A Versatile Multichannel Filter Bank with Multiple Channel Bandwidths

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ABSTRACT:

The FFT is an important core to which we couple an M-path partitioned filter and commutator to build high performance spectrum analyzers and channelized transmitters and receivers. With slight modifications of the system the channelizer and spectrum analyzer can perform secondary processing tasks such as arbitrary sample rate changes. Output sample rates can be adjusted to be a multiple of channel spacing or a multiple of the channel symbol rate. With minor additional processing the channelizer can also coherently combine signals from adjacent frequency bands to synthesize arbitrary bandwidth super channels from standard prototype channels.

I. INTRODUCTION:

The most common form of an M-path channelizer performs M-to-1 down-sampling of an input series by delivering M-successive input samples to the input ports of an M-path partitioned low-pass filter. Each output port of the M-path filter contains an aliased time signal caused by the input down-sampling. In the standard channelizer the aliases are the M-to-1 spectral folds of the Nyquist zones formerly centered on the M-multiples of the output sample rate.

The alias components in each path have different and unique phase profiles partly due to the time delays induced by the commutator process and partly due to the phase shift response of each path in the M-path filter. When phase rotators matching the k-th multiple of the M-roots of unity are applied to the output time series from each path, the phases of the aliased k-th Nyquist zone in each path filter are aligned. When the phase aligned alias terms are added they form a coherent sum of that spectral component. On the other hand, the phase profiles of the remaining Nyquist zones are aligned with the M-roots of unity and are destructively canceled when summed. Intuitively, the extraction of the time series from any selected aliased Nyquist zone is possible because the time series from each path supplies one of the M-equations required to solve for the M-unknowns, the aliased components from the M Nyquist zones.

When the time signals residing in multiple aliased Nyquist zones are to be separated from the M-fold aliased baseband signal, the collection of phase rotators and coherent sums is most efficiently applied to the output of the M-path filter by the inverse fast Fourier transform (IFFT). This common structure of the M-path down-sampler and channelizer is shown in figure 1.

We note that the M-path polyphase channelizer performs three distinct operations and that these operations occur in different segment of the channelizer. The first task is the selection of the number of Nyquist zones to be separated by the channelizer. Here the number of zones or channels is defined by M, the size of the IFFT. The M in the M-point transform defines both the width of the successive Nyquist zones and the spacing between channel spectral centers as f_S/M, where f_S is the input sample rate. The second task performed by the channelizer is the definition of the channelizer spectral response which includes pass-band and stop-band boundaries as well as pass-band and stop-band ripple. The channel spectra match the aliased spectrum of the prototype low-pass from which the M-path filter was partitioned. The third task is that of resampling from the input sample rate of f_S to the output channel sample rate of f_S/M. It is obvious this process occurs in the commutator which delivers M input sample to the polyphase system for it to compute 1 output sample from each channel. Since three different processes are responsible for the channelizer parameters of channel spacing, channel bandwidth, and channel sample rate we can independently select and adjust them to obtain useful variations of the basic channelizer.

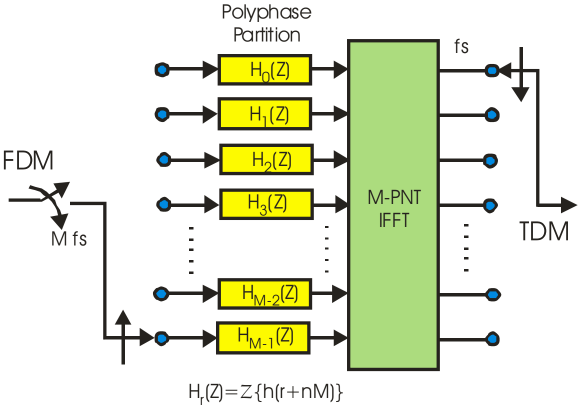

Figure 1. M-to-1 Down-Sample, M-Path Polyphase Channelizer.

