The ABC's of Arbitrary Waveform Generation

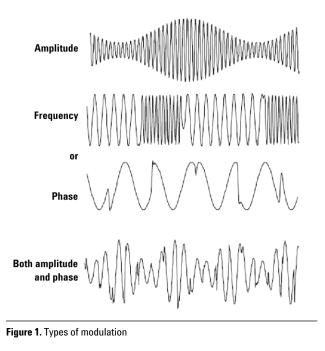Application Note

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Agilent Technologies

I. Introduction

1.1 Signal simulation

In the old days, signal generation was fairly straight-forward. Analog signals were generated as CW tones which had some amplitude, center frequency and starting phase. Signal generation became more sophisticated with the introduction of VCOs, which allowed users to dynamically vary the carrier frequency (FM) and phase (PM) over time. They could also vary the envelope of that signal (AM). Some issues that affected the quality of the generated waveform were stability and phase noise of the VCO, as well as distortion and bandwidth limits on the modulation.

Digital signal generation is different. Instead of outputting sinusoids, digital generators output a series of discrete voltage levels. This makes it possible to flexibly create a wide range of signals with a single set of hardware. Any *arbitrary* signal within the bandwidth of the digital signal generator can be described mathematically, stored in the digital memory and then be played out. This is the origin of the term arbitrary waveform generator (AWG).

There are limitations, however. The bandwidth of the AWG, which is related to the sample rate, determines the range of carrier and modulation frequencies which can be produced. The voltage resolution of the generator, often expressed as the number of *effective bits,* describes the accuracy of each output voltage. This translates into noise and distortion (spurious responses) in the output waveform.
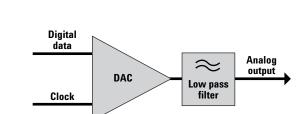

Figure 1. Types of modulation

Figure 2. Basic AWG block diagram

1.2 Bandwidth and accuracy

Until recently, digital-to-analog (DAC) converter technology forced serious trade-offs. If a user wanted flexibility and ease of use, they could use an AWG. But the DAC resolution typically degraded at higher sample rates and modulation bandwidths. So the performance was lacking (particularly for high-speed modulation) compared to traditional analog techniques.

Modern high-speed DAC technology essentially eliminates this trade-off. For example, the proprietary DAC in the N6030A AWG achieves 500 MHz of modulation bandwidth, while keeping distortion products to < -65 dBc. In addition to a high performance DAC, it is important to have a low phase noise clock. This is because the clock sets the timing of the output transitions from the DAC. Any jitter (phase noise) on the clock directly translates into time variations of the transitions on the analog output, producing spurious responses.

Since it is difficult to directly produce very high frequency carriers from a DAC with good fidelity, upconversion is often employed. The AWG is used to produce the comparatively narrow-band modulation information. This is placed on a high frequency RF or microwave carrier using a variety of techniques. The end result is that the flexibility, modulation bandwidth, and fidelity of the AWG are preserved, while producing the signal at the carrier frequency of interest.

Traditional analog techniques for signal simulation have limitations that an AWG avoids. For frequency modulation, VCOs may not have adequate tuning range while preserving phase noise. Calibration of phase, amplitude and frequency modulation is challenging. If several carriers are needed, separate VCOs are required for each, significantly adding to the complexity. An AWG can accurately produce these signals, as well as radically different types of modulation such as impulses or ramps. These are very difficult to achieve using traditional analog techniques (particularly with a single set of hardware). With an AWG any type of modulation that can be described mathematically within the modulation bandwidth of the AWG (essentially all waveforms) can be produced simply and accurately.

1.3 Function generators

Function generators are used to produce a variety of analog output waveforms. They are similar to an AWG in that they are based on DAC technology, which provides flexibility in the different type of waveforms that can be produced. Typical outputs are sine, triangle and square waves, though many function generators also allow arbitrarily programming the output waveform. The function generator is designed to be very easy to use for simple waveforms. An AWG is best used for more advanced waveform generation requiring higher fidelity outputs.

Key differences of an AWG as compared to a function generator include:

- Higher sample rate

- Better fidelity

- Lower noise

- Sophisticated sequencer

- Extended memory

- Synchronization of multiple units

- Multiple high-performance reconstruction filters

- High-level software interfaces for waveform generation

II. Sampling basic

2.1 DAC Signal generation

To better understand how an AWG operates, let's briefly refresh our understanding from undergrad studies of sampling theory basics. This involves a comparison between a continuous analog waveform and a digital representation consisting of a series of discrete sampled values.

