

Creating Calibrated UWB WiMedia Signals

Application Note

This application note details the procedure required for signal path calibration when applied to Ultra-Wideband (UWB) signal generation using the following methods:

- Direct RF signal generation
- IF signal generation using an upconverter

In this application note, solutions such as the AWG Series arbitrary waveform generators with RFXpress software tools will be described.

Why Calibration?

To provide high data rates, the FCC in 2002 approved the unlicensed use of UWB devices in the spectrum of 3.1 GHz to 10.6 GHz for short range communication. The term UWB is used when the bandwidth of the signal is greater than 20% of the carrier frequency. That is:

$$\text{Fractional Bandwidth} = \frac{(f_H - f_L)}{f_C} > 20\%$$

Or

$$\text{Total Bandwidth} > 500 \text{ MHz}$$

The WiMedia specification divides the UWB frequency spectrum into six Band Groups with five Band Groups (1 to 4 and the 6th) consisting of three bands each and the fifth Band Group consisting of two bands. Each of the bands within a Band Group has a bandwidth of 528 MHz. The WiMedia specification defines several Time-Frequency Coding (TFC) sequences where signals are frequency hopped between the bands within Band Group, thus having a bandwidth between 528 MHz to 1.584 GHz.

Using Tektronix RFXpress software, there are three ways to generate the WiMedia signals:

- Direct RF: Using an arbitrary waveform generator, the AWG7122B with optional Interleave operation with up to a 24 GS/s sample rate, Band Group 1 to Band Group 6¹ can be directly generated at RF with ease.
- Using upconverters: An IF signal can be generated using an AWG and using an external mixer to up convert to the required RF frequency.
- Using external IQ modulators: An external modulator can be used to modulate the signals, with the AWG generating the hopped I and Q baseband signals, thus reducing the necessity of an external hopping synthesizer and complex switching.

¹ Using a Tektronix AWG7122B with option 6, BG5 requires calibration.

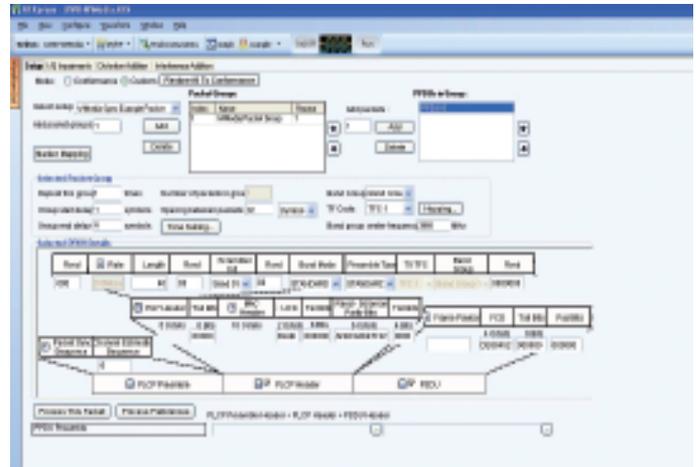


Figure 1. Tektronix RFXpress software for generating WiMedia signals.

To create a proper test signal, it is necessary that the signal spectrum within the band of interest has flat amplitude and a linear phase response. The whole test setup (consisting of an AWG, an upconverter or an IQ modulator) used to generate the WiMedia UWB signals may not have a flat response in the wide frequency band defined in the WiMedia specifications. Also due to the path loss and the cables, the band edges might degrade.

To maintain the integrity of the signals over 1.584 GHz, pre-distorting the waveform becomes necessary, therefore the need to calibrate the whole system.

Basic Method

The basic method of reference calibration is to generate a known (golden) signal using the correction device (an AWG) to the appropriate measurement device (an oscilloscope). Capturing and comparing the measured signal to the golden reference will make it possible to obtain the appropriate correction data for both amplitude and phase.

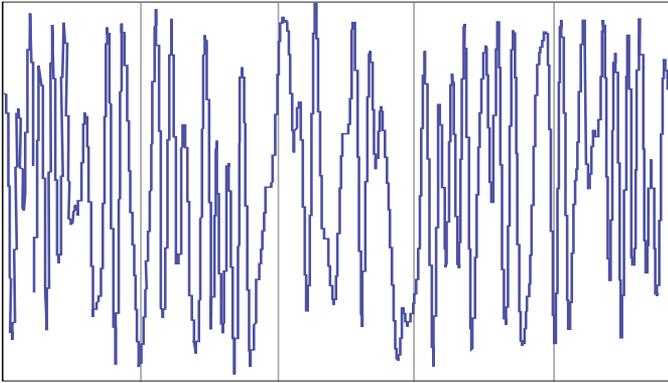


Figure 2. Channel Estimation Signal.

