# Design Considerations for Channelizer Based Receivers in Generalized Frequency Division Multiplexed OFDM Systems

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## ABSTRACT

An OFDM signal delivered to receiver's DFT can be easily partitioned when the signal components have been assembled in a single modulator. This is because the signal contains the phase, frequency, and time aligned basis set components of the IDFT. In order to demodulate a composite signal set formed by multiple users each contributing a disjoint subset of the basis set, their transmissions must be coordinated to assure their separate contributions are time and frequency aligned at the receiver's antenna to maintain their mutual orthogonality required for DFT based demodulation. When a large number of users access the single receiver, it becomes quite difficult to coordinate transmission time and frequency offsets of each user, to assure orthogonality in the DFT. Channelizers hold the promise of user orthogonality as a channelizer property as opposed to a DFT property. Here we consider and demonstrate one channelizer contender for cell site receivers.

## I INTRODUCTION

OFDM is the signaling waveform of choice when the channel through which the signal is delivered exhibits significant multipath spreading. The OFDM symbol spans a fixed time interval and the wave-shape in that interval is formed as the weighted sum of multiple sinusoids with integer number of cycles spanning the interval. The sampled data version of these multiple sinusoids coincide with the basis set of a discrete Fourier transform (DFT). At the modulator we form the weighted sum of sinusoids by an inverse fast Fourier transform (IFFT). In the absence of channel induced distortion, we can use the FFT to project the composite wave-shape upon the basis vectors to determine the amplitudes of each of the received sinewaves. With appropriate and minor modifications, involving a guard interval between adjacent symbols and insertion of a cyclic extension in that interval, we avoid channel induced signal distortion in the symbol interval and preserve the orthogonality of the signal components.

The receiver can collect signals from more than one source with each source presenting for detection, a set of weighted sinusoids of disjoint basis vectors: for example one source might deliver sinusoids corresponding to positive frequencies while a second source delivers sinusoids corresponding to negative frequencies. In order for the receiver's FFT to successfully project the received signal components upon its basis set, the intervals from the two sources must be precisely time aligned, they must have precisely the same carrier frequency and they must have approximately the same signal strength. These conditions must be satisfied for sources at different distances from the receiver and with different velocity vectors between platforms hence with different Doppler shifts. The way this multiple access problem is resolved today is to have the cell site track the range and range rate to each user and direct offset transmission start times for each user so that all the separate signals from the users arrive at the receiver antenna at the same time.

The cell cite also direct each user to offset their carrier frequencies to be aligned with the receiver's carrier frequency. As we increase the bandwidth of next generation cell systems by an order of magnitude and as the number of multiple access users increases proportionally, it becomes apparent that the current control process will not be able to manage the signal alignment task.

A number of approaches have been proposed to modify the modulation format. A number of them rely upon the use of channelizers to decouple the signals received from different users. These proposed options include Generalized Frequency Domain Multiplexing (GFDM), Universal Filtered Multi-Carrier (UFMC), Filter band Multi-Carrier (FBMC) and a number of others. The common attribute of these alternate modulation schemes is the passband bandwidths of the channelizer will supply the desired orthogonality between the multiple users and the OFDM signal sets within each channel will no longer have to be time aligned nor carrier frequency matched to maintain their mutual orthogonality. The design of the channelizers and the design of the

OFDM signal set in the channels are coupled and interact in interesting ways which have not been examined in earlier papers. We study one particular option to illustrate the coupling and the options involved in the modulation and channelizer designs.

## II SC-OFDM MODULATORS

The modulation we have chosen to examine is shaped SC-OFDM. In particular the time domain input signal is a QPSK vector containing 32 time samples. The processing of this vector is shown in figure 1. The input vector is brought to the frequency domain by a 32-point FFT. The 32 spectral samples are repeated and inserted in a 96 point frequency domain array. The widened spectrum is weighted by a 48-sample 50 percent excess bandwidth SQRT Nyquist spectral weight vector. This spectral weighted vector is returned to the time domain by a 96-point IFFT as a SQRT shaped and 1-to-3 interpolated version of the original input time series vector. A 24-sample segment of the 96 point array is appended as a cyclic prefix to the beginning of the array to form a 120 point sequence for each shaped SC-OFDM symbol. Figure 2 shows the time series form the shaped SC-OFDM demodulator operating at 1-to-3 up-sampled rate from the modulator and the 3-to-1 down-sampled samples corresponding to modulator input samples. We also see here the spectrum formed at the modulator output shaped by the SQRT Nyquist spectral weights and the spectra formed at the demodulator output shaped again by the SQRT Nyquist spectral weights set.

