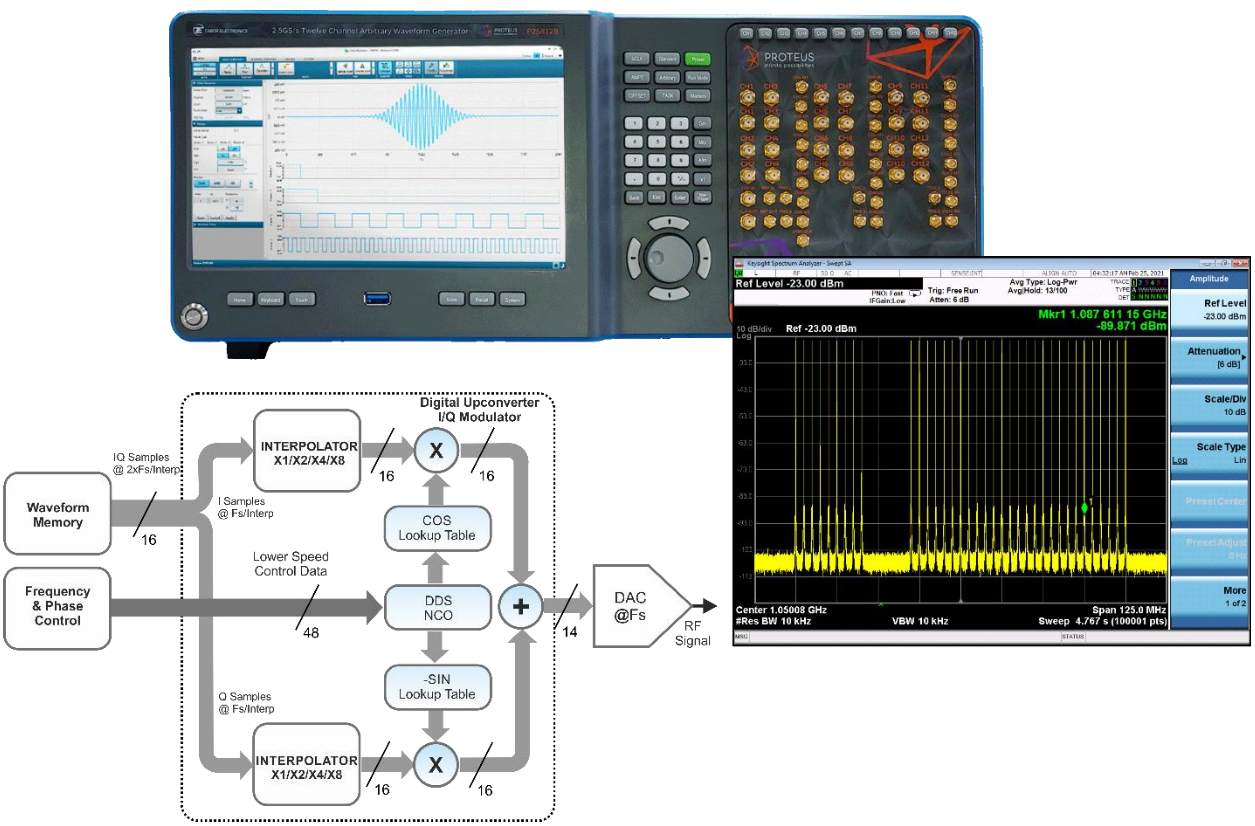
RF Signal Generation with Digital Up-Converters in AWGs

White Paper

Rev. 1.0



4 Implementation of the DUC in the Proteus Family

Block Diagram

The Proteus family of products (fig. 4.1) incorporates DUC in the P258X (optional) and P948X products, regardless of the platform (B, D, or M). The main differences between the P258X and P948X are maximum sample rate (2.5GS/s vs. 9GS/s) and the 8-bit DAC mode available in the P948X products so direct generation without interpolation or digital up-conversion is possible up to 9GS/s. The PXIe modules can incorporate two or four channels. Channels are grouped in pairs (ch1&ch2, ch3&ch4) so two channel instruments incorporate one pair while four channel instruments incorporate two pairs. Each pair shares the same dynamic memory bank, so the connection is shared among the channels. The overall maximum transfer rate for each pair is 10GBytes/s. This means that 16-bit samples can be transferred to all channels up to 2.5GS/s while the 8-bit mode allows for 9GS/s transfer to one of the channels in the pair (Ch1 for the first pair and Ch3 for the second pair).