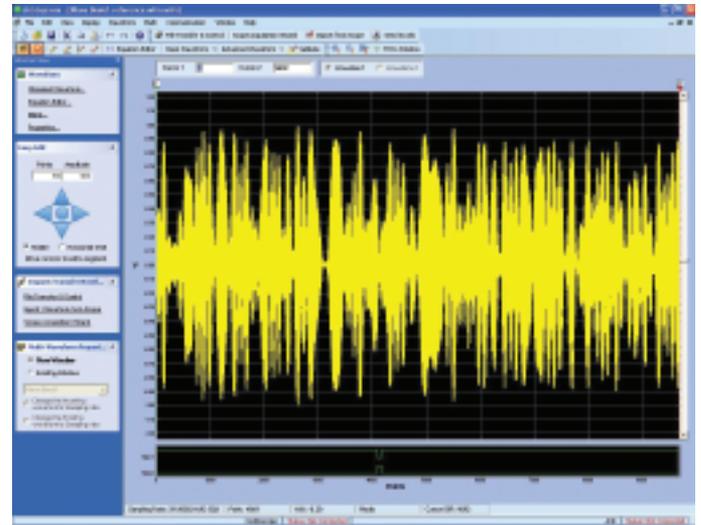


Figure 3. Reference Signal: Channel Estimation Signal after modulation.

Golden Reference Signal

The calibration procedure requires generating a signal with known amplitude and phase distributions over the band of interest. Additionally, it is highly desirable that the signal shows the representative PAPR (Crest Factor) to contain the effect of non-linearities in the system so that the total system performance can be represented. This will result in a higher repeatability and accuracy while lowering the number of averages and processing time to reach the expected results.

A candidate signal meeting these criteria is the channel estimation sequence as defined in the UWB-MB-OFDM WiMedia standard, as shown in Figures 2 and 3. It shows the following characteristics:

- Frequency components are limited to the location of the OFDM carriers defined for UWB-MB-OFDM signals.
- All the carriers show the same amplitude.
- Phase distribution is known and phase values are limited to four different levels (-135° , -45° , 45° , and 135°) easing the handling of phase wrapping and estimating fine delay.
- Peak-to-Average-Power-Ratio (PAPR) is just 5.8 dB.
- As the time-domain signal is obtained by performing an IFFT over a strictly defined frequency-domain amplitude and phase distribution, it can be seamlessly sequenced without any spectral leakage effect.

Acquisition Requirements

Signals to be analyzed must be acquired through an oscilloscope with a sufficient sampling rate. This means that the total signal content must be within the Nyquist frequency ($Sr/2$).

The capability of a Tektronix real-time oscilloscope with enhanced bandwidth (DSP-based technology) is required to acquire the signals. Signals are acquired at the maximum sampling rate so as to get the best amplitude/phase response necessary for high accuracy calibration. The record length must be selected to obtain enough frequency-domain resolution. Additional acquisition time must be allowed for, in order to get precise FFT analysis window positioning (alignment) without the requirement for an additional trigger signal.

Analysis Methods

Frequency domain analysis for UWB signals may be performed on the raw time-domain signal or after demodulation and/or downconversion. The latter method must be performed when a real complete UWB signal is used for calibration, as this is the only way to reach the required frequency domain resolution over a single symbol (128 samples).

Raw time-domain signal analysis is feasible only when the signal repeats so that the required frequency domain resolution can be obtained by extending the analysis over a high number of symbols. This is the case with a previously defined calibration signal.

Raw time-domain signal analysis is highly desirable as it avoids many of the side effects of direct digital down conversion (typically implemented by under sampling/decimation) such as image rejection, poor signal-to-average-noise ratio, and susceptibility to aliased signals. The RFXpress software uses the raw time-domain signal analysis because this gives the best possible calibration results.