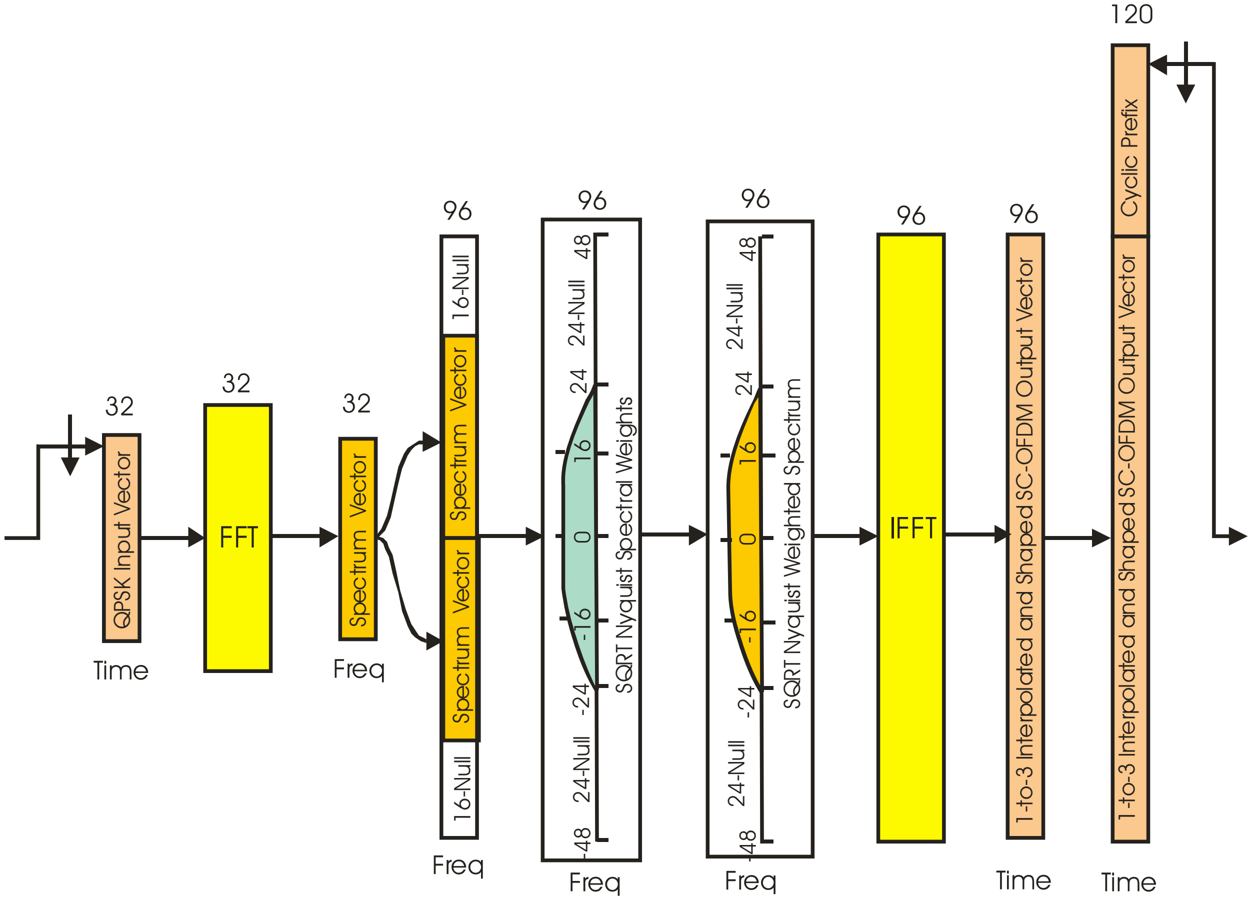


Figure 1. Signal Flow through Shaped Single Carrier OFDM Modulator. 32-Point Input Time Vector, 32-point FFT Frequency Vector. Expanded Vector for 48-Point 50 Percent Excess BW Shaped SQRT Nyquist Weight. Shaped Frequency Vector 1-to-2 Up-sampled for 96 Point Frequency Vector, Sample Rate Twice Two Sided Bandwidth. 96-Point FFT, 96 Point shaped and 1-to-3 Interpolated Modulation Time Series