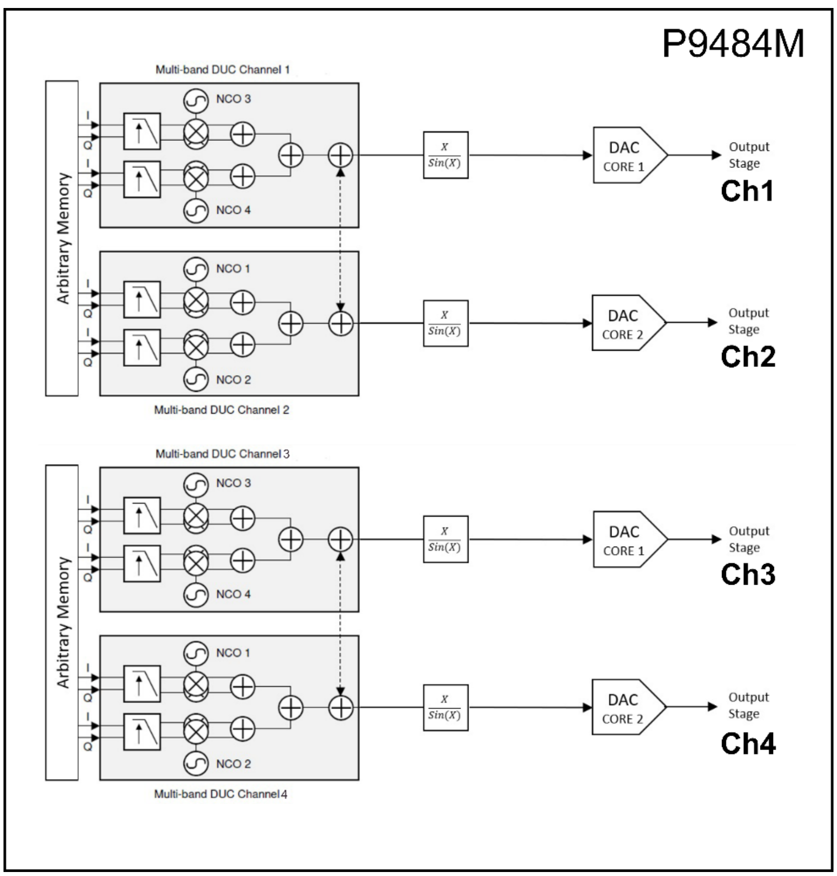


Figure 4.1: Block diagram of the Tabor Proteus P2584M and P9484M when used in the DUC mode. Notice the availability of two independent DUCs per channel. Each DUC can be fed with their one IQ baseband waveforms. There are several IQ modes using the available DUCs in different ways to offer more carriers per channel or more modulation bandwidth.

DUC Modes

When it comes to the DUC, the block diagram shows that there are two independent DUCs for each channel (fig. 4.2). Each DUC incorporates its own NCO so the carrier frequency can be set to different frequencies all over the tuning frequency range (DC up to the current sample rate). Interpolators can implement interpolation factors 1x, 2x, 4x, and 8x. One (ONE Mode) or both (TWO mode) DUCs can be used at a given moment. However, the maximum sample rate and modulation BW depends on the interpolation factor and the number of DUCs being used. Additionally, there is a switchable connection between the output of the DUC block in one of the channels of each pair and an adder connected to the output of the other channel of the same pair, so the combination can be fed to the corresponding DAC while the other DAC remains inactive (HALF Mode). In this way, modulation bandwidth and data rate can be doubled as I data is fed only to the DUC of one of the channels while Q data is fed to the other. In this mode, just the I path for each DUCs is used while the two NCOs are set to the same frequency, while the relative phase is set to 90o. In other words, each DUC block generates half of the IQ modulation.

