWG5000 and AWG7000 signal generators series offer different capabilities and options to fit most wireless applications.*

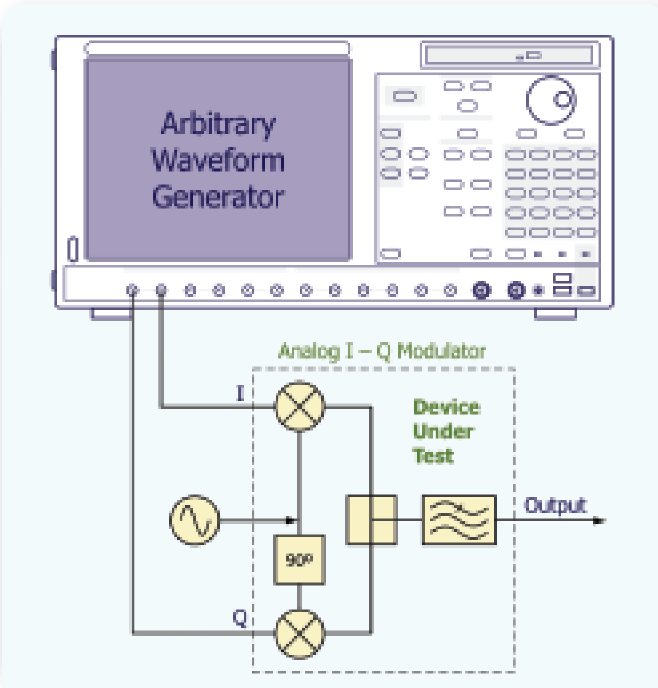
To illustrate, here are some common AWG test examples…

Transmitter — I-Q Modulator Testing

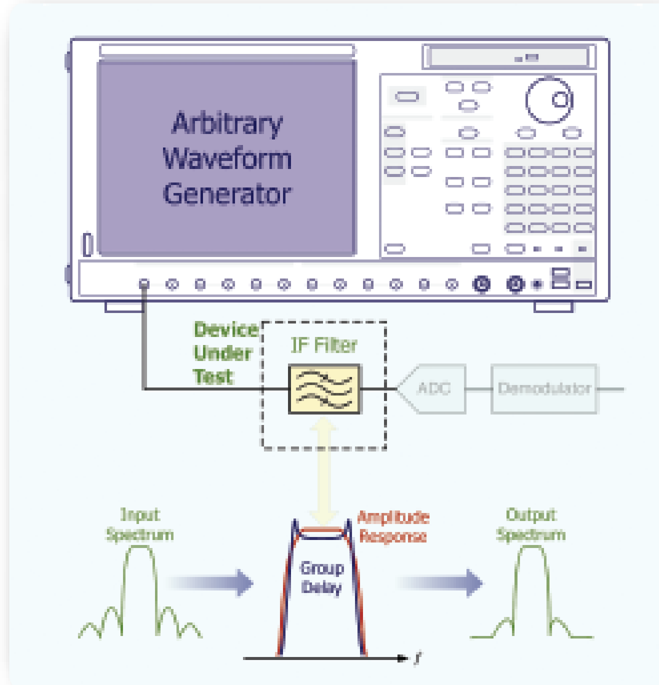
Modem engineers pay particular attention to modulator performance as a key element in achieving the theoretical performance of the chosen modulation.

Many digital wireless designs use analog I–Q vector modulators that can suffer from a variety of issues. Quadrature error, I–Q gain imbalance, non-linearities and a host of other problems can cause these components to distort symbol constellations, robbing data link performance. The digital modulation S/N ratios shown earlier are theoretical performance limits. Poorly constructed symbol constellations with distortion will require greater S/N levels, which translate into shorter data link transmission distances.

Testing the vector modulator requires two analog inputs, one for the I-channel and one for Q-channel. The I and Q channels must also be properly synchronized and filtered to generate a good quality modulated IF signal. Once the input stimulus is correctly applied to the vector modulator, its performance characteristics are then easily measured with a real-time spectrum analyzer.



▶ **Figure 13.** *Wide bandwidth and high frequency digital wireless applications often use analog vector modulators. The AWG's precisely timed I–Q outputs are ideal for testing these components or generating high frequency modulated signals.*



▶ **Figure 14.** *IF filters strip away interference from the desired signal spectrum. IF filters can also be key contributors to undesirable group delay distortion of the received signal. The AWG easily generates a wide range of test spectrums to evaluate interference reduction versus distortion of the received signal.*

The AWG can generate the needed test stimulus to sort out which modulators are suitable for the data link by placing the AWG in I–Q output mode. This sets the phase of the two outputs used to drive the modulator to produce excellent phase synchronization and amplitude match between channels. Degradation measured after modulation must then be caused by delays, losses or non-linearities internal to the vector modulator.

The AWG's flexibility in storing many waveforms allows easy adjustment of base-band filtering when compiling test stimulus waveforms. Saving several waveforms made with different filter alphas allows engineers to quickly evaluate the spectral performance of each vector modulator under different conditions. This can be important because spectral re-growth created in the modulator varies with drive level and adds to the filtered base-band spectrum. Selecting the optimum combination of modulator drive level and filter alpha to meet spectral regulatory requirements is easy using several test waveforms generated on the AWG.

IF Filter Effectiveness and Impairment Testing

When designing a wireless data link, IF filters are usually added to transmitters and receivers for cleanup of spectral issues.