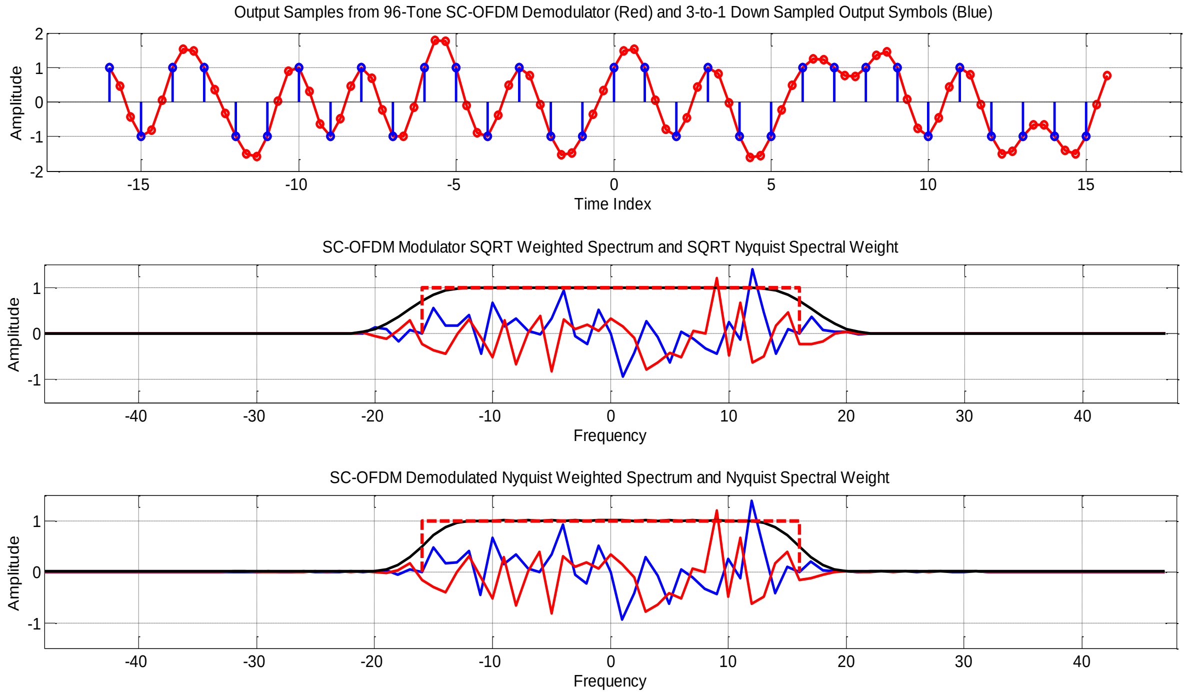


Figure 2. Top Subplot: Time Series Output from Cascade Shaped SC-OFDM Modulator and Demodulator (Red) and the 3-to-1 Down-Sampled Demodulated Samples (Blue) and next two Subplots, Spectra and Shaping Filter at Modulator Output and Demodulator Output Respectively

Successive symbol sequences are formed by the modulator and presented to the synthesis channelizer filter bank for spectral confinement and spectral translation to the desired channel center frequency. The synthesis channelizer has been designed to accept 48 kHz bandwidth signals sampled at 96 kHz. The synthesis channelizer is designed for 48 kHz spacing of channel center frequencies. We form a number of SC-OFDM signal sequences to supply inputs to numerous channel center frequency ports of the synthesis channelizer. We do this so that we can test the analysis channelizer that extracts channels from the composite signal and we are interested in the filter bank's ability to separate channels with and without adjacent channel occupancy.

## II Polyphase Synthesis and Analysis Filter Banks

We now examine the specifications of the synthesis channelizer. Figure 3 presents sketches of a number of spectra illustrating the relationships between signal spectra, channel spectra, and channel filter spectra. As commented upon earlier, the two sided bandwidth of the shaped SC-OFDM signals is 48-kHz and the modulation signals were formed at a 96 kHz sample rate, a rate twice the two sided bandwidth.