The processing chain in the DUC uses 16-bit integer arithmetic and the DUC only works in the 16-bit mode, so all the baseband waveforms are defined as a set of 16-bit IQ pairs. The resolution of the DAC itself is 14-bit. It is important to use a higher resolution for samples and all calculations in order to keep calculation noise (coming from integer arithmetic rounding in the interpolation FIR, multiplier, and adders) below the resolution of the DAC, so the quality and RF performance of the final signal is not degraded. FIR filters in the interpolator are optimized for usable bandwidth, flatness, and stop-band attenuation. The number of coefficients depends on the interpolation factor being applied. The filter roll-off is designed to maximize the usable bandwidth so the maximum attenuation is not reached under the Nyquist frequency for the waveform before interpolation. Instead, the maximum attenuation band starts close to the image frequency of the maximum frequency of the flat-response band. It is necessary, then, to make sure that the maximum frequency component of the waveform before interpolation is not larger than this frequency.

There is a numerical 6dB independently switchable attenuator at the output of each one of the two DUCs in the Proteus' DUC block. The main purpose of this attenuator is avoiding clipping when the DUC is operated in the TWO mode. As two IQ modulated signals are added together and NCOs are independent, the worst peak for the combined RF signal will be twice the one for each of the component RF signals. If both IQ waveform are normalized for the maximum DAC range, attenuating both signals by 6dB before adding them, will avoid any chance of clipping the DAC. At first sight, the same result could be obtained by dividing all the I and Q samples by two. However, although this method would avoid clipping as well, the effective resolution of the baseband data would be reduced to 15-bits, and calculation noise would be noticeably higher than calculating each RF signal with 16-bit, and then rounding the result to 15-bit (dividing by two) before the adder. This is a simple but effective approach when peak power is the same for both RF signals. However, when power (or peak-to-peak amplitude is different), then a joint normalization may be better. Keep in mind that sampling for both IQ signals (and waveform length as well) is the same for both DUC in the TWO mode. The normalization procedure must find the maximum

