12th CONASENSE Symposium 2022:
"6G Communications, Services, and Sustainability"

Channelizers in Modern Communication Systems

27-28 June 2022

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Munich, Germany

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JACOBS SCHOOL OF ENGINEERING
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Channelizers represent the most dramatic application of multirate signal processing based on the use of aliasing to move spectral bands between selected offset spectral locations. At the simplest level, we use M-to-1 down sampling in ***Analysis Filter Banks*** to move multiple frequency bands from their respective equally spaced offset center frequencies to baseband. The aliases are separated by their unique phase profiles.

We also use 1-to-M up sampling in ***Synthesis Filter Banks*** to move Multiple baseband frequency bands to selected equally spaced offset center frequencies. Distinct phase profiles guide the aliases to center frequencies in different Nyquist zones.

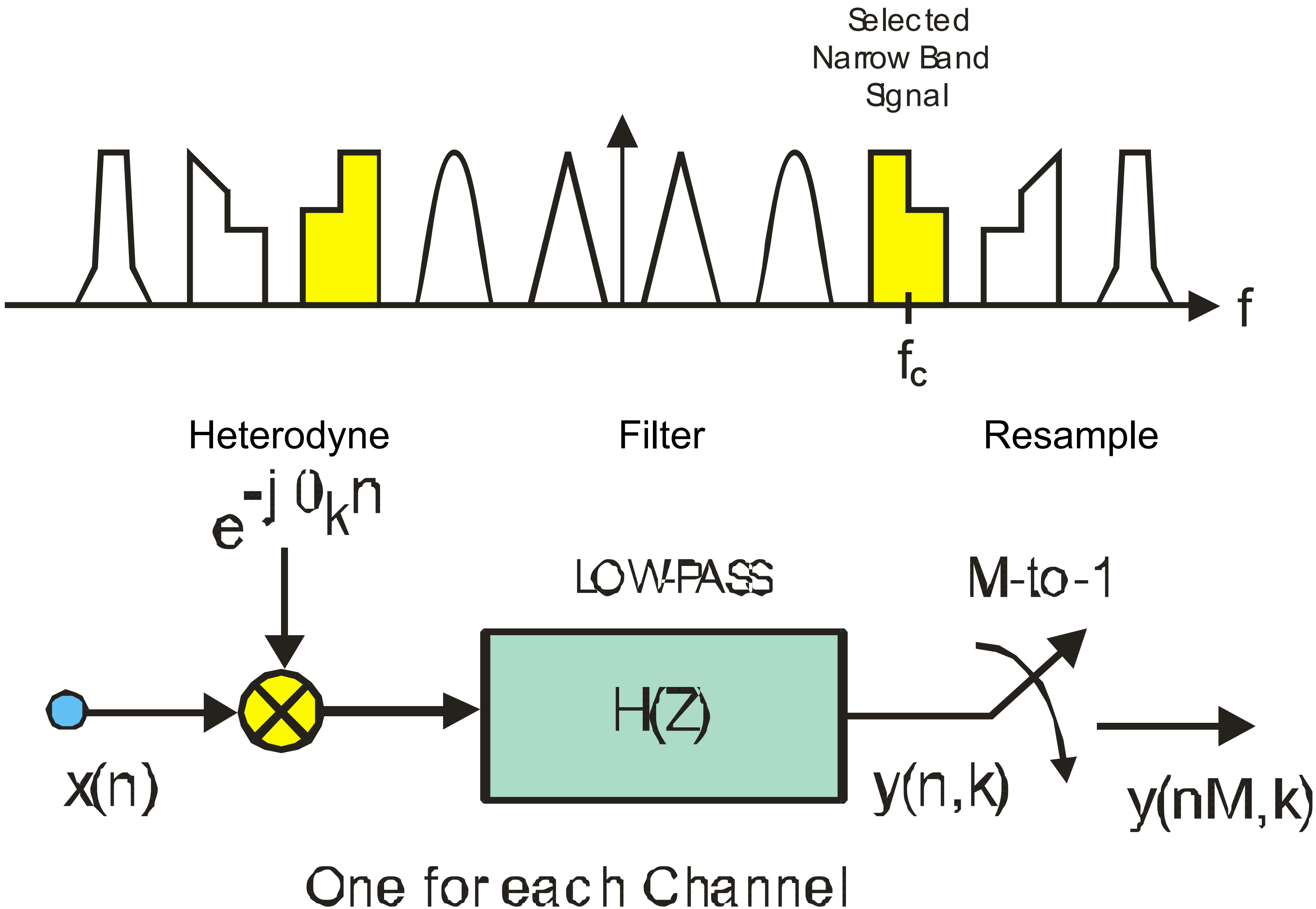
The ***Analysis and Synthesis Filter banks*** are implemented by dual algorithm signal flow graph structures.

The cascade of the A***nalysis and Synthesis Filter Banks*** lead to a very rich collection of desirable and efficient signal processing applications. Advances in algorithm development have been many and are deserving of wider distribution. We do that in this presentation!

Quick Review of Simple
Polyphase Filter Banks

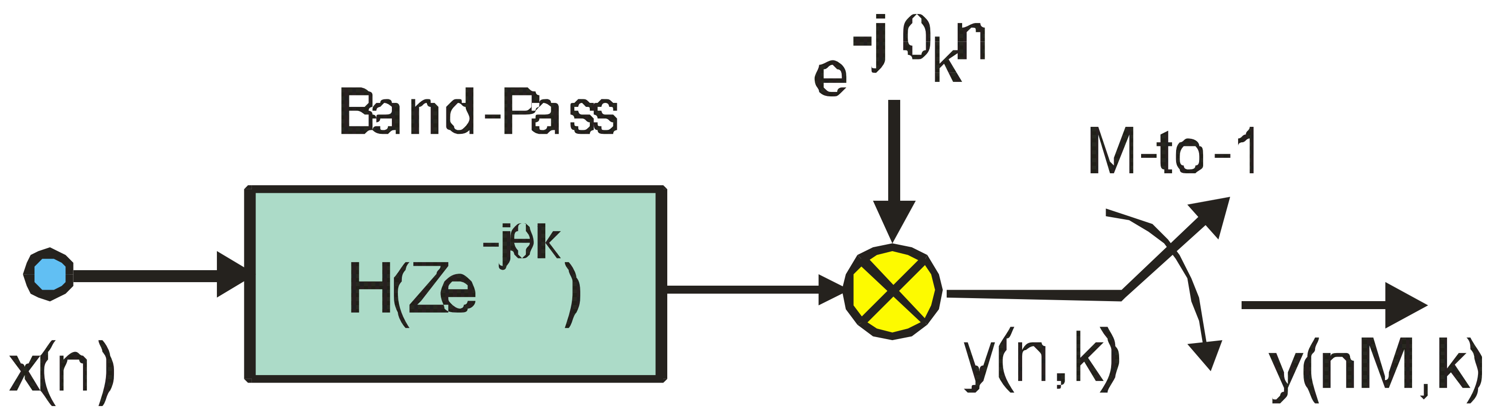
The Equivalency Theorem
The Polyphase Partition
The Noble Identity

Standard Downconverter: Heterodyne, Filter, Resample



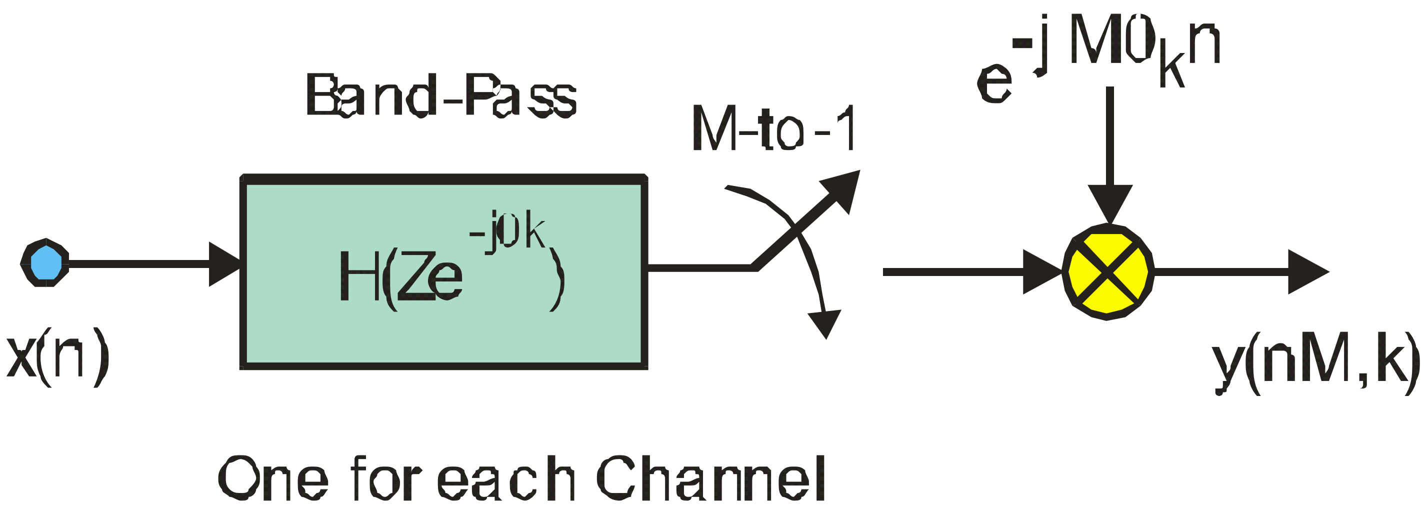
The Equivalency theorem

Slide Heterodyne Through Filter: Converting Low-Pass to Band-Pass



One for each Channel

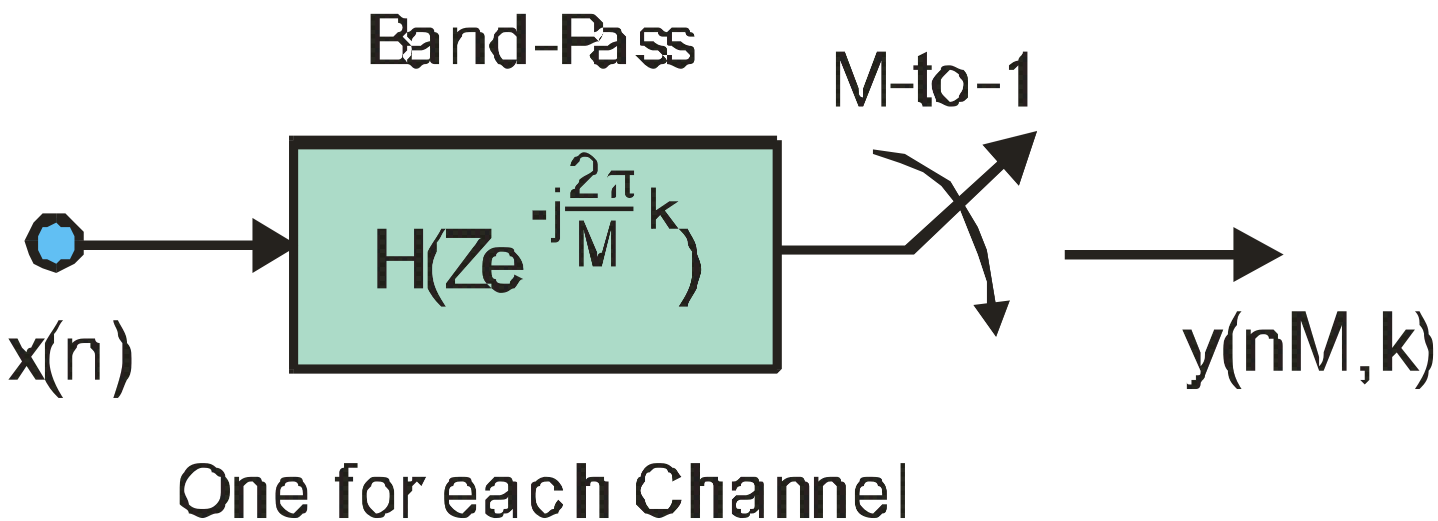
Slide Heterodyne Through M-to-1 Down Sampler: Aliases Heterodyne Frequency



When $M \cdot \theta_k = k \cdot 2\pi$ is congruent to 2π, $M \cdot \theta_k = k \cdot 2\pi$

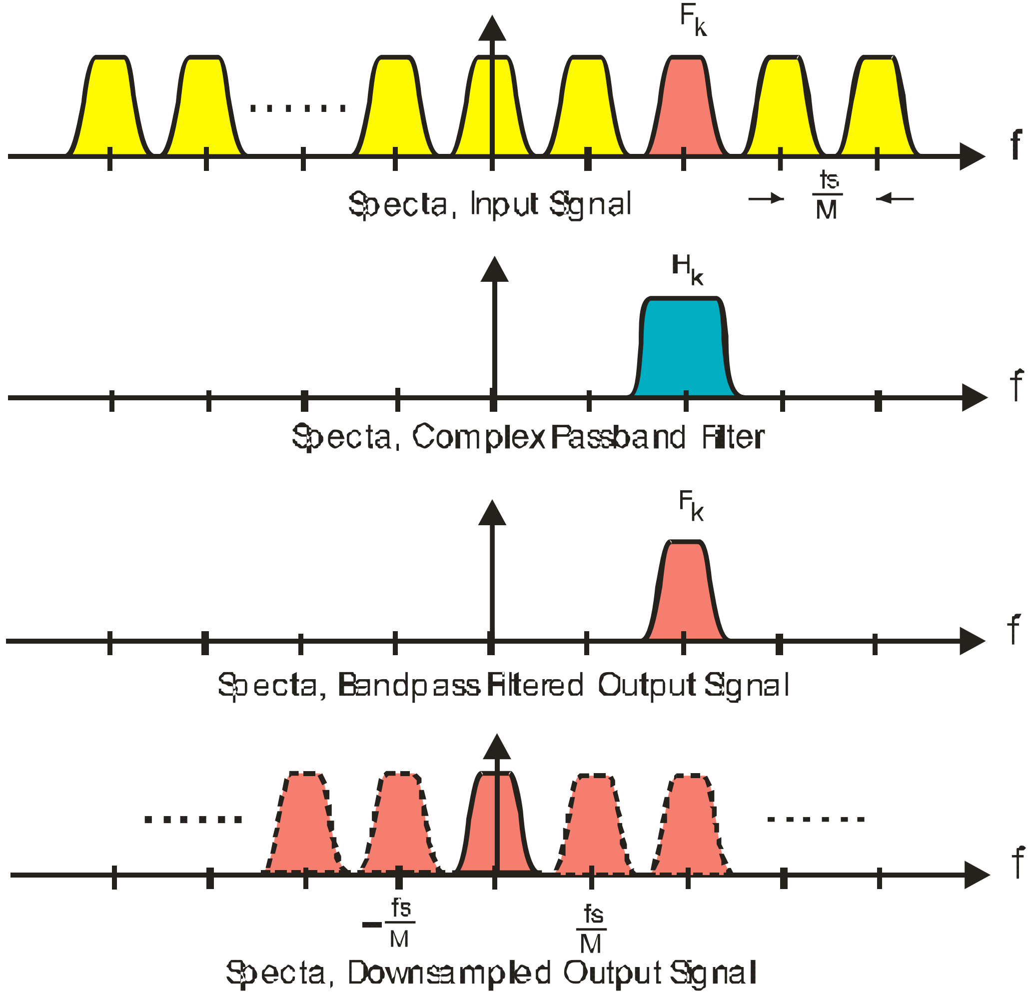
or $\theta_k = k \cdot \frac{2\pi}{M}$. *Then* $M \cdot \theta_k = k \cdot 2\pi$ and the sequence aliases to DC

Discard Trivial Heterodyne: Now a Scalar Multiply by Unity

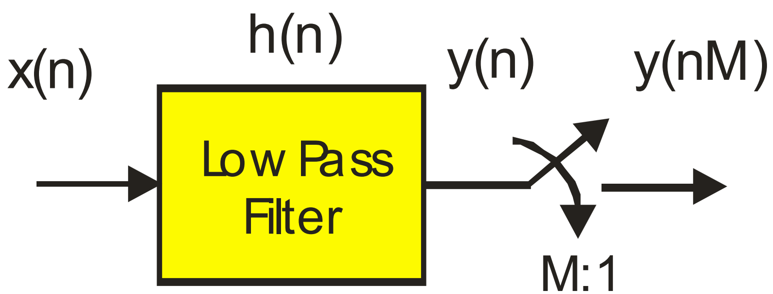


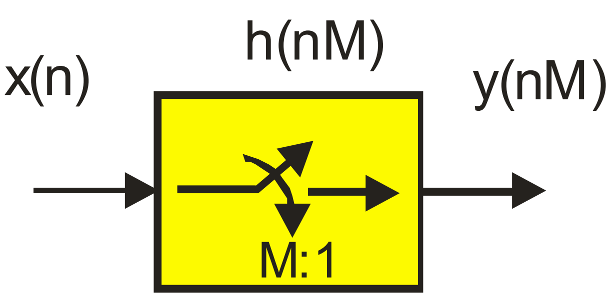
Alias by Down Sampling Replaces Output Heterodyne
No Heterodyne at Input Port or at Output Port!

Spectral Response of Signal in Resampled Pass Band Filter



Rather than Resample the output of a filter, we can resample the impulse response of the filter and the modified filter will resample the time series!

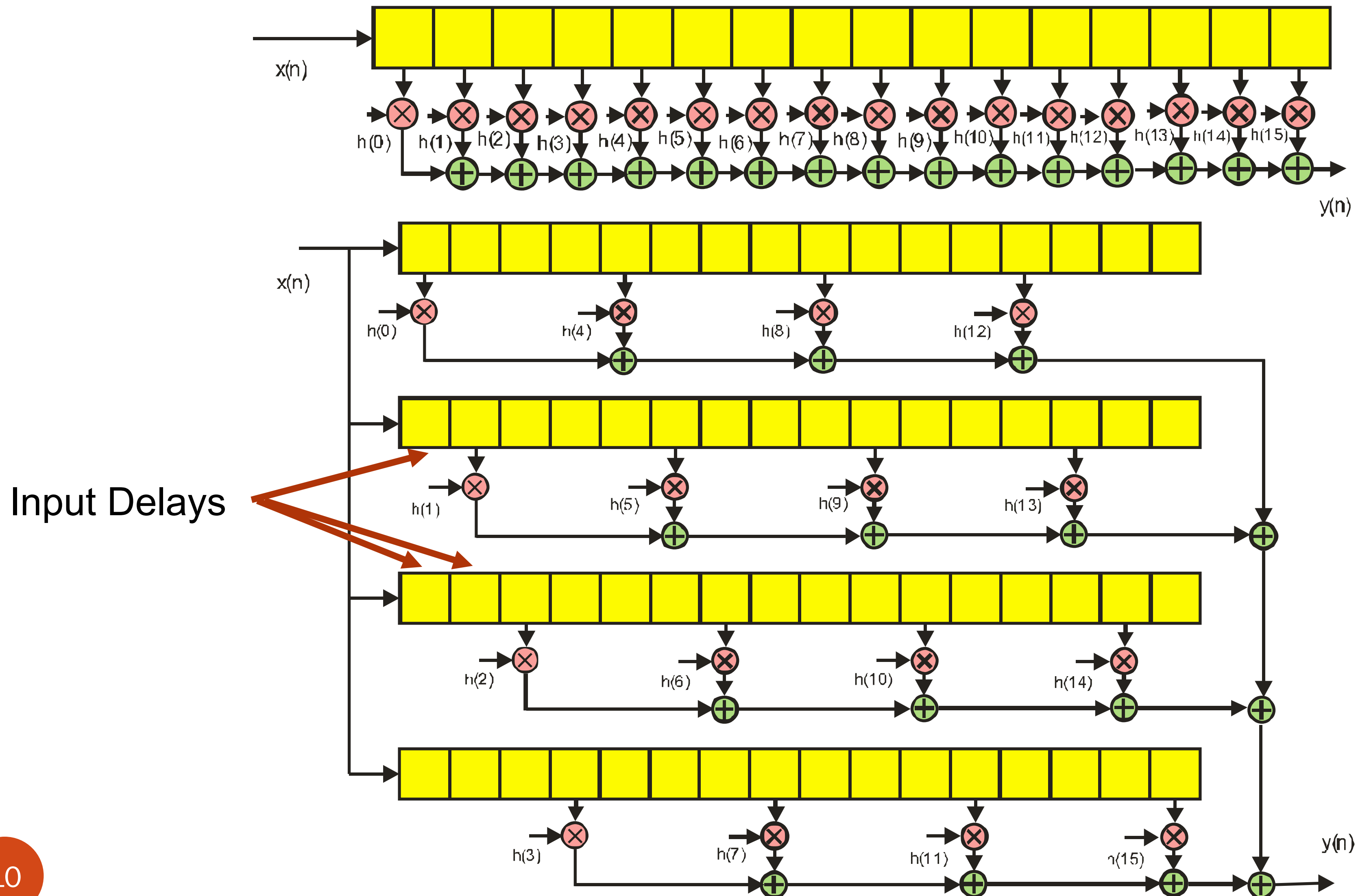




Re-sampled
Low Pass Filter

Embed the M-to-1 resampler in the filter to avoid computing output samples destined to be discarded!