IF filters remove unwanted internal frequency conversion products, strip off external sources of interference to the desired signal, and supplement limited or periodic digital filter responses. At first glance, the steeper, sharper and narrower the IF filter can be made around the desired modulation spectrum, the better.

IF filters however, add group delay which distorts the desired in-band signal. Thus to minimize distortion of the desired signal, filters should be made wider and smoother with more gradual out of band attenuation.

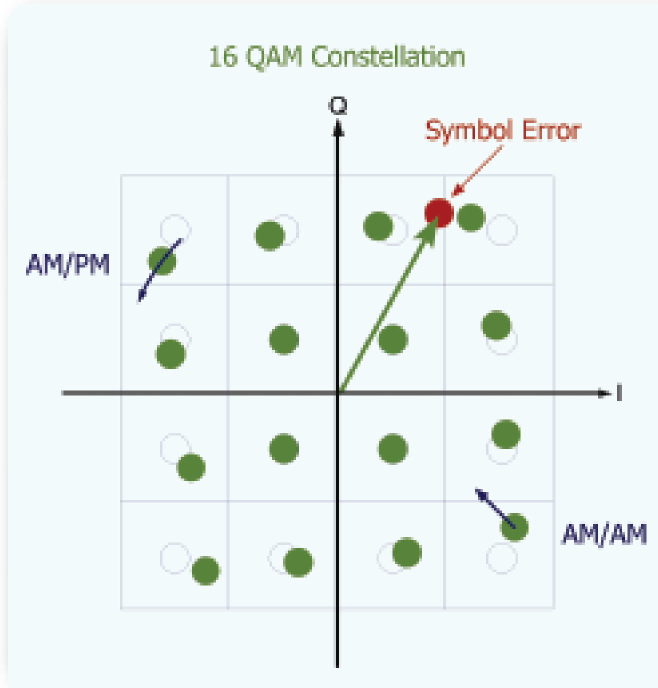
Selecting an IF filter becomes a classic engineering tradeoff between interference protection and in-band signal performance. Complex digital modulations and IFs that must support a variety of modulation types can make it difficult to determine the optimum filter.

The AWG simplifies IF filter selection by allowing the engineer to judge a filter's effectiveness and impairment of the desired signal using easily generated and realistic worst-case signal scenarios.

First, the desired digitally modulated signal is synthesized. Then adjacent interfering signals and spurious are digitally added to the desired signal at the appropriate levels. Next, the composite multi-carrier waveform is loaded into AWG memory and played out through the IF filter. Amplitude attenuation of the input spectrum is then easily measured after the filter to judge its effectiveness.

Impairment of the desired signal can then be quantified by comparing its Error Vector Magnitude (EVM) measurement before and after filtering. EVM is a popular modulation quality measurement done on the real-time spectrum analyzer or vector signal analyzer that compares a reference digital modulation to the measured modulation's signal. The magnitude of the error vectors between the two signals becomes a measure of how badly the desired signal has been distorted from the reference.

The combination of the AWG and RTSA can provide complex stimulus-response testing for difficult to specify components like IF filters. Measuring interference attenuation and composite EVM distortion of the desired signal helps the engineer choose the best combination of interference protection and desired signal performance loss.

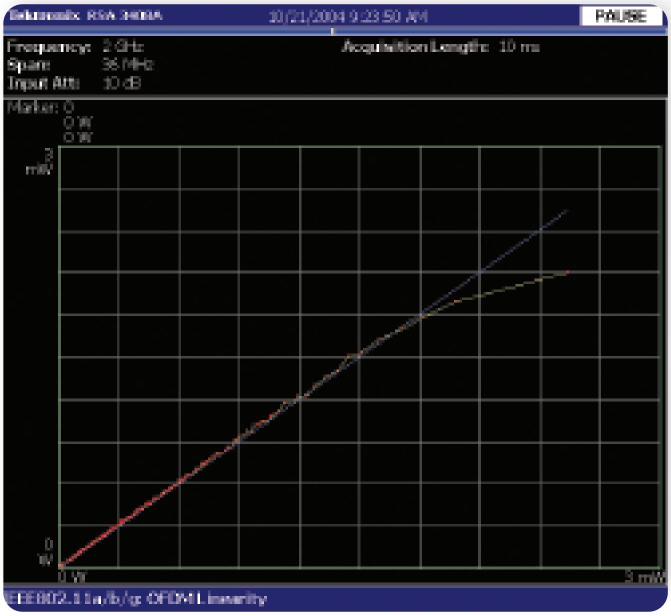


▶ **Figure 15.** *Non-linearities such as AM/AM and AM/PM can distort symbol constellations causing errors. Accurately characterizing these non-linearities often requires a modulated test signal.*

Transmitter — RF Power Amplifier Linearity

Another complex stimulus-response application gaining popularity in recent years is measuring Power Amplifier (PA) non-linearities.

Quadrature modulations are susceptible to power amplifier non-linearities. Large vector amplitudes in the modulated signal can be distorted by non-linearities in the PA, causing unintentional additive modulation. Amplitude Modulation to Amplitude Modulation conversion (AM/AM), and more importantly for most digital modulations, Amplitude Modulation to Phase Modulation conversion (AM/PM), can cause symbol errors by distorting the transmitted symbol constellation.



▶ **Figure 16.** *Using a digitally modulated signal from a Tektronix AWG, the dynamic linearity of a power amplifier can be accurately measured on a RSA3408A.*

Traditionally, AM/AM and AM/PM have been easily measured on a vector network analyzer using a sine wave stimulus of the input port to the amplifier, while observing the amplitude and phase responses at the output port of the PA. Unfortunately, for many applications the measurement results using this method are not sufficiently accurate to be of value.