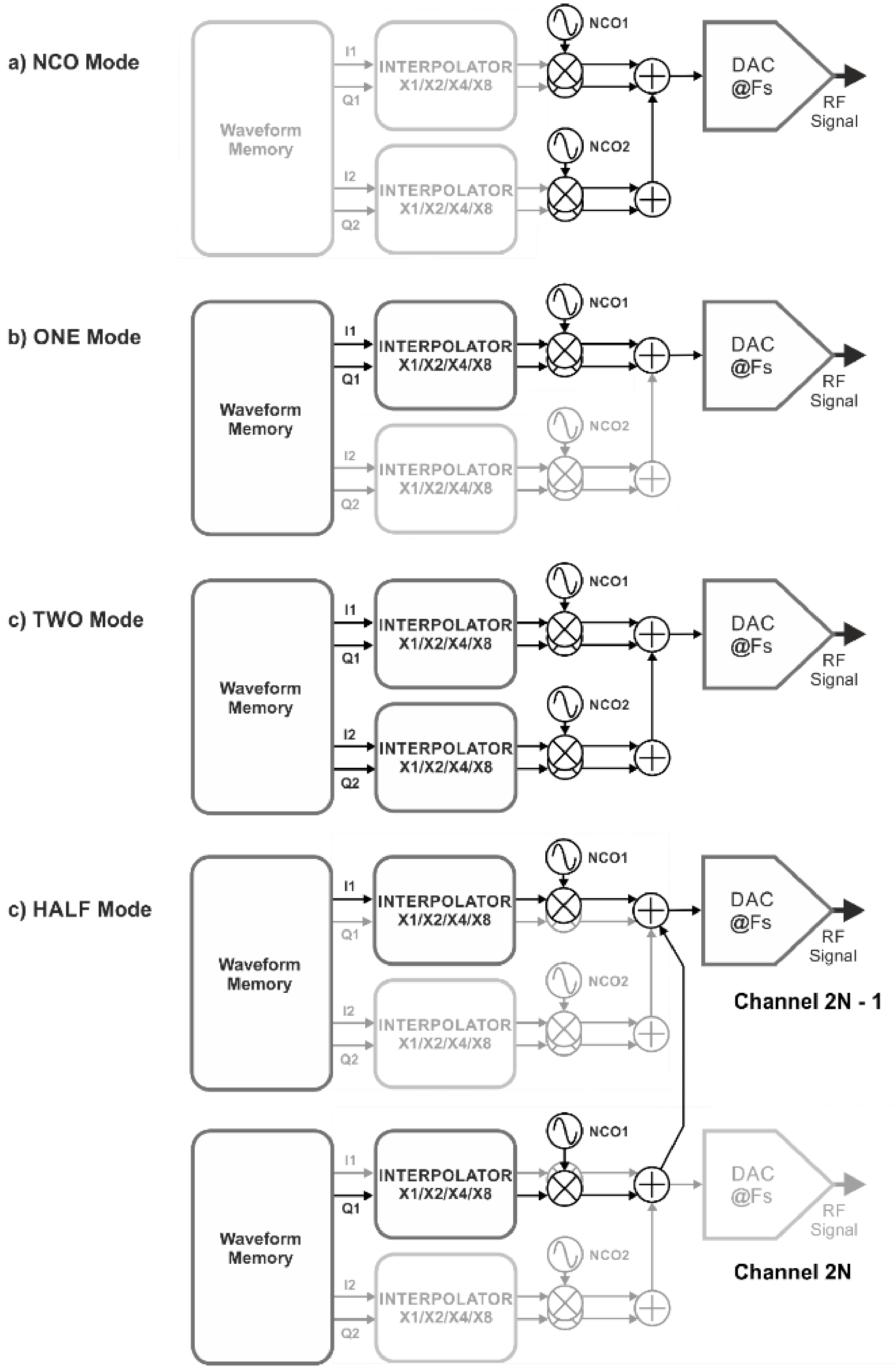


Figure 4.2: There are 4 DUC modes in the Tabor Proteus product. One of them, the NCO mode (a), uses the internal NCOs to generate sinewaves with controlled frequency and phase. The ONE mode (b) uses just one of the NCOs for each channel while the TWO mode (c) uses both, although it reaches half of the modulation bandwidth. Finally, the HALF mode (d) combines one DUC from each channel pair to double the modulation bandwidth for half the channels.

peak of the combined envelope waveform and make sure that the worst case never goes beyond the clipping level. If the overall DAC range is normalized to the -1.0/+1.0 range, if any of the resulting RF the 0.5/+0.5 limits, then the resulting samples can be multiplied by two and then activate the numerical 6dB attenuator for that IQ pair so this will optimize signal quality without modifying the relative power of both signals.

Phase can also be set for each NCO. This is the initial phase for the NCO when operation starts. As the starting instant for all the NCOs in pair, module, or system is deterministic, the phase control allows for relative phase adjustment of all the carriers. This is especially meaningful when the carrier frequency is the same for all the channels. As all the NCOs are referred to the sampling clock, and this can be based in the same frequency and time references. The initial phase will be kept indefinitely, easing applications where relative phase control is mandatory, such as Phase-Array Radars, MIMO, Beamforming, or Quantum Computing. Phase, like frequency, can be changed “on the fly”. This means that a new relative phase setting can be set (i.e. to change the direction of a beam) without interrupting signal generation, unlike some other DUC-equipped AWGs in the market.

The Proteus DUC can also be used in the NCO mode. In this mode, no IQ data is read, and the only working elements in the DUCs are the NCOs. This mode can be used to generate multiple CW signals without the need to define a “dummy” DC IQ waveform. When set to the same frequency, all the NCOs are coherent, and the relative phase can be controlled accurately, making this multi-channel CW RF generator highly suited for applications as Phase Array Radar, Beamforming, or any application where multiple L.O. with tightly controlled relative phases.