II. CHANNELIZER PARAMETERS.

In the previous section we commented that the three parameters of channel spacing, channel bandwidth, and channel sample rate could be independently selected and controlled. Figure 2 shows a set of options illustration possible relationships between these parameters. This set does not exhaust the list of possible options. Note that in the 4 cases shown here, the channel spacing is the same and equal to f_S/M. This tells us that the IFFT is of length M and that the filter is likely an M-path filter.

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The channel bandwidth of the first option is less than the channel spacing while the channel bandwidth of the second option is equal to the channel spacing. The filter bandwidth is controlled and defined in the design of the low pass prototype filter that is partitioned to become the M-path structure. The first filter option would likely be selected for a communication receiver that needs to separate adjacent spectral bands while the second filter option would likely be selected for a spectrum analyzer which must monitor and report the energy content in contiguous gap free spectral intervals. In these first two options the sample is shown to be f_S/M telling us that this is a maximally decimated filter bank with M-input samples for 1-outpt sample.

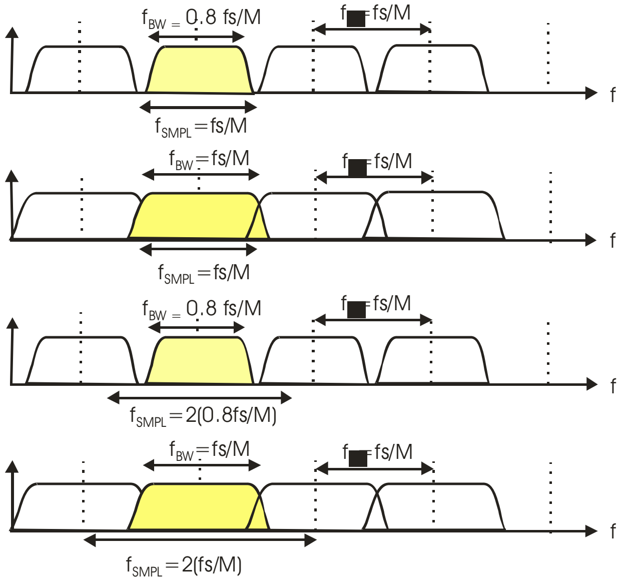

Figure 2. Some Channelizer Parameters Relating Channel Spacing, Channel Bandwidth, and Channel Sample Rate.

The third and fourth options shown in figure 2 match the channel spacing and channel bandwidths of the first two options but differ in output sample rates. In the third option, the output sample rate is equal to twice the channel symbol rate, a rate greater than the channel spacing. This option is desired for communication receivers that like to perform the synchronization and equalizations tasks required for signal demodulation at 2-samples per symbol. In the fourth option, the output sample rate is twice the channel spacing. The advantage of this option is two-fold. First it satisfies the Nyquist sampling criteria of the channelized signals for signal bandwidths less than or equal to the channel spacing and second it avoids the spectral folding at the channel band edge for channel widths equal to the channel spacing. This desired property is illustrated in figure 3.

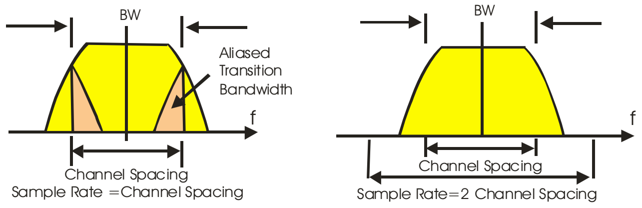

Figure 3. Channel Spectral Folding when Sample Rate Equal to Channel Spacing and No Spectral Folding when Sample Rate Equal to Twice Channel Spacing.

III. M/2 Down-Sample in Polyphase Filter Bank.

We now modify the M-path polyphase filter to perform the sample rate change from the input rate f_S to the output rate $2f_S/M$. We have presented one form of this modification in an earlier paper but we choose to present the derivation here in a slightly different form to be consistent with the dual form we present in a later section of this paper. We develop and illustrate the modification with the aid of Figures 4a through 4d. Figure 4a presents the structure of the M-path filter implementation of the polyphase partition shown in eqn-1 for the specific M-path filter partition.