Polyphase (M-Path) Partition for 4-to-1 Down Sample

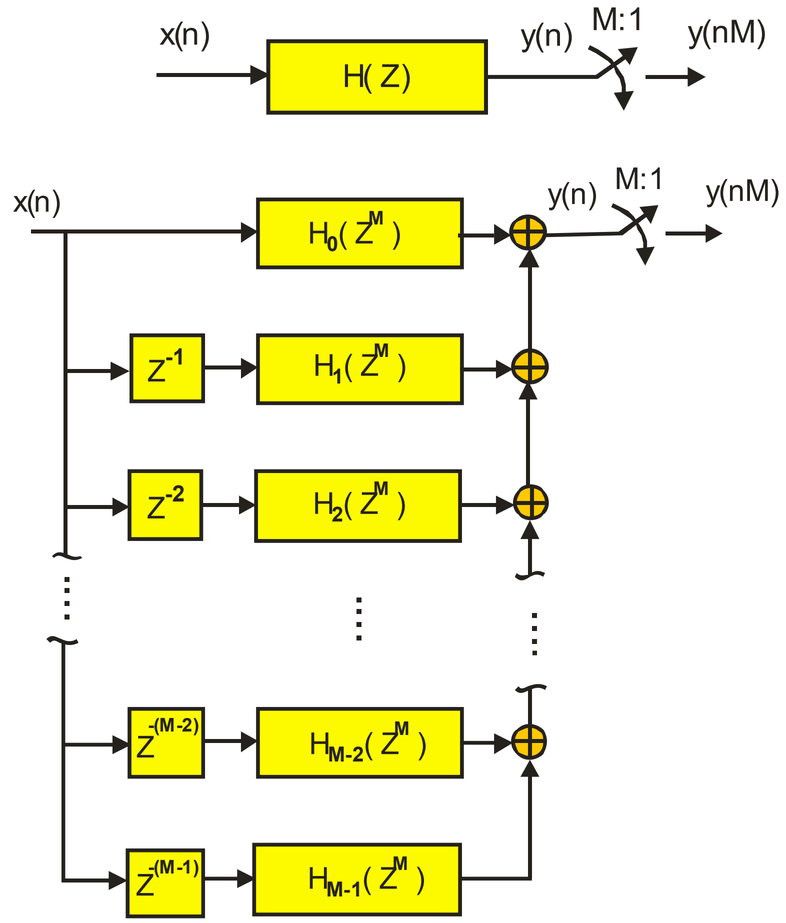


Polyphase Partition of Low Pass Filter
1-Path to M-Path Transformation

$$H(Z)=\sum_{n=0}^{N-1} h(n) Z^{-n}$$

$$H(Z)=\sum_{r=0}^{M-1} \sum_{n=0}^{N-1} h(r+nM) Z^{-(r+nM)}$$

$$H(Z)=\sum_{r=0}^{M-1} Z^{-r} \sum_{n=0}^{N-1} h(r+nM) Z^{-nM}$$



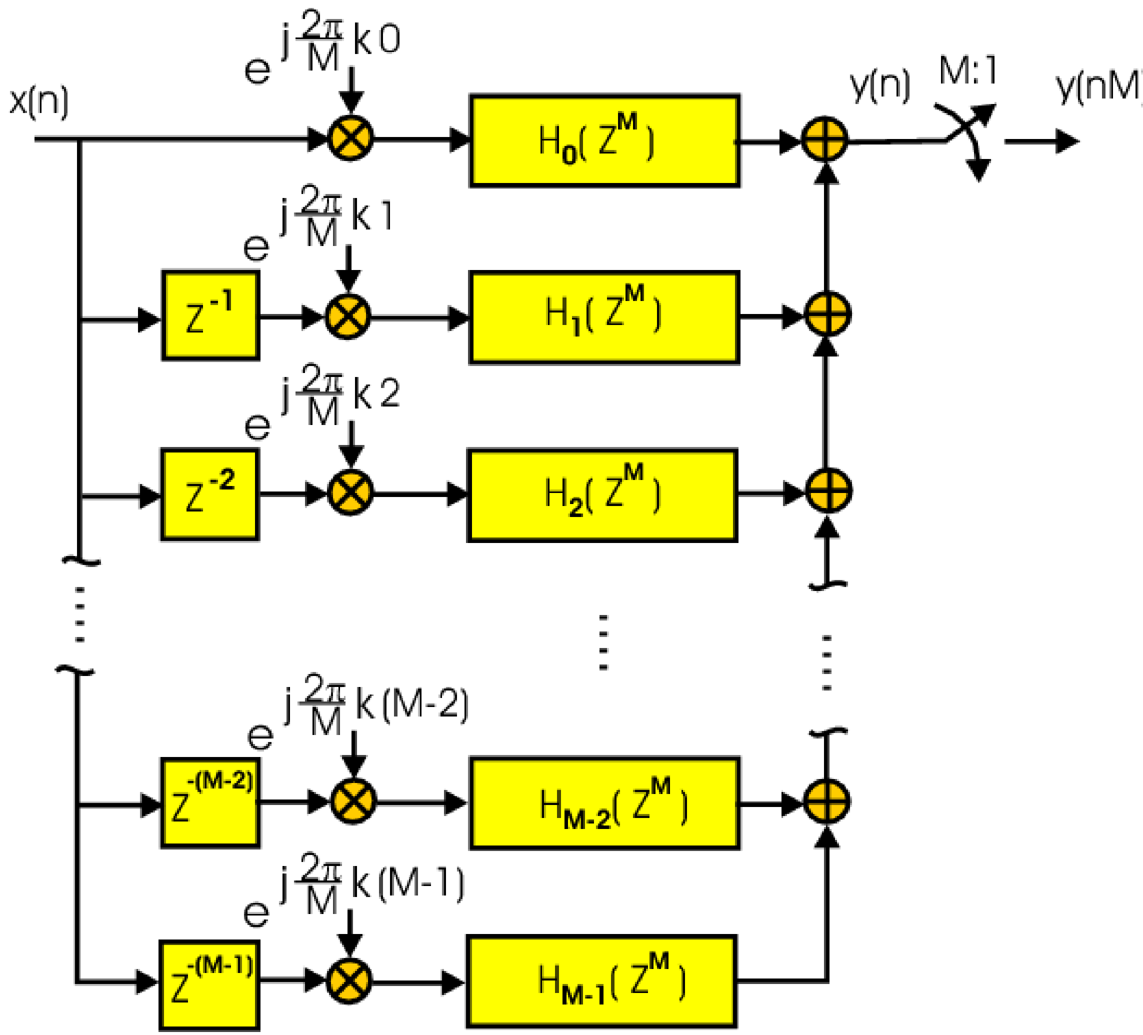
M-Path Partition Supports M-to-1 Down Sample as well as Rational Ratio M-to-Q Down Sample!

Polyphase M-Path Narrowband, Resampling Filter

$$G(Z) = \sum_{r=0}^{M-1} e^{j\frac{2\pi}{M}k} Z^{-r} \sum_{n=0}^{N-1} h(r+nM) Z^{-nM}$$

$$M \cdot \theta_k = k \cdot 2\pi$$

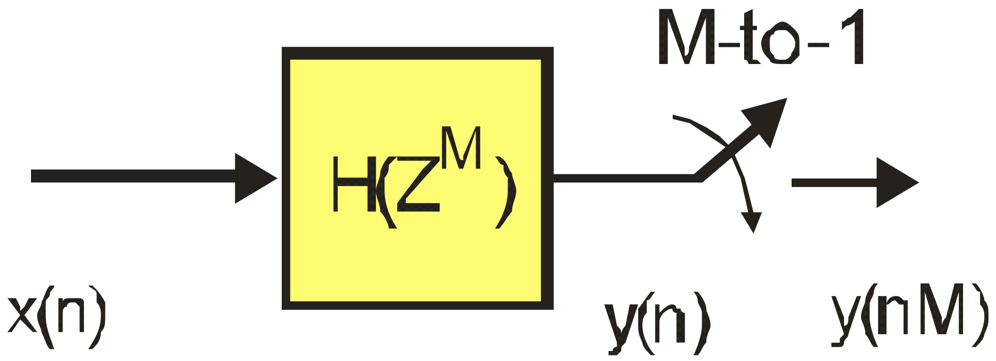
$$\text{or} \quad \theta_k = k \cdot \frac{2\pi}{M}$$

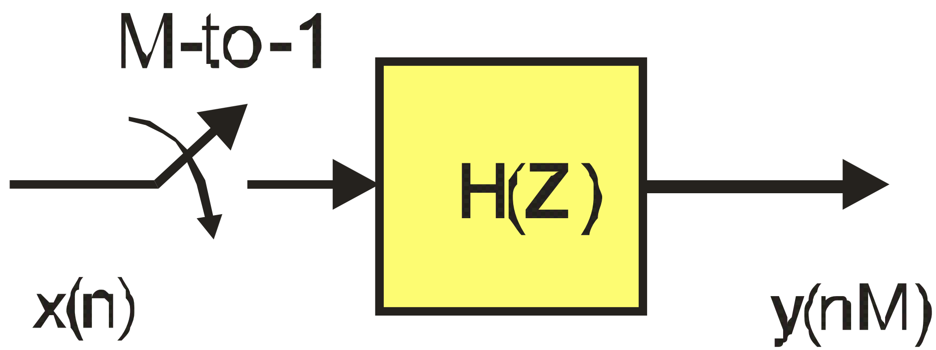


Noble Identity

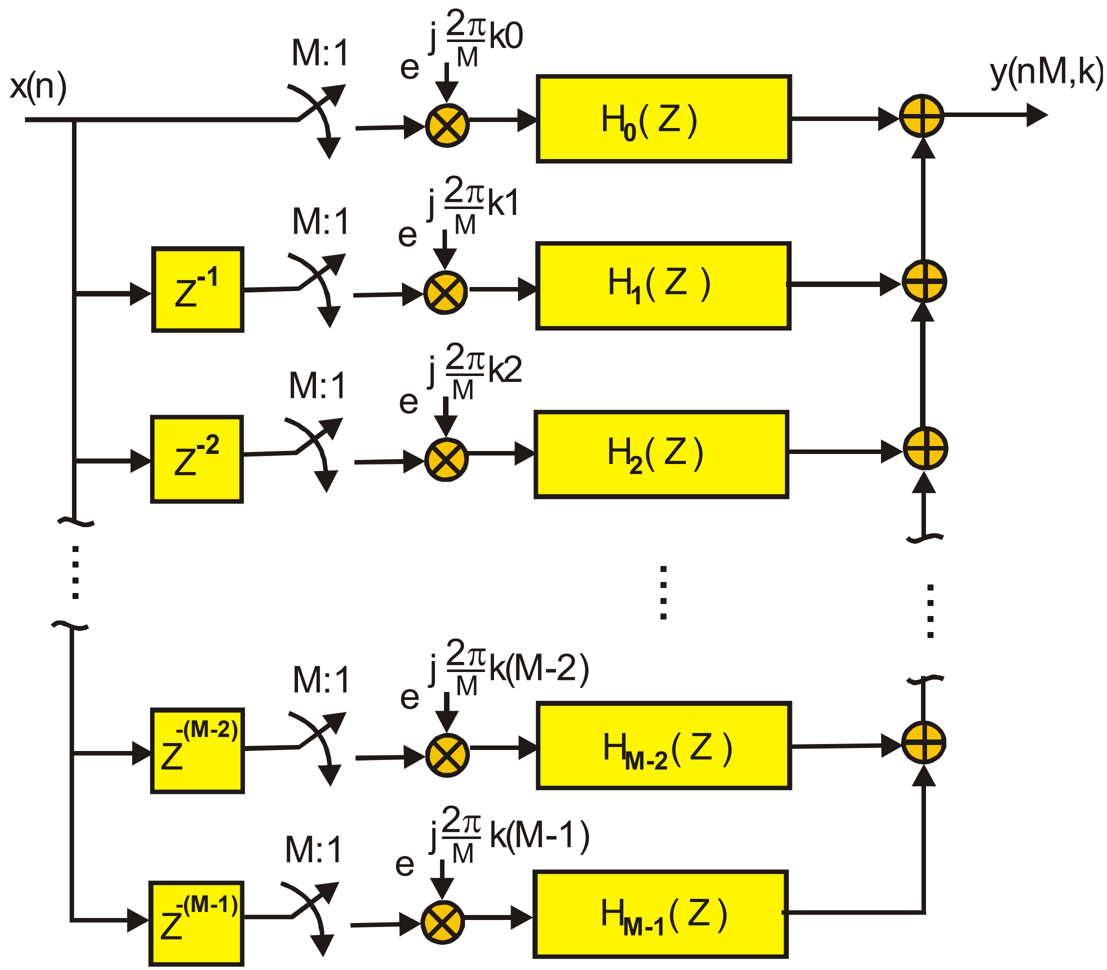
Interchange Order of Filter and Resampler

M-Intervals of Delay at Input rate is the same as 1-Interval of Delay at Output Rate



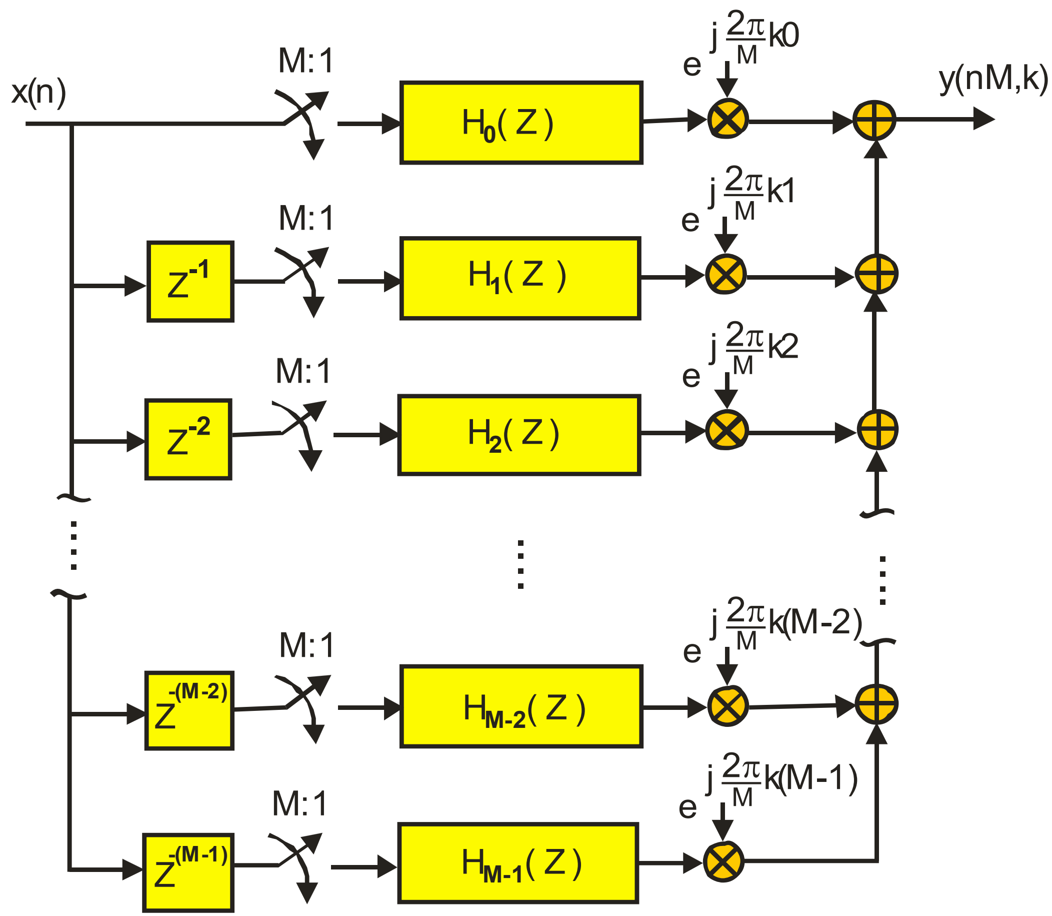


Apply Noble Identity to Polyphase Partition



Don't make samples complex on the input to path filters!

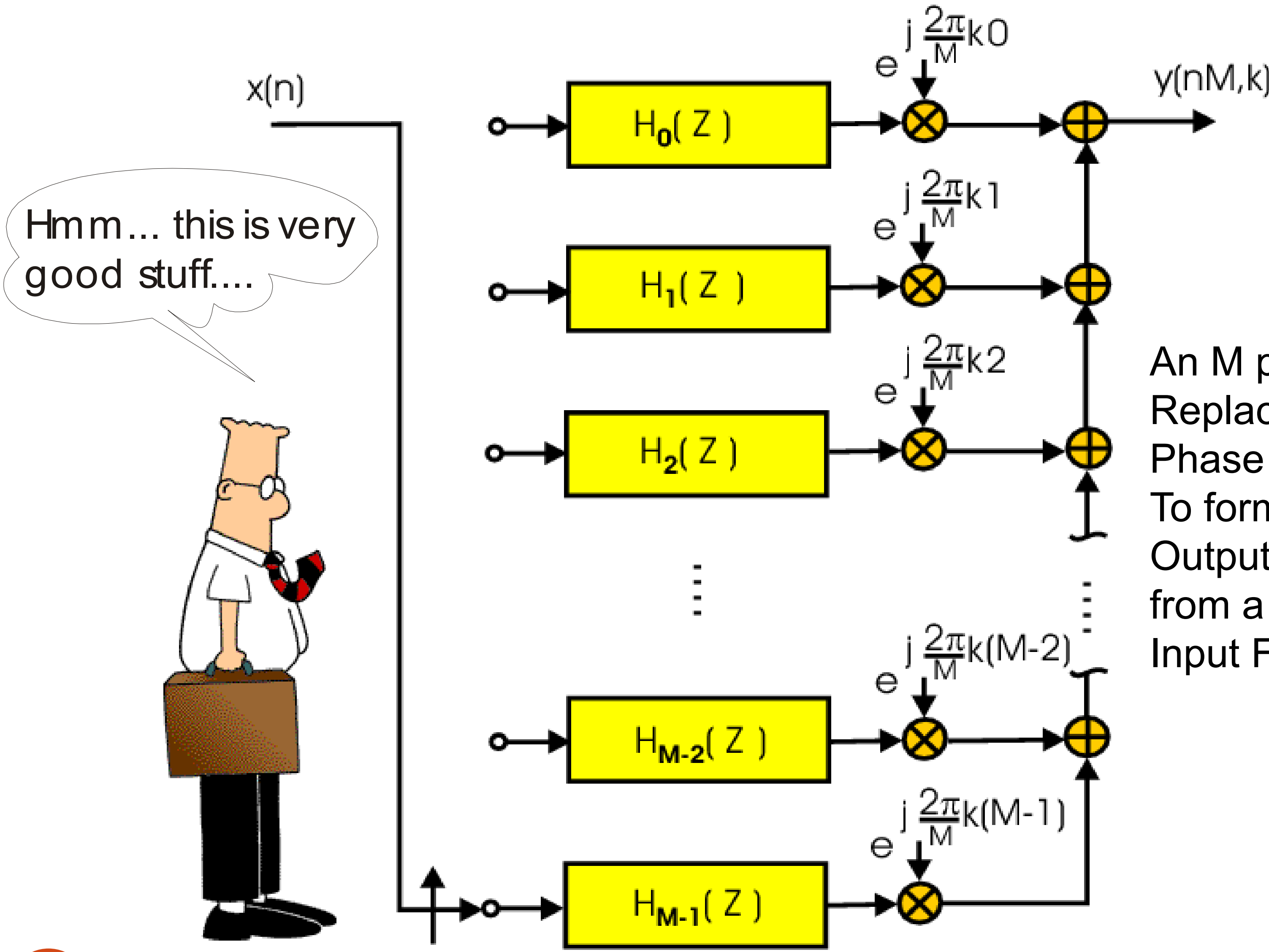
Move Phase Spinners to Output of Polyphase Filter Paths



