Polyphase Channelizer Performs Sample Rate Change Required for both Matched Filtering and Channel Frequency Spacing

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Abstract: We present here the design and implementation of a polyphase filter bank channelizer with an embedded square-root shaping filter in its polyphase engine that performs two different resampling tasks required for the spectral shaping and for the M-channel channelization. In particular, in the example we cite, the shaping filter performs 1-to-48 resampling from input symbol rate to output sample rate while the IFFT performs 1-to-40 resampling to form a 40 channel channelizer.

1. Introduction

Traditional Polyphase Filter banks are formed from three building blocks, an M-port commutator, an M-path polyphase partition of a prototype low-pass filter and an M-point IFFT. These blocks can be arranged to perform an M-channel channelizer that, by down-sample aliasing, down-converts, band-limits, and re-samples by M-to-1 an input time series compose of up to M-equally spaced frequency division multiplexed (FDM) channels to form M-interlaced time division multiplexed (TDM) channels. When assembled to perform this task the components are ordered as input commutator, polyphase filter, and IFFT as shown in figure 1.

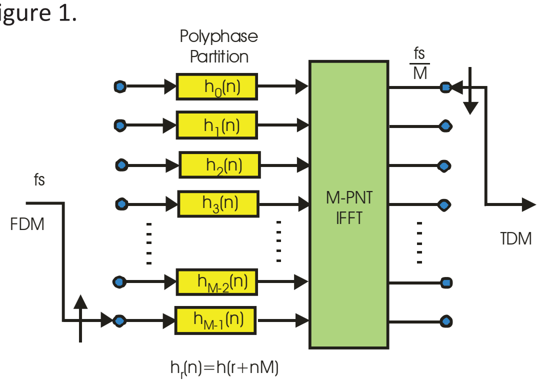

Figure 1. M-path Polyphase FDM-to TDM Channelizer.

These same blocks can be arranged to perform the dual task of an M-channel channelizer that, by up-sample aliasing, up-converts, band-limits, and re-samples by 1-to-M up to M input time series to form an output time series composed of M-equally spaced frequency division multiplexed (FDM) channels. When assembled to perform this task the components are ordered as IFFT, polyphase filter, and output commutator as shown in figure 2.

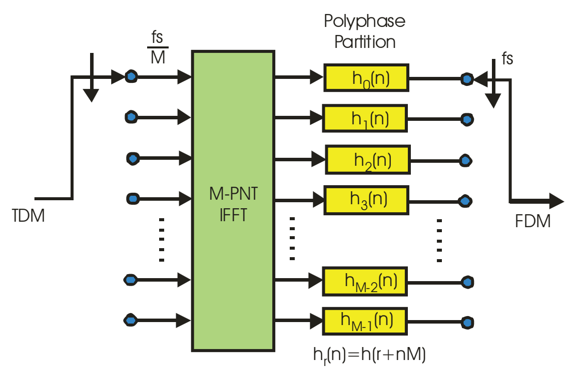

Figure 2. M-path Polyphase TDM-to FDM Channelizer.

The up-converter and the down-converter options of figures 1 and 2 are seen to be performed by dual graphs which by virtue of their linear time varying structures perform the opposite tasks of up-sample and down-sample channelization. In the two forms shown here the frequency spacing between adjacent spectral channels is determined by the IFFT and is always f_S/M. As shown, the down-sampling formed in figure 1 is M-to-1 while the up-sampling formed in figure 2 is 1-to-M.

2. Non-Maximally Decimated Filter Bank

There are a number of scenarios where we desire that different up-sampling and down-sampling tasks be performed in the channelization process. We now present an example of a typical down sampling task of an FDM-to-TDM channelizer. The system we consider is presented with 32 channels separated by 6-MHz center frequencies. The symbol rate of each channel is 5-MHz and each channel has been shaped by a sqrt Nyquist filter with 20% excess bandwidth. We select a 40-point IFFT to make available 8 channels to span the folded transition bands caused by the sampling

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process. These channels are considered overhead channels and are discarded. Use of the 40-point IFFT requires an input sample rate of 240-MHz to obtain the required 6-MHz channel spacing.