Coupling and de-coupling capacitors used in many power amplifier designs, along with transistor thermal effects, give rise to a modulation 'memory effect' that dynamically changes the AM/AM and AM/PM. This necessitates measuring AM/AM and AM/PM with a modulated signal instead of a static sine wave for realistic non-linearity measurements, like those used for Digital Pre-Distortion (DPD) of multi-carrier PA systems.

The AWG's memory is loaded with the complex digital modulation waveform of the actual signal used by the data link, as an RF stimulus for test.

Special linearity measurement software is available for the real-time spectrum analyzer that detects the distortion of the AWG signal by the PA to measure the dynamic AM/AM and AM/PM.

The AWG can play an important role in testing key transmitter components like vector modulators, IF filters and power amplifiers.

Let's now turn our attention to see how the AWG is routinely applied to the receiver side of the data link.

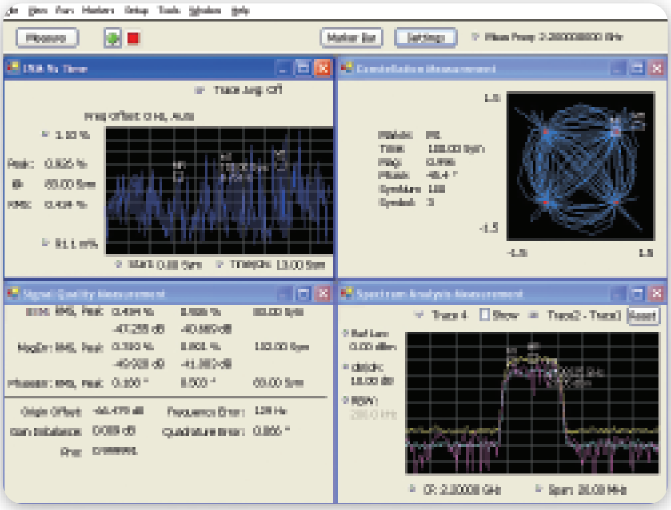
Receiver — Demodulator Testing at IF

Digital demodulator development requires a variety of testing stimuli for characterizing performance. Measurements of the time required for acquiring the digital signal's carrier, the permissible frequency offsets of the received signal, and the S/N or Carrier to Noise Ratio (C/N) required for a given BER, are all commonplace. Demodulator testing generally requires an IF stimulus using the digital modulation signal.

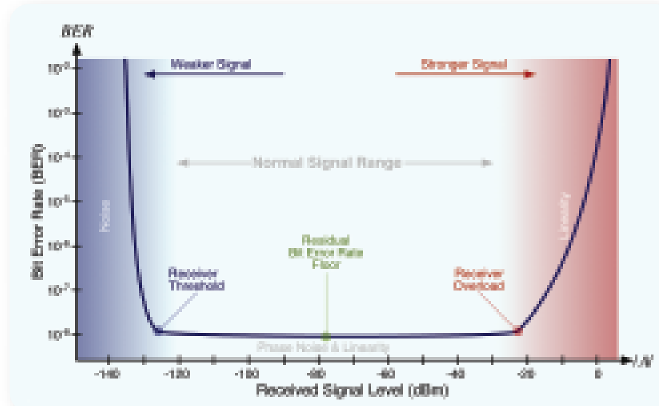
Measurements like carrier acquisition time, simply use an impairment free digital modulation, where carrier offset measurements impair the correct signal by changing its center frequency slightly.

C/N ratio measurements use the digital modulation waveform with noise added to it. Adjusting the amount of noise added to the modulation waveform while observing the BER enables one to quantify the demodulator's threshold performance.

In addition to generating impaired signals for demodulator performance testing, the AWG is often used for production functional testing. Many demodulators sense syndrome errors to initiate switching antennas or modulation types. These features can be quickly tested with the AWG by developing a battery of waveform sequences. The AWG has a variety of event marker outputs that can be triggered when it changes waveforms to correlate demodulator responses to the particular waveform in the test battery.



▶ **Figure 17.** *Threshold C/N ratio and EVM modulation quality measurements taken at a given BER show how close the QPSK demodulator is to the theoretical performance.*



▶ **Figure 18.** *BER is a strong function of received signal level and varies based on noise and distortion. Since some noise and distortion is always generated in the signal source, residual BER measurements require the actual transmitter for accurate characterization. Threshold BER, limited by receiver noise, and overload BER, limited by receiver distortion, can be accurately measured with a Tektronix AWG.*

The very high sample rate of the AWG7000 or high dynamic range of the AWG5000 enable most IF signals to be directly generated with these instruments, avoiding the need for an external modulator.

Receiver — RF Functional Testing

Similar to demodulator testing at IF frequencies, for many radios the very high sample rate and vertical resolution of the AWG series allows it to generate their RF signals directly. Using interleaving between two DACs, some configurations of the AWG7000 can produce 20 GS/s, allowing it to generate RF signals at 5 GHz with four times over-sampling. The AWG7000 can directly modulate RF signals for testing basic receiver functionality.

With the addition of an attenuator and Bit Error Rate Tester (BERT), an AWG can test receiver threshold. Threshold tests are an efficient way to determine if large portions of the receiver are working correctly. To test threshold, the AWG's memory is loaded with the modulated signal waveform. Amplitude is then varied to the threshold level while measuring the BER to determine if the unit passes or fails.