IQ Waveform Data Formats in Proteus

Once calculated, normalized, and scaled, IQ complex waveforms must be quantized and concerted to 16-bit unsigned integers, before being transferred to the target waveform memory. As previously mentioned, each channel pair (two of them in a single PXI module) shares the same DDR bank with a capacity of up to 16GSamples (8-bit mode) or 8GSamples (16-bit mode). Each bank can be segmented in up to 64K segments. Waveform segments are the real target for waveforms being downloaded. Real waveforms are stored as a series of samples read sequentially (“true arb” architecture). However, complex (IQ waveforms) cannot always be handled as two independent segments, as each channel can only access one segment at a time. The solution for this issue is reading complex waveforms as a single entity, so both components are stored in the same segment. The simplest way to do it, and the best one to minimize intermediate buffering, is storing IQ waveforms as interleaved pairs (I1, Q1, I2, Q2…, In, Qn). This is the format used for the ONE DUC mode in Proteus (fig. 4.3). This is the formatting procedure to follow:

1. Calculate I and Q waveforms
2. Joint normalization
3. Interleaving (I, Q, I, Q)
4. Download to target segment
5. Segment size = 2 x I/Q waveform size
6. Select segment for target channel (1-4)

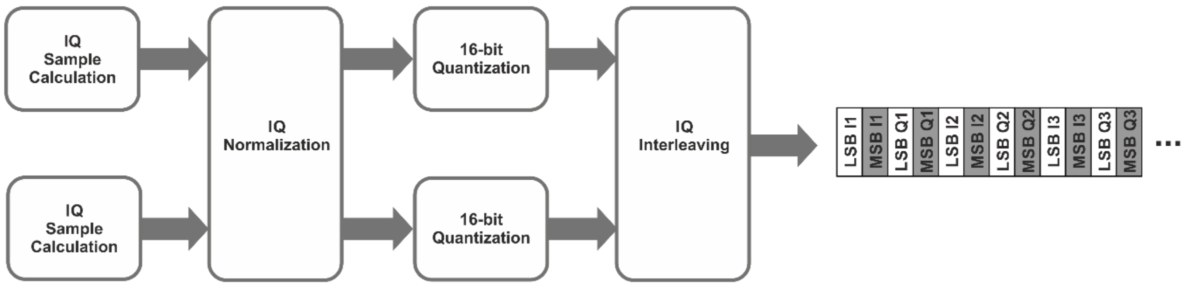


Figure 4.3: IQ waveform data must be stored properly for play-back. In the ONE mode, data must be arranged as a single segment with the I and Q samples interleaved.

The maximum overall data rate for this mode is 2.5GS/s (16-bit) so the maximum sample rate for each component would be 1.25GS/s (1.125GS/s for 9GS/s DAC conversion rate and 8x interpolation) and the resulting modulation BW would be slightly larger than 1.0 GHz.

The TWO mode is more complex, as two sets of IQ pairs must be transferred to a given channel. The resulting two sets of IQ pairs must be doubled interleaved to be downloaded to a single segment (fig. 4.4). The binary data to be sent to the segment must be properly formatted, so the transfer to the waveform memory is aligned with the DUC block requirements. This is the sequence of formatting actions to be carried out:

1. Arrange the 16-bit samples in the I1, Q1, Q2, I2 sequence
2. Split all the 16-bit samples in two bytes
3. For each group of four samples, take the MSB bytes following the interleaving sequence shown above (I1M, Q1M, Q2M, I2M)
4. You must perform the same operation for the LSB bytes (I1L, Q1L, Q2L, I2L)
5. Obtain the final waveform data by interleaving the MSB and LSB groups built in the previous steps (I1M, I1L, Q1M, Q1L, Q2M, Q2L, I2M, I2L)

As the overall data rate (5GBytes/s) stands here as well, the maximum sampling rate for each one of the IQ components is 625MS/s and modulation BW will be close to 600MHz. However, as interpolation factor depends on the ratio between the DAC sampling rate and the baseband interpolation ratio, and currently the maximum interpolation factor implemented in Proteus is 8x, the maximum DAC sampling rate supporting the two mode is 625 * 8 = 5,000MS/s = 5GS/s. Future product improvements will allow for higher interpolation factors (16x) so the TWO mode will be feasible up to the maximum DAC sampling rate (9GS/s).