Make Data complex at the output of the Path Filters

Want Phase Spinners at Path Filter Output Ports

Resampled M-Path Narrowband Filter

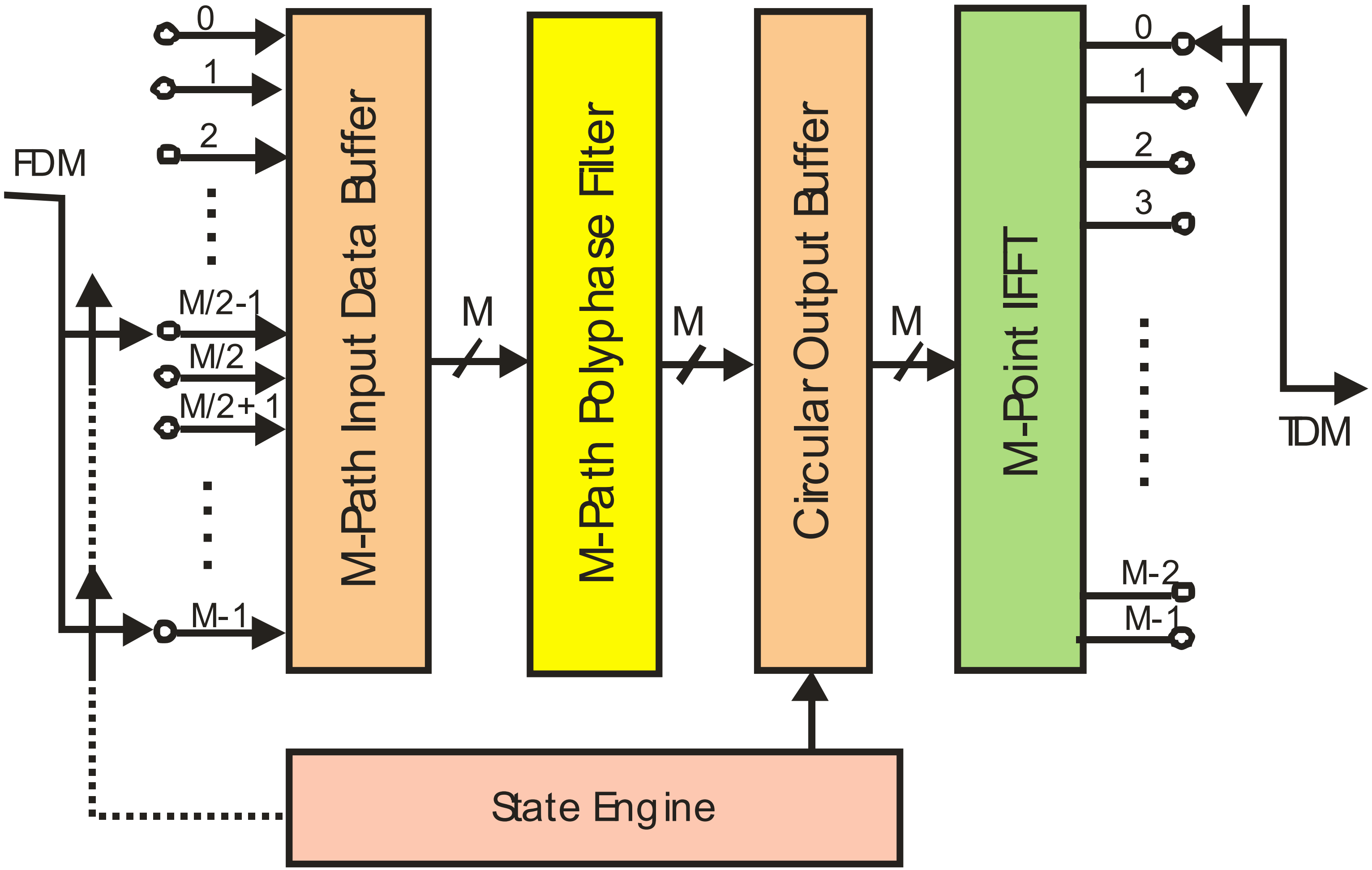


An M point IFFT Replaces Output Phase Rotators To form Multiple Output Channels from a Single M-Path Input Filter

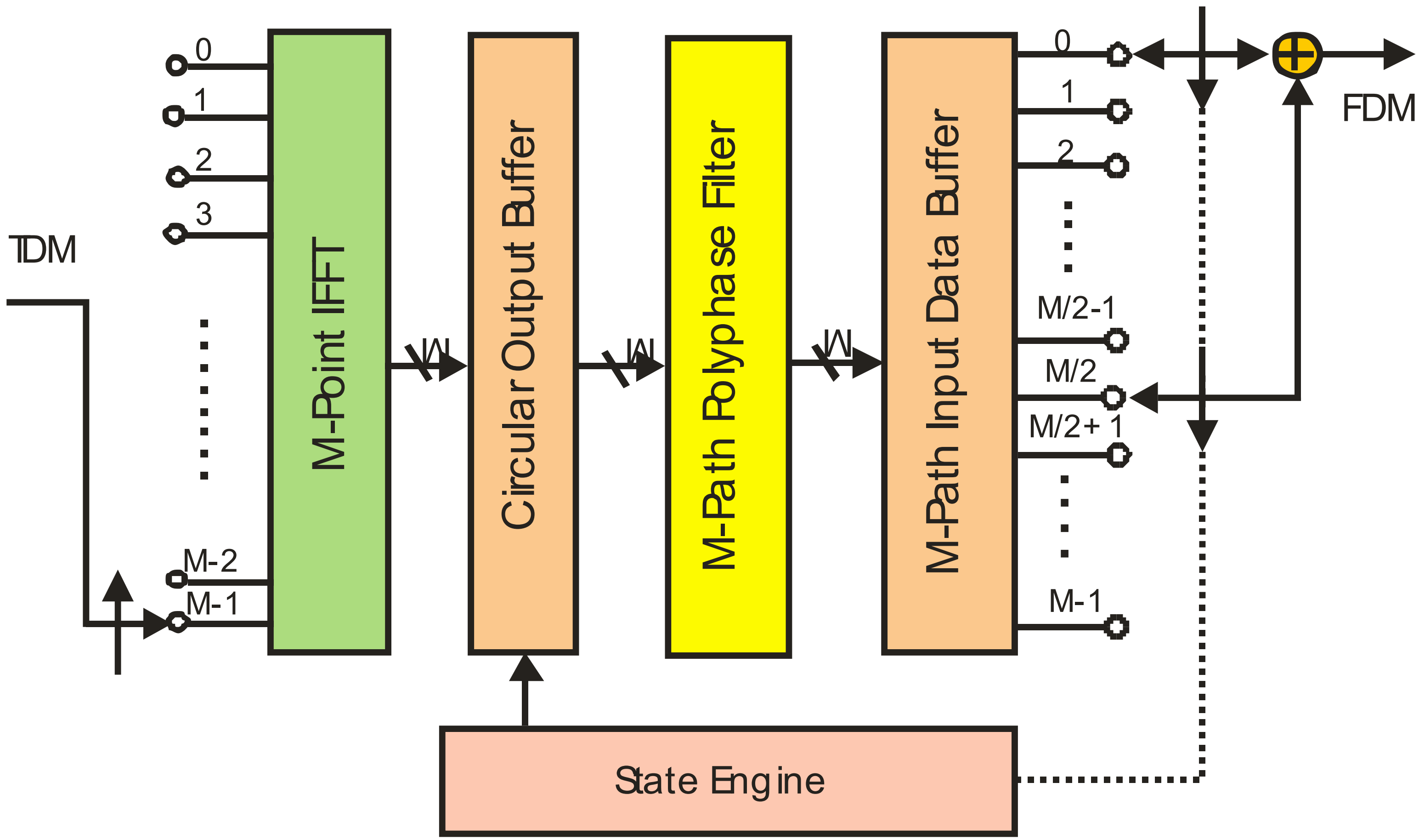
Channelizer Parameters

- Center frequencies, hence channel spacing, and the number of paths in filter partition defined by length M of IFFT.
- Channel bandwidth and spectral characteristics, in-band ripple, out-of band attenuation, and transition BW defined by prototype low-pass filter in polyphase partition.
- Channelizer output sample rate determined by input commutator span of P inputs per M-point IFFT output.
- Three parameters are independent and adjustable.

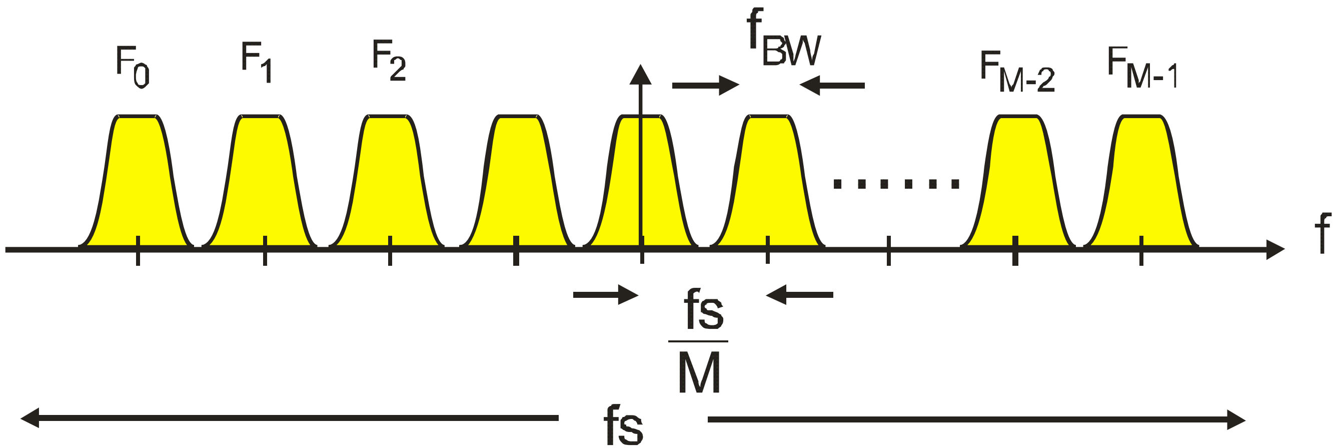
M/2-to-1 Analysis Channelizer



1-to-M/2 Synthesis Channelizer (Dual Function)



Performance Specifications for 50-Channel Polyphase Channelizer



Chan Spacing:
192 kHz
Chan Width:
128 kHz
Sample Rate:
256 kHz

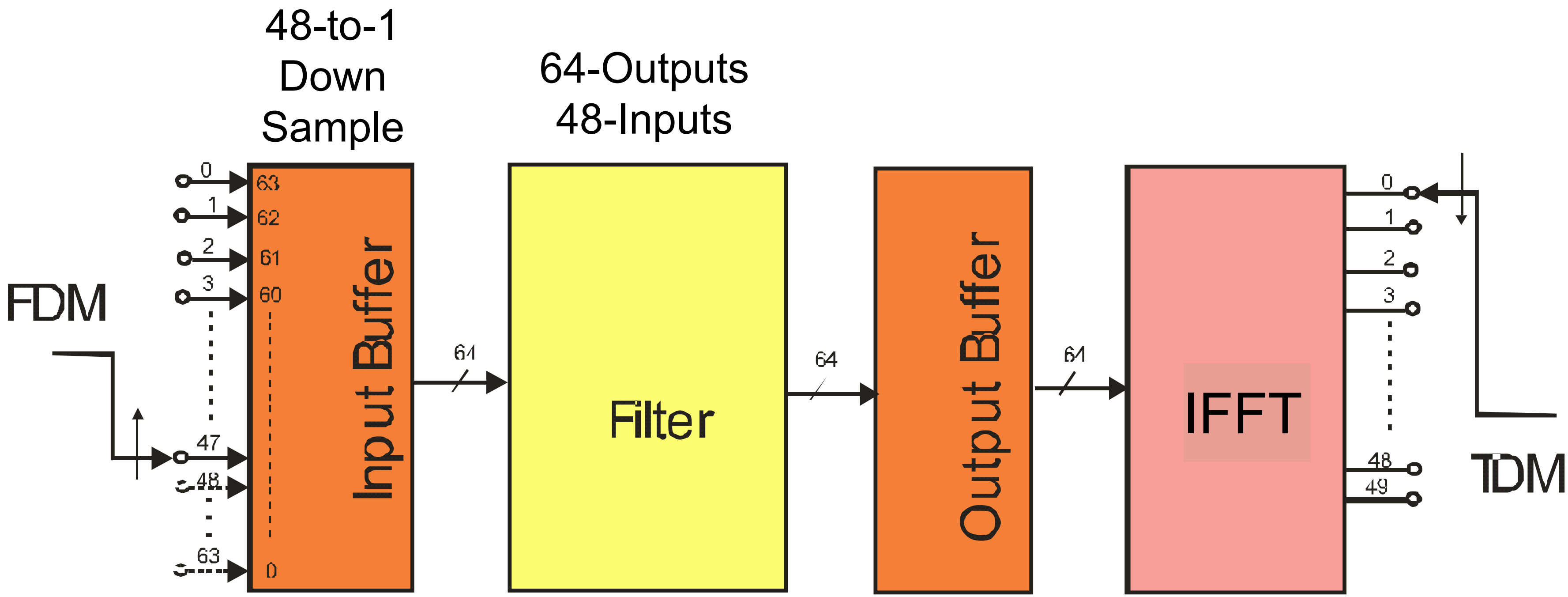
α

BW

Output Rate 2*128

$f_{s\text{-}output}$ = 256 kHz

Interesting Channelizer: 128 kHz Wide Channels, Spaced at 192 kHz, Sampled at 256 kHz



channel

= 12.288 MHz

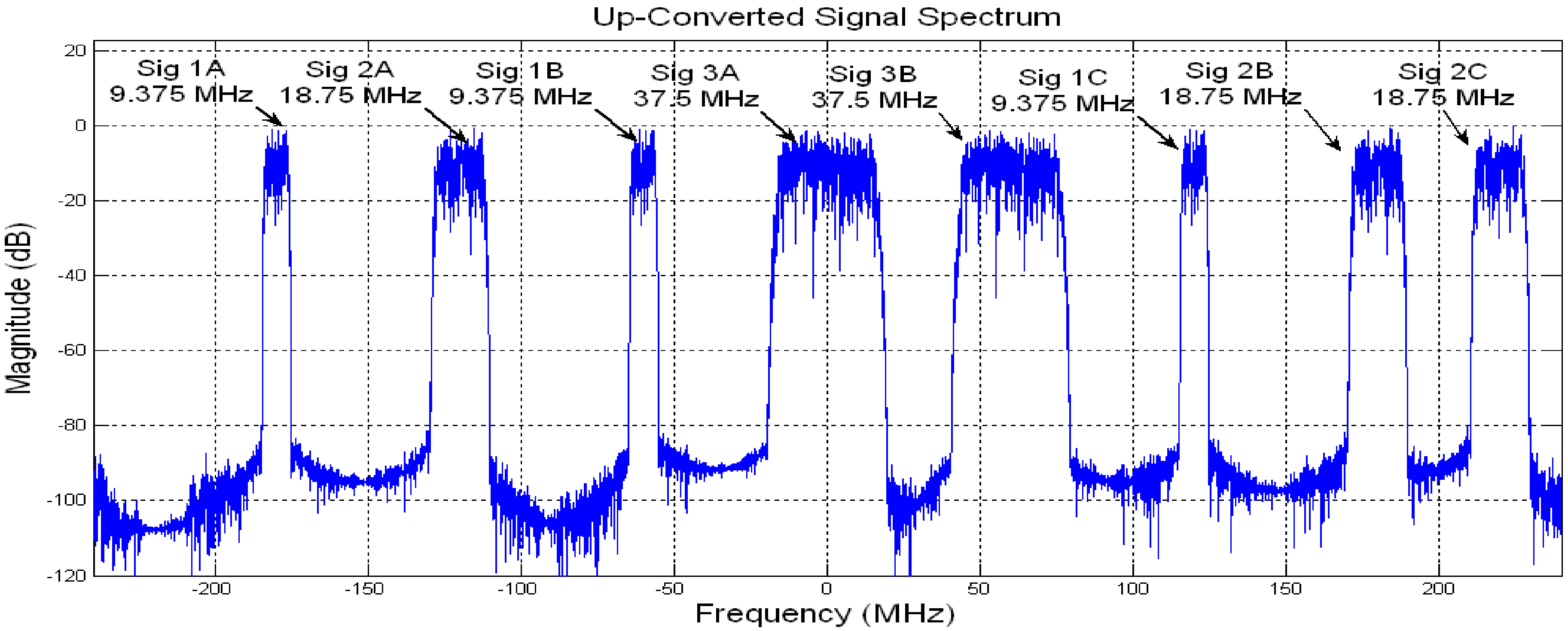
= 192 kHz

out

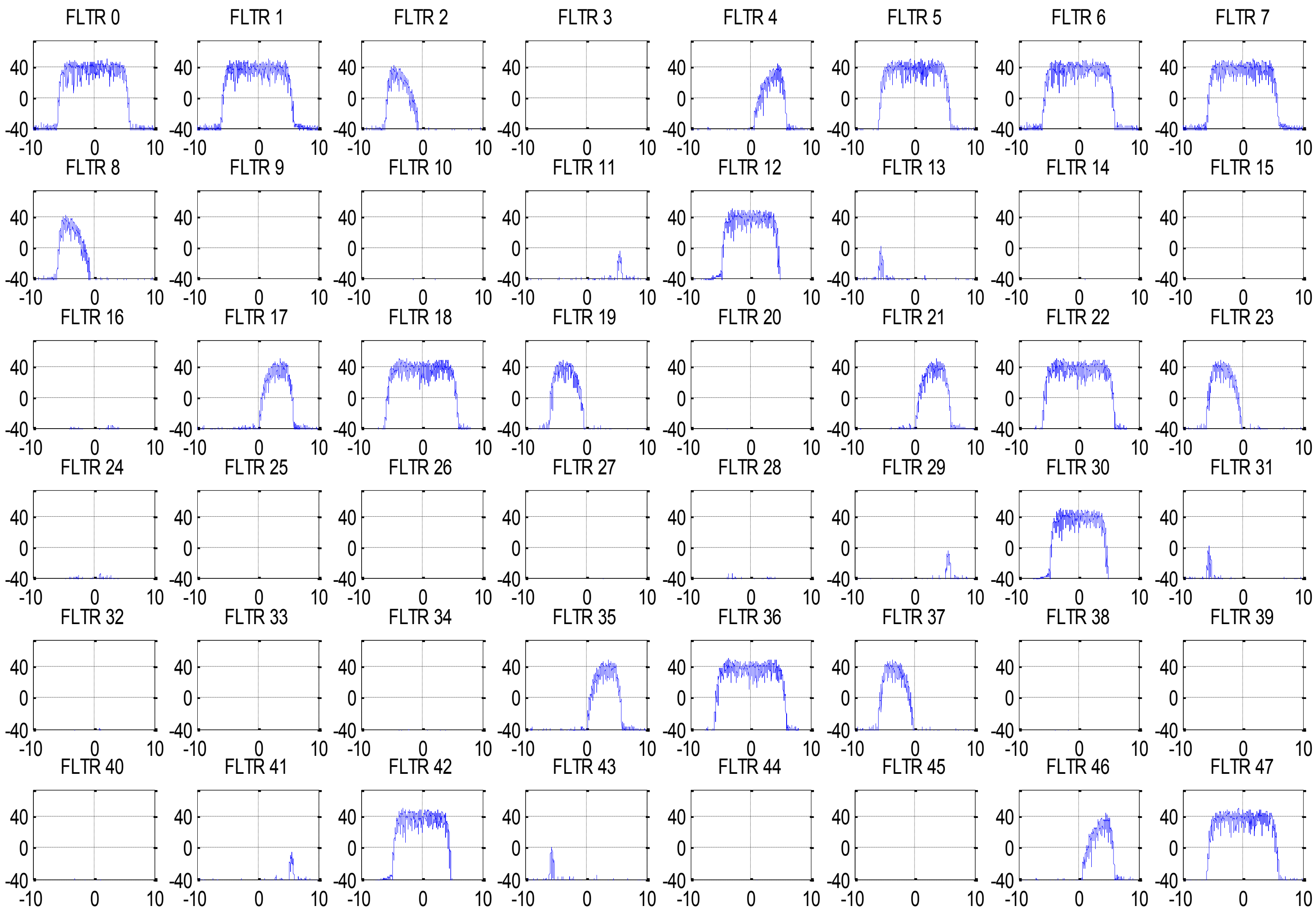
= 2 f_{symbol}

Ratio of Input Rate to Output Rate = 12288/256 = 48-to-1

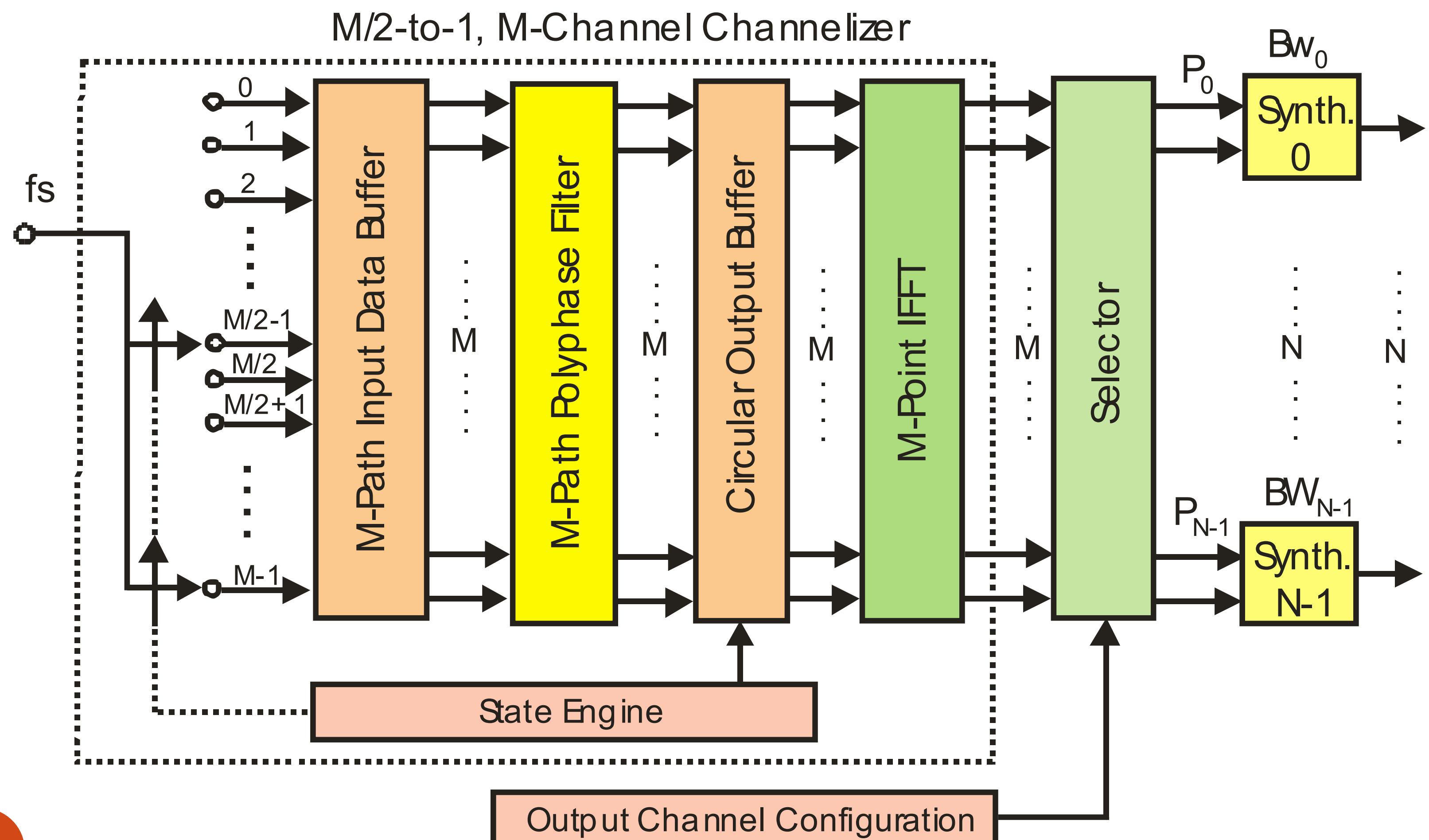
Multiple BW Channels Presented to Analysis Channelizer