A word of caution about BER testing with the AWG is probably prudent. Accurate receiver BER measurements with the AWG are only possible near receiver threshold and receiver overload. But why is this?

At threshold, symbol errors are made because random noise dominates the desired signal. The AWG easily reproduces noise-dominated signals, allowing accurate measurement of the receiver's BER performance. Similarly, symbol errors made at receiver overload are usually due to over-driven components in the receiver's front end, chiefly the first mixer. Thus measuring the receiver's overload BER by over-driving it with an AWG will produce accurate results.

However, the residual BER error floor mechanism differs from the threshold and overload mechanisms. Combined transmitter and receiver phase noise adds to the PA's non-linearities to dominate the error generation mechanism in the normal operating signal range. Since the AWG does not contribute the same phase noise and non-linearities found in the transmitter, the BER measured in the residual BER floor will not be the same as that measured with the actual transmitter.

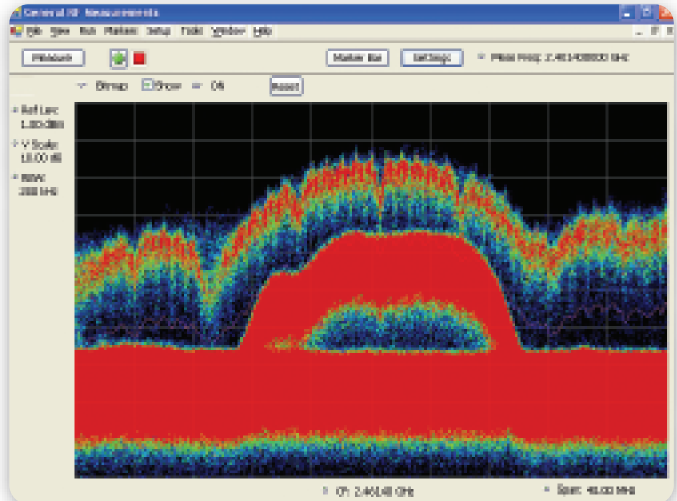
Using the AWG to generate RF signals for basic ‘flat’ spectrum fading for receiver threshold tests is a popular application, but the AWG can do a great deal more.

Receiver — Equalizer Performance Evaluation

The transmission channel can distort the modulated signal in more complex ways than flat absorptive fading. Multi-path fading can take on a variety of forms such as Rician fading where a strong Line-Of-Sight (LOS) signal dominates the receive energy, or Rayliegh fading where the receive signal is composed of all scattered signals and no LOS exists. Receive signals can also undergo dispersive frequency selective fading where certain spectral frequencies are notched out of the signal. A variety of different channel models exist to characterize the many possible distortions with which the transmission channel can impair the receive signal.

The AWG’s flexibility in programming the arbitrary waveform is invaluable for testing receiver performance with signals that are impaired by the channel. Digital wireless receivers that operate in challenging multi-path filled environments are typically equipped with some form of transmission channel equalizer.

Testing the real-world effectiveness of equalizers was once a challenging proposition as transmission channels change with atmospheric fluctuations and antenna position. Now, a battery of composite signals that sum together different combinations of line-of-sight and multi-path components can be compiled into the AWG’s memory. The impaired signals can then be used to test the effectiveness of different channel equalizer designs.



▶ **Figure 19.** *This DPX™ spectrum shows a nearby laptop (stronger signal) and distant access point (weaker red signal) WLAN exchange. Multi-path distortion causing a spectral notch or dent in the access point’s signal is clearly visible.*

Receiver — Interference Susceptibility

Testing a receiver’s ability to withstand interference can also be accomplished with the AWG. Threshold to Interference (T/I) testing measures the susceptibility of the receiver’s threshold to degradation caused by interference. The challenge with T/I testing is that susceptibility to interferers must be measured at different frequency offsets from the desired signal and different power levels.

The AWG’s ability to store a variety of interferers and sum their signal to the desired RF signal is very useful for characterizing T/I performance.

As wireless spectrum crowding continues, interference testing is growing in importance for many devices. The AWG is a far more practical solution to T/I testing than previous generations of custom built signal sources.

RF Spectral Environment Simulation

Sharing many similarities with interference testing, there are a growing number of digital wireless applications that seek to simulate an entire RF environment or frequency band. For example, a war ship might need to test its RF receiver systems before leaving homeport. Intelligence officers need to train radio operators on how to search the frequency bands for useful signals. UWB designers need to test data links with broadband interferers. These scenarios all require the generation of complicated spectral environments over huge bandwidths.

Generating an entire RF spectral environment with many conventional signal generators is usually cost prohibitive. However, a single AWG7000 can simulate or play back up to 5 GHz of RF signal spectrum at a time. Plus, the AWG's spectral output can be changed arbitrarily to mimic vastly different spectral environments.

If high fidelity spectral environments are needed to simulate large signal strength differences, a few AWG5000s can be used in conjunction with external up-converters. While using multiple AWG5000s to cover the same bandwidth that the AWG7000 covers can be more costly, it enables dynamic range improvements of up to 24 dB.

In addition, the AWG5014's four output channels can create a considerable amount of spectrum from a single instrument and is far less costly than using dozens of conventional signal generators to synthesize a spectral environment.