The synthesis channelizer was designed with channel spacing of 48 kHz to match the signal bandwidth contained in each channel and was designed to accept signals at 96 kHz. The 2-to-1 oversampled input series presents an unoccupied spectral span between spectral replicates that enables us to design channel filters with wide transition bandwidth. The wide transition bandwidth permits us to design channelizer filters with reduced number of taps. The reduced number of taps means we will insert a smaller number of additional channel taps to the physical signal path between modulator and demodulator.

For this exercise we chose to design a 32-path polyphase filter that performs a 1-to-16 up-sample. Since the input signals have a sample rate twice the modulation bandwidth, the output sample rate from the syntheses channelizer will be 32 times the separate channel bandwidths or 1.536 MHz. The complexity of the filter bank in terms of, number of taps per path, hence number of multiplies per input sample is independent of the number of channels so that the results we demonstrate in a moment will prove to be valid for any number of channels. The length of the prototype filter is determined from the standard design equation shown in equation (1) as the ratio of sample rate to transition bandwidth times

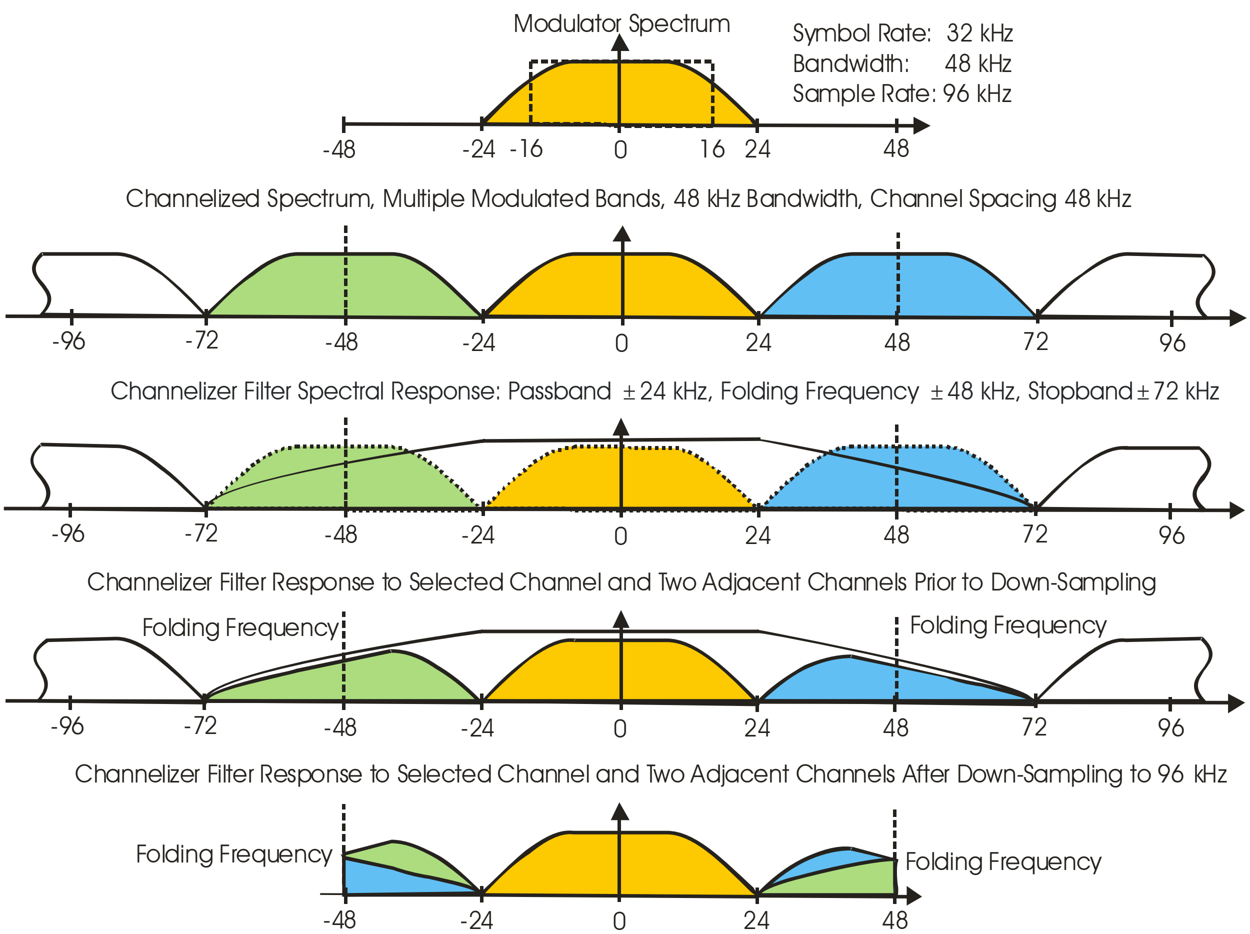


Figure 3. Spectra of 48-kHz Bandwidth Modulation Signal Sampled at 96 kHz, of Multiple-Channel Channelized components with 48-kHz bandwidths Separated by 48-kHz Center Frequencies, of Channelizer Channel Spectral Shape Showing Passband, Stop-band, and Folding Frequencies, of Channel Filter Response to Selected Channel and two Adjacent Channels Bands prior to Down-Sampling, and of Channel Filter Response Following Down-Sampling.

a term proportional to out-of-band attenuation in dB, A(dB)/22.

$$N \cong \frac{f_{smpl}}{f_{trans}} \frac{A(dB)}{22} \qquad (1)$$

As seen in figure 3 the two sided bandwidth of the prototype low-pass is 48 kHz and the transition bandwidth of the filter is also 48-kHz. So the filter length N for a nominal 66 dB stop band attenuation, as shown in equation 2, is 96. When the filter weights are partitioned in a 32 path filter, we find that each path contains only 3-weights.

$$N = \frac{32 \cdot 48\ kHz}{48\ kHz} \frac{66}{22} = 32 \cdot 3 = 96 \qquad (2)$$

Passing through both synthesis and analysis filters we would have a composite impulse response of 5 samples. Thus the additional channel length due to the modulated signal passing through the synthesis and analysis filter banks is only 5 taps; but we have a surprise coming! Figure 4 shows the Impulse response and the frequency response of the prototype low pass filter embedded in the 32-path channelizes. Here we see the wide transition bandwidth of the filter extends through the adjacent channels and overlaps the edge of the next adjacent channels. The transition crosses the next adjacent channel edge below their -40 dB levels so their alias contribution back into the center channel is greater than 80 dB below full scale. Figure 5 shows the impulse response of the synthesis filter