$H(Z)$ [redacted] (1)

where $H_r(Z^M)$ [redacted]

Note the M/2-to-1 rather than the conventional M-to-1 down-sample operation after the output summing junction. In figure 4b we apply the noble identity [1] to the polyphase paths and pull the M/2-to-1 down-sampler through the path filters which convert the polynomials in Z^M operating at the high input rate to polynomials in Z^2 operating at the lower output rate. Note the paths are now polynomials in Z^2 rather than polynomials in Z as is the normal mode that we identify in the maximally decimated filter bank. Figure 4c shows the second application of the noble identity in which we again take the M/2-to-1 down-sampler through the $Z^{-M/2}$ parts of the input path delays for the paths in the second or bottom half of the path set. In figure 4d the M/2-to-1 down-sampling switches and their delays are replaced with a two pronged commutator that deliver the same sample values to path inputs with the same path delay. Here we also merged the Z^{-1} delays in the lower half of filter bank with their path filters. Figure 5 shows and compares the block diagrams of the path filters in the upper and lower half of this modified polyphase partition.

The final modification to the polyphase channelizer is the time alignment of the shifting time origin of the input samples in the M-path filter with the stationary time origin of the phase rotator outputs of the IFFT. We can understand the problem by visualizing a single cycle of a sine wave extending

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over M samples being inserted in the input data register, the first column of the polyphase filter in segments of length M/2. We can assume that the data in the first M/2 addresses is phase aligned with the first M/2 samples of a single cycle of the sine wave offered by the IFFT. This is shown in figure 6.