2.2 Sampled signals

Analog signal generation involves creating a *continuous* waveform with the desired voltage variation versus time. A common analog signal is a CW carrier that is modulated, typically to add some information content. In the example below, a VCO and amplitude modulator are used to produce this complex modulation.

Digital signal generation is fundamentally different. The desired output waveform is sampled with uniform time spacing, and the voltage values are output from a DAC. The sample rate determines the bandwidth, the maximum frequency that can be output from the DAC. The number of bits of resolution sets the binary representation of the output voltage produced at each time sample. Fewer discrete output levels decrease the dynamic range (ratio of the maximum to the minimum output levels). Simply having a certain sample rate or number of bits of resolution does not *guarantee* a desired level of performance–but they are a necessary prerequisite. Other limitations in the DAC, clock generation circuitry, and output amplifiers can degrade the bandwidth or dynamic range below the theoretical maximum.
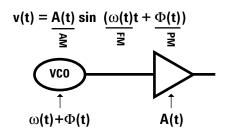
$$v(t) = \underset{\text{AM}}{A(t)} \sin \left(\underset{\text{FM}}{\omega(t)t} + \underset{\text{PM}}{\Phi(t)} \right)$$

Figure 3. An example of analog modulation

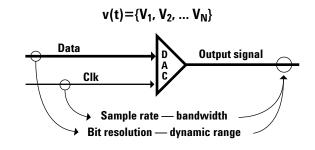$$v(t) = \{V_1, V_2, \dots V_N\}$$

Figure 4. Digital sampled waveform

2.3 Sample rate and aliasing

Let's review how sample rate relates to analog bandwidth. Consider again the case of a simple sinusoid. As shown in Figure 5, if we sampled this sinusoid (circles), Nyquist says we can completely reconstruct the original signal if sufficient samples exist. As we reduce the number of samples, there comes a point where the number of samples is insufficient to unambiguously create the original signal (Figure 6). Instead of creating just the sine wave, we can also realize the flat dashed wave. This is called aliasing.

So, how often do we need to sample the original signal to avoid aliasing? Our friend Nyquist says you must sample at *greater* than 2x the signal bandwidth.
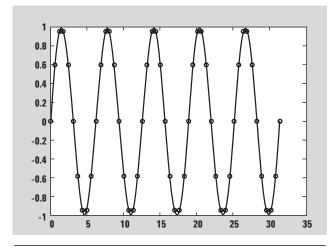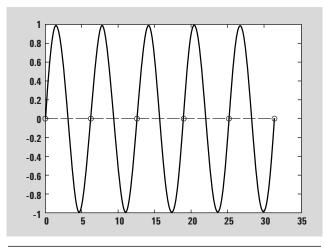

Figure 5. Sampled sinusoid

Figure 6. Sampled sinusoid with aliasing

2.4 Images and filtering

Nyquist doesn't tell the whole story, however. Figure 7 shows our ideal DAC outputting a series of impulses to make our waveform. The spectrum of the ideal DAC yields the signal frequency of interest plus a family of related signals located at multiples of the sampling frequency ($Fsig \pm n*Fs$).

Real-world DACs produce stair steps at their output, not impulses as sampling theory suggests. That is, they output a set of discrete voltages which are held for one time period of the sample rate. Since the transfer function then looks like a $\sin(x)/x$ function (also called a sinc function), the amplitude of the images are attenuated as we move up in frequency. This is also called the zero-order hold effect. Note that the nulls in the spectrum occur at multiples of the sample rate. The spectrum including the sinc roll-off is shown in Figure 8.
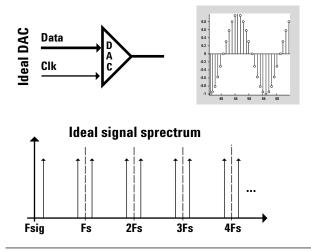

Ideal signal sprectrum

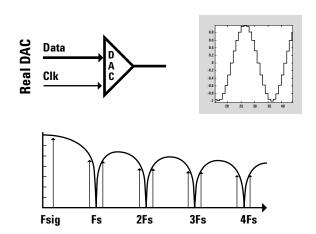**Figure 7.** Output from an ideal DAC

Figure 8. Output with sinc roll off

We can filter out these higher order images with a simple Low Pass Filter (LPF), to reconstruct the original signal. Because the LPF is removing the higher-order images (which are aliased) to reconstruct the desired waveform, the filter is also commonly referred to as an "anti-aliasing filter" or a "reconstruction filter."