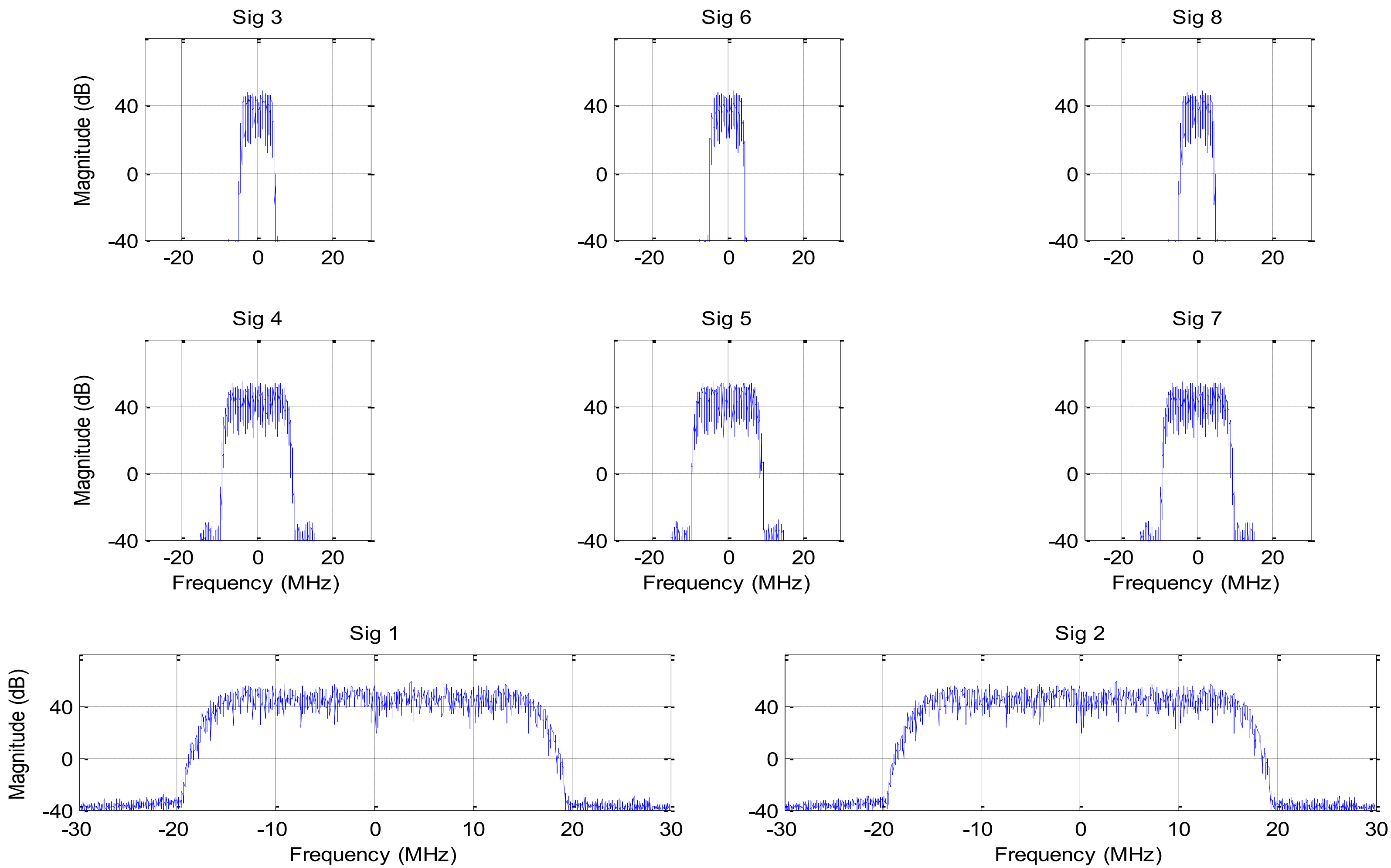
Partitioned spectral Components from Single Multi-Channel Analyzer



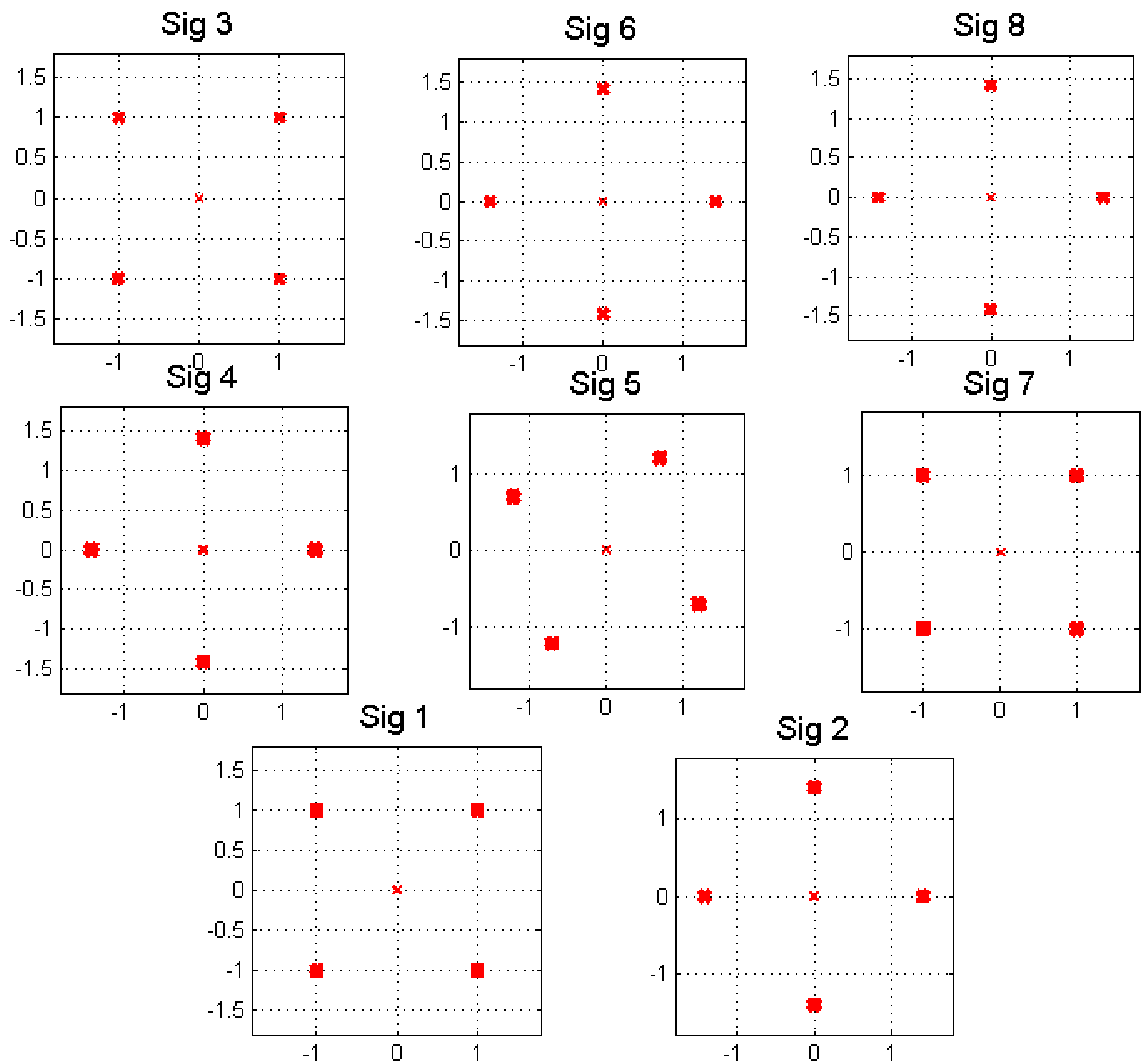
Reassemble Decomposed Broadband Signals Using Short Synthesis Filters formed by Multiple Channel Analysis Channelizer



Reassembled Wide band Channels from Short Synthesis Channelizers

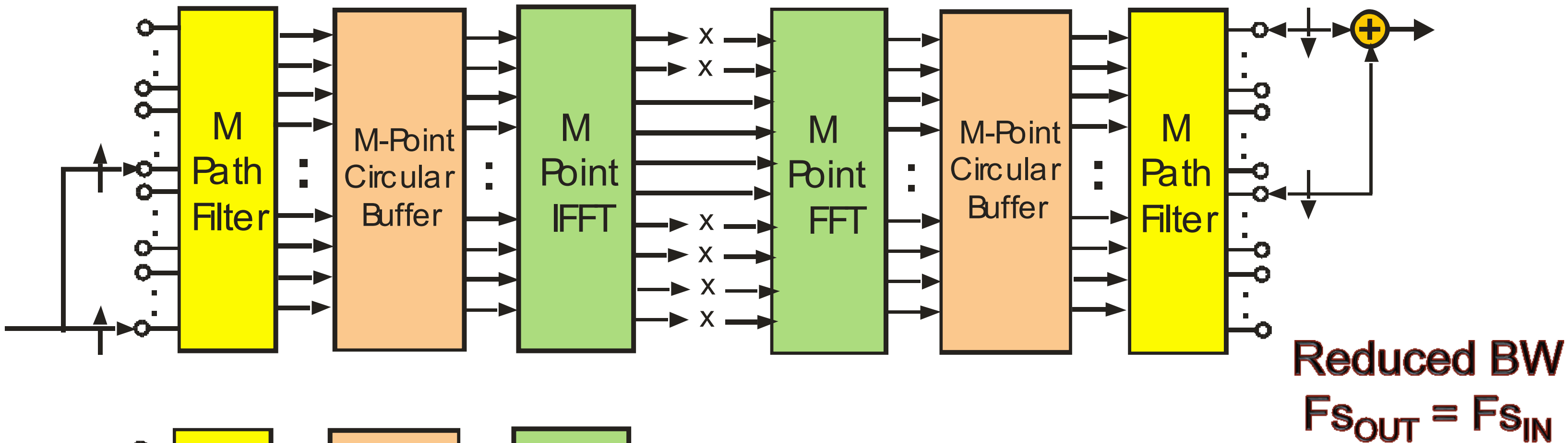


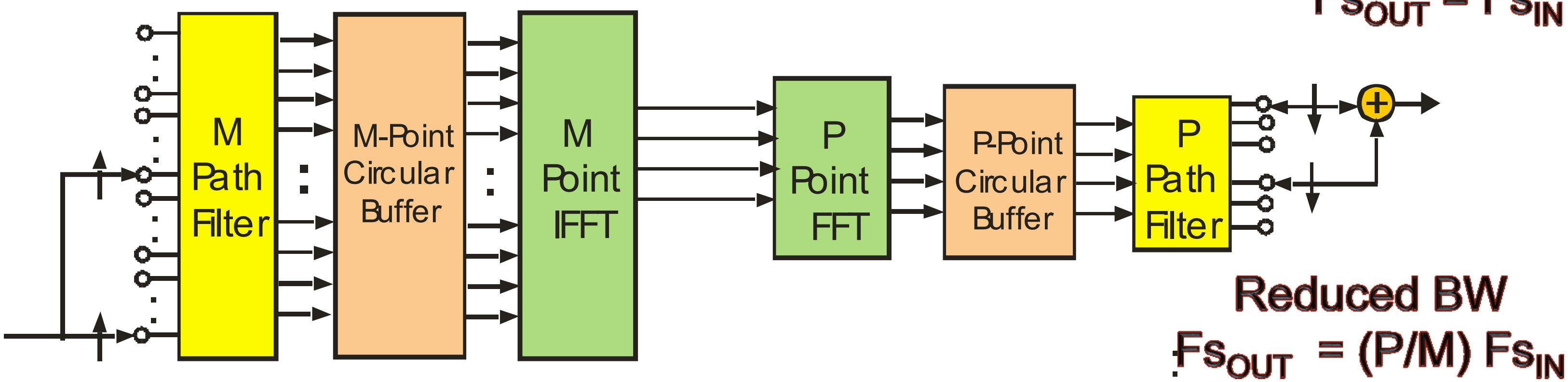
Signal Fidelity Preserved under Multiple Sub-Channel Disassembly and Reassembly



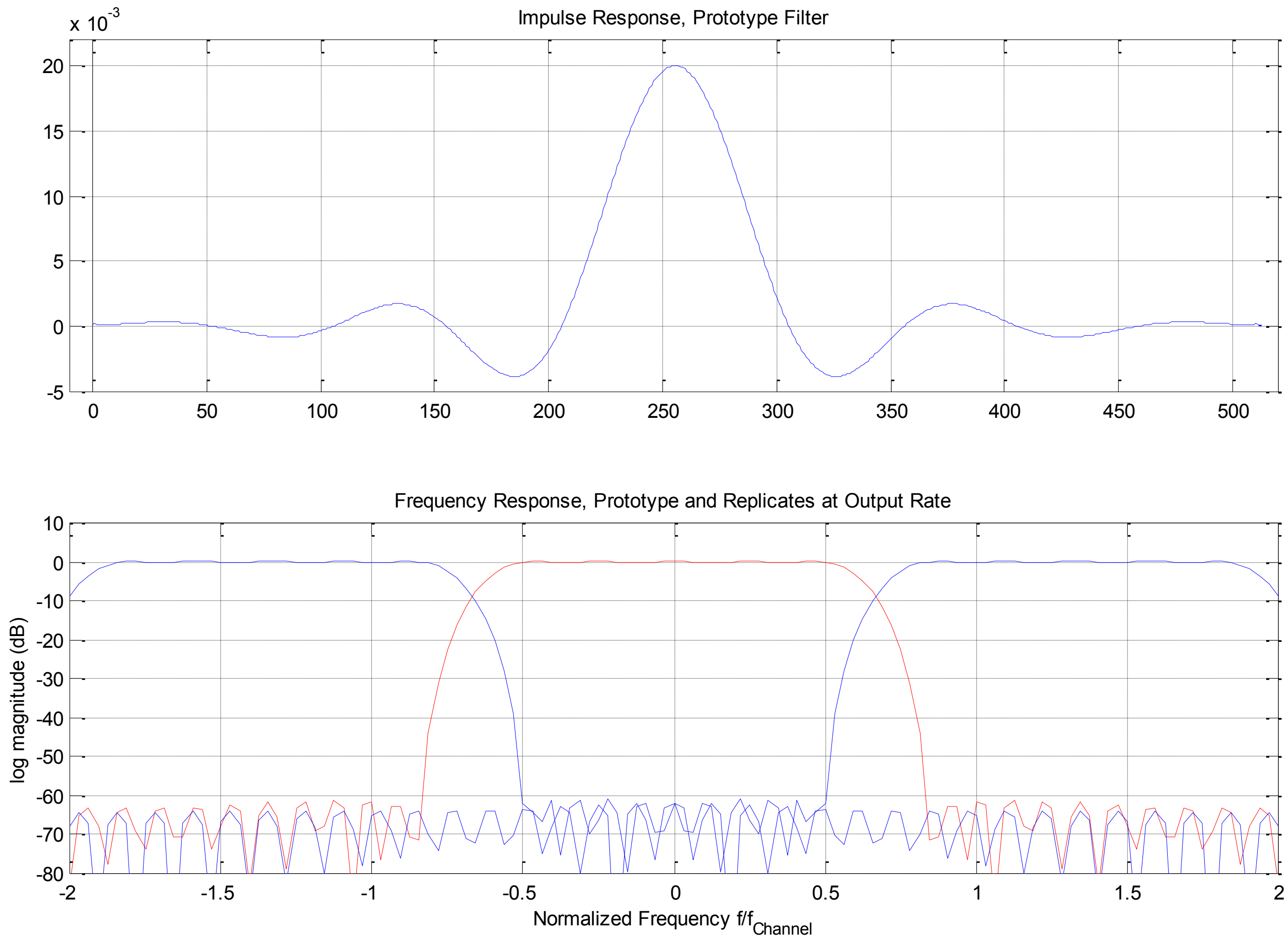
Variable BW Super Channel Filter from Cascade of Input Analysis and Output Synthesis Filter Banks

Change Bandwidth with Binary Mask, Change Sample Rate with Transform Size

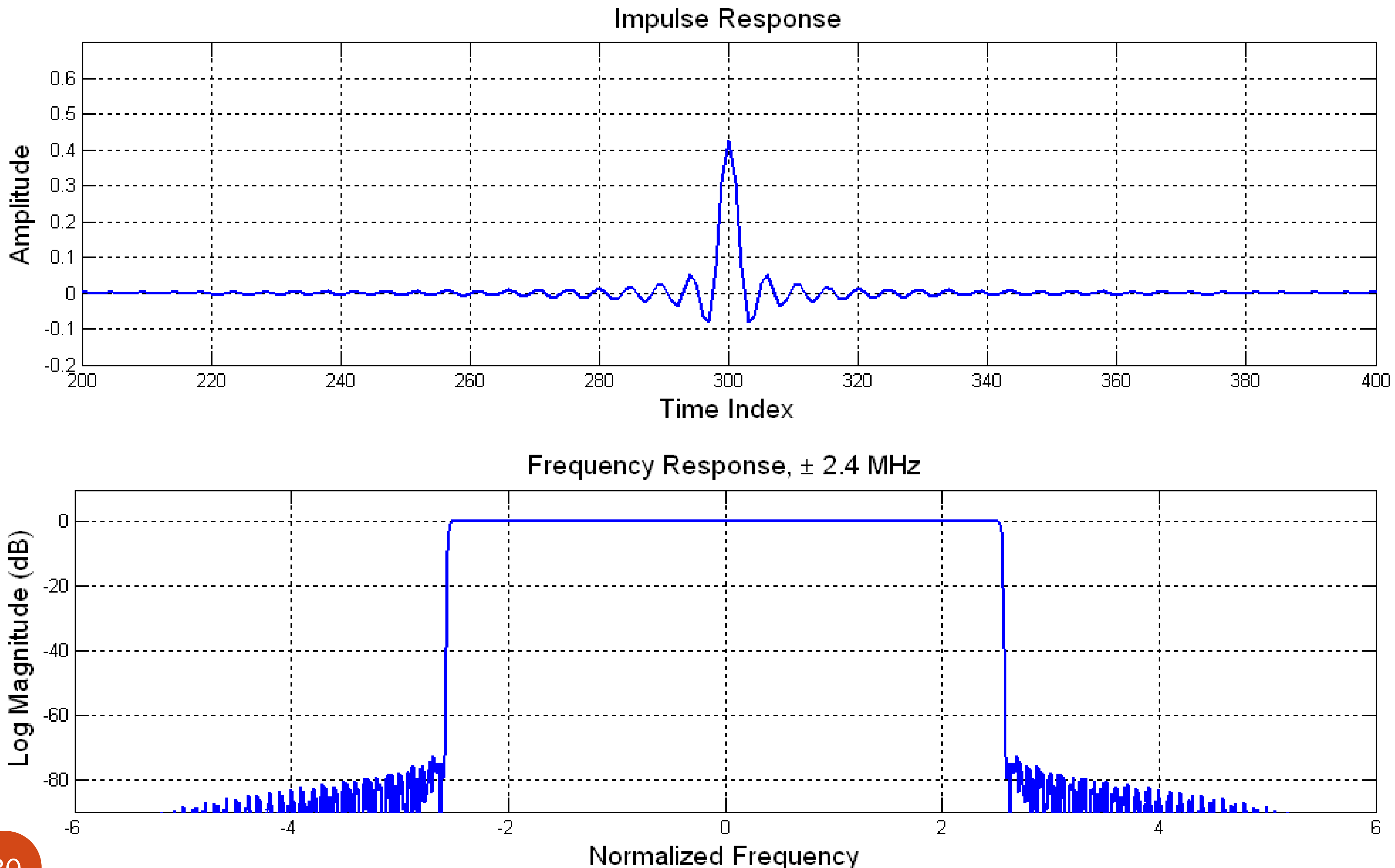




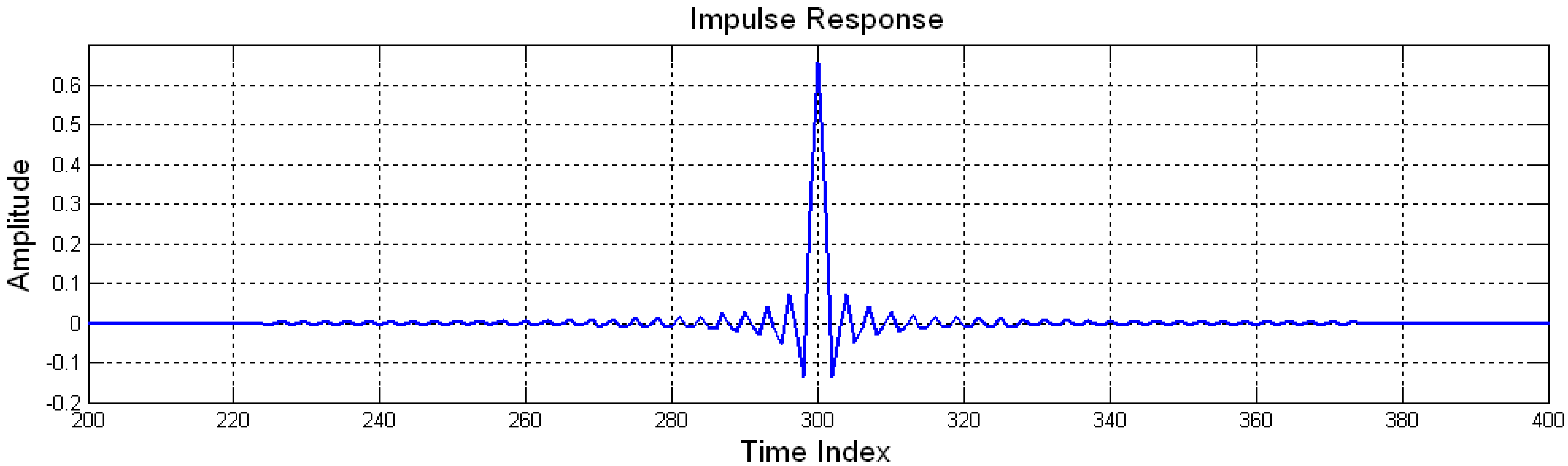
Time and Frequency Response of Prototype Filter at Output Sample Rate