Generating Modulated Signals with the AWG

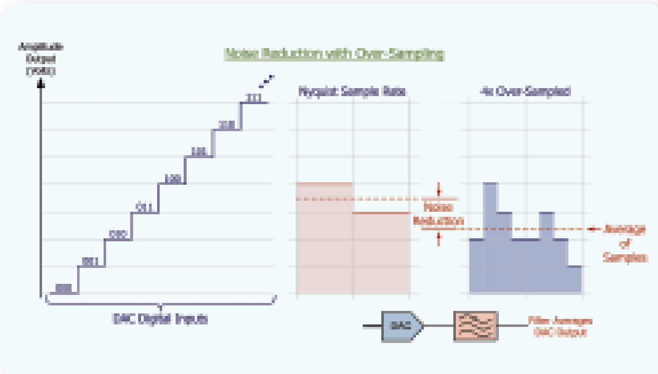
As we have seen from the preceding wireless test examples, there are three basic approaches to AWG test signal generation: base-band I-Q, IF signal and direct RF signal generation. In the following section we will explore the advantages and disadvantages of each approach, as well as how arbitrary waveforms are compiled into the memory of the AWG. This will provide a basic understanding of how to choose the best approach for each application within the limitations of the AWG. It will also provide insight into which AWG model is best suited for each application.

Generating Base-Band I-Q Signals

Generating base-band I–Q signals with the AWG offers some advantages beyond just having two outputs to drive a modulator. The wide AWG bandwidth relative to most modulation bandwidths usually allows a significant level of over-sampling.

The DAC output of the arbitrary waveform generator produces some level of quantization noise. Since the desired signal is reproduced from discrete quantized steps, each step may not represent the exact amplitude value needed, which gives rise to quantization noise.

For many applications, a simple approach to minimizing quantization noise is to select an arbitrary waveform generator like the AWG5000 that uses many bits to represent each signal sample. At base-band, the 14-bit resolution of the AWG5000 is often sufficient to prevent the noise floor from becoming a problem.



▶ **Figure 20.** *Over-sampling a signal many times higher than the Nyquist rate allows the filter after the digital-to-analog converter to average out the noise level more accurately, lowering the quantization noise.*

Another approach to lowering the quantization noise floor is to employ over-sampling techniques. If the signal is sampled at the Nyquist rate, or twice the highest frequency of the desired signal, the quantization noise will be the greatest. Over-sampling the signal, at a rate higher than the Nyquist rate, lowers the quantization noise. This is because the filter following the DAC averages the over-sampled signal, providing a better approximation of the true signal level needed.

Reducing the quantization noise by over-sampling increases the dynamic range. Since base-band I–Q signals are at the lowest possible frequency, the highest level of over sampling is possible. Thus the I-Q modulator approach has a distinct dynamic range advantage.

Applications demanding the highest possible modulation dynamic range may find it advantageous to use an AWG with a high rate of over-sampling and an external I-Q modulator. Wideband signals that do not fit with in the AWG5000's bandwidth capabilities can achieve good noise floor results using the AWG7000 and over-sampling.

The disadvantage to generating digital modulations with the base-band I–Q approach is that it requires an external analog vector modulator, which can also introduce a variety of undesirable constellation distortions.

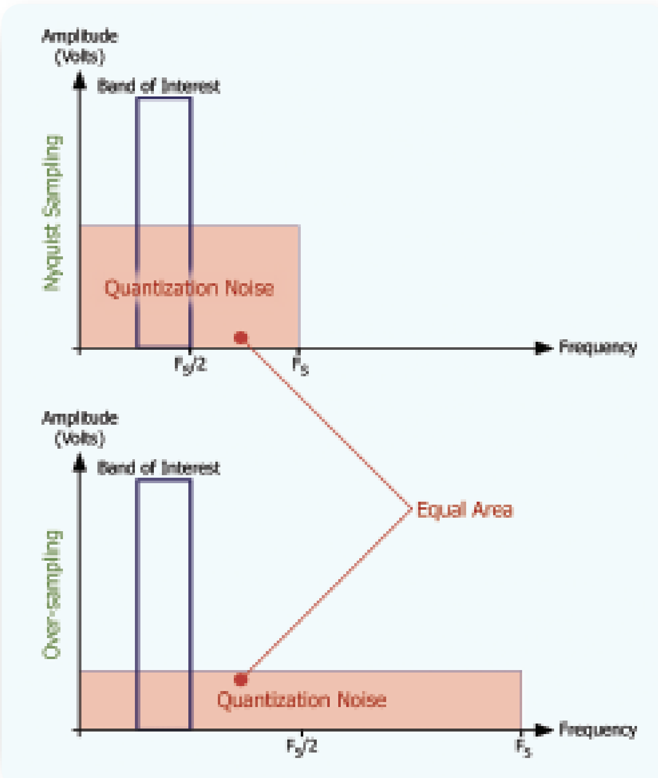
IF Generation

To avoid the external modulator, direct IF synthesis may be preferable. Direct IF synthesis allows I–Q modulated signals to be digitally constructed into a single modulated IF output. This avoids the potentially damaging distortions that external analog vector modulators can introduce. Summing I and Q channels digitally gives excellent I–Q phase and amplitude matching along with ideal symbol timing.

Many IFs are easily within the AWG's frequency range. The AWG5000's 1.2 GS/s can over-sample a 70 MHz IF by 17 times with 14 bits of dynamic range, providing a quantization noise floor near the thermal noise floor of -174 dBm/Hz. A 20 GS/s AWG7000 can over-sample a narrowband 70 MHz IF by 285 times and a 500 MHz IF by 40 times. This level of performance allows for significant noise reduction with over-sampling even for popular wide bandwidth IF frequencies like 500 MHz.