at its output rate 1536 kHz and then the analysis filter at its output rate 96 kHz. Note that when down sampled 3-to-1 to symbol rate, the polyphase filter samples, indicated by solid red 'o's, contribute no ISI. This proved to be a pleasant surprise. We pay no cyclic prefix penalty when we use the properly designed channelizer. This awareness runs counter to a number of papers we have seen that address the expected channel lengthening due to the channelizer's presence in the signal delivery path.

## III Channelizer Performance

The upper subplot of figure 6 shows the time response of a single shaped SC-OFDM modulator operating at its output rate of 96 kHz (red) and the interpolated 1-to-16 time response of the 32-path polyphase filter bank operating at output sample rate of 1536 kHz. We note the 3-sample delay at inserted in the input sequence to align it with the output sequence. In this subplot the channelizer had, only one input port active, the one at DC, labeled in the lower subplot as channel 0. The lower subplot of figure 6 shows the spectrum from the 32-path channelizer operating with seven modulated input sequences. We also see here as an overlay, the frequency response of the prototype low pass filter which characterizes the frequency response of each channel filter in the channelizer.

Figure 7 shows the spectra from short sequences in the 12 channels -5 through +6 identified in figure 6. These signals were extracted from the composite input signal by the 32 channel analysis filter bank. The time series processed for each subplot are of the 96 samples of the shaped SC-OFDM symbols described in the earlier sections. It is useful to compare the channelized spectra of figure 7 with the composite spectrum of figure 6. Remember the channels are spaced 48 kHz apart but have been sampled at 96 kHz. This means that each channel output contains at its center the selected input channel spectrum as well as half of the spectra in the two left and right adjacent channels. For instance, subplot(3,4,6) in figure 7, labeled chan(0) presents the spectrum of chan(0) of figure 6 and since the adjacent channels are not occupied the spectrum is isolated. On the other hand, subplot(3,4,7) in figure 7, labeled chan(1) presents the spectrum of chan(1) of figure 6. Since chan(1) of figure 6 is not occupied the center of the spectral display in subplot(3,4,7) is empty. What we do see in this subplot on the left side of the display is the spectral energy from chan(0) in the subplot (3,4,6) to the immediate left. Interesting, and at first a bit confusing, chan(2) the spectral span to the right of chan(1), as seen in figure 6, is empty yet the right hand side of the spectral display of chan(1) contains spectral energy. This energy is the alias from the left hand side of the same spectral plot. It might be useful to revisit the bottom subplot of figure 3 that shows the spectral edges of the channelized signal contains energy from the left and right neighbors at their left and right positions but also contain aliased components from the left and right neighbors at the wrapped right and left positions.