Finally, the HALF mode uses half of one of the DUCs in each channel of a given pair, using just one of the DACs after adding the output of each block. In this case, waveform data is stored as two independent segments in the same DDR bank and segment assignment is done as a direct real only waveform to each participating channel. This is the formatting procedure:

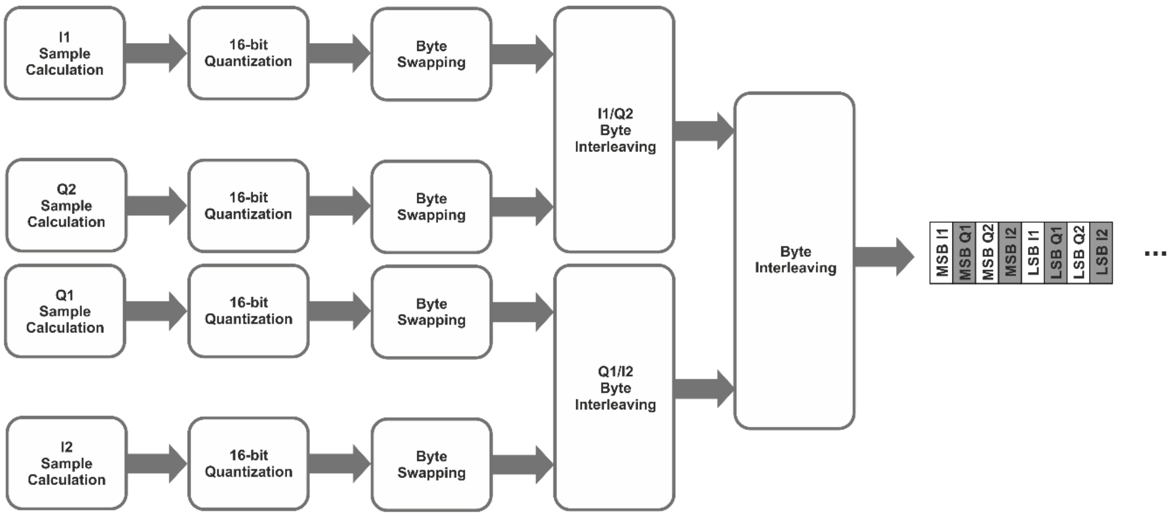


Figure 4.4: The TWO mode requires interleaving the IQ1 and IQ2 sample pairs together in such a way the DUC can use the data immediately and latency is minimized. Here, the dual-level interleaving process is shown.

1. Calculate I and Q waveforms
2. Joint normalization
3. Download I waveform to segment A
4. Download Q waveform to segment B
5. Segment size = I waveform size = Q waveform size
6. Select Segment A for target active channel (1 or 3)
7. Select Segment B for associated phantom channel (2 or 4)

NCO for each channel must be set to the same frequency and phase. When the mode is activated, the "phantom" channels will not output any signal, and the active channel will work exactly as it was in the ONE mode, although the I and Q quadrature modulated components come from different DUCs (each one using a different, but synchronized and coherent, NCO). The main advantage of this mode consists in increasing by a factor of 2 (up to 2.5GS/s) the sampling rate for each one of the components, so modulation BW goes beyond 2.3GHz. At a 9GS/s DAC sampling rate, and using the x4 interpolation factor, baseband sampling rate will be 2.25GS/s so modulation BW will go beyond 2GHz.

Resources & Contact

For more information on Microwave signal generation challenges and solutions, review the following resources:

- White Paper: Multi-Nyquist Zones Operation-Solution Note
- White Paper: Direct Generation/Acquisition of Microwave Signals
- White Paper: Effective Number of Bits for Arbitrary Waveform Generators
- White Paper: Multi-Tone Signal Generation with AWGs
- Solution Brief: Envelope Tracking – Solution Note
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