If we use the 40-point IFFT to form the 40-to-1 down-sampling of figure 1, we would obtain an output sample rate matched to the channel spacing of 6-MHz. In consideration of standard modem processing following the channelization we desire an output sample rate of 2-samples per symbol which is 10 MHz. Thus we need to perform a 24-to-1 down sampling within the 40-path and 40-point IFFT structure. We accomplish this computing the output of the 40-path polyphase filter and 40-point IFFT every time we deliver 24 input samples to the polyphase filter with the offset input commutator.

We modify the structure of figure 1 to accommodate this 24/40 or 3/5 fractional input by the addition of a cyclic input data buffer and a cyclic output buffer between the polyphase filter and the IFFT along with minor changes in the commutator operation and a small state engine to coordinate their altered mode of operation. This modification is shown in figure 3. We will demonstrate the use and performance of this structure at the end of this paper. Surprisingly, the alternate resampling operation of the TDM-to-FDM channelizer is not the dual of this structure.

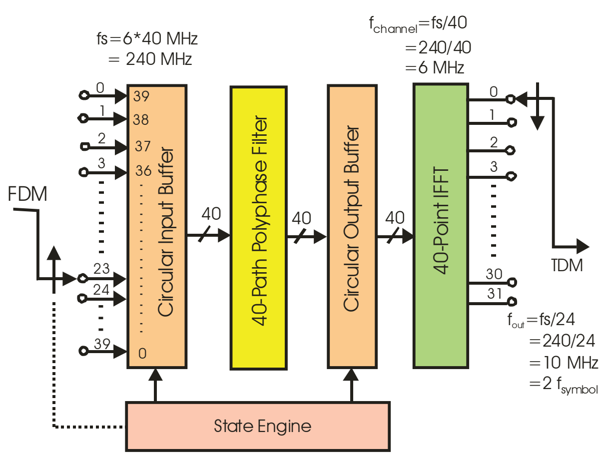

Figure 3. 40-Path Polyphase FDM-to TDM Channelizer with 24-to-1 Down-Sampling.

The TDM-to-FDM counterpart of the structure we just examined must perform the shaping filter processing which included the resampling in the shaping filter and the resampling in the IFFT based channelizer. As described earlier the IFFT is selected to be 40 points with output spectral spacing of 6 MHz for which we have selected a 240 MHz sample rate. The input symbol rate delivered to the shaping filter is 5 MHz. Thus the shaping filter in increasing the sample rate from the 5 MHz input rate to the 240 MHz output rate must perform a 1-to-240/5 or 1-to-48 interpolation.

Herein lays our problem: We need two sample rate changes in the polyphase filter bank. We can realize both by recognizing the sample rate changes occur at different points in the polyphase process. The 1-to-40 sample rate change occurs in the 40-point IFFT and the 1-to-48 sample rate change occurs in the interface between the commutator and the polyphase filter. We now understand that the commutator has to address 48-output ports not the 40 paths which we lock to the IFFT size! The insight to understand this variant of the polyphase filter comes from examining the resampling process embedded in the one-dimensional prototype filter that must exist prior to the polyphase partition. We start by inserting a 40 point sinusoid extended by 8-samples to 48 points in the first 48 input registers. Then shift 48-points and add the appropriate phase shift to the shifted sequence to phase align with the next sequence placed in the first 48-input registers. This is shown in figure 4. The shift is an end-around loading of the original 40 input points which can be performed by forming an 80-sample, or two-cycle, copy of the IFFT output. A two dimensional version of this extension and circular shift of the input array from successive IFFT outputs is seen in figure 5.

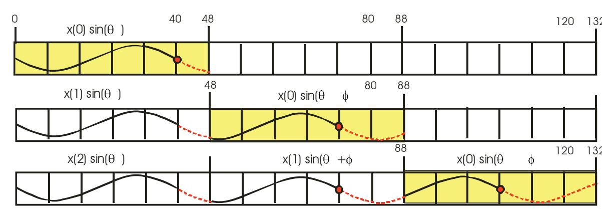

Figure 4. One Dimension Prototype Filter with Lowest Frequency Sinusoid of 40 Samples Extended to 48 Samples and Shifted in Stride of 48 and Phase Aligned by 8-Samples Shift.