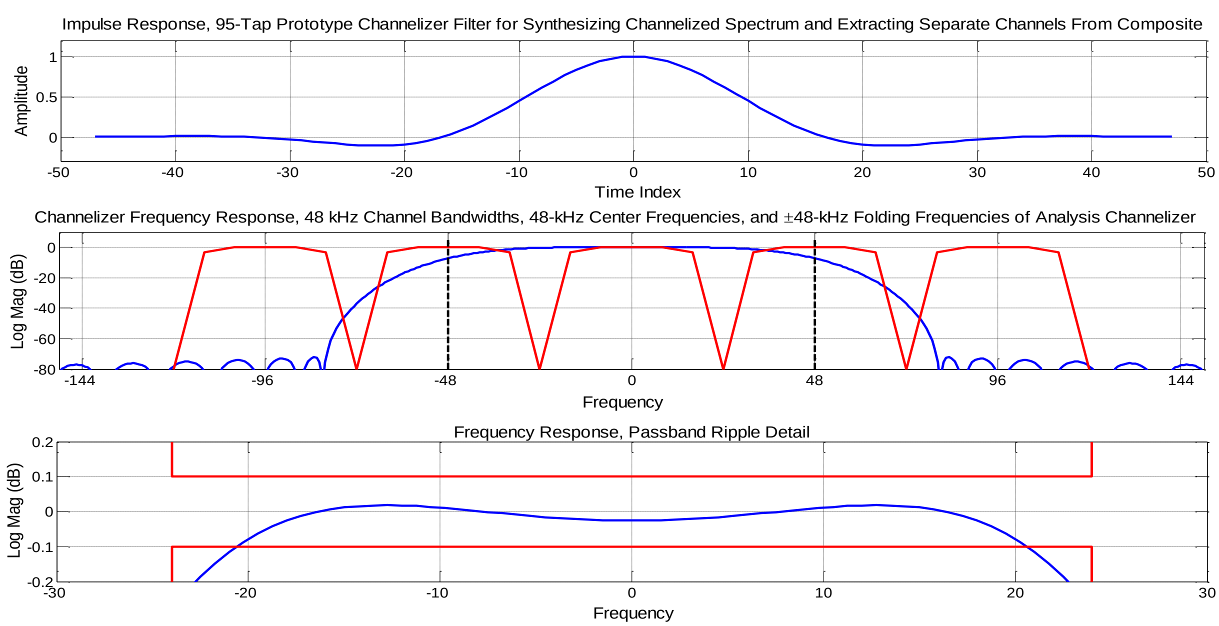


Figure 4. Impulse Response and Frequency Response of Prototype Low-Pass Filter Embedded in M-Path Synthesis and Analysis Channelizers