Note that as we increase the fundamental frequency, the images also change; that is, images above the frequency of each null increase in frequency and images below the null decrease in frequency at the same rate. The dashed line in Figure 9 is called the folding frequency (also called the Nyquist frequency). It represents the highest frequency one can generate without the higher ordered images folding into the signal of interest. Though Nyquist says the output bandwidth can be up to (but not including) Fs/2, with real-world DACs we can get only about 40% of Fs. This leaves room for the LPF to roll off by the Fs/2 point. So, the rule of thumb for all DACs is that the BW is <40% of Fs.

2.5 DAC bit resolution

We have shown that the DAC samples at discrete points in time. Similarly, we don't have infinite resolution in the output voltage from the DAC. Consider again the case of a sinusoid, as shown in Figure 10. As we decrease the bit resolution, we see a smaller number of stair steps in the output voltage. A smaller number of discrete voltage levels results in lower dynamic range—a reduced ability to see small signals in the presence of large ones.

Figure 10. Discrete voltage levels in DAC output

Figure 9. Output with a reconstruction filter

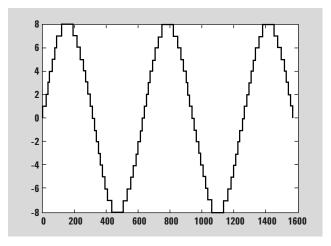Each bit of resolution doubles the number of discrete voltage levels we can generate. For example, going from 6 to 7 bits doubles the voltage resolution of the output signal. Going from 7 bits to 8 bits doubles our resolving power again. So every time we double our resolving power, it's the same as 6 dB in voltage. The rule of thumb is that you get 6 dB of dynamic range for every bit of DAC resolution.
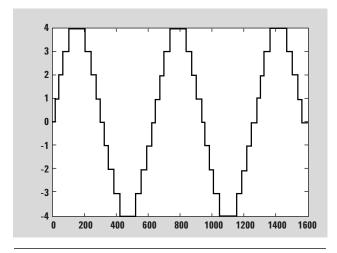

Figure 11. Output with fewer bits of resolution

Figure 12. Number of voltage levels per bit

2.6 Other DAC effects

You might think that with 15 bits of resolution in the N6030A, we should have 90 dB of dynamic range. There are, however, other limitations. Images and sample clock feed-through can distort our signal. These can be largely removed by the reconstruction filter. We also have harmonics of the signal that fall within the passband of the reconstruction filter. These cannot be easily removed. There may also be non-harmonic spurs which creep into the passband, as well as noise from the environment. All of these eat into the dynamic range of our DAC. So, the effective number of bits (ENOB) is equal to the datasheet bits minus 2, 3 or 4 bits. In the case of the N6030A, we have an ENOB of about 11 bits across the full 500 MHz bandwidth.

Figure 13. Real world dynamic range

III. Waveform types

3.1 Signal upconversion

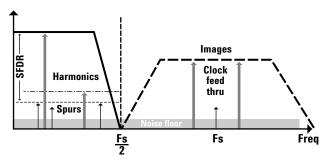AWGs are commonly used to generate three types of signals: Baseband, IF, and I/Q. The first comes directly from the AWG outputs. The second two involve upconversion onto a microwave carrier. This enables the flexible waveform generation capability of the AWG to be extended over the full RF and microwave spectrum, which is of interest for a wide range of applications.

3.2 Baseband signals

Baseband signals extend from DC to some upper limit defined by the sample rate—the so-called Nyquist limit. Because of the difficulties in achieving good fidelity, direct generation of microwave signals from a baseband DAC is typically impractical. External upconversion of the AWG output is usually employed for very high frequency operation. The advantage of baseband signals is that the full BW of the DAC is utilized, up to 40% of the sample rate. The disadvantage of baseband is that it is difficult to upconvert a signal which extends all the way down to DC (a so-called "0 IF" signal) with a simple mixer—because the negative spectrum is also upconverted, resulting in images.

Other upconversion techniques can be used with baseband signals (I/Q modulation is discussed in a later section). Keep in mind, however, that there are many applications that directly make use of the baseband signals. These include component and subsystem test. Baseband is the simplest method of generating a signal from an AWG.