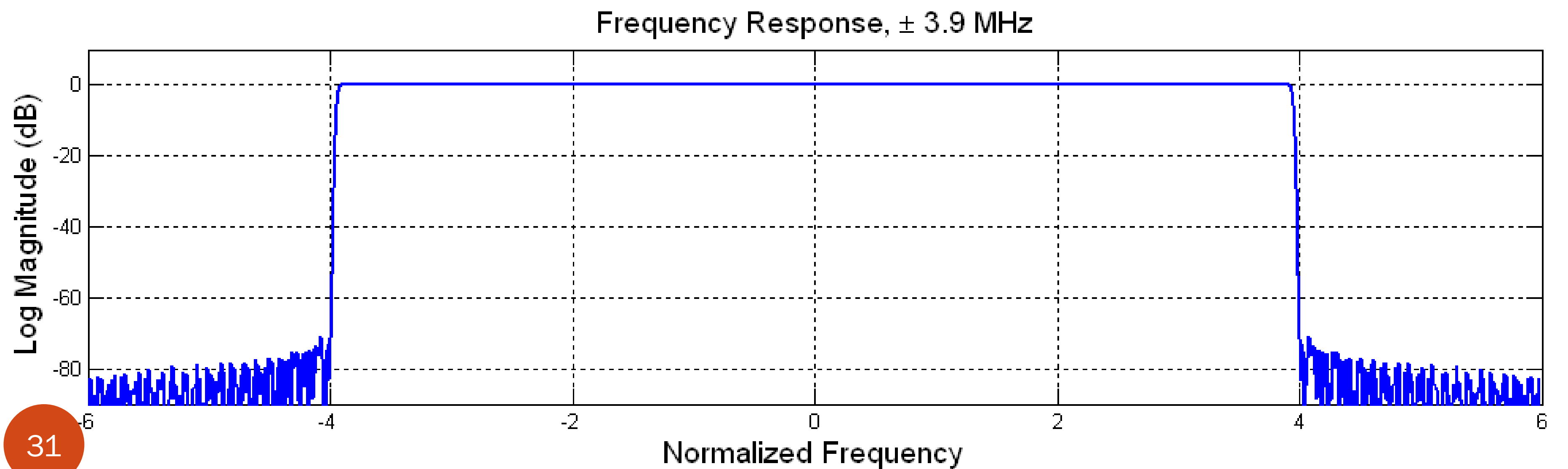


Impulse response and Frequency Response 25-Enabled Ports: 2.4 MHz Bandwidth

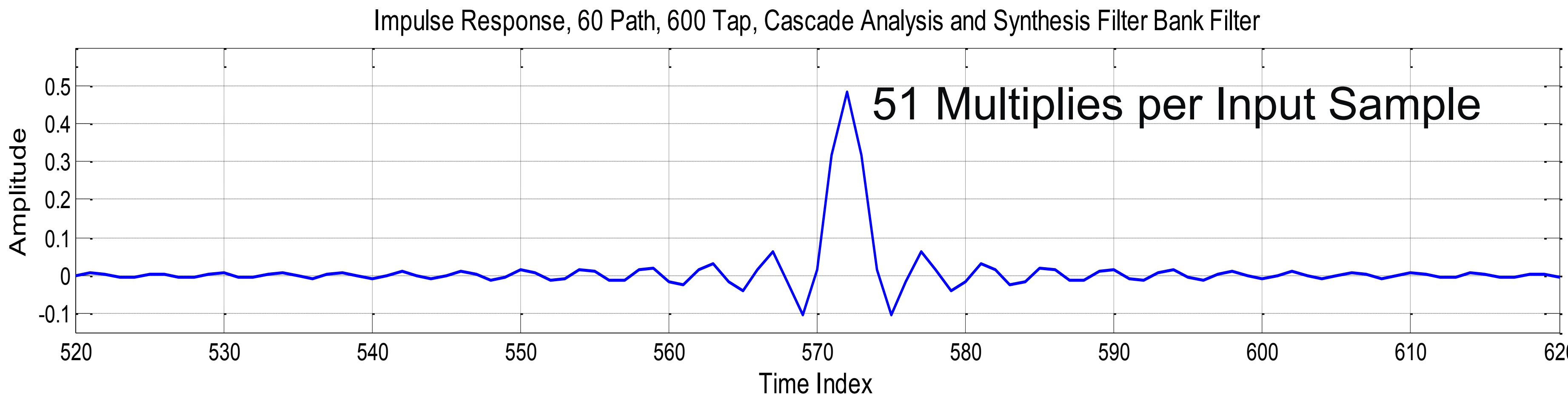


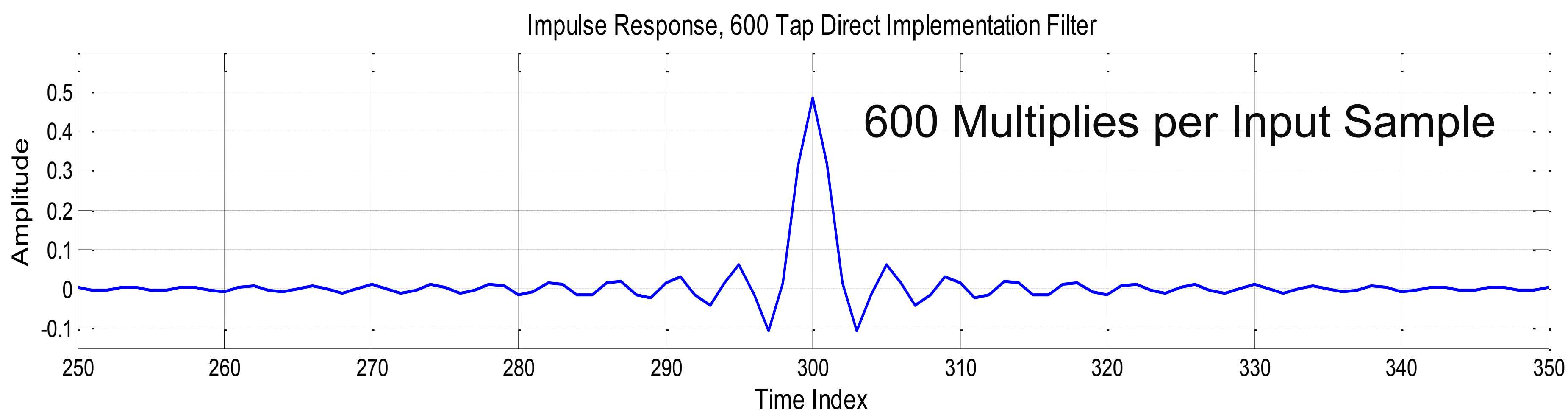
Impulse Response and Frequency Response
40-Enabled Ports: 3.9 MHz Bandwidth



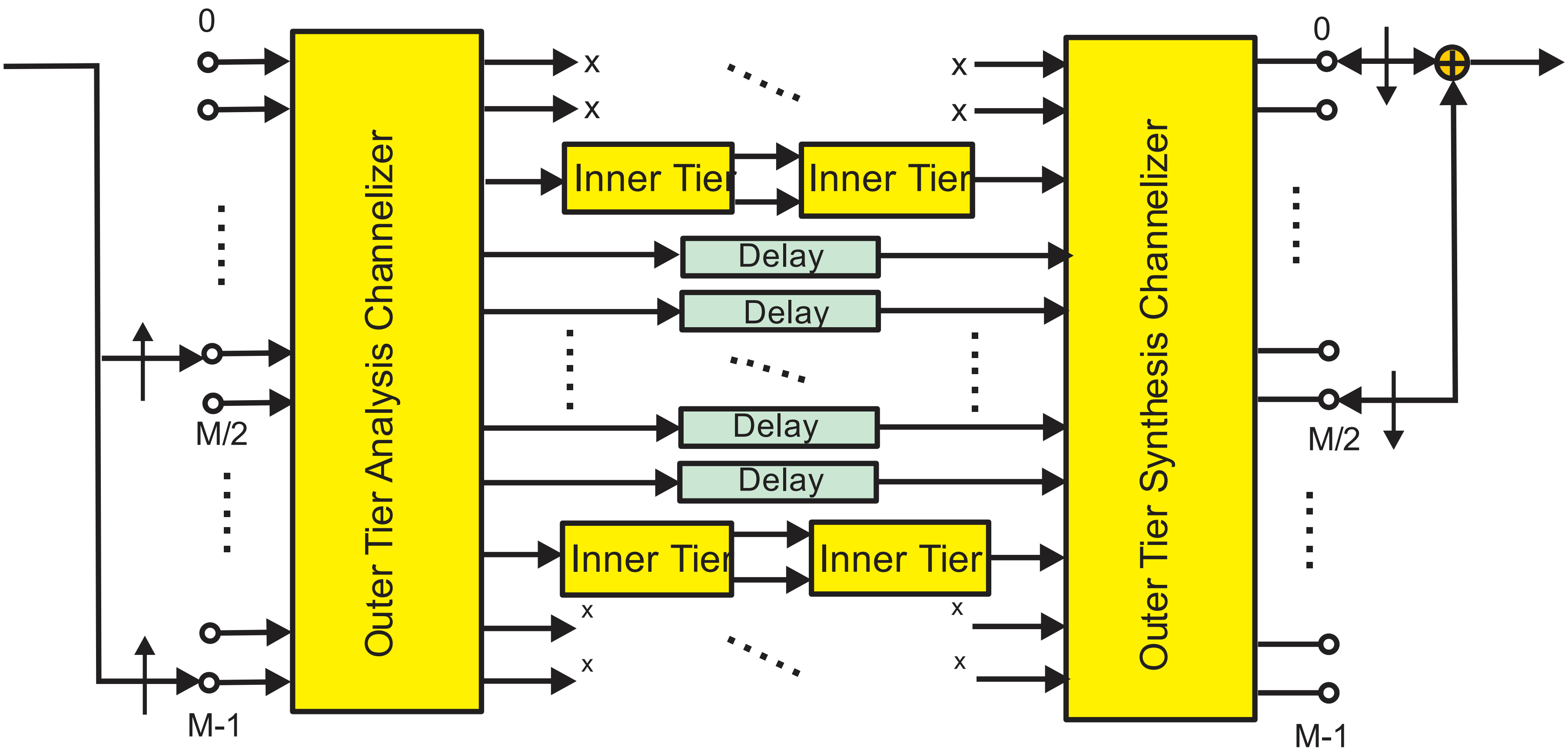


Order of Magnitude Reduction in Arithmetic Operations Per Input Sample



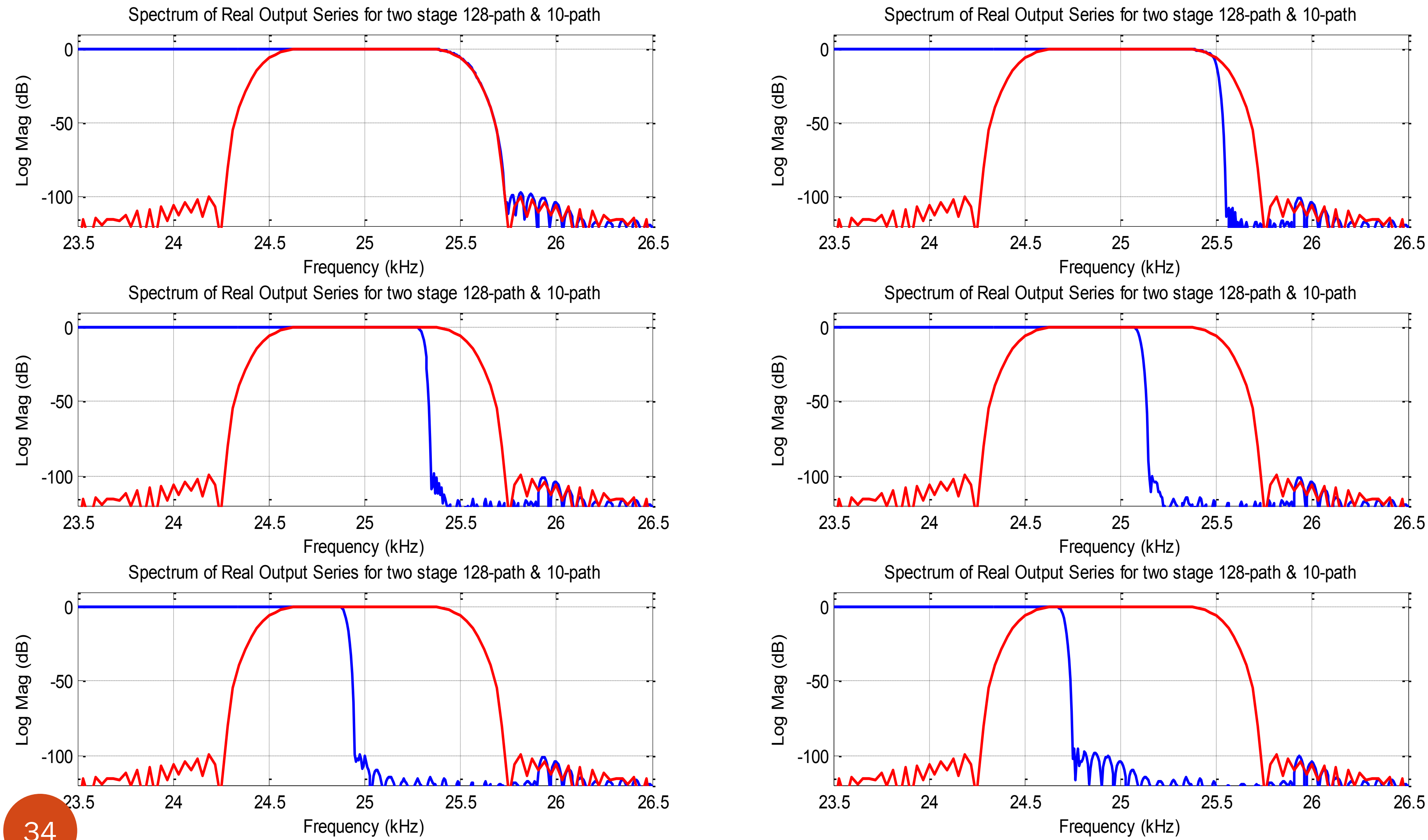


Cascade Inner and Outer Tier M-and-L Path Channelizers



Changes Output BW from Multiple of Channel Spacing to Arbitrary BW

Spectral Resolution of Outer Tier 128-Path Filter and of Enabled Inner Tier 10-Path Filter



Recent Enhanced Channelizer Options

- Full Variable Bandwidth in Super Channels
  Interleave Wider and Narrower Bandwidth
  Equally Spaced Channel Prototype Bands

- Even or Odd Indexed Frequency Bin Centers

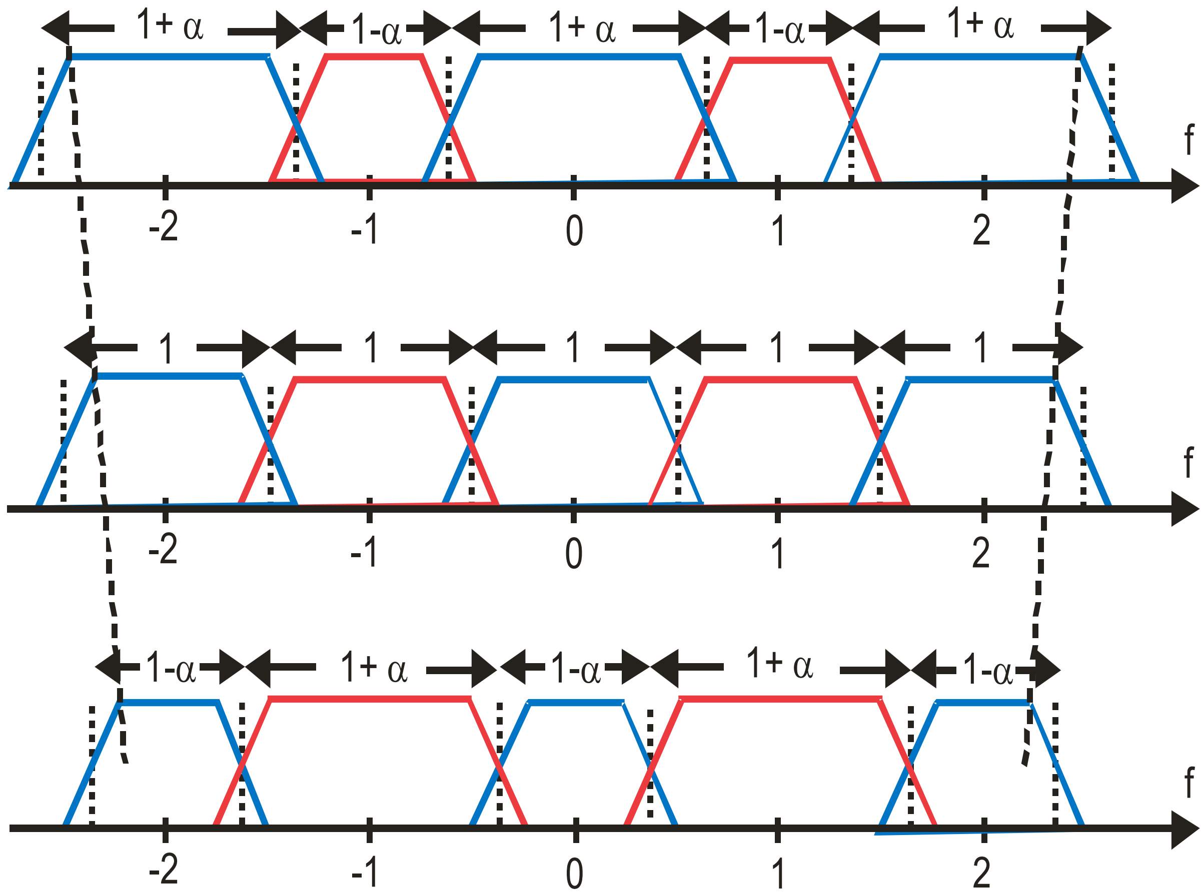
- Fragmented and Defragmented Bands

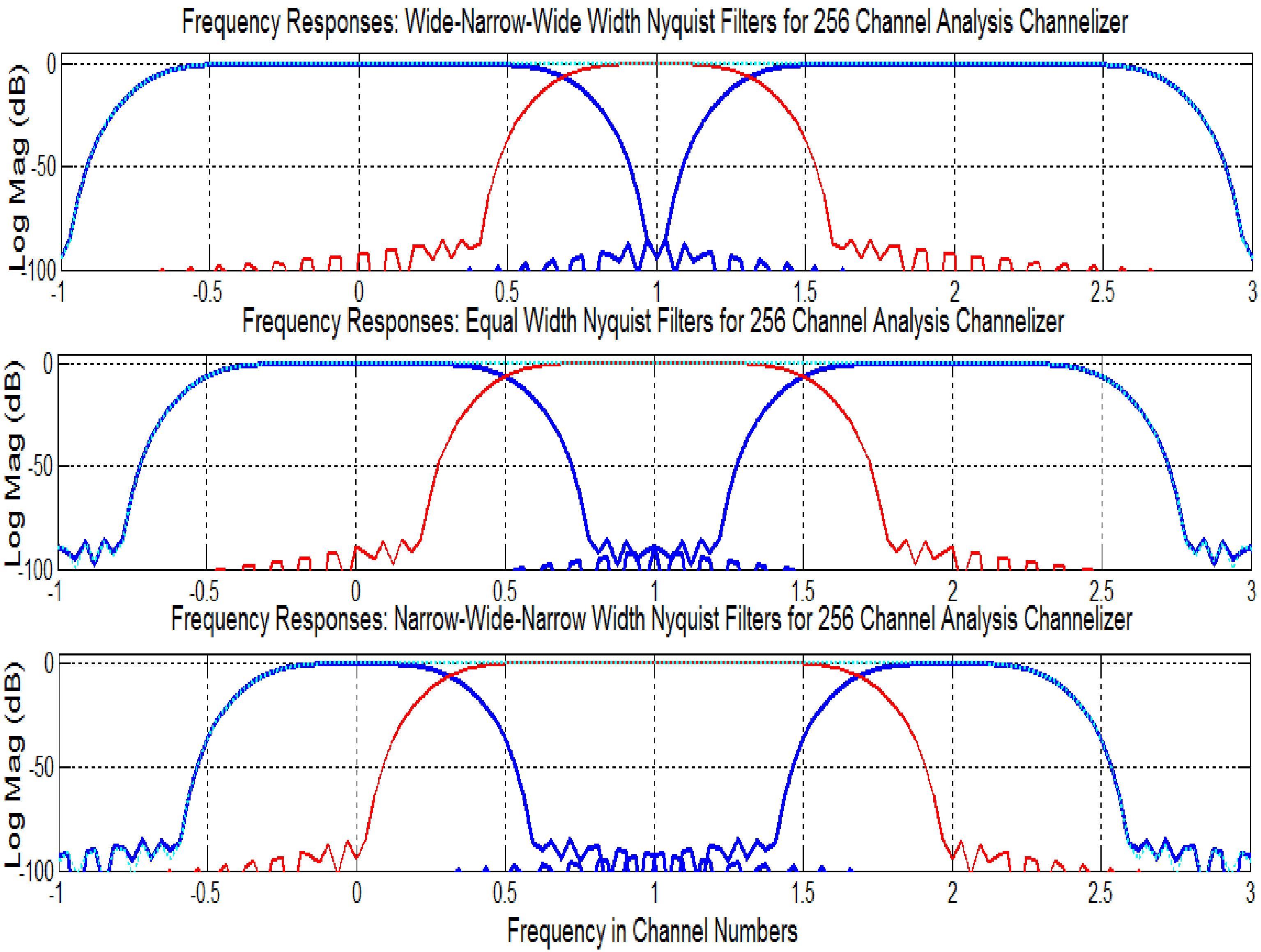
Change Bandwidth of Alternate Channels Reminiscent of Frequency Response Masking