A disadvantage of IF generation is that the higher sample rates needed consume available AWG memory faster.

Once generated, IF signals can be up converted to RF frequencies for receiver tests. Using an external up-converter, the RF frequency is limited only by the up-converter's frequency range. Up-converting the IF signal to an RF frequency adds the complexity of additional external components. Direct RF generation eliminates the need for external components and may be preferable for RF testing if AWG performance is sufficient.



▶ **Figure 21.** *Increasing the over-sampling rate spreads out the quantization noise, lowering the noise floor.*

RF Generation

Direct synthesis on the AWG enables creation of wide bandwidth RF signals without the need for external modulators and up-converters. The carrier frequency is limited by the sample rate and analog bandwidth requirements.

The AWG7000's unmatched 20 GS/s sample rate has opened up a variety of new RF direct synthesis applications.

Like IF signal generation, direct RF synthesis gives excellent I–Q phase and amplitude matching.

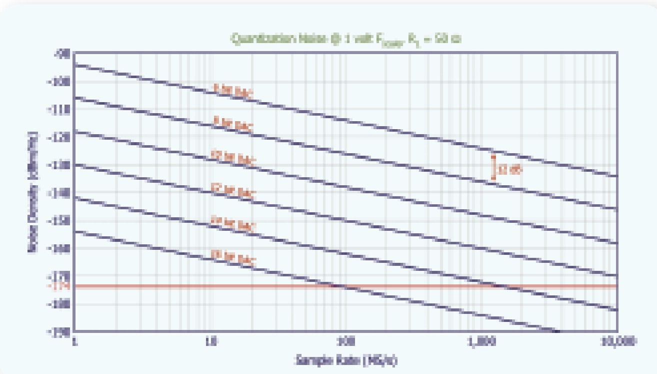
▶ **Figure 22.** *UWB signals can be directly generated on the AWG7000.*

Depending on the desired RF frequency, direct RF generation on the AWG may not allow substantial over-sampling, so quantization noise is often a significant concern.

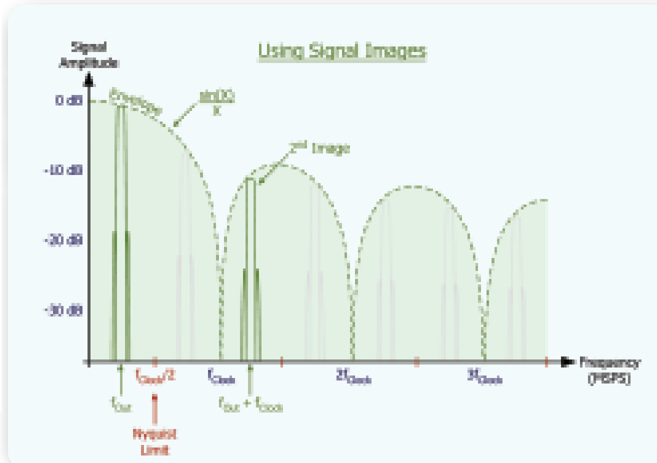
As the sample clock is driven up in frequency to accommodate the RF signal, DAC linearity tends to decrease. Without over sampling, DAC linearity is essential to maximize the Spurious Free Dynamic Range (SFDR).

The AWG7000's DACs offer up to 10 bits of linear digitization range at very high sample rates. The AWG5000's DACs offer up to 14 bits of linear digitization range for truly outstanding SFDR. However, like all DACs, operational factors can decrease linearity and reduce the Effective Number Of Bits (ENOB) the converter can actually resolve. Sample rate is a critical parameter that can affect the DAC's ENOB and decrease linearity. Thus as higher sample rates are used to directly generate RF signals, linearity and the SFDR of the AWG decrease.

Depending on the digital modulation's complexity and S/N ratio required for error free transmission, one must verify that the AWG's SFDR capability exceeds the required S/N ratio.



▶ **Figure 23.** *Adding bits of resolution to the AWG and increasing the sample rate lowers the quantization noise power spectral density. The AWG7000's high sample rate and the vertical bits of resolution found in the AWG5000 enable low noise floors at a variety of frequencies and bandwidths.*



▶ **Figure 24.** *The unfiltered DAC output is a sinc function composed of many mixing products and harmonics. Image products can be selected for higher frequency outputs.*

Another important consideration when using the AWG for direct synthesis RF applications is the memory usage rate. The AWG7000 supports up to 64 million sample points while the AWG5000 supports up to 32 million sample points. However, as the sample clock rate increases, so too will the speed at which the waveform memory is depleted.

One approach that allows us to get around the rapid exhaustion of waveform memory is to use waveform sequencing. Sequencing allows portions of repetitive waveforms to be recycled over and over again. For example, a BPSK signal is made up of four waveform segments, 0° ▶ 180°, 180° ▶ 0°, 180° ▶ 180°, and 0° ▶ 0°. Each RF waveform segment can be stored in the fast AWG memory and recalled based on bit patterns either delivered to the AWG or generated in a PN (Pseudo Noise) sequence internal to the AWG. This greatly reduces the memory needed to generate long complex waveform record lengths.

A rich set of sequencing commands on the modern AWG allows an endless number of program branches, jumps and loops for continuous generation of modulated signals.

Under-sampling or sub-Nyquist sampling can also reduce memory usage. The unfiltered DAC output is a sinc function (sinx/x) rich in harmonic energy. Usually, a low pass filter only allows the fundamental frequencies below the Nyquist rate to pass, assuring alias free signal reproduction from the DAC. This low pass filter can be replaced with a band-pass filter to select higher frequency signal images. Thus, the DAC is clocked at half the frequency, reducing the number of sample points needed by one half.