3.3 IF upconversion

One method of translating the AWG output up to a microwave frequency is by using a local oscillator (LO), a simple mixer, and a filter to reject the LO and image.

The mixed signal sidebands are centered around the LO frequency, with a modulation frequency range determined by the bandwidth of the AWG output. It is important to construct an AWG waveform with a "digital IF." This eliminates signal content near DC in the AWG output. After upconversion with the mixer, either the upper or lower modulation sidebands can be filtered (eliminating the LO and the opposite sideband), provided the sidebands are sufficiently far from the LO frequency.
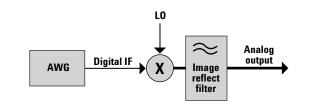

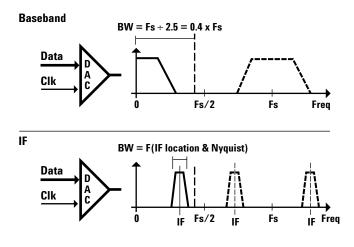
Figure 14. IF Upconversion with a mixer

Figure 15. Baseband and digital IF comparison

IF upconversion has the advantage that it requires only simple mixer hardware. Because it is possible to filter after upconversion with a mixer, spurious mixing products can be eliminated. The disadvantage of IF is limited modulation bandwidth. The choice of the digital IF frequency is constrained in several ways:

- The Nyquist limit and steepness of the reconstruction filter in the AWG (before mixing) set the highest modulation frequency from the AWG. Starting with the digital IF frequency, the maximum frequency of the modulation sidebands must not exceed this upper frequency limit. For example, a digital IF centered at 400 MHz would have a maximum bandwidth of ± 100 MHz in the N6030A. This argues for setting the digital IF frequency closer to DC.

- The lower extent of the modulation sidebands around the digital IF frequency, must be sufficiently far from DC. The digital IF frequency offset and the steepness of the image reject filter skirts, determine the effectiveness of filtering out the LO after mixing. This constraint suggests setting the digital IF frequency higher to achieve good LO feed-through suppression and low in-band attenuation and distortion.
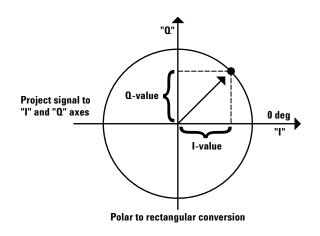
To simultaneously meet these two requirements requires a reduction in the modulation bandwidth. Typical usable IF bandwidths are ~25% of the sample rate, or ~325 MHz in the case of the N6030A at 1.25 GS/s.

3.4 I/Q upconversion

A simple way to view amplitude and phase of a signal is with the polar diagram. The carrier becomes a frequency and phase reference and the signal is interpreted relative to the carrier. Polar diagrams are the basis of many displays, although it is common to describe the signal vector by its rectangular coordinates of *I* (In-phase) and *Q* (Quadrature). On a polar diagram, the I axis lies on the zero degree phase reference, and the Q axis is rotated by 90 degrees. The signal vector's projection onto the I axis is its "I" component and the projection onto the Q axis is its "Q" component.

To produce I/Q modulation requires two baseband channels from the AWG, together with a quadrature modulator.

The full modulation bandwidth of both AWG channels is preserved, so the modulation bandwidth from the I/Q modulator is *twice* that of each individual AWG channel. In the case of the N6030A, 1 GHz of modulation BW is produced and placed on a microwave carrier. Thus I/Q upconversion has approximately three times the modulation bandwidth of IF. In addition, it is not necessary to have separate image reject filters for each LO frequency, as are required for IF upconversion. Without careful calibration, however, image and LO feed-through spurs from an I/Q modulator can be a serious limitation.
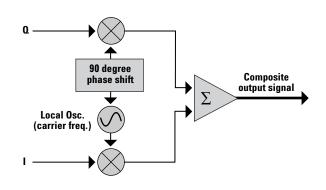

Figure 16. I/Q format

Figure 17. I/Q upconversion of an AWG

IV. Modern AWG architecture

4.1 Understanding an AWG

An AWG consists of more than just a DAC. Modern AWGs have sophisticated sequencers for storing and playing waveform data as well as markers and triggers interfacing with the external environment. DAC clocking and analog output blocks also provide essential functions. For many applications, including phased array radar and MIMO, it is important to have the waveform outputs from multiple channels fully synchronized. In this section we will consider the important points of each of these major blocks in a wideband AWG.