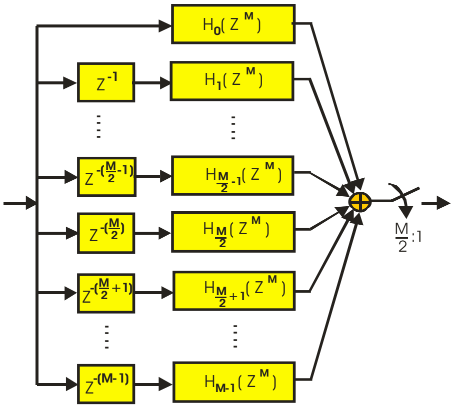

Figure 4a. M-Path Filter and M/2 Down-Sample

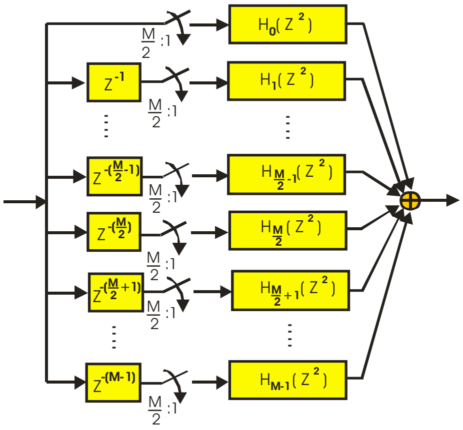

Figure 4b. Apply Noble Identity to Path Filters

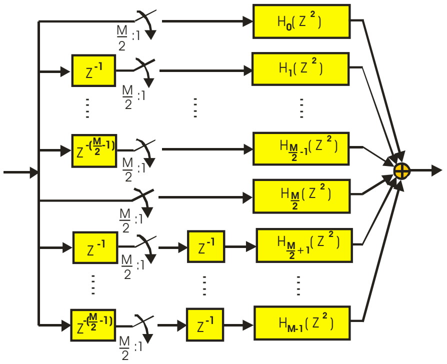

Figure 4c. Apply Noble Identity to Delays in Path Delays

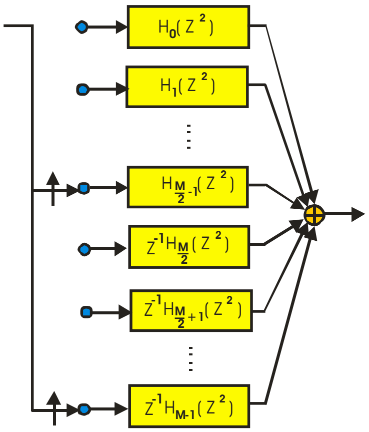

Figure 4d. Commutator Replaces Path Delays

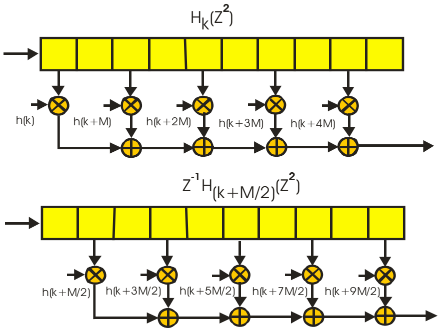

Figure 5. Path Filters with and without Extra Delay

When the second M/2 input samples are delivered to the input data register the first M/2 input samples shift to the second half of the M-length array. Its original origin is now at address M/2 but the IFFT's origin still resides at address 0. The origin shift between the two sine waves causes the input sine wave in the register to have the opposing phase of the sine wave formed by the IFFT. What we are observing is the sinusoids with an odd number of cycles in the length M array alias to the half sample rate when down sampled M/2-to-1. We can respond to this by phase reversing the odd indexed IFFT sinusoids on alternate outputs. Alternatively, knowing that phase shift and time delay are equivalent for a sine wave we can perform M/2 point circular shifts of alternate M-length vectors formed by the polyphase filter before presenting the vector to the IFFT. The circular shifts that perform the required phase reversals of successive input vectors presented to the IFFT are illustrated in figure 7.

IV. CHANNELIZER PERFORMANCE.

We designed and simulated a 128 path polyphase channelizer with a prototype 1536 tap low pass filter. The partitioned 128 path filter contains 12 taps per path. The 128-path filter operates as a 64-to-1 down sampling channelizer. If we hypothesize a 128 MHz input sample rate, then the channel

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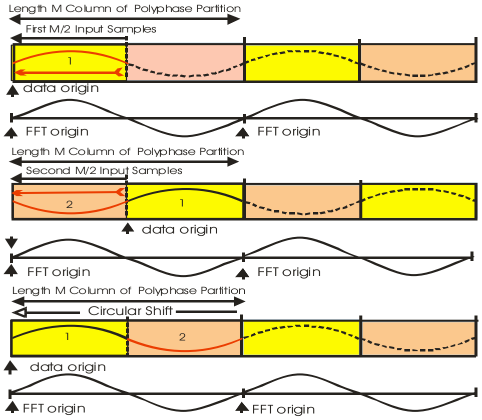

Figure 6. Illustrating Phase Reversal of M-Point Sinusoid Input to M/2 Path-Polyphase Filter.

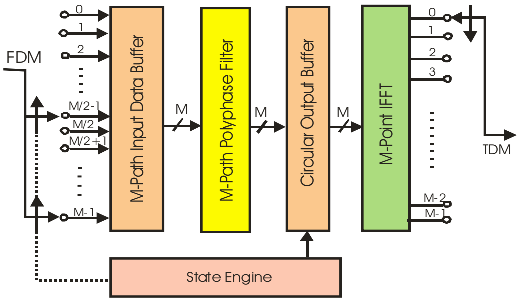

Figure 7. M/2 Down-Sampled M-path Polyphase Channelizer

spacing of the channelizer is 1 MHz and the sample rate per channel is 2 MHz. The prototype filter is designed so that adjacent channel filters cross at their -6 db level. This means the filter is a Nyquist filter and broader bandwidth channels can be synthesized by simple summations of the adjacent channel signal components. We describe this process in the next section. The frequency response of the channels in the channelized receiver is shown in figure 8. Note the 100 dB dynamic range of the filter design.