Frequency Analysis Resolution and Time Domain Window Selection

Basic resolution in FFT based analysis is obtained by dividing the acquisition sampling rate by the number of samples used in DFT calculations.

$$Resolution = \frac{Acquisition\ Sampling\ Rate}{Number\ Of\ Samples}$$

| Sample Rate | Record Length @ Df = 400 KHz | Record Length @ Df = 300 KHz |
|---------------|---------------------------------|---------------------------------|
| 20 GSamples/s | >50,000 samples | >67,000 samples |
| 25 GSamples/s | >62,500 samples | >85,000 samples |
| 40 GSamples/s | >100,000 samples | >133,000 samples |
| 50 GSamples/s | >125,000 samples | >167,000 samples |

Table 1. Minimum record lengths to obtain FFT resolution of 400 KHz and 300 KHz.

Accurate and useful analysis requires the resolution to be better than the UWB basic carrier spacing (4,125,000 Hz). Complete carrier separation and accuracy necessitates using time-domain windows to improve the flatness of the resulting frequency domain data.

Flat-top window is especially desirable as it gives an excellent amplitude (and phase) accuracy (0.01 dB) so it eliminates the undesired “scallop” effect. Unfortunately, flat-top window is not very selective in the frequency domain. If the 60 dB attenuation bandwidth (9.1 Df) is taken as a reference, then Df should be better than 10 times the OFDM basic carrier spacing leading to a value around 400 KHz.

The following table shows the minimum record length for different combinations of sampling rates to obtain an FFT resolution of 400 KHz and 300 KHz.

| Sample Rate | Reference Record Length |
|---------------|-------------------------|
| 20 GSamples/s | 4848 samples |
| 25 GSamples/s | 6061 samples |
| 40 GSamples/s | 9697 samples |
| 50 GSamples/s | 12121 samples |

Table 2. Sample rate and corresponding reference signal length.

| Sample Rate | Record Length |
|---------------|--------------------------------|
| 20 GSamples/s | 65536 + 2424 = 67960 samples |
| 25 GSamples/s | 65536 + 3031 = 68567 samples |
| 40 GSamples/s | 131072 + 4849 = 135921 samples |
| 50 GSamples/s | 131072 + 6061 = 137133 samples |

Table 3. Sample rate and corresponding record length.

Time-domain Alignment

Correct phase analysis requires applying the FFT algorithm to signals properly aligned in the time domain.

Although phase analysis could be theoretically obtained by using standard hardware techniques such as triggering, this option is not desirable for the following reasons:

- It requires a second connection between the AWG being calibrated and the calibration oscilloscope for the synchronization signal.
- Even to connect that signal, proper alignment will require precise delay adjustment to compensate for differential delay including the effect of different bandwidth.
- Marker signals may inject some jitter due to their timing granularity.

Signal correlation is an alternative method that does not show any of the above problems. Correlation compares a signal with another. When similar signals are aligned in time, the output of correlation shows a peak. The proposed alignment method takes a reference signal consisting of a single channel estimation symbol modulated at the target carrier frequency.

For a given oscilloscope acquisition there will be several alignment events, as the signal repeats seamlessly. In any case, as the record length will be slightly larger than the FFT analysis length, the correlation should be limited to the central region of the acquisition. There will be one perfect alignment setting in $\pm(\text{Reference Signal Length})/2$ samples around the central location. Limiting the search area also speeds up the process as correlation is time consuming.

$$\text{Reference Signal Length} = \frac{\text{Acquisition Sampling Rate} \times 128}{528 \text{ MHz}}$$

It is necessary that the length of the acquired signal contains at least one FFT frame and the FFT frame be a power of 2. The analysis area may be shifted by half the reference signal length. The minimum acquisition length that would be required to be captured on the oscilloscope so as to obtain an FFT resolution in the region of 300-400 KHz is given above.