4.2 Digital data generation

Sample data for the AWG is pre-calculated using a high-level utility such as Matlab®. The processor then loads this sample data into high-speed waveform memory inside the AWG. For a very high-speed AWG (operation in excess of 1 GS/s), the rate the data is read exceeds the speed of common semiconductor memories. This does not pose a fundamental problem, since the data can be read in parallel. It is then multiplexed inside the high-speed digital logic in the AWG that drives the DAC.
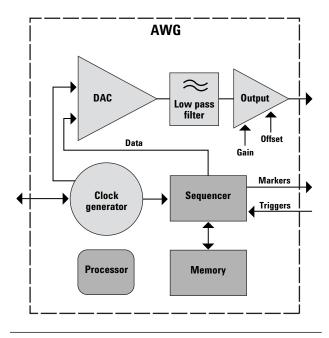
In the case of the N6030A the waveform data is read eight samples at a time. This sets the "granularity" of the waveforms, which must always be specified in sets of eight samples. The AWG has a significant amount of waveform memory (up to 16 million samples, in the case of the N6030A). However, at the full sample rate of the AWG (1.25 GS/s) this represents only 12.8 ms of waveform play time.

Many common user scenarios for an AWG involve much longer play times. For example, a radar signal from a rotating antenna as seen by an approaching aircraft, might have characteristics that vary over timescales of tens of seconds. One approach to addressing this requirement is to include much more memory in the AWG (several *billion* samples). This is typically done using DRAM. A practical limit (based on expense and space) is perhaps 10 G Samples—which still represents only 8 seconds of playtime. Moreover to load all this memory from the processor requires tens of minutes (or even longer in many cases).

An alternate approach is to make much more efficient use of the waveform memory using a sequencer. This takes advantage of the repetitive nature of most waveforms, and uses looping to reuse waveform memory. Sequencers have differing levels of sophistication. A simple sequencer takes sections of waveform memory and allows them to be repeated a specified number of times. More sophisticated sequencers support two levels of nested loops so that complicated waveforms can be more efficiently described. Thus, a complicated radar pulse, such as a frequency chirp, can be described in a section of unique waveform memory. Then, another section of "off" time can be repeated some number of times. Finally, the outer loop takes this entire radar pulse (at some repetition interval) and repeats it a specified number of times. In this way, scenarios of seconds (or even minutes) can be created that easily fit in the waveform memory. The sequencer memory and waveform can be downloaded by the processor in one second or less.
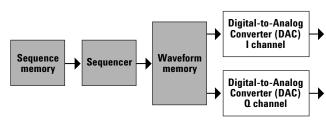

Figure 18. AWG block diagram

Figure 19. Basic AWG sequencer

The digital logic that forms the sequencer and multiplexer can be implemented in different ways. Discrete digital logic or ASICs are often used for these very high-speed applications. These approaches lack flexibility, however. In the case of the N6030A, a field-programmable gate array (FPGA) is used. This makes it possible to reprogram the functionality of the digital logic, including the sequencer, to add enhancements for specific user requirements. These upgrades can be made in the field as a downloadable application that is part of an instrument software upgrade. Some common applications are:

- Dynamic sequencing. Directly access up to 16,000 sequencer scenarios in real-time through an external digital connector.

- Additive white Gaussian noise (AWGN). Add noise to simulate transmission impairments.

- Direct digital synthesis (DDS). Augment the sequencer to include frequency offsets, and phase and gain shifts for radar simulation.
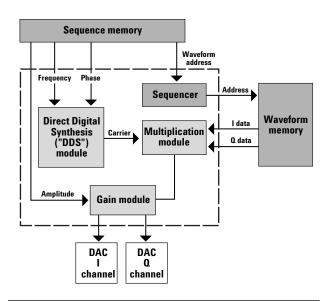

Figure 20. Advanced FPGA upgrade: DDS sequencer

4.3 Markers and triggers

In using an ARB, it is often important to control the waveform playback and sequencer based on external events. To alter the sequencer operation in an AWG, hardware and software triggers can be used. For example, a series of narrow pulses might be produced by the AWG, but after a trigger is received a wide-band chirp is produced. The exact timing of the start of the chirp relative to the trigger may be important. This is particularly an issue in the case of phased array applications, where multiple AWG units are synchronized together and must be triggered nearly simultaneously.