To demonstrate the channelizer performance we designed and simulated a modulator that forms multiple signal channels with 4-MHz channel spacing. Twelve of its sixteen channels contain QPSK signals with 2 MHz symbol rates and 3-MHz bandwidth. One channel contains a narrow band QPSK signal with 0.5 MHz symbol rate and 1-MHz bandwidth. One set of three channel bands share a wideband QPSK signal with 8-MHz symbol rate and 12 MHz bandwidth. The spectrum of the modulation test signal is shown in the upper half of figure 9. The lower half of figure 9 shows the complex signal trajectories from the positive frequency indices 0-to-31 of the 128 channel channelizer. The variance or spread of these trajectories is proportional to the energy content in that channelized channel. Note that channels 1, 2, and 3 cover the 2-MHz band centered at 1 MHz and channels 9 through 19 cover the 12-MHz band centered at 14 MHz. A plot of signal variance versus channel index is a valid representation of the input signal power spectrum. Figure 10 is a log magnitude plot of signal variance of each channel versus channel index. Note from the markers on this plot that the signal bandwidth of the 2-MHz bands are spanned by 3-channel bands while the 1-Mhz signal band is spanned by a single channel filter and the 12 MHz signal band is spanned by 11 channel bands.

V. PARTITIONING AND COMBINING CHANNEL BANDWIDTH.

The channelizer we presented in the previous section outputs complex time series from 1-MHz wide channels at 2-MHz sample rate. If we have need for finer resolution channel portioning we simply deliver the complex time series to a second tier channelizer which can further partition the selected band. The second tier channelizer is a replica of the first tier channelizer. It is implemented as an M_2-path polyphase filter with an IFFT of length M_2 which interact to channelize and down sample M_2-to-1. As an example, selecting M_2 to be 16, will process the 1-MHz bandwidth channel signal sampled at 2-MHz to form 62.5 kHz sub channels at 125 kHz sample rate.

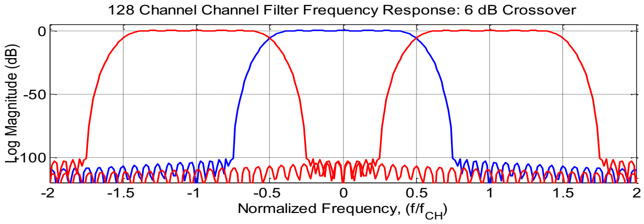

Figure 8. Frequency Response of Three Adjacent Channel Bands

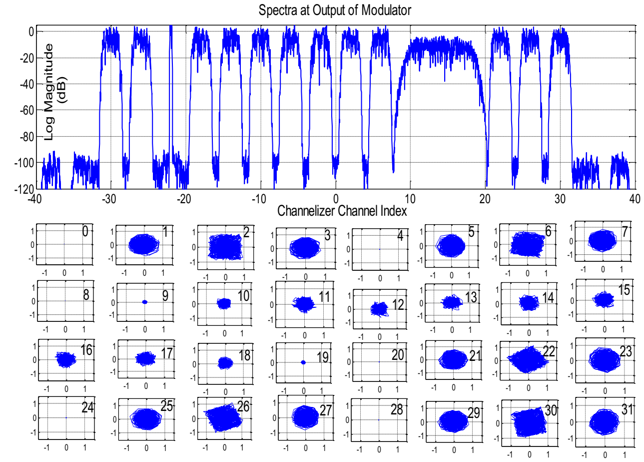

Figure 9. Input Spectrum and Channel Complex Output Signal from 32 Positive Index Channels of 128 Channel Channelizer

We quickly see that we have easy access to enhanced resolution channelization of any of the time series formed by the base-banded, filtered and down-sampled time series obtained from the first tier channelizer. In one option, we can cover each output channel of the first spectral partition with a second tier channelizer to partition the entire spectrum into higher resolution channels. In another option, we can have a background spectral sniffer identify channels containing signals of interest and direct a second tier channelizer to partition selected channels.

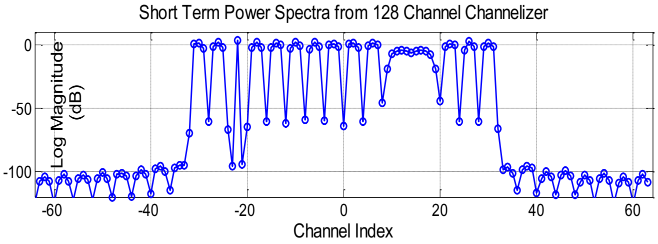

Figure 10. Channel Time Series Variance versus Channel Index.