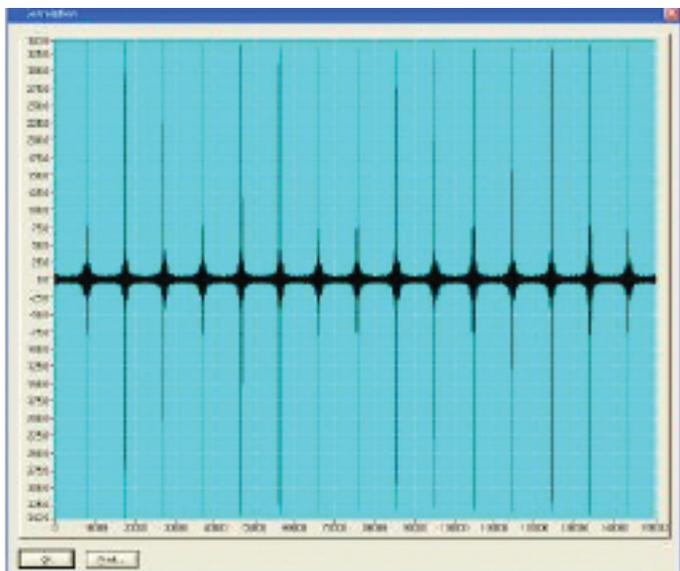


Figure 4. Correlation signal over the entire record length.

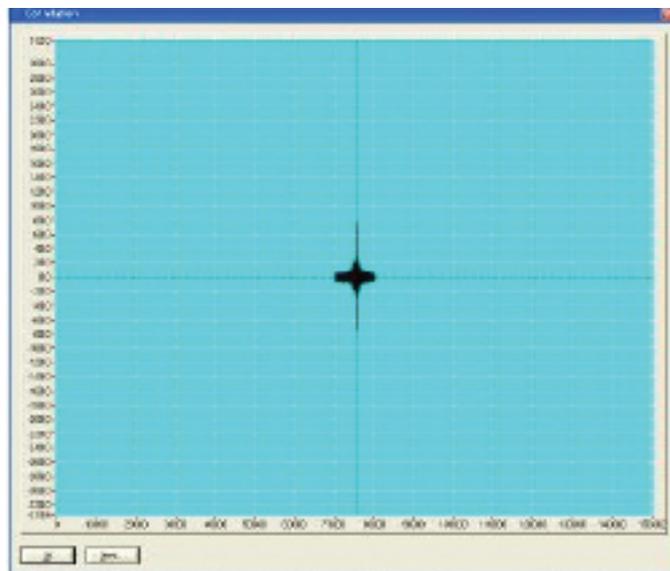


Figure 5. Correlation signal in the central region.

Correlation

The correlation algorithm consists of multiplying the samples in the reference signals by the corresponding samples in the analyzed waveform to obtain one of the samples of the correlation waveform. The same process is repeated around the area of interest by shifting the analysis window by one sample. The region to cover is the central area of the acquired signal and the size of the area is equal to the

reference signal length. The correlation waveform will show peaks when the reference signal is properly aligned. There are positive and negative peaks due to the instantaneous carrier phase alignment between both waveforms. The search algorithm takes the absolute value of the correlation signal and looks for the maximum value. The obtained value will define the FFT analysis area. Figures 4 and 5 show the correlation signal over the entire record length and in the center region respectively.

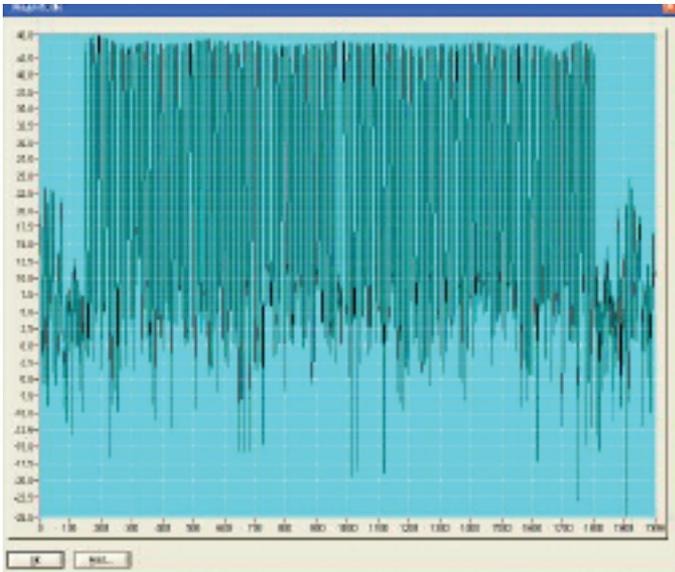


Figure 6. Magnitude plot.