There are two types of hardware triggers: synchronous and asynchronous. In the case of asynchronous triggers, there is an uncertainty of at least one sample clock cycle as to when the triggers are registered into the sequencer state machine. If the sequencer operates at a sub-multiple of the sample clock rate (8x lower in the case of the N6030A), the uncertainty is greater. Thus, with an asynchronous trigger, the uncertainty can be more than 1 ns. In many applications, uncertainties of 50 ps or less are desirable.

By using a synchronous trigger, the trigger uncertainties are greatly reduced. The sequencer state machine is assumed to operate at a sub-multiple of the sample clock rate, called the SYNC clock. In the case of the N6030A, this lower speed SYNC clock can also be used to synchronize multiple AWG units. It is necessary to insure that the correct timing relationships are achieved to guarantee consistent synchronous trigger operation. The trigger input must occur within a valid timing window with respect to the SYNC clock. The analog output from the N6030A is then produced a fixed number of sample clock cycles later, and has an output timing jitter relative to the sample clock of approximately 400 *femtoseconds*.

In addition to the triggers, markers outputs are useful for synchronizing external equipment. A common application is to trigger an oscilloscope on the start of a repetitive waveform. Modern AWGs typically have several markers and triggers. The N6030A has four of each.

4.4 Analog output

Flexibility and accuracy in the analog outputs are one of the key performance parameters of an AWG. If the output amplifiers have distortion or nonlinearities, any advantage of a high performance DAC will be lost. Many high-speed systems have differential inputs. To test them, it is desirable to have an AWG that can provide single-ended as well as differential outputs.

It is possible to vary the gain and offset of the AWG output by changing the waveform values that are programmed into the DAC. For smaller signals and large offsets, this requires the use of valuable dynamic range in the DAC output. Hence, most AWGs have the ability to adjust the gain and offset after the DAC. In the case of the N6030A, the adjustments can be made for both single-ended or differential output modes. There is also a DC coupled, amplified, single-ended mode that supplies twice the out-put voltage. This comes at the expense of some non-linear distortion that reduces the spur-free dynamic range specification.

4.5 Clocking

The sample clock is used by the DAC to output successive samples of the analog output. In modern AWGs there is typically an internal clock, as well as provision for accepting an external clock. The external clock can cover a wide range of frequencies.

Any errors in the timing of the clock edge translate directly into timing errors in the analog output. Timing errors are related to phase noise. Specifically, the integral of the phase noise across the bandwidth of the AWG is proportional to the timing jitter. Consider a carrier at the maximum frequency of an AWG (500 MHz, in the case of the N6030A). Phase noise on this output signal will set the limit on how much clock phase noise is acceptable, before it begins to degrade the noise performance of the AWG output. For example in the N6030A, the output noise is very low, <–150 dBc/Hz. Due to the frequency ratio of the 1250 MHz sample clock to the 500 MHz output signal, a clock phase noise floor of –142dBc/Hz would double the output noise (3 dB increase). The internal clock in the N6030A has a noise floor of –160 dBc/Hz, and thus does not contribute significantly to the overall noise performance.

4.6 Synchronization

It is important in many applications to have multiple AWG channels with a known timing relationship. These include phased array radar and MIMO communications systems applications. In a dual channel AWG, such as the N6030A, there is fixed timing between the two channels. The sequencer points to waveform addresses in both channels' waveform memories simultaneously. By constructing mathematical waveforms that have the proper timing relationship, the desired outputs are obtained.

For many applications, more than two synchronized channels are required. This necessitates synchronizing the sequencers and multiplexers in multiple, separate AWGs. In the N6030A, this can be accomplished using the interconnect cabling shown in Figure 21. In this example, 8 AWGs (a total of 16 channels) are synchronized.
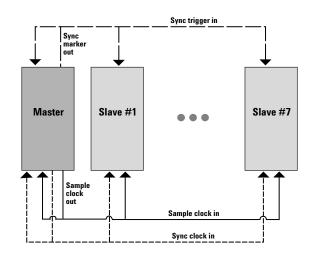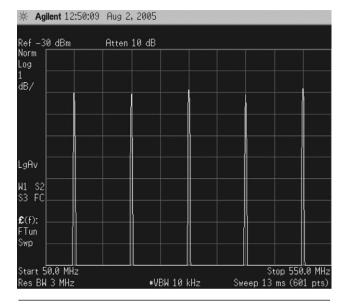

Figure 21. Synchronization of multiple AWG units

4.7 Calibration and stability

There are a variety of effects that cause the raw analog output from an AWG to differ from the mathematical description in the waveform memory. The zero-order hold roll-off has been described previously. In addition, there are amplitude and phase distortions in the reconstruction filters. It is typically very difficult to completely eliminate all these effects in the analog hardware. Fortunately, the ability to create arbitrary waveforms in the digital data makes it possible to predistort the original waveform to compensate—provided the system response is known.