The disadvantage of this approach is that sub-sampling reduces the available dynamic range. The sinc function amplitude drops off as higher frequency images are selected. Since noise level remains constant, SFDR can fall. Again, careful consideration of the required S/N ratio versus the available SFDR is prudent when using sub-sampled operation.

It is also important to select the appropriate AWG for sub-sampling applications. While the AWG7000 offers very high sampling rates, the deep dynamic range of the AWG5000 can provide better SFDR performance using sub-sampling techniques at the lower frequencies.

Choosing a sample rate and compiling the waveforms are important considerations for getting the most out of the available AWG memory.

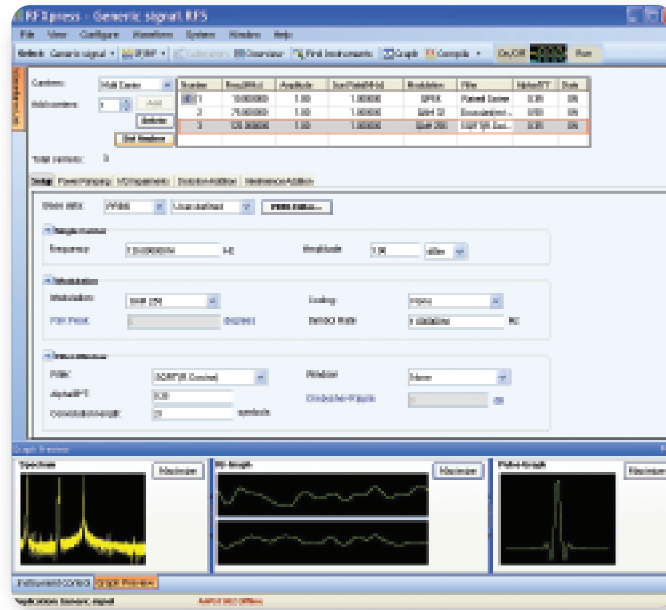
Compiling Complex Signals

There are several ways to compile complex digital modulation signals for AWG playback.

Front panel commands and formulas can be used to create waveforms. Predefined waveforms like sine, square, ramps and triangle waves can simply be entered in with the AWG's new streamlined user interface. User defined waveforms can also be created by applying math functions as well as cut and paste editing. Sequencing can also be used to piece together different waveforms. Sequencing commands include: Repeat Count, Wait for Trigger, Go-to-N and Jump, enabling endless combinations of waveform segments to be assembled straight from the AWG's touch screen.

RFExpress™ is a Personal Computer (PC) based program available from Tektronix that enables extensive waveform generation in a convenient Windows desktop environment.

RFExpress features an extensive array of flexible base-band I–Q modulation generation capabilities. Modulations such as BPSK, QPSK, OQPSK, π/4QPSK, DQPSK, 16 QAM through 1024 QAM, 8PSK, O-8PSK, GMSK, FSK, AM, FM and PM, are all easily generated with variable rates and Nyquist filtering. I-Q impairments such as quadrature error, gain imbalance, constellation skew and non-linear effects such as AM/AM and AM/PM can also be applied to the modulations to simulate less than ideal conditions.



▶ **Figure 25.** *RFExpress offers powerful waveform generation capabilities for Tektronix AWGs, like this multi-carrier QPSK example.*

RFExpress is also capable of defining multi-carrier IF and RF signals. Each carrier's frequency, symbol rate, modulation type, base-band filtering and data source can be independently defined. With up to 512 carriers, entire spectral environments can be digitally synthesized and downloaded to the AWG for playback.

To assure the desired signal has been correctly synthesized, RFExpress is equipped with a variety of graphical setup conformation aids. Visual confirmation of waveform setup in the time domain, frequency domain, constellation, eye diagram and pulse shape can all be accomplished inside RFExpress, prior to downloading waveforms to the AWG.

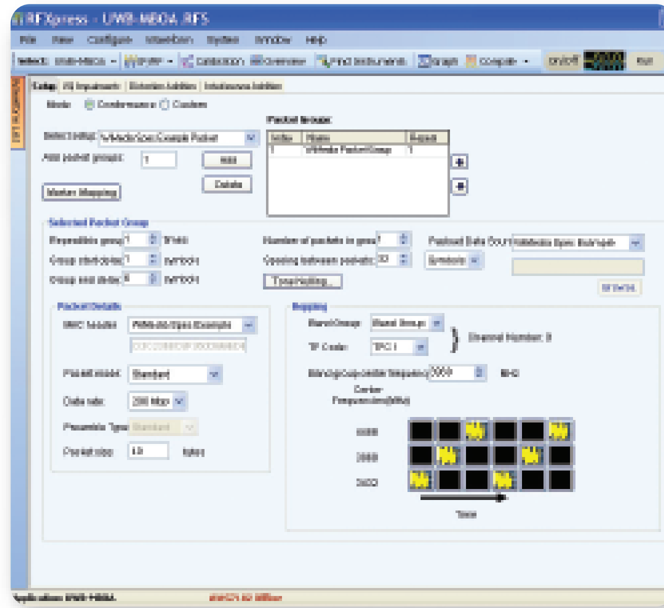
Another important feature of RFExpress is its connectivity. Not only does the software allow convenient connectivity to the AWG, but it also allows connectivity to Tektronix' leading oscilloscopes. This enables wideband capture of signals with the oscilloscope via RFExpress, followed by download of the captured signal to the arbitrary waveform generator for playback. Thus live 'off-the-air' RF signals can be captured and played back many times. This capability is particularly useful for consistent testing of complex signal fading problems.