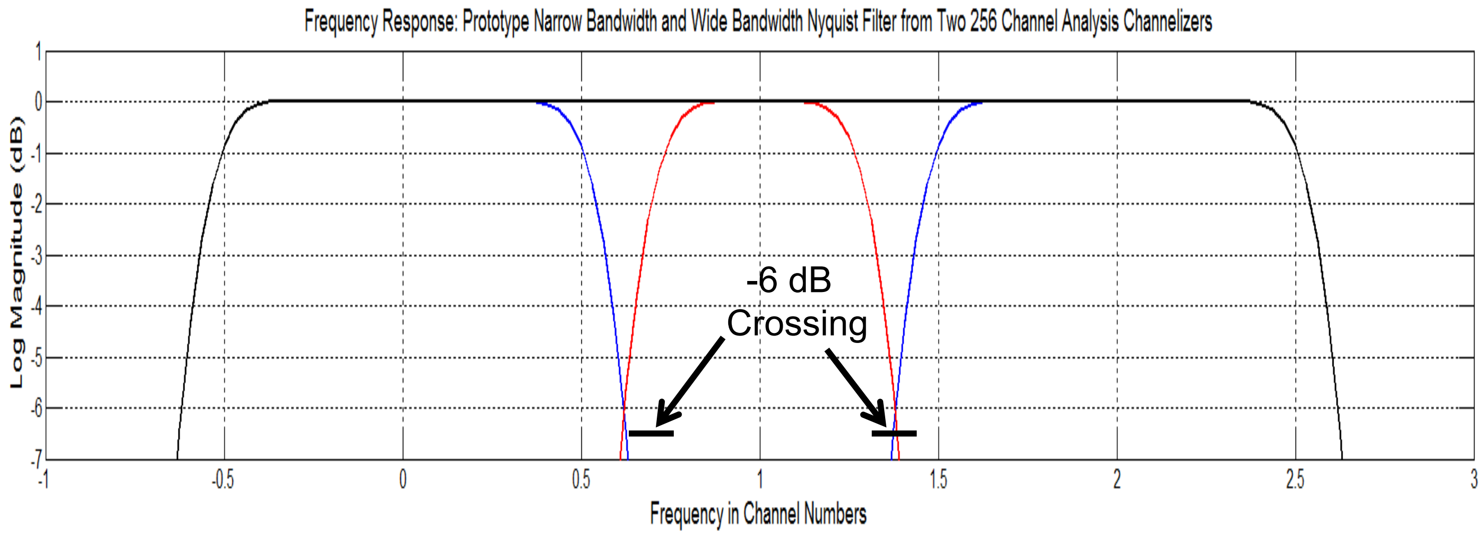
W-N-W BW Interleaved Channels! Modified Polyphase Channelizer.

Equal BW Channels! Standard Polyphase Channelizer.

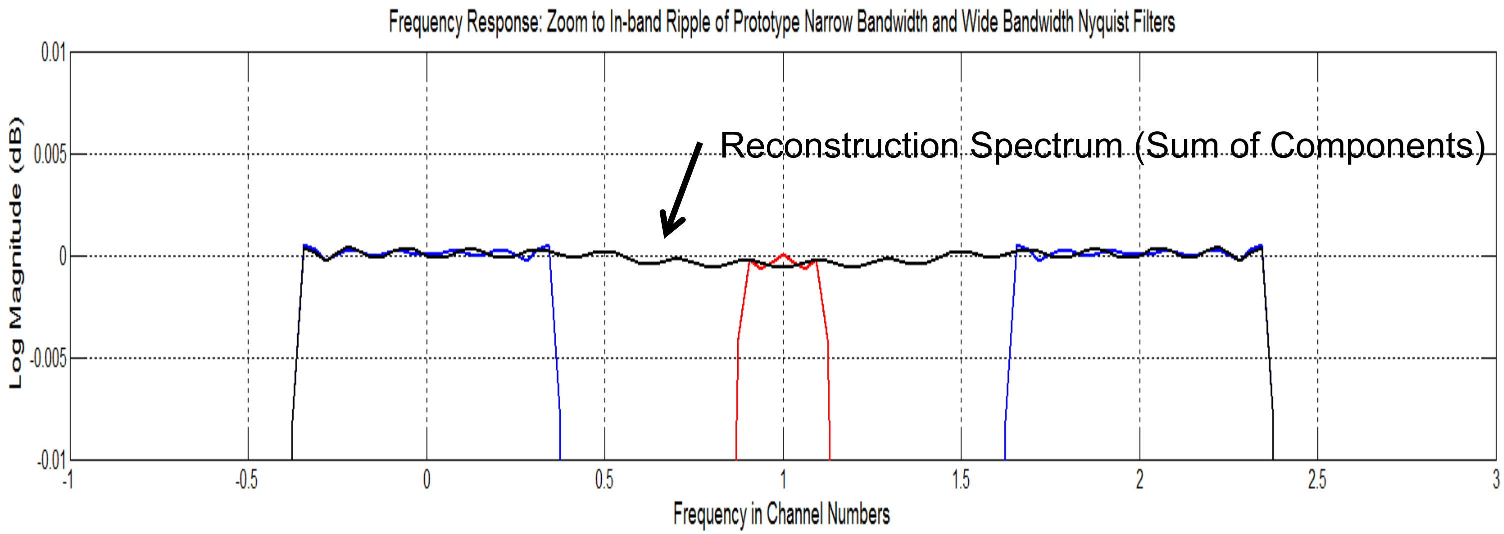
N-W-N BW Interleaved Channels! Modified Polyphase Channelizer.



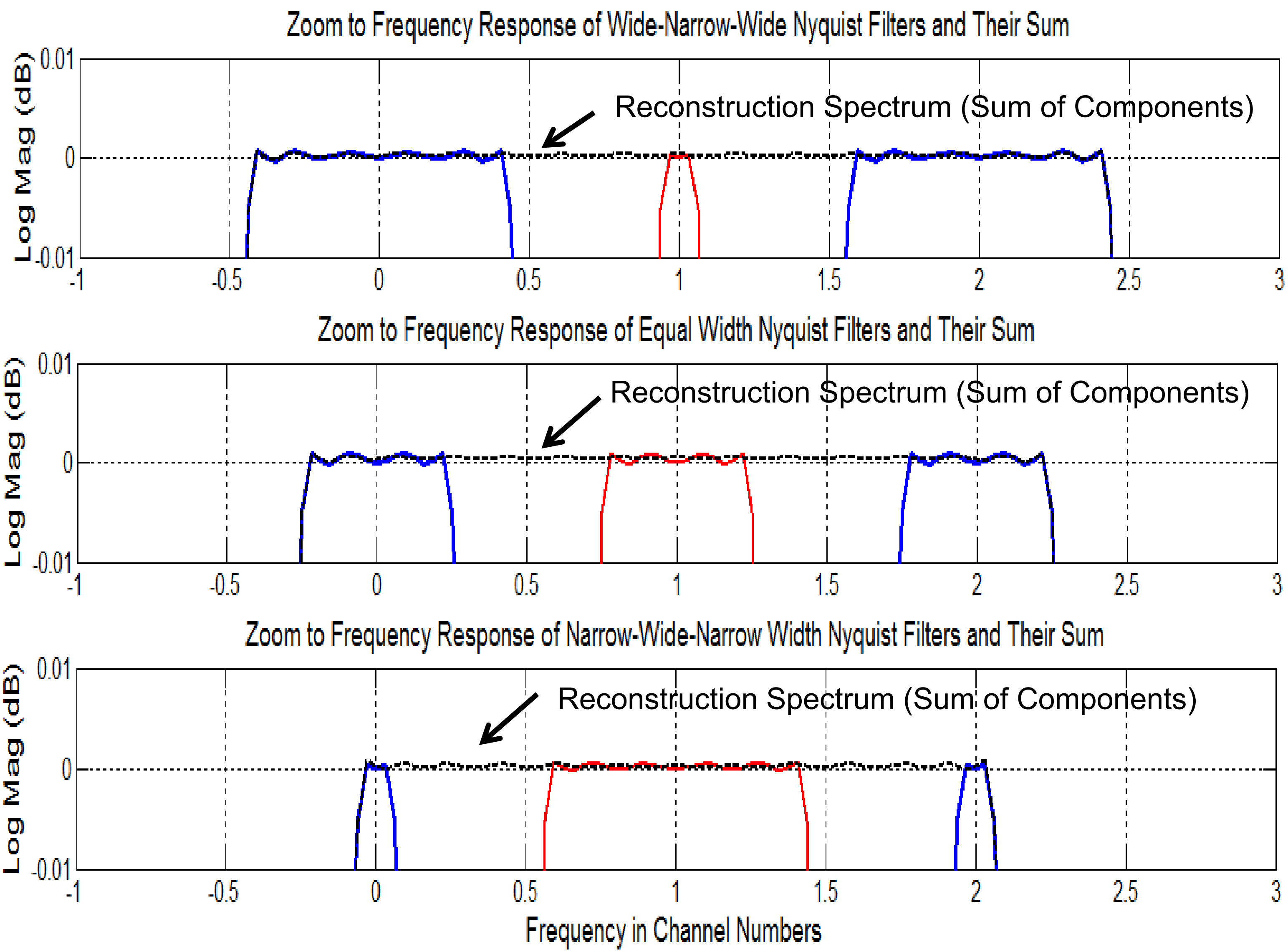

Frequency Responses: Wide-Narrow-Wide Width Nyquist Filters for 256 Channel Analysis Channelizer
Log Mag (dB)
0
-50
-100
-1
-0.5
0
0.5
1
1.5
2
2.5
3
Frequency Responses: Equal Width Nyquist Filters for 256 Channel Analysis Channelizer
Log Mag (dB)
0
-50
-100
-1
-0.5
0
0.5
1
1.5
2
2.5
3
Frequency Responses: Narrow-Wide-Narrow Width Nyquist Filters for 256 Channel Analysis Channelizer
Log Mag (dB)
0
-50
-100
-1
-0.5
0
0.5
1
1.5
2
2.5
3
Frequency in Channel Numbers

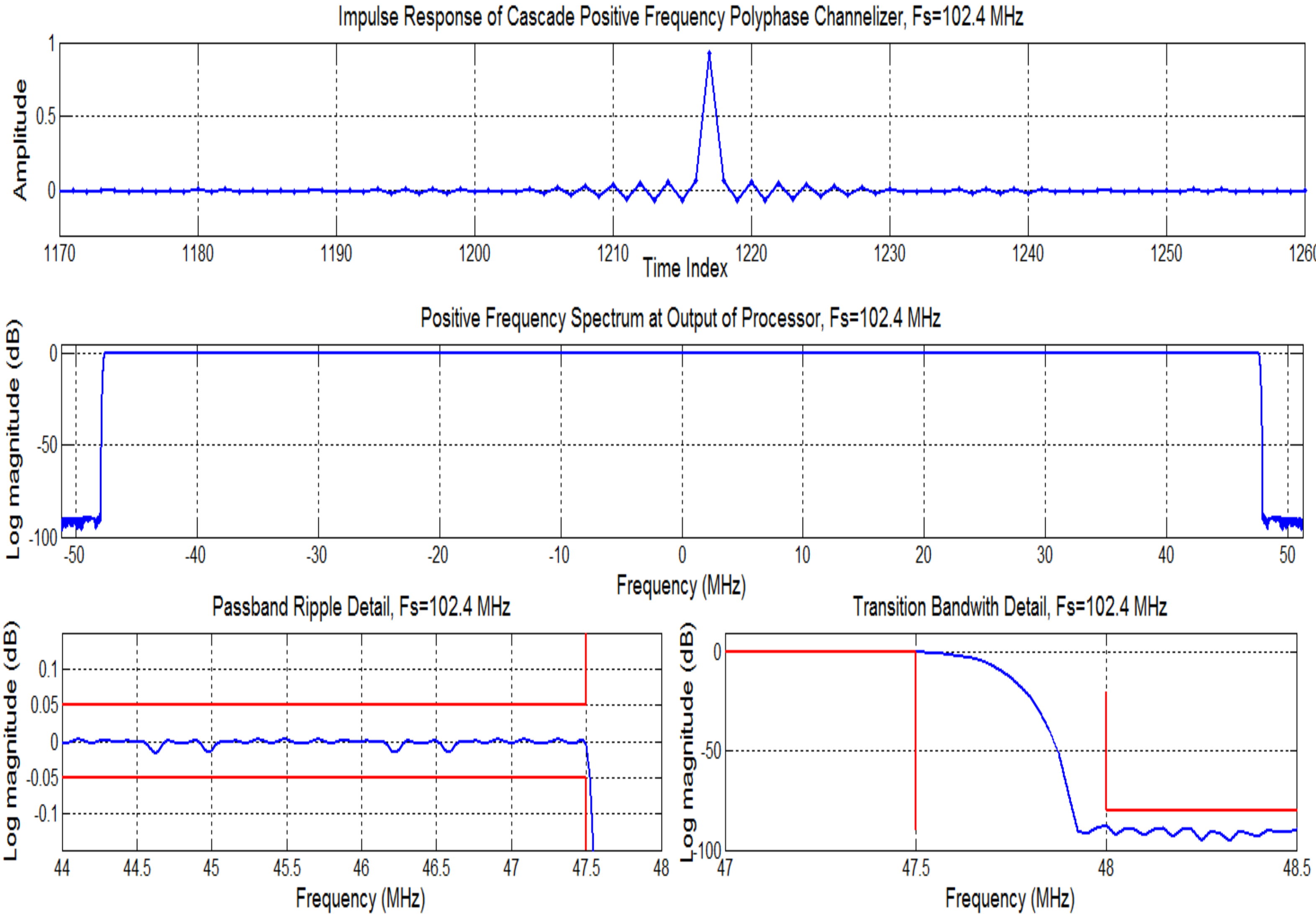


Frequency Response: Prototype Narrow Bandwidth and Wide Bandwidth Nyquist Filter from Two 256 Channel Analysis Channelizers
Log Magnitude (dB)
Frequency in Channel Numbers
-6 dB
Crossing
1
0
-1
-2
-3
-4
-5
-6
-7
-1
-0.5
0
0.5
1
1.5
2
2.5
3

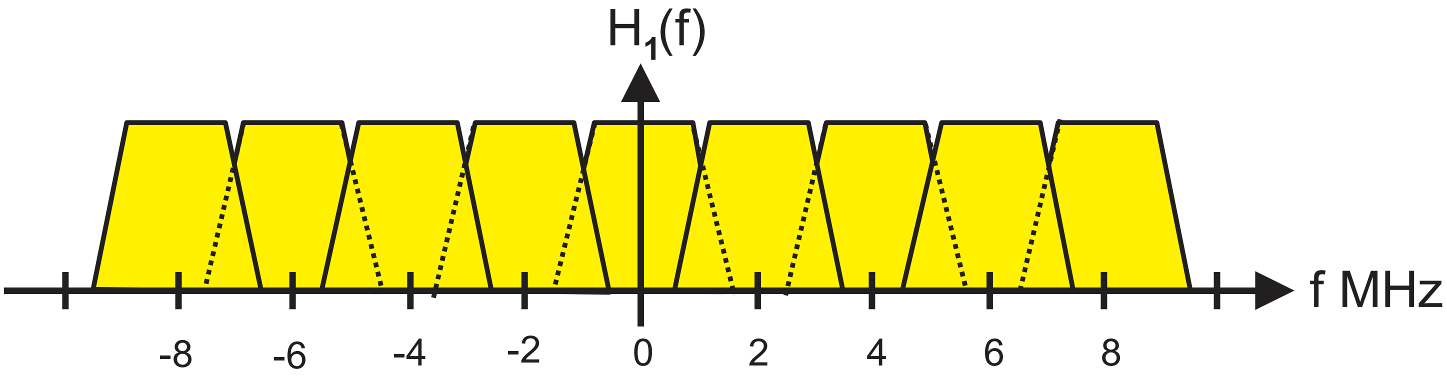


Frequency Response: Zoom to In-band Ripple of Prototype Narrow Bandwidth and Wide Bandwidth Nyquist Filters
Log Magnitude (dB)
Frequency in Channel Numbers
Reconstruction Spectrum (Sum of Components)
0.01
0.005
0
-0.005
-0.01
-1
-0.5
0
0.5
1
1.5
2
2.5
3

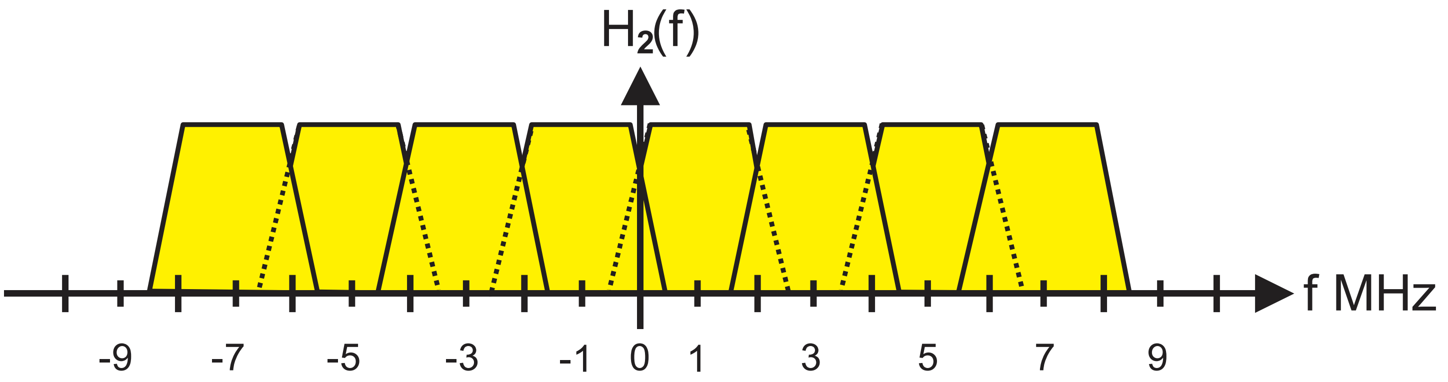

Zoom to Frequency Response of Wide-Narrow-Wide Nyquist Filters and Their Sum
Reconstruction Spectrum (Sum of Components)
Log Mag (dB)
0.01
0
-0.01
-1
-0.5
0
0.5
1
1.5
2
2.5
3
Zoom to Frequency Response of Equal Width Nyquist Filters and Their Sum
Reconstruction Spectrum (Sum of Components)
Log Mag (dB)
Zoom to Frequency Response of Narrow-Wide-Narrow Width Nyquist Filters and Their Sum
Reconstruction Spectrum (Sum of Components)
Log Mag (dB)
Frequency in Channel Numbers


Impulse Response of Cascade Positive Frequency Polyphase Channelizer, Fs=102.4 MHz
Amplitude
Time Index
Positive Frequency Spectrum at Output of Processor, Fs=102.4 MHz
Log magnitude (dB)
Frequency (MHz)
Passband Ripple Detail, Fs=102.4 MHz
Log magnitude (dB)
Frequency (MHz)
Transition Bandwith Detail, Fs=102.4 MHz
Log magnitude (dB)
Frequency (MHz)