In the N6030A, a complex (amplitude and phase) calibration is performed in the factory. The user is then provided with the option of predistorting the waveforms on download to provide a calibrated response. One issue with predistortion is that the amplitude out of the DAC can be attenuated, but it cannot be increased beyond full-scale. Thus, to apply predistortion, some frequency components are attenuated. This results in a lower overall output amplitude and dynamic range with the corrections turned on. The calibrated output from a multi-tone waveform with 5 equal amplitude tones with 100 MHz spacing is shown in Figure 22. On a scale of 1 dB / division, the output is very flat.

Figure 22. Calibrated AWG output performance

V. Signal creation

5.1 Signal creation overview

In this section we will consider several common waveform types and describe some methods and tricks to efficiently create them using the waveform memory and sequencer. The waveforms are created using a high-level programming language. For the examples described here, the code was developed in Matlab. Waveforms can be downloaded directly to the N6030A from Matlab. They can also be saved as a binary file and then loaded using the N6030A GUI-based utility.

For ease of download, the examples can be accessed by going to the Agilent webpage: **www.agilent.com**, searching using the keyword *N6030A*, and then choosing the link for *Signal Creation Examples.* The detailed code (or waveform files) are not included there, only an overview of the constraints and suggested approaches for each case.

5.2 CW tone

A sine wave with the desired phase can be easily created in Matlab. Typically, the amplitude is auto-scaled to full-scale during download. There are, however, constraints on the frequency that can be chosen. It is desirable to have an integer number of cycles in the waveform; otherwise there will be discontinuities as the waveform is played repetitively. This will produce spurs in the spectrum of the single tone at the repetition rate of the waveform.

To avoid discontinuities, the following must be considered:

• The total number of samples in the waveform must be a multiple of 8.

• Total number of samples in the waveform must be greater than or equal to 128.

• ,There must be an integer number of cycles of the desired frequency in the waveform.

This constraint can be summarized as:

*(Fs * # samples) / (8 * Fm)* **is an integer**

where *Fs* is the sample frequency and *Fm* is the modulation frequency. For longer waveforms, the frequency resolution obtainable for *Fm* is better—but at the expense of requiring more waveform memory.

5.3 Multi-tone waveforms

The constraints for a multi-tone waveform are similar to those for a single tone waveform (which is actually a special case of the multi-tone).

The multi-tone has some additional considerations:

• The waveform length must be chosen so the all the waveforms have an integer number of cycles

• The phase difference between the tones determines the crest factor. Often a random phase term is applied to each tone to reduce the crest factor and to maximize the magnitude of the individual tones without exceeding full-scale on the DAC.

The first constraint can be determined by taking the minimum *# samples,* calculated using the single tone equation above, for each of the multi-tones. Then the required waveform length for the multi-tone signal is the least common multiple of the individual waveform lengths.

5.4 Radar signals

Common radar signals are time-gated pulses and chirps. In creating a time-gated pulse, it is necessary to add a pulse-shaping envelope to the pulse to eliminate frequency "splatter." This is energy created away from the carrier frequency of the pulse, due to the abrupt edge in time as the pulse turns on and off. Typically a raised cosine pulse envelope filter is used. Other parameters of a pulsed radar waveform include the pulse repetition frequency, the pulse width and the carrier frequency.

In some cases the radar pulse is chirped. Then, the pulse is often best created in the frequency domain, and inverse-transformed back to the time domain. A short turn-on and turn-off section can be included, shaped with a raised cosine envelope. These turn-on and turn-off sections are typically at a constant carrier frequency. The sequencer can be used to piece together individual waveforms for the different sub-sections of the total composite pulse.

Figure 23 shows an example of a 1GHz chirp produced using I/Q modulation. The measurement is made at baseband, using the 89601A Vector Signal Analyzer software, as measured on an oscilloscope. With the N6030A calibrations described previously, the linear frequency vs. time, and flat amplitude response vs. frequency of the chirp are shown.