Note that the circular buffer of figure 5 is circularly shifted 8-samples prior to accepting the next 40 point input vector form the 40-point IFFT. This vector is copied into the 40-point second half extension buffer to more easily accomplish the following circular shift. The 48-rows of the circular buffer are used to form inner products with the 48-path polyphase shaping filter to form the 1-to-48 up-sampled output vector. The circular buffer is then circularly shifted 8-rows to obtain successive 48 point sequences phase aligned at their boundaries. After each cyclic shift, a new 40 point input vector is formed by the 40 point IFFT and is extended to 48 points in the polyphase filter and an addition 40 points in the 40 point buffer extension.

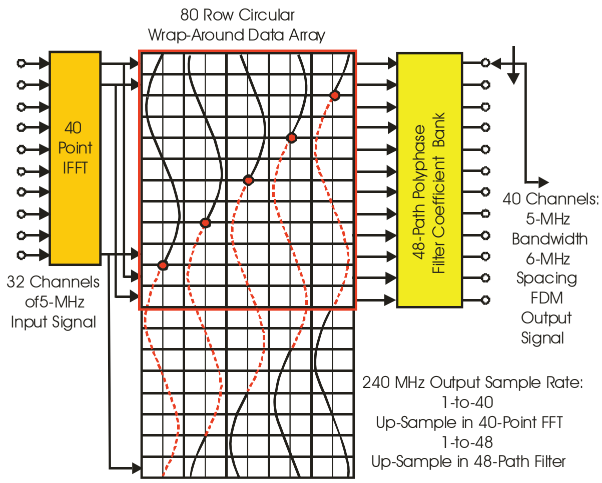

Figure 5. Two Dimension Partition of Prototype Filter with Lowest Frequency Sinusoid of 40 Samples Extended to 48 Samples and Shifted in Stride of 48 and Phase Aligned by 8-Samples Shift.

The circular shift of the 8-point extension in the 48 path polyphase filter is equivalent to a phasor rotation of (8/40)*2π or 2π/5 per input sample to the 40-point IFFT. This phase shift per sample is the same as a heterodyne of spectral terms formed by the polyphase channelizer. Table 1 shows the frequency offset for the IFFT bin indices due to the phase progression in the polyphase filter. It also shows the phase spinning to be applied to the input data corresponding to each IFFT bin to correct for the phase offsets. The signals samples fed to the different input bins of the IFFT in figure 5 are successively phase rotated in accord with the required compensating phase to bin-center each spectral term in spite of the phase progression due to the rotation of the circular buffer feeding the polyphase filter.

Table 1. Frequency Shift and Offset Correction

IFFT Bin Modulo-5	Phase Rotation Frequency Offset	Correcting Frequency Offset
0	0 ·2π/5	0 ·2π/5
1	-1 ·2π/5	+1 ·2π/5
2	-2 ·2π/5	+2 ·2π/5
3	+2 ·2π/5	-2 ·2π/5
4	+1 ·2π/5	-1 ·2π/5

3. System Demonstration

One of the most informative tests one can perform on a polyphase TDM-to-FDM channelizer is an impulse response test. We simply place a single unit amplitude sample at IFFT index *"k"* followed by enough zeros to sweep through the polyphase arms (20 in our case) and examine the time series and spectrum of the output response. When *"k"* is *"0"*, the output of the IFFT is 40 samples of DC and as the DC steps through the polyphase filter successive output samples sweep the impulse response of the prototype filter. The time response and spectrum of this operating condition is shown in figure 6.