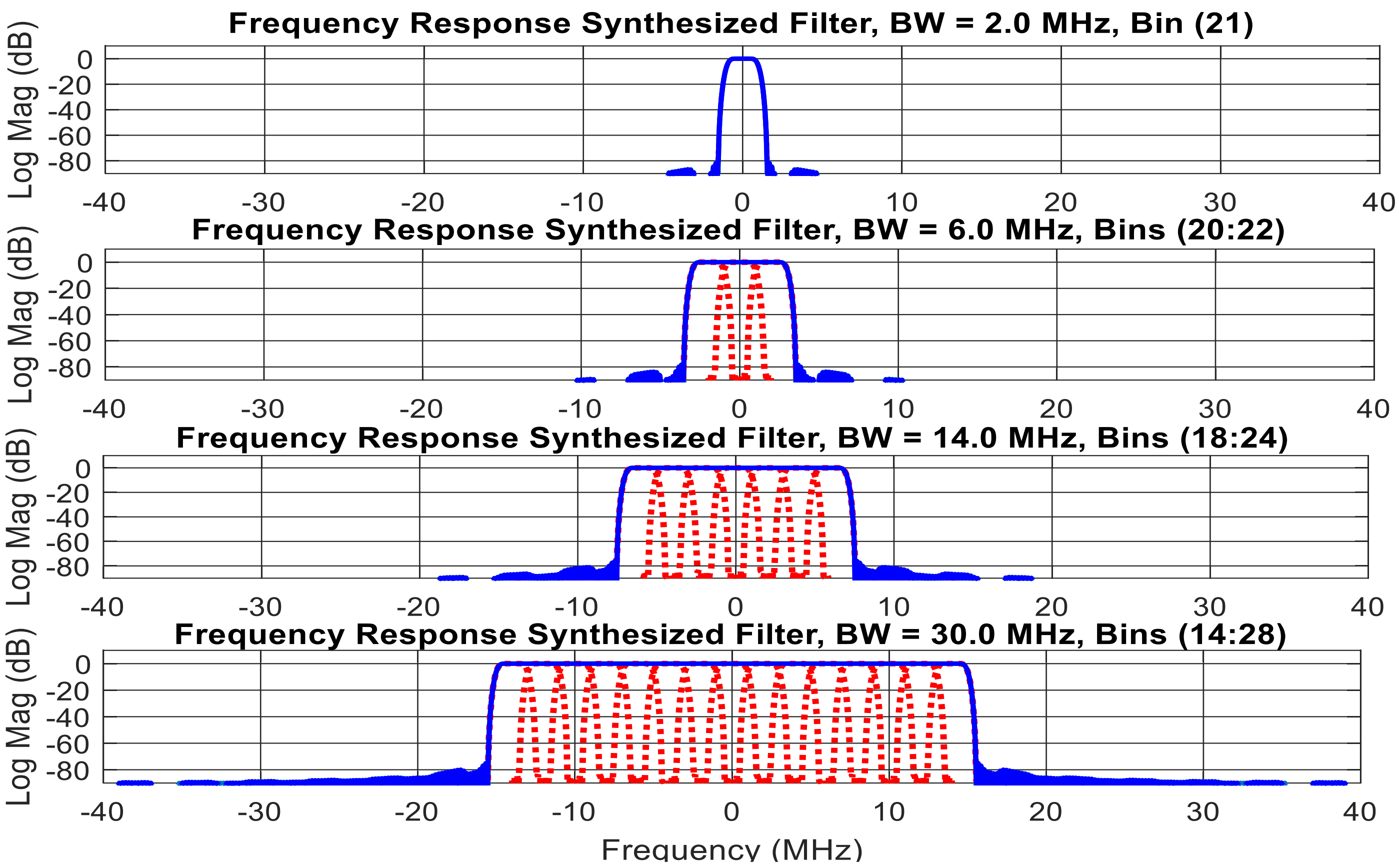
Even Indexed Channelizer



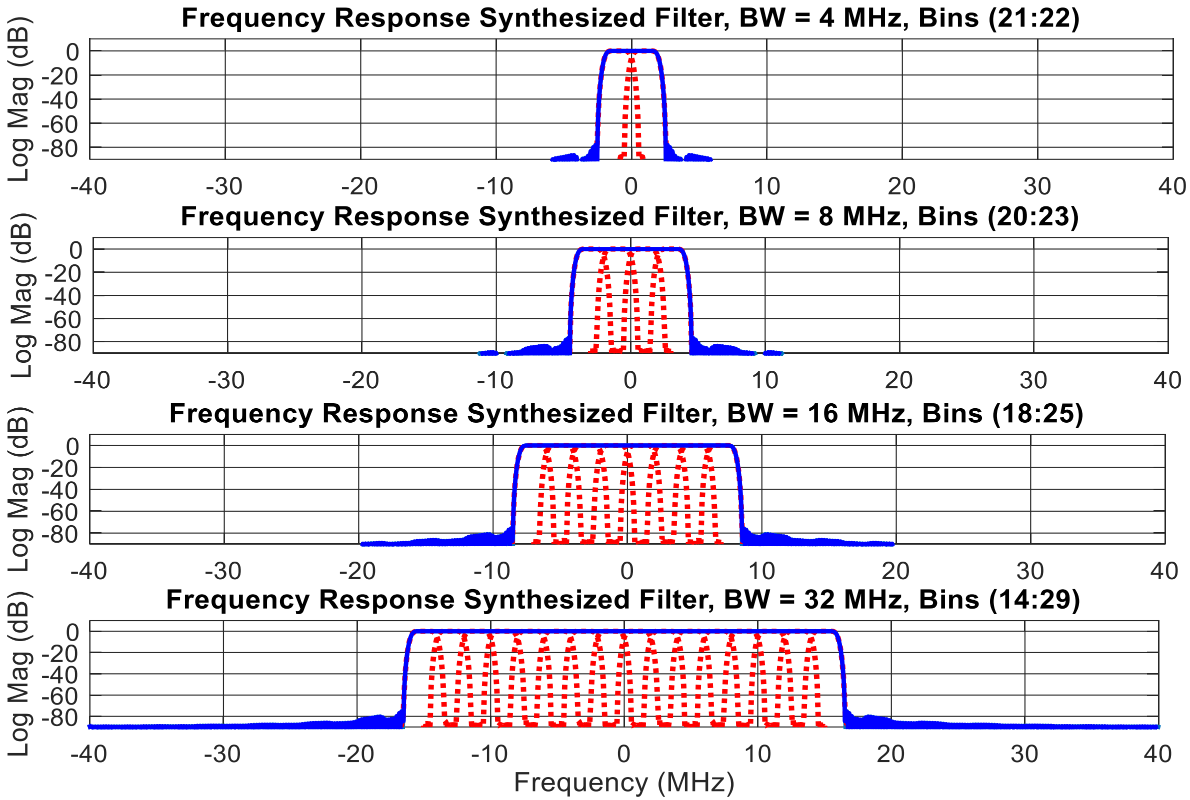
Odd Indexed Channelizer



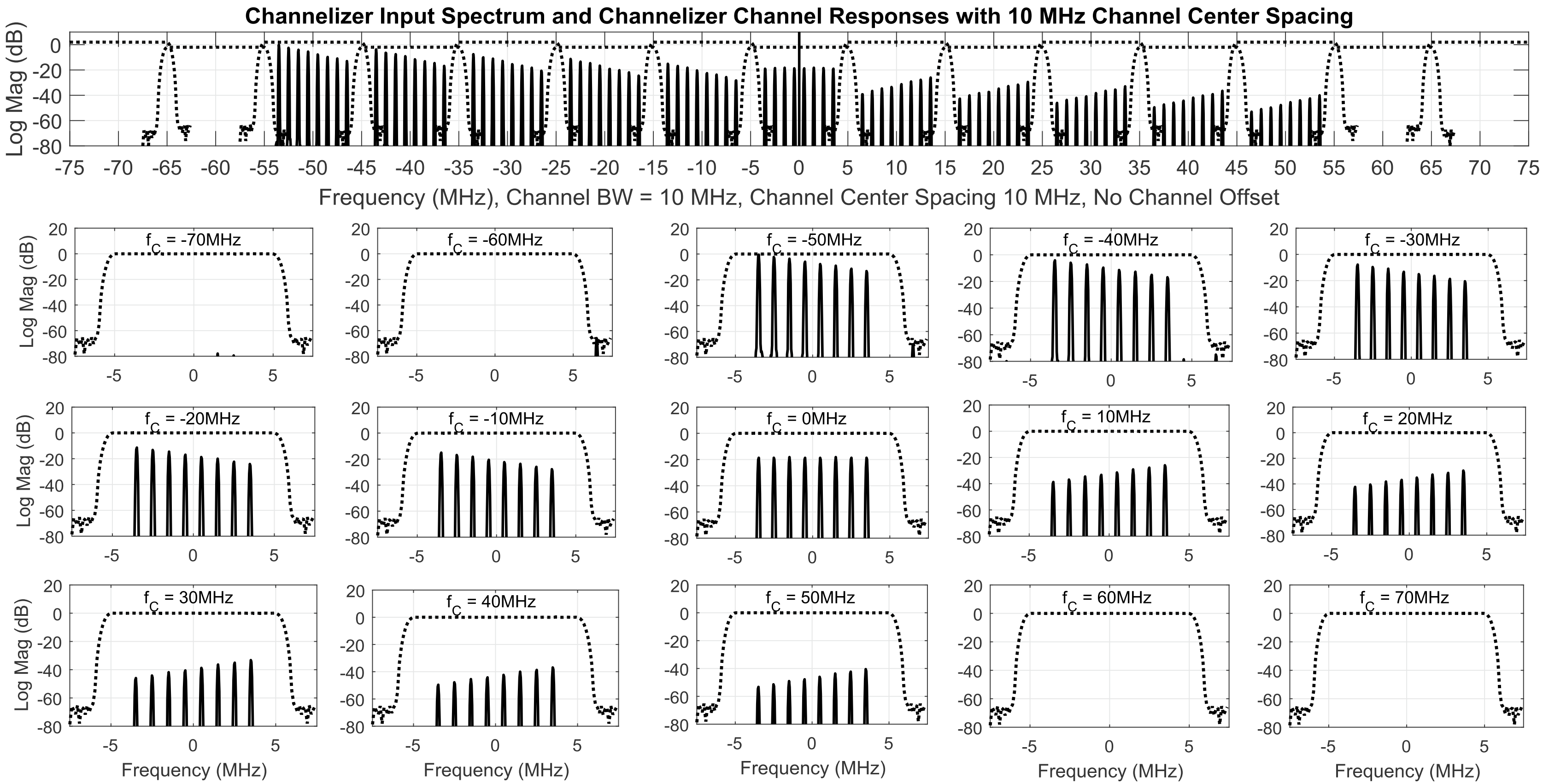
Center Frequencies:
Match Roots of Z^N-1, N Roots of 1, exp(j 2π k/N)



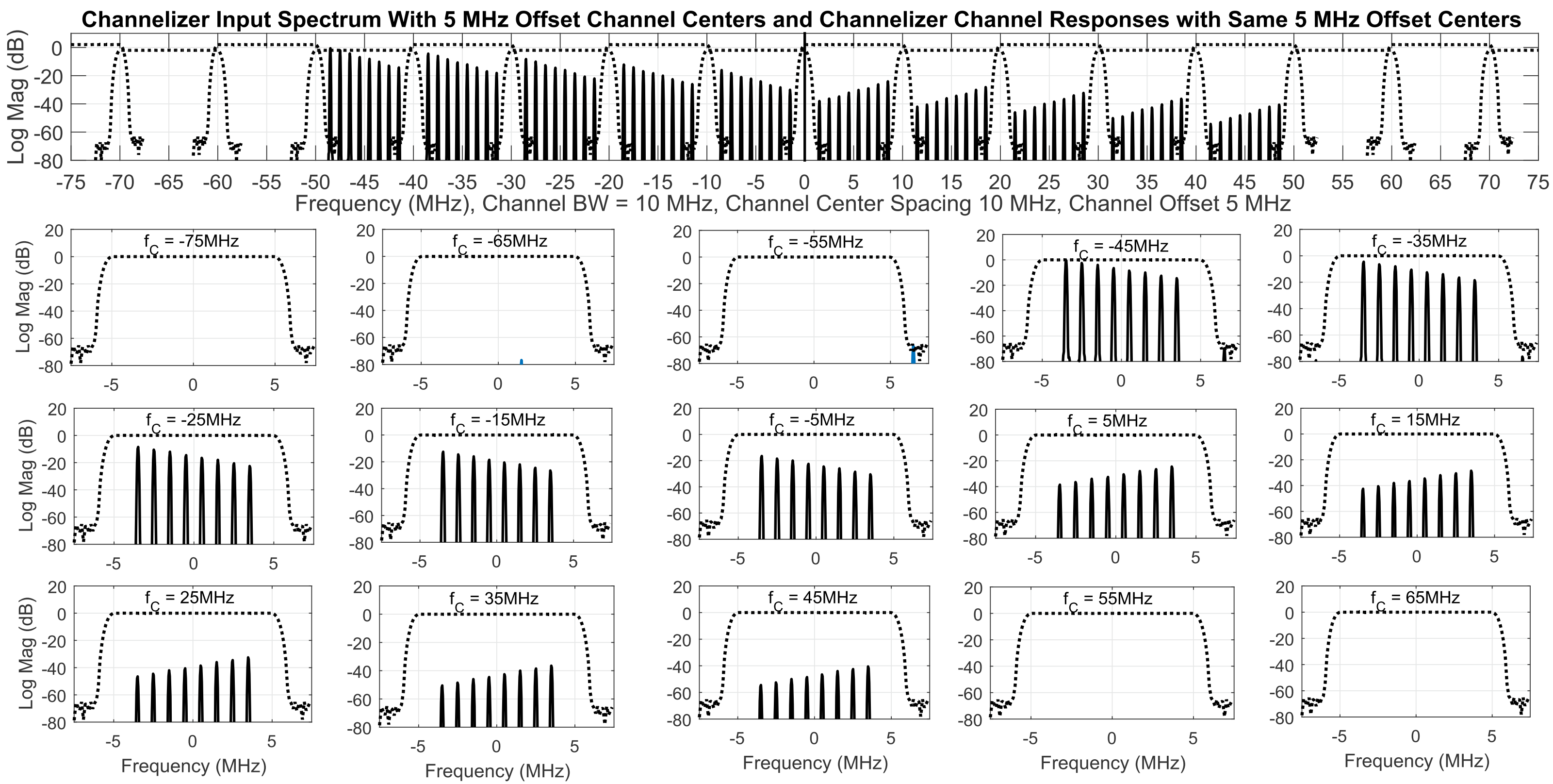
Center Frequencies:
Match Roots of Z^N+1, N Roots of -1, exp(j π /N) exp(j 2π k/N)



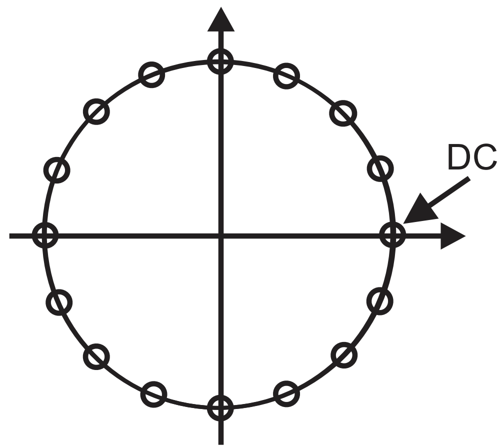
Even Indexed Frequency Bins
Even Multiples of Half Channel Width



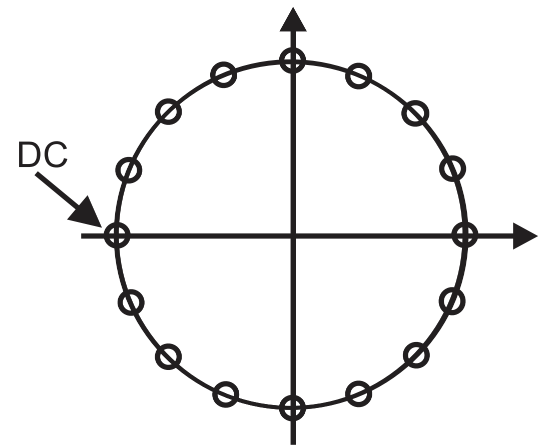
Odd Indexed Frequency Bins
Odd Multiples of Half Channel Width



Symmetry of Zeros at DC and at fs/2 of a 16 Point DFT

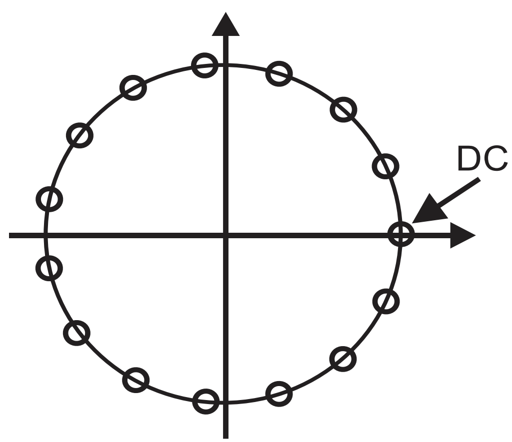


DC at Index 0
of 16 Point DFT

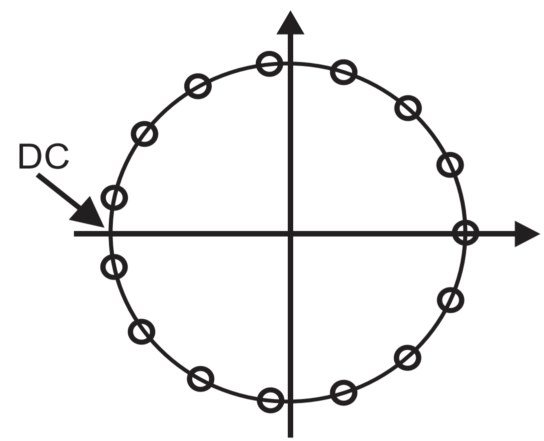


DC at Index 8
of 16 Point DFT

Asymmetry of Zeros at DC and fs/2 of a 15 Point DFT

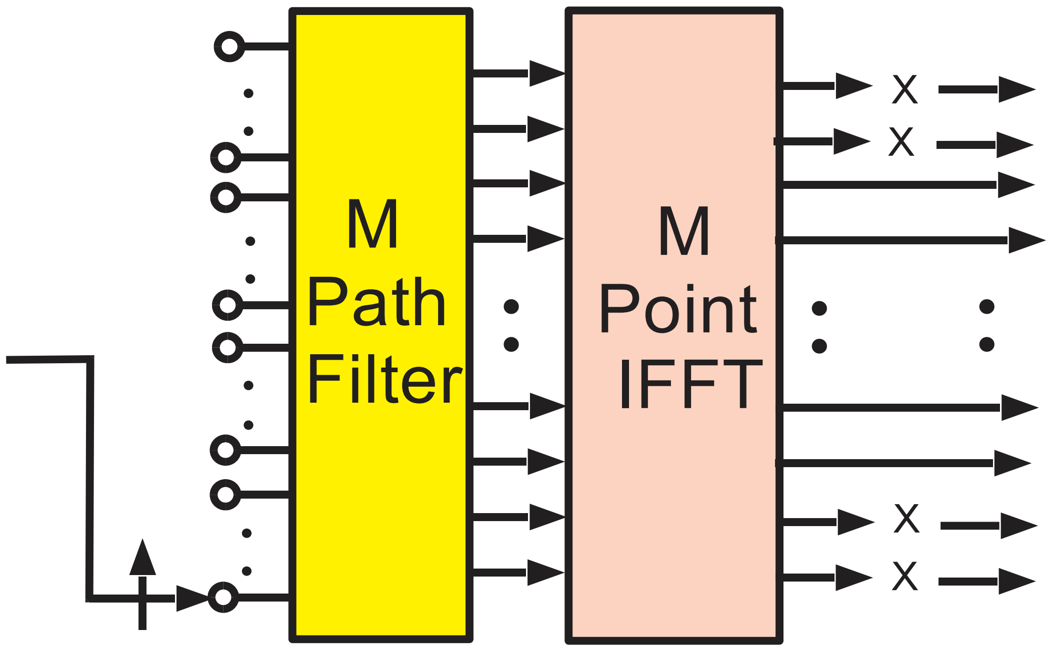


DC at Index 0
of 15 Point DFT

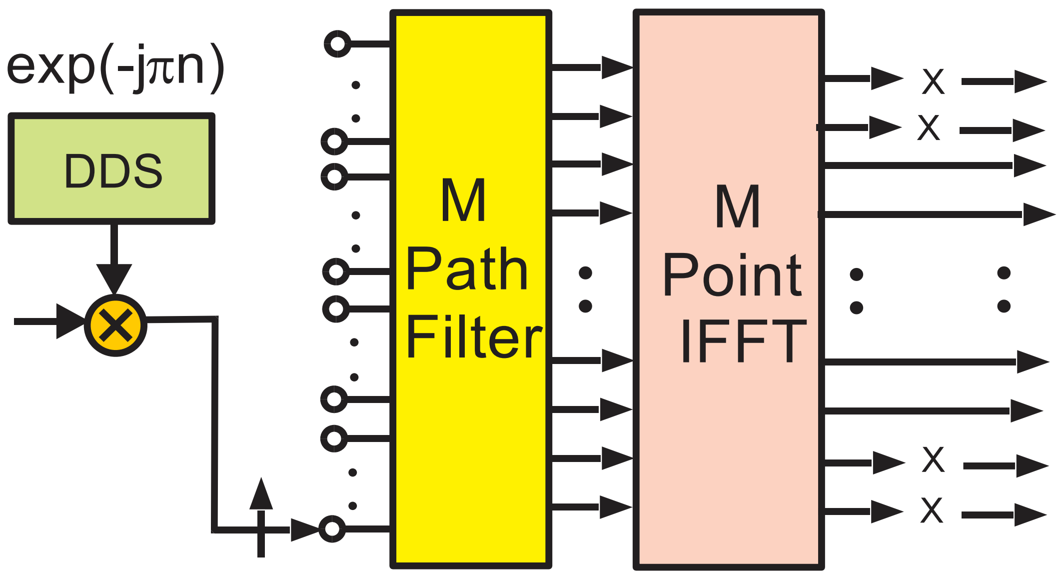


DC at Index 7.5
of 15 Point DFT

M-Path Channelizer For Even Indexed DFT Bin Centers



M-Path Channelizer For Odd Indexed DFT Bin Centers
Options: Shift Input Spectrum Half a Bin,
Shift Input Spectrum to fs/2