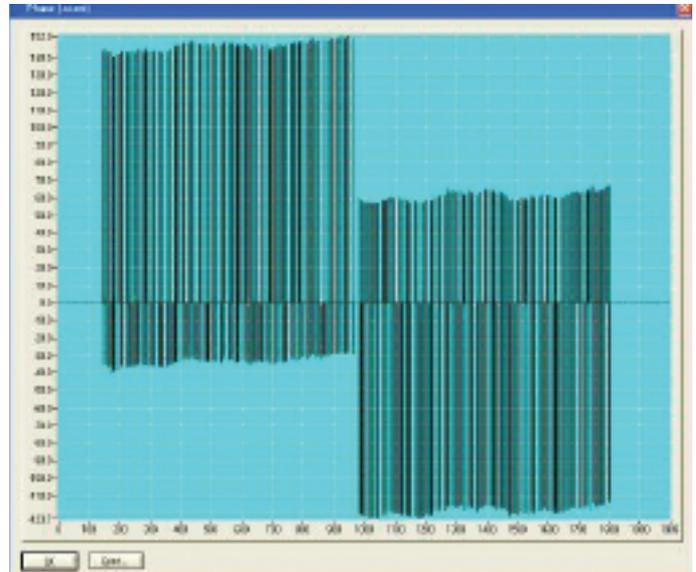


Figure 7. Phase plot.

Raw Data Processing

Once the analysis region is selected, the FFT algorithm is applied to the real values of that region. The resulting real and imaginary values must be processed to obtain the required magnitude and phase values. This process may take place between the complete frequency domain waveform or just at the discrete frequencies of interest.

Magnitude and phase are obtained using the following equations:

$$Amplitude[i] = 10 \times \log_{10} (real[i]^2 + Imag[i]^2)$$

$$Phase[i] = arctg(imag[i], real[i])$$

Where “arctg” is a four quadrant arctangent function.

Figures 6 and 7 show the amplitude and phase plot obtained using the above equations.

Amplitude calculation is straightforward. The phase process requires an extra step because phases are shifted $\pi \cdot i$ as the signal is shifted by half the analysis length. The Phase shift may be handled by adding 180° to every two samples.

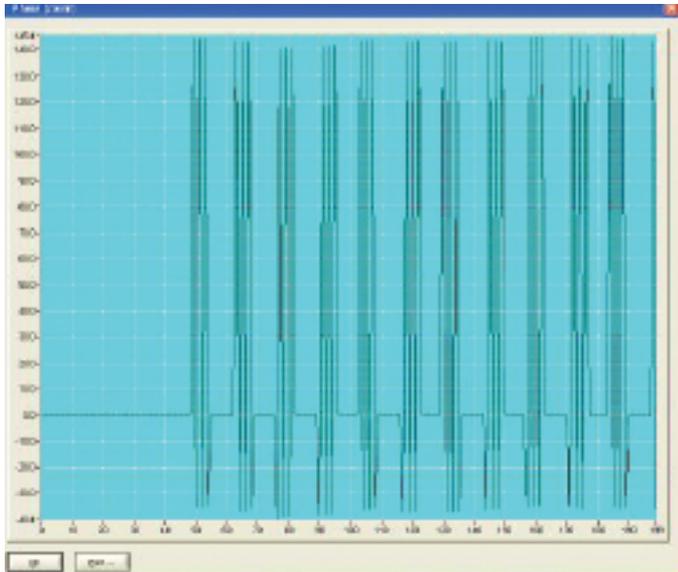


Figure 8. Phase response showing 180° shift.

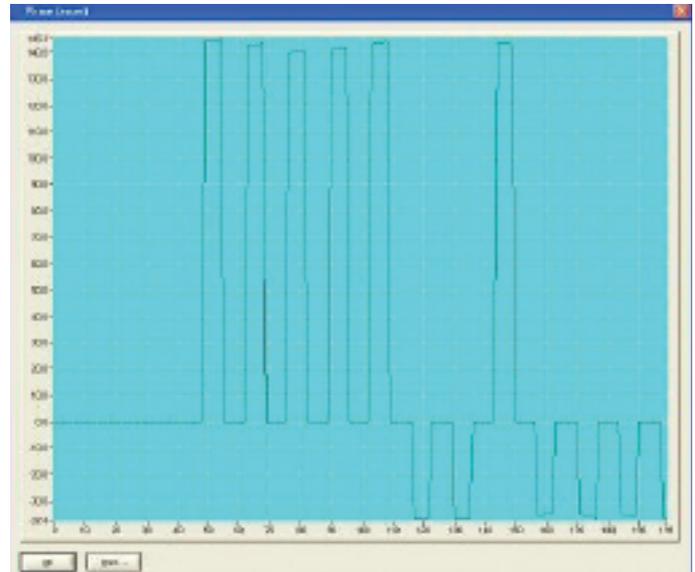


Figure 9. Phase after shift removal.