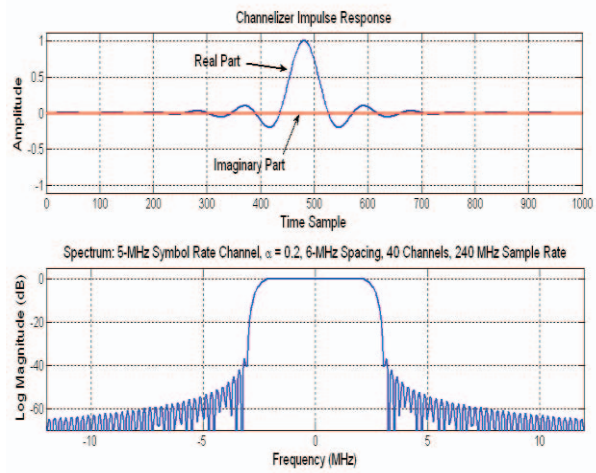

Figure 6. Input Index "0" Impulse Response and Spectrum of Channelizer Shown in Figure 5.

When *"k"* is *"1" "*, the output of the IFFT is 40 samples of a single cycle sinusoid and as the sinusoid steps through the polyphase filter successive output samples for a heterodyned to the first Nyquist zone version of the prototype filter's impulse response. The time response and spectrum of this operating condition is shown in figure 7.

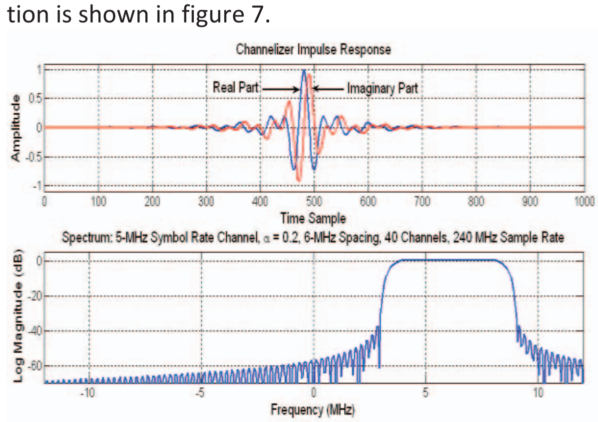

Figure 7. Input Index "1" Impulse Response and Spectrum of Channelizer Shown in Figure 5.

Figure 8 shows the spectrum obtained from the modulator of figure 5 when the input port to the 40 point IFFT has 7-active input sequences. In particular the active ports were 0, 1, 3, 5, 34 (-6), 35 (-5), and 37 (-3). We see the signals have been appropriately shaped and band limited by the underlying sqrt Nyquist filter an aliased up to the 6-MHz separated Nyquist zones corresponding to the cited active port numbers.

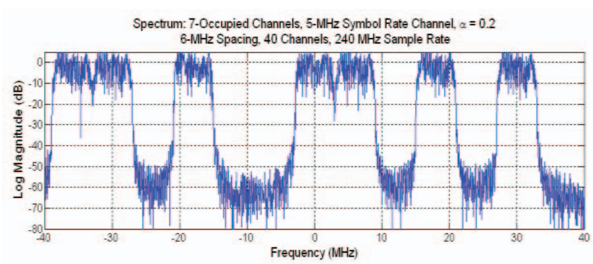

Figure 8. Spectrum at Output of Channelizer Shown in Figure 5 for 7 Active (or Enabled) Input Ports of IFFT.

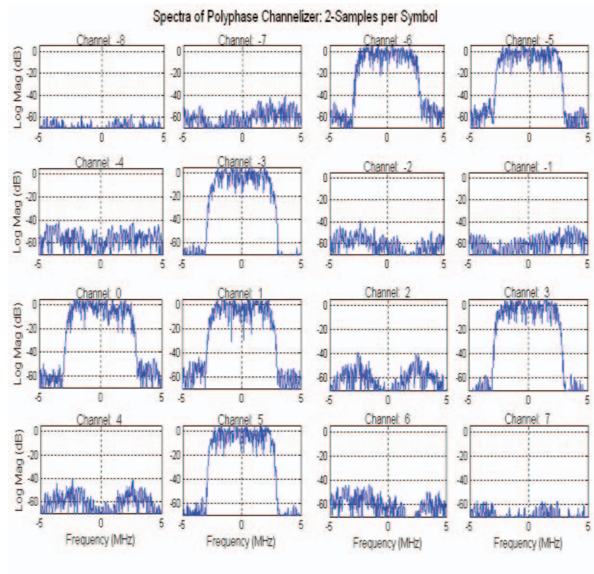

Figure 9. Spectra at Output of Channelizer Shown in Figure 3 showing extraction of 7 Active (or Enabled) channels of the Channelizer of Figure 5.