RFExpress has many more features ranging from extensive user defined modulations, standards support, UWB and Wi-Media® capability to specialized calibration corrections. RFExpress is truly an ideal tool for generating digital representations of waveforms to be played back with the AWG.

In addition to RFExpress, other third party waveform creation tools are also available for programming specialized waveforms for the AWG series.

Digital radio engineers working on Software Defined Radios (SDR) where modulation is defined entirely in software, typically select popular mathematical development tools such as MATLAB®, Mathcad® or Excel® to create signal characteristics. The AWG can import text data files from these programs for programming the arbitrary waveform memory. The AWG of course supports earlier Tektronix AWG waveform files like .wfm, .pat and .seq.

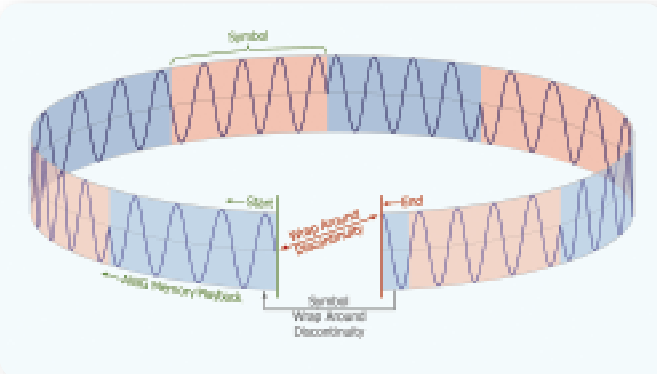
So there are many ways to generate the digital representations needed to take full advantage of the arbitrary waveform generator's flexibility to play back signals from digital memory.



▶ **Figure 26.** *RFExpress with optional application standards supports complex modulations like Ultra Wide-Band (UWB) and Wi-Media signals.*

Wrap Around Considerations

Continuous signal playback from the AWG generally requires repeating the compiled waveform or segments of it. Carrier phase and frequency at the beginning and end of the signal to be repeated in memory must meet. Discontinuities between the start and end of the waveform will cause spectral spreading as well as the potential for demodulator carrier recovery control circuits to become unlocked.



▶ **Figure 27.** *When the end of the AWG's waveform memory is reached during a continuous looping playback, wrap around discontinuities can result. Unwanted wrap around transitions cause spurious and loss of carrier and symbol synchronization.*

Similarly, symbol transitions, error correction encoding and multiplexing protocols may also need to meet at the wrap around point for flawless continuous operation.

Wrap around issues are particularly important for continuous Frequency Division Duplexed (FDD) signals. Unlike Time Division Duplex (TDD) signals that take turns sending and receiving information back and forth across a data link, FDD signals are continuous and always on. This means there is no convenient break in transmissions with the FDD signal, to line up waveform ends for a glitch free wrap around in memory.

One simple solution is to use an integer number of carrier and symbol cycles. Coordinating the length of the memory recording, symbol rate, carrier phase and symbol cycles so the ends meet at exactly the right place will eliminate most wrap around glitches. Modulations like GMSK that permit a certain level of ISI or $\pi/4$ DPSK that only allow differential phasor movements may require a unique symbol sequence at the end of the recording to prevent wrap around glitches.

Circular convolution of the base-band filter with the symbol sequence can also be used to eliminate wrap around glitches from symbol misalignment. Numerically, circular convolution on large numbers of sample points can be a slow process. In a production environment, the time required to execute a convolution process is particularly important.

With care, wrap around discontinuities can be eliminated allowing continuous playback waveforms from the AWG. To make the process easy, the RFExpress waveform development software's built-in features address wrap around discontinuities making glitch-free playback easy to accomplish.

Outlook

AWGs are becoming increasingly useful and important in wireless RF applications. The growing sample rates, resolution, linearity and waveform memory lengths have made the AWG more versatile for wireless applications. Thanks to more bits of DAC resolution and higher over-sampling rates, traditional limitations in dynamic range, bandwidth and frequency are now disappearing.

Understanding the tradeoffs between base-band I–Q, IF and direct RF generation techniques is invaluable for getting the most out of the AWG. In the end, proper application of the modern AWG allows it to rival many specialized custom-built signal generators at a fraction of their cost.

The Tektronix AWG product line delivers fantastic waveform generation flexibility, enabling it to produce today's most challenging digital wireless signals. Combined with RFExpress and intuitive front panel menus, sophisticated multi-carrier I–Q modulations with signal impairments can be easily generated.

The AWG5000 is an ideal source for generating complex digitally modulated wireless test signals at frequencies primarily below 379 MHz. The AWG5000's 14 bit resolution and up to 4 outputs sampling at 1.2 GS/s provide superior signal fidelity and test convenience.

The AWG7000's 20 GS/s offers industry-leading performance. Cutting edge UWB applications and compressed radar pulses requiring more than 5 GHz of bandwidth can effectively be supported with the AWG7000.

The arbitrary waveform generator of the past that was once limited to low frequency base-band applications with limited dynamic range, has given way to a new generation of AWG that is fast becoming a test bench essential for RF and microwave engineers.

Many engineers are now using AWGs for their most difficult RF test stimulus applications. Tektronix invites you to see for yourself what a modern arbitrary waveform generator can do for wireless test, by arranging for a demonstration today.

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