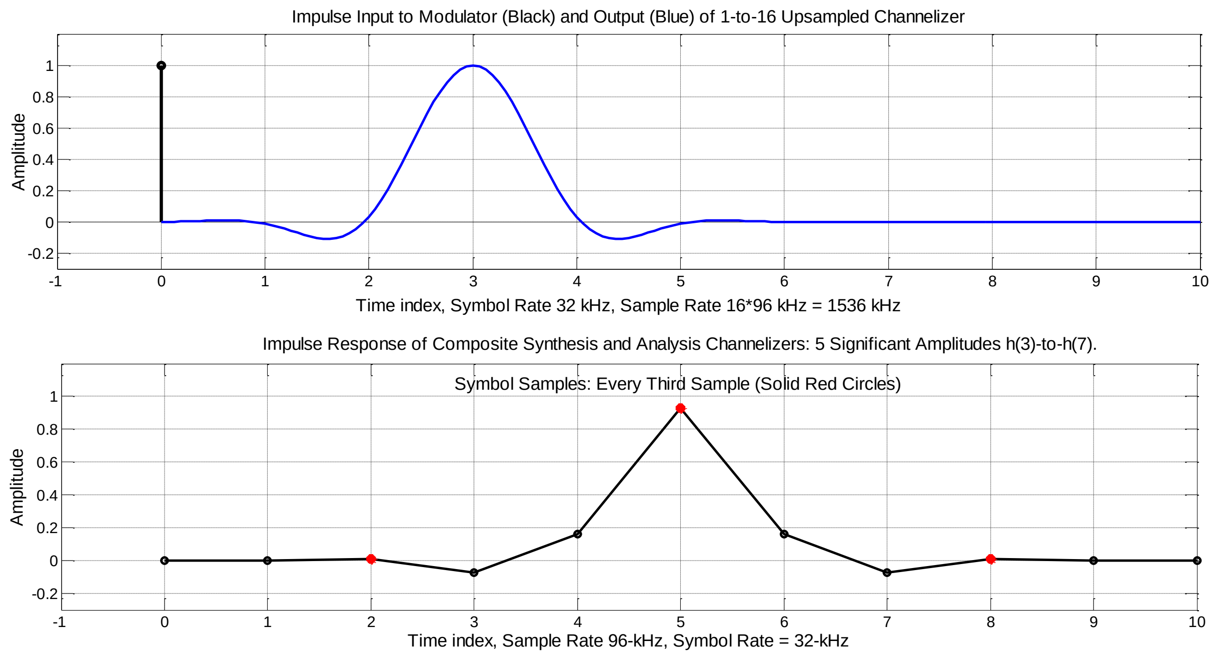


Figure 5. Impulse Response of Synthesis Channelizer at 1536 kHz Sample Rate, and of Cascade Analysis and Synthesis Filter Banks at 96 kHz Output Sample Rate and at 3-to-1 Down Sampled Symbol Rate 32-kHz

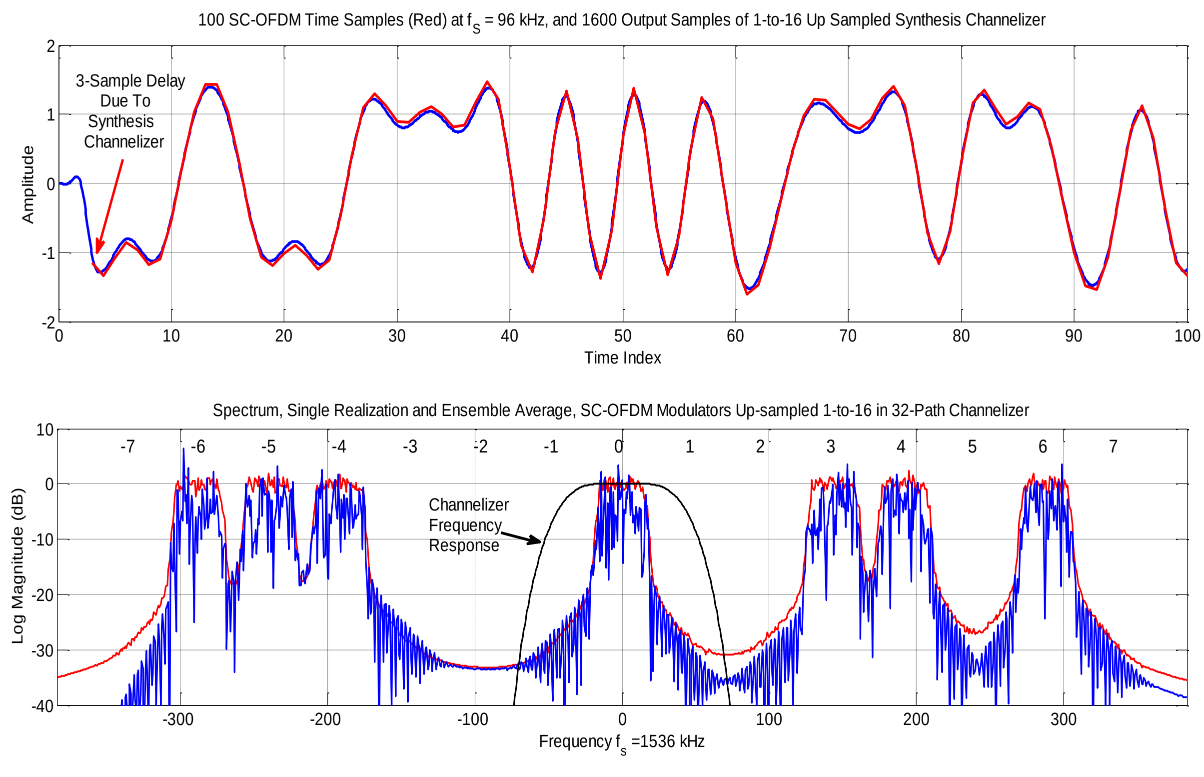


Figure 6. Upper Subplot: Offset Input Sequence and Output Sequence for Single Baseband Modulated SC-OFDM Signal. Lower Subplot: Spectrum of 32-path Channelizer with Seven Active Output Channels and Spectrum of Channelizer Frequency Response