In addition to creating waveform descriptions in Matlab, many can be generated using the N7905A Waveform Generation Tool box and the N7620-SW1 Pulse Builder software. These are GUI-based utilities that produce many common radar waveforms.
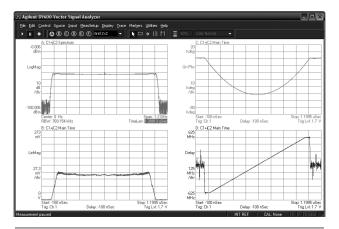
5.5 Digital communications

A number of Matlab functions can be used to simply create communications modulation formats, such as FSK, QPSK, AM, FM and others. One limitation is the overall unique playtime of the waveform memory, which is on the order of 10 ms. For lower data rate formats, it is not possible to capture a large number of information bits in the waveform memory. The sequencer can be used to repeat a short, fixed bit pattern, however.

Figure 24 shows a 600 MHz bandwidth offset QPSK signal measured at baseband with corrections applied in the N6030A. The measurement is performed on an Infiniium 54855A oscilloscope using the VSA software. An exceptional 1% Error Vector Magnitude (EVM) is demonstrated using the internal corrections in the N6030A.
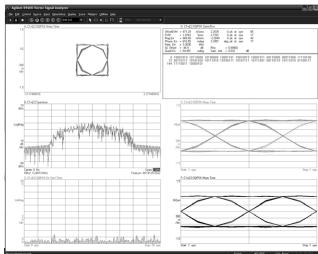

Figure 23. 1 GHz chirped radar waveform

Figure 24. Offset QPSK signal

5.6 UWB waveforms

Ultra wide band (UWB) signals using a multi-band OFDM format are of interest for short range interconnect. The IEEE 802.13.3a standard requires 3 bands of 528 MHz each. Using I/Q modulation, the N6030A can create one of these channels, which can later be placed on a carrier at the desired center frequency.

UWB waveforms can be created using the ADS software with the UWB exploration kit as shown in Figure 25, or using the N7622A pulse builder application.

Figure 26 shows an example mask measurement of an upconverted UWB signal, using the ADS software. Figure 27 shows an upconverted UWB EVM measurement of 3.2% using the N6030A and the ADS software.
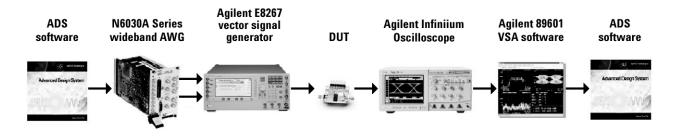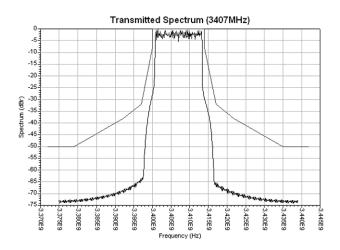

Figure 25. ADS UWB measurement system

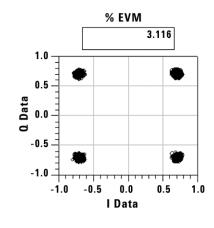**Figure 26.** Baseband UWB signal and mask

Figure 27. ADS EVM measurement of a UWB signal

5.7 MIMO waveforms

MIMO systems use multiple, separated transmitters with orthogonally coded data at the same frequency to overcome multi-path interference. Sophisticated algorithms in the receiver identify the multi-path delays and use them for additional transmission capacity. Synchronization of the AWG channels is crucial to obtain repeatable waveform outputs from the multiple units. Figure 28 shows four synchronized MIMO waveforms obtained from two N6030A units. Figure 29 is a VSA display of a MIMO system employing 64-QAM modulation and operating at a center frequency of 140 MHz. This measurement involves sending repetitive symbols a with a data rate of 36 Mb/s.
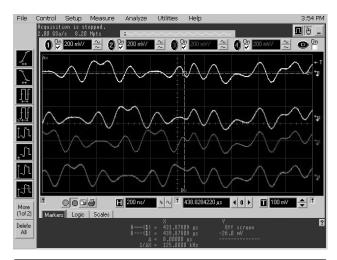

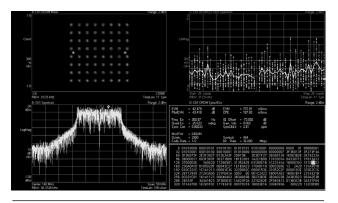**Figure 28.** Four synchronized MIMO waveforms

Figure 29. Four channel MIMO system using 64-QAM

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