Figure 9 shows the spectra obtained from the polyphase channelizing demodulator of figure 3 when processing the signal formed by the channelizing modulator of figure 5. In particular the demodulator processed the signal with the spectrum shown in figure 8. Here the occupied bins were 0, 1, 3, 5, 34 (-6), 35 (-5), and 37 (-3). We see that the 5-MHz wide spectra in the occupied bins have bins extracted at a 10 MHz sample rate while the unoccupied bins have been appropriately recognized as being empty by the 5-MHz wide filters which were not affected by the adjacent channel spectra even though the output sample rate is 10 MHz. We have demonstrated that the non-maximally decimated channelizer of figure 3 can successfully separate with a 40 point FFT signals spaced by 6-MHz intervals with 5-MHz bandwidths resampled from 240-MHz to 10-MHz output rate.

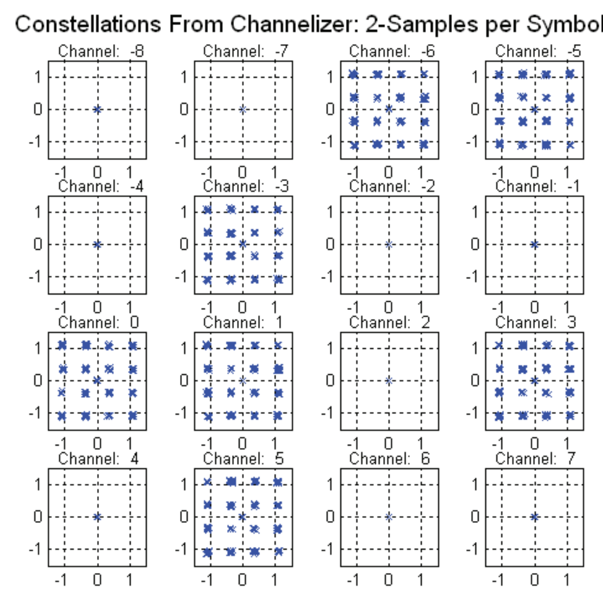

Figure 10. Constellations: Output of Channelizer Shown in Figure 3 showing extraction of 7 Active (or Enabled) channels of the Channelizer of Figure 5.

Figure 10 shows the constellations obtained from the output of the receiver channelizer of figure 3. The resampling polyphase receiver channelizer exhibits a bin specific phase offset related to the phase progression of the circular buffer in the modulator channelizer. These known offsets were removed by applying a compensating constant phase correction for each channelized frequency bin.

4. Closing Comments

We have presented the design and implementation of two interesting polyphase filter banks for both modulation and demodulation channelization. The unique attribute of these filter banks is that they perform shaping and channelization while implementing two different sample rate changes. The changes in the modulator are a 1-to-40 sample rate change embedded in the 40-point IFFT and a 1-to-48 sample rate change embedded in the 48-path polyphase filter. The changes in the demodulator are a 24-to-1 sample rate change embedded in 40-path polyphase filter and the 40-to-1 sample rate change embedded in the IFFT. The

1-to-40 and 40-to-1 sample rate changes associated with the IFFT are necessary to alias the signals to and from the multiple Nyquist zones defining the channelizers. We showed how the circular filter buffer of the modulator was configured to follow the phase progression of the 1-to-48 up-sampling that can be traced in the one-dimensional prototype shaping filter. We also identified the progressive phase corrections required in the modulator to cancel the bin-specific phase rotation caused by shifts of the circular buffer.

We comment this design is one of a number of modulator-demodulator polyphase filter banks that we have enjoyed designing for specific commercial applications. We plan in the near future to present a potpourri of related design tricks similar to those presented here that expand the number of ways a polyphase filter bank can be applied to the channelization task.

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