The signals we presented to the channelizer in the previous section had bandwidths which were wider than the channelizer filter bandwidth. We have already addressed the task of partitioning a selected band into narrower bands. We now address the dual task of combining the outputs of contiguous narrowband channels to synthesize wider bandwidths. Remarkably this is a trivial task. The background sniffer or the spectral estimate obtained from the first tier channelizer can easily identify wide bandwidth input signals which are spanned by a number of the narrow bandwidth channelizer bands. All the time series from the identified bands have been down-sampled and translated to baseband by the channelizing process. To reassemble the original wider bandwidth signal we have to up-sample each time series and translate each spectral region to its proper offset frequency and simple add their signal components. This we note is the dual operation of the analysis receiver channelizer and this dual task is performed by the dual synthesis channelizer. The dual channelizer, formed by an M3 point IFFT and an M3 path polyphase filter performs an M3/2-to-1 up-sampling function as it combines the time series from selected adjacent bands output from the first tier channelizer. The form of the dual channelizer or combiner is shown in figure 11.

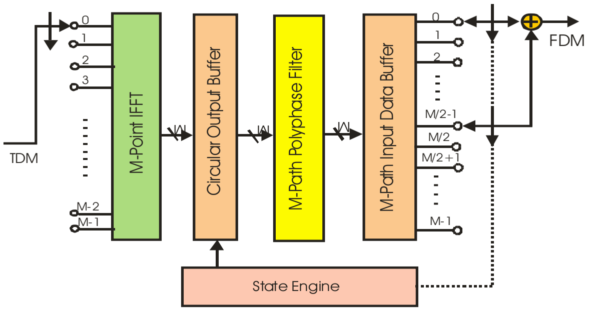

Figure 11. Channel Combiner Synthesizes Wide BW Channels

Figure 12 shows the spectrum obtained from the time series output by the super channel formed from the first tier filter bins 9-to-19. Figure 13 shows the block diagram of the proposed two tier channelizer. The first tier is the 128 path initial channelizer that forms multiple 1-MHz wide channels sampled at 2.0 MHz.

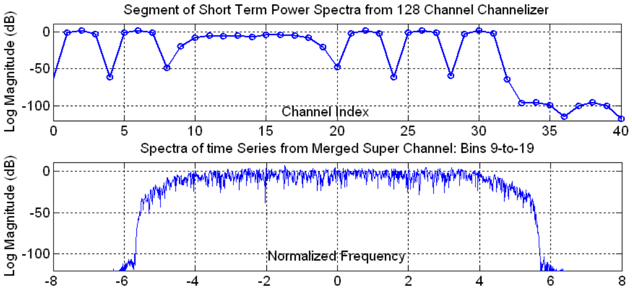

Figure 12. Spectrum Formed from Channelizer and Synthesized Super Channel

The second tier offers the option of further spectral partition or of spectral merging with 16-path polyphase channelizers. As shown the system is capable of offering three different levels of spectral partition. These second tier processing blocks can be assigned dynamically to spectral regions that require the additional partitioning or merging. A number of different length second tier channelizers can be used to widen the range of available bandwidths.

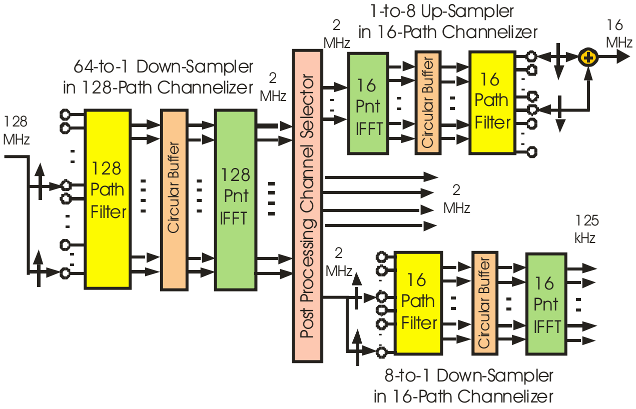

Figure 13. Block Diagram of Two Tier Channelizer with Second Tier Channel Combiners and Channel Partitioners

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