Phase Wrapping Handling

Ideal channel estimation signals show phases transitioning between +135° and -45° for the lower sideband and +45° and -135° for the upper sideband. Actual values in the resulting phase waveform will not follow this range due to the following reasons:

- Absolute phase will depend on the carrier phase that should be seen as random value.
- Tiny residual group delay coming from alignment errors due to the timing granularity of the correlation process.
- Phase impairments - these values are to be obtained by the algorithm.

The combined phase shift may take the absolute values to go beyond the arctangent function limits of $\pm 180^\circ$, making it important to take care of the phase wrapping effects. An evident solution is processing the phase waveform to unwrap it before calculating the correction. This solution and the additional phase normalization (so average phase = 0) is necessary to show the right phase values in graphs as shown in Figures 8 and 9.

A simpler, more straightforward solution is processing the error signal.

Basically it takes the following steps:

- For each carrier frequency the raw difference between the ideal and actual carrier phase is obtained.
- This value may range from -360° up to +360°. These phase differences must be limited to the $\pm 180^\circ$ range by adding or subtracting 360° to the value if it goes under -180° or over +180°.
- The resulting raw phase correction array may be shifted to its average value so the common phase error component is eliminated and the overall correction is minimized.



Figure 10. Instrument setup.

Amplitude Processing

Although amplitude processing is straightforward, correction data cannot be obtained from the relative errors around the average value at a given band within a band group.

The reason is that doing so will result in amplitude imbalances between different bands in the same band group, which will show up as amplitude changes as the signal hops. This means that the absolute values must be stored and processed at correction time to normalize the amplitude to all the bands at the same consistent value.

Using RFXpress to Calibrate the System for WiMedia Signal Generation from an AWG7122B

This note provides for a procedure to generate and apply corrections for distortions in the system while generating Direct RF WiMedia signals using an AWG7122B with product option 06, Interleave operation with up to a 24 GS/s sample rate.

In this example procedure we will generate a WiMedia compliant Band Group 5 UWB signal.

Instruments needed:

- The Tektronix AWG7122B with option 06 is used to generate the RF WiMedia signal.
- The Tektronix oscilloscope is used to capture the signal.

Instrument Setup

The AWG7122B is operated in the interleave mode. The AWG interleave output channel is connected to channel 1 of the Tektronix oscilloscope as shown in the instrument set up in Figure 10.

Note: Make sure that the instruments are individually calibrated using the calibration verification procedures provided in the instruments.

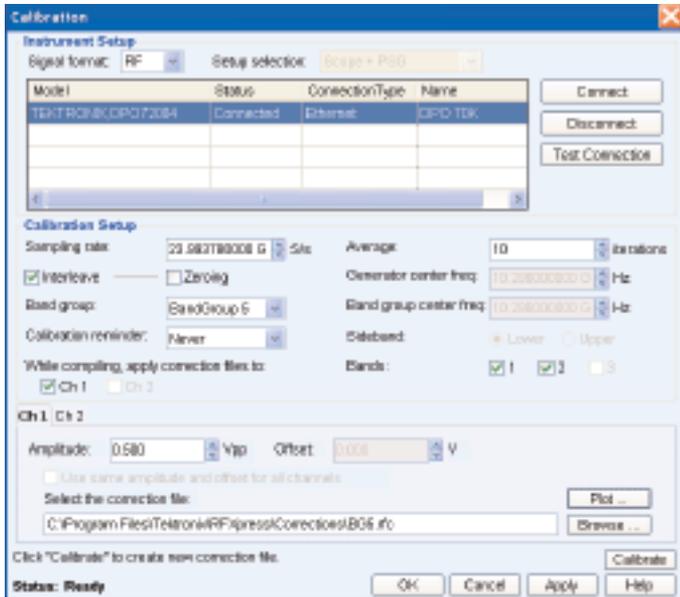


Figure 11. Calibration dialog.