The Polyphase Filter Sees the Sign Changes of The Input Samples Because the Array has an Odd Number of Samples

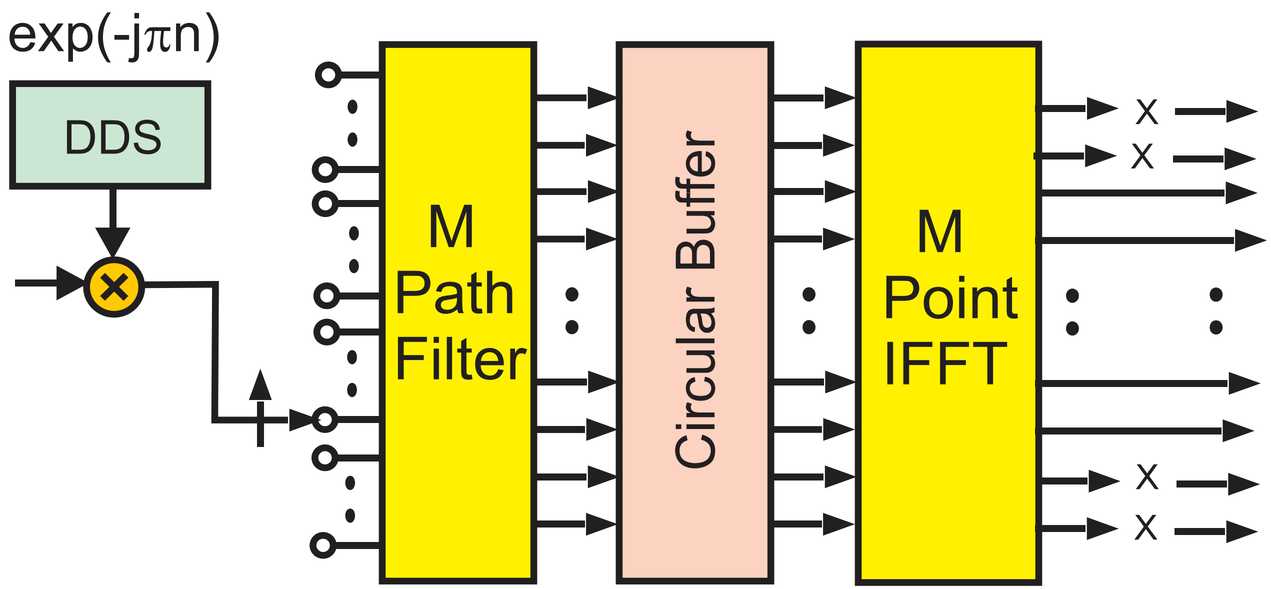
15 New Inputs with sign

data	sign	data	sign
new		old	
n	+	n-15	-
n-1	-	n-16	+
n-2	+	n-17	-
n-3	-	n-18	+
n-4	+	n-19	-
n-5	-	n-20	+
n-6	+	n-21	-
n-7	-	n-22	+
n-8	+	n-23	-
n-9	-	n-24	+
n-10	+	n-25	-
n-11	-	n-26	+
n-12	+	n-27	-
n-13	-	n-28	+
n-14	+	n-29	-

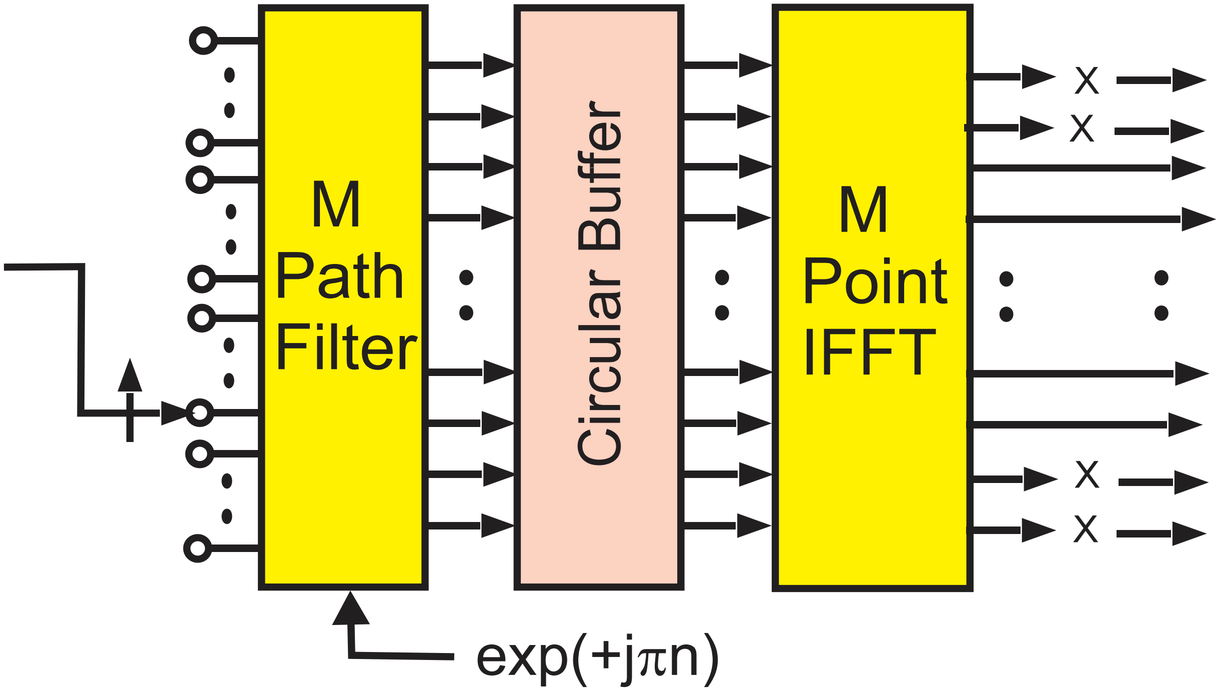
15 New Inputs with sign

data	sign	data	sign
new		old	
n+15	-	n	+
n+14	+	n-1	-
n+13	-	n-2	+
n+12	+	n-3	-
n+11	-	n-4	+
n+10	+	n-5	-
n+9	-	n-6	+
n+8	+	n-7	-
n+7	-	n-8	+
n+6	+	n-9	-
n+5	-	n-10	+
n+4	+	n-11	-
n+3	-	n-12	+
n+2	+	n-13	-
n+1	-	n-14	+

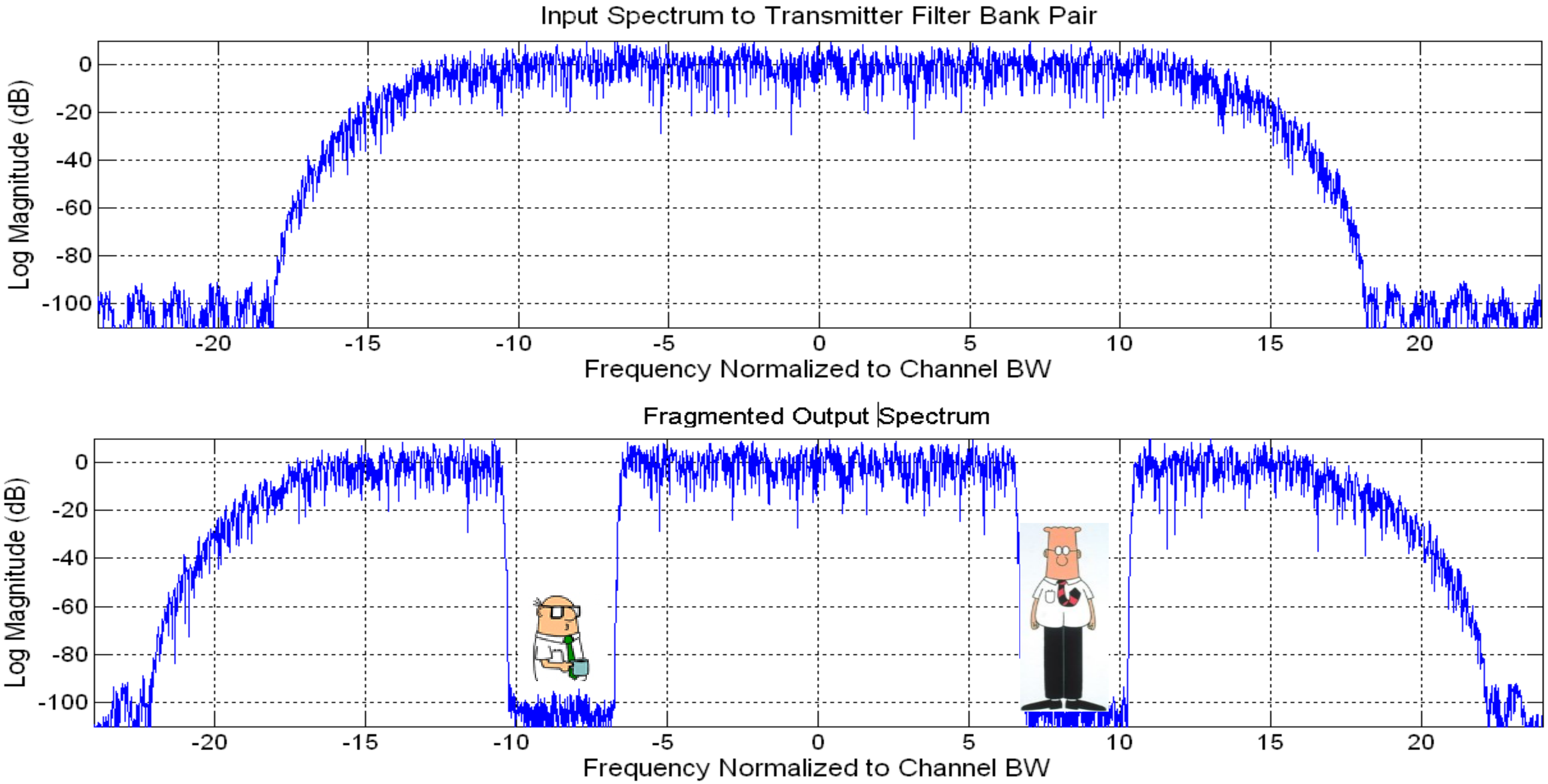
Perform a Non-Maximally decimated Filter with an Even Number of Input Points



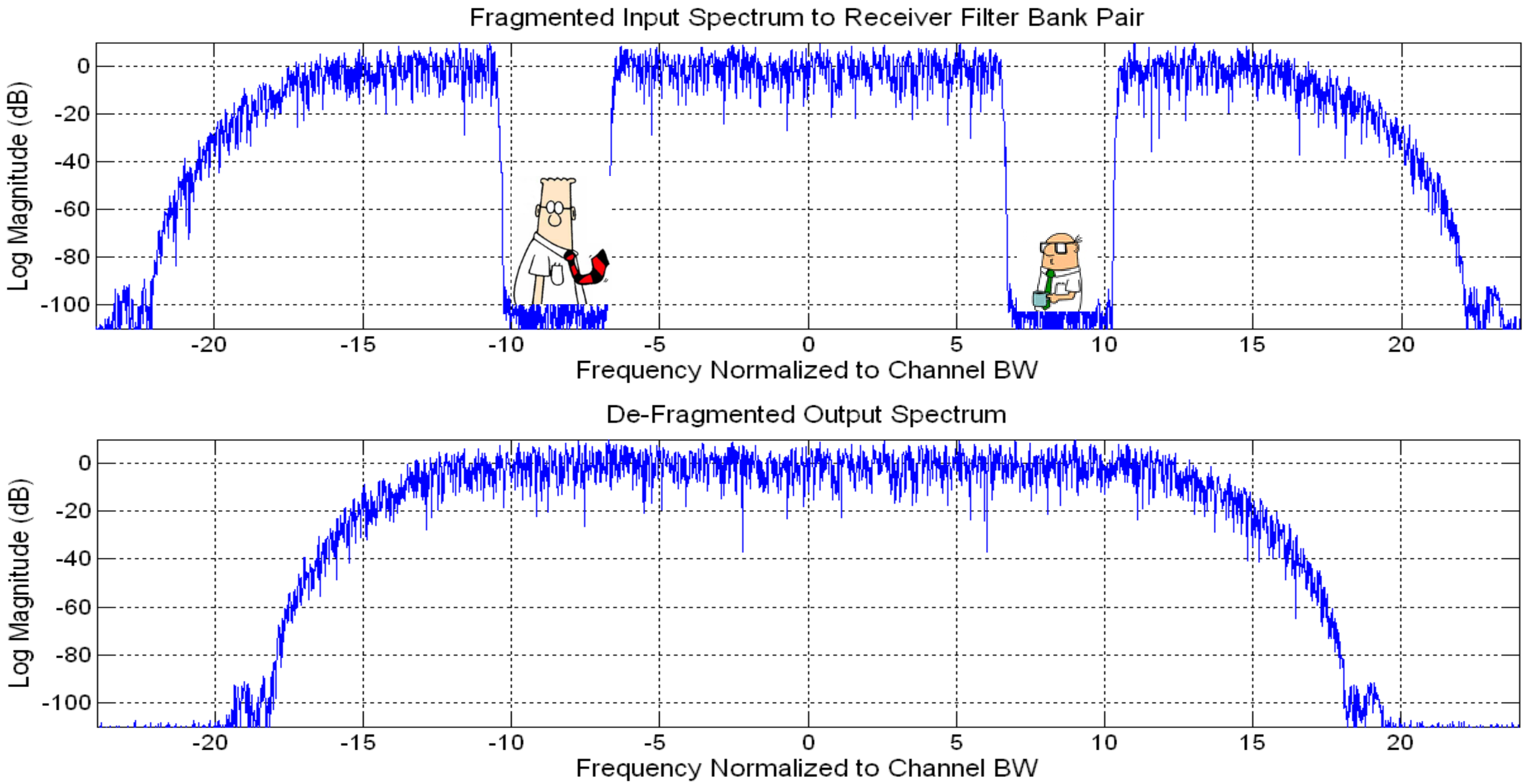
The Rotators of the Non-Maximally Decimated Filter with an Even Number of Input Points can be Embedded in the Filter Weights



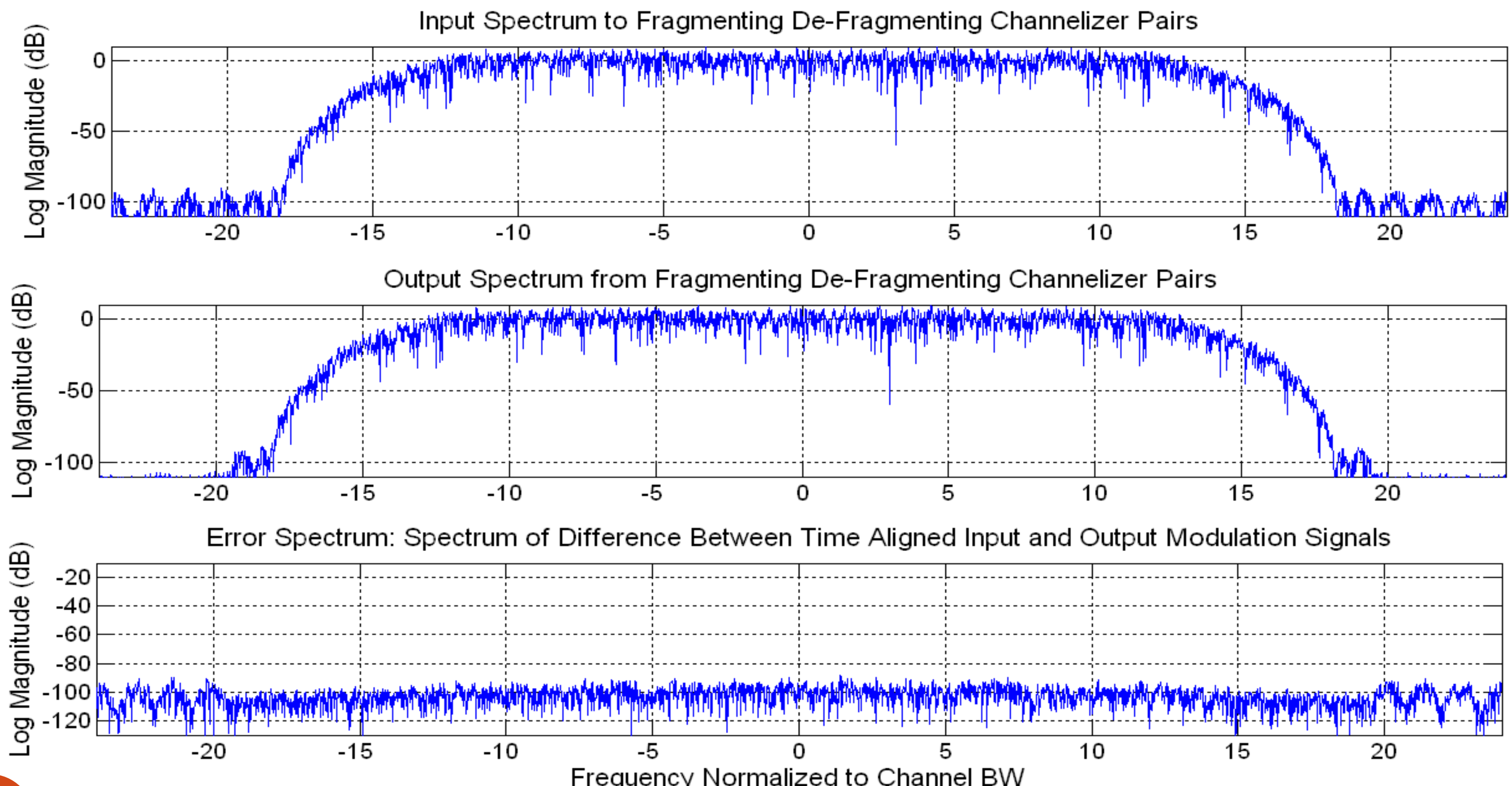
Modulation Spectra at Input and Output of Transmitter Fragmenting Channelizer Pair



Modulation Spectra at Input and Output of Receiver De-Fragmenting Channelizer Pair



Spectra: Input Modulation Signal at Transmitter Side and of Output Modulation Signal at Receiver Side of Fragmenting De-Fragmenting Channelizer Chain and of Difference Between Time Aligned Input and Output Signals



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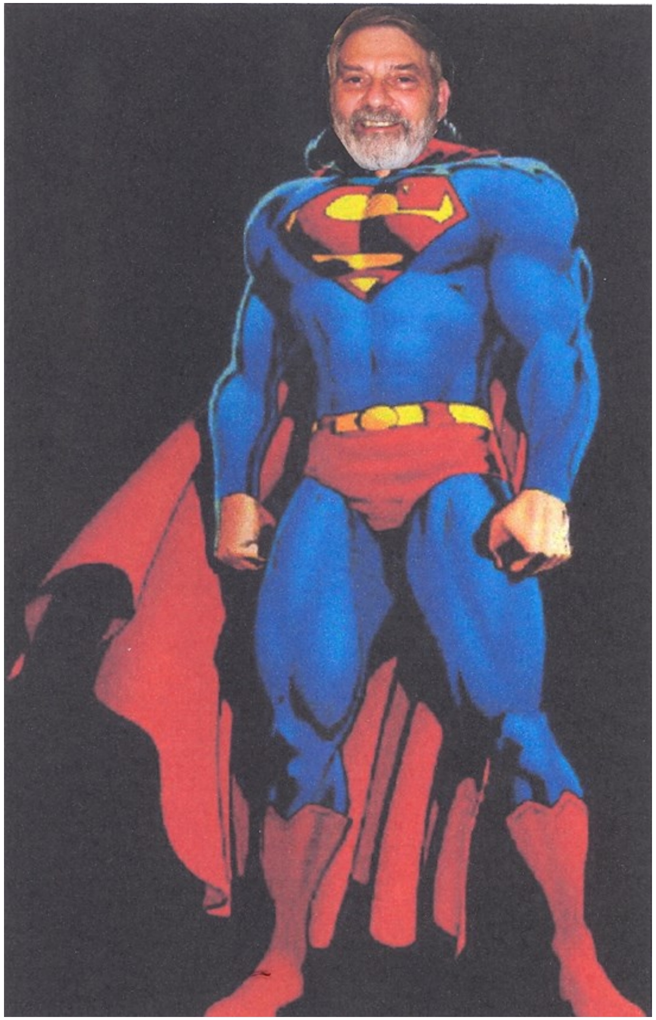
Dilbert, is it true that DSP makes the world go around but multirate signal processing supplies the music for the ride?



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Is Open For Questions