Procedure to Generate the Correction File

1. In RFXpress, select WiMedia Application. Click Calibration and the following dialog, as shown in Figure 11, will guide you through the calibration process.
2. Select the Signal Type as RF.
3. The list in the grid is populated with instruments found on the local subnet with their Model, Status, Connection Type and Name (Alias). For example, select the oscilloscope (as shown in Figure 11), then select Connect, and the Status will update to "Connected".
4. Select Interleave, in order to generate signals with sampling rates of 23.993786 GS/s.
5. The Sample Rate field is used to set the AWG sample rate. Set the sample rate to 23.993786 GS/s.
6. The Average field is used to generate statistically averaged correction data by multiple captures of the signals on the oscilloscope. Set the Average to 10.
7. Set the Band Group to Band Group 5.

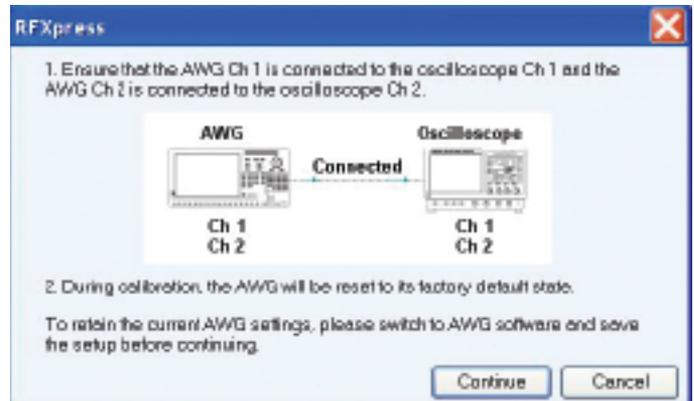


Figure 12. Warning message.

8. Select the band to be calibrated. Note that the Band Frequencies are calculated in accordance with the WiMedia specifications, that is: Band Group Center Frequency -528 MHz, Band Group Center Frequency +528 MHz.
9. Select the channel (channel 1) for which the correction file is to be generated.
10. Set the Amplitude for channel 1 to 0.5 Vpp.
11. Under the select Correction File provide the path and the file name where the correction data is to be stored.
12. Click the Calibrate button.
13. An alert message, as in Figure 12, appears, prompting you to check the connection. Check the connection and click continue.
14. Note that during calibration, the AWG will be re-set to the factory default state.
15. Test signals will be generated for each of the bands and captured from the oscilloscope. When using RFXpress, the status of the entire process is shown in the calibration dialog.
16. The Error Correction for the setup is generated and stored in a file with extension *.rfc.



Figure 13. Spectrum before calibration.



Figure 14. Spectrum after calibration.

Applying the Correction File

1. To apply the correction, in the Calibration menu select the correction file just generated and click OK.
2. Generate a WiMedia signal with following specs:
 - a. Select IF/RF as the Signal format
 - b. Select the WiMedia example packet from Setup
 - c. Set the Band Group to Band Group 5.
(Band Group 5 Center Frequency of 10296 MHz.)
3. In Compile Settings, set the Over sampling to 3.60, which will set the sampling rate to 23.993786 GS/s. Make sure CH1 is selected under Correction File.
4. Compile.
5. The Correction will be applied to the UWB WiMedia waveform created.

Summary

This application note described the procedure that can be used for signal path calibration when applied to UWB signal generation using:

- Direct RF signal generation
- IF signal generation using an upconverter

Solutions such as AWG Series arbitrary waveform generators with RFXpress software tools were explained.

To maintain the integrity of the signals over the whole band, pre-distorting the waveform becomes necessary, therefore the need to calibrate the whole system. Examples of pre-and post-calibration are shown in Figures 13 and 14.

Figure 13 shows the spectrum of the Band Group 5 signal captured on the oscilloscope and analyzed using the Tektronix UWB oscilloscope software. This degradation in the frequency response of the Band Group 5 signal is due to the analog bandwidth upper boundary of the AWG. This kind of difference in the spectrum could also arise due to the bandwidth of the cables.

Figure 14 shows the spectrum after correction is applied to the signal. Now the flatness of the signal is improved.

Similar to the direct sampling advantage of oscilloscopes, the AWG utilizes direct RF synthesis which can minimize the need for continued calibration. Controlled thermal behavior, low drift in time, and lack of external equipment can allow a calibrated signal to remain within acceptable limits over a long period of time.

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