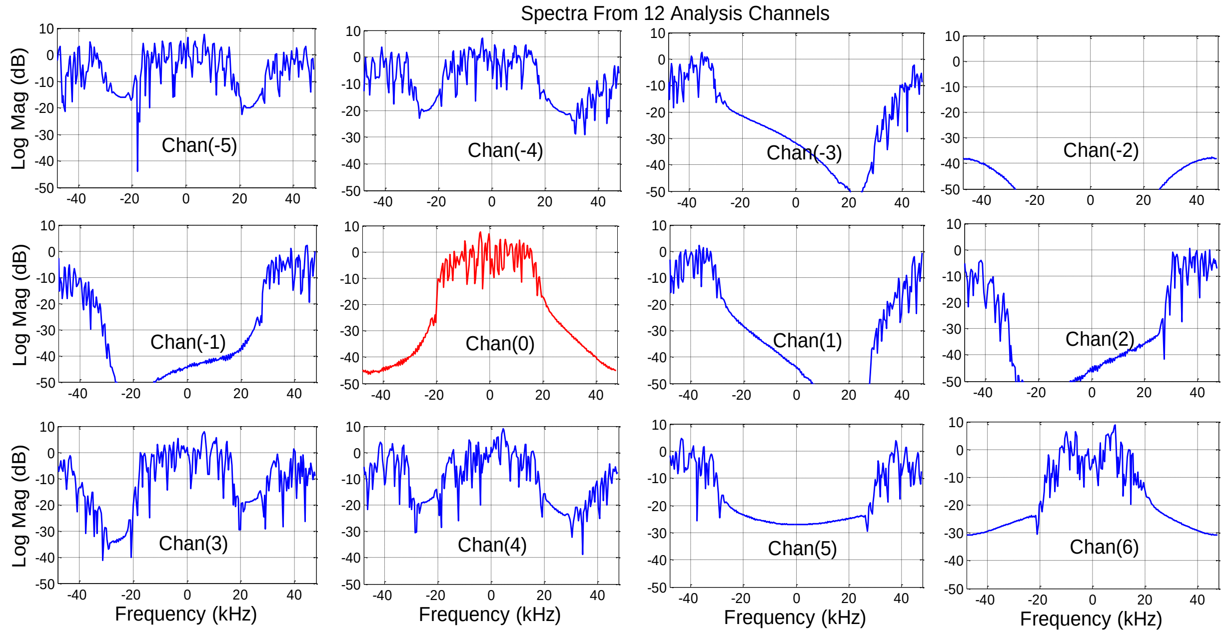


Figure 7. Spectra from 12 Analysis Channels of 96 Sample Modulation Sequences Separated by the 32 Path Polyphase Analysis Filter Bank. Modulation Symbol Rate 32 kHz, Modulation Two Sided Bandwidth 48 kHz, Channel Sample Rate 96 kHz, Channel Spacing 48-kHz. Spectral Tiles are 50% Overlapped. Channel (1) Frequency -48 kHz is same as Channel (0) Frequency 0 kHz and same as Channel (-1) Frequency +48 kHz.

During normal operation of the Shaped SC-OFDM demodulator, the receiver identifies the 120 sample block boundaries of the received signal, discards the 24 samples of cyclic prefix, and transforms the remaining 96 symbol samples to form the spectrum of the modulation time segment. The top subplot of figure 8 shows the real and imaginary parts of one 96 sample segment. We see here the spectral span bracketing zero frequency is the desired spectral contribution from channel -5 while the spectral spans about the half sample rate are the undesired contribution from the adjacent channels -6 and -4. The center subplot of figure 8 shows the spectrum of the upper subplot scaled by the SQRT Nyquist filter spectral weights. We see that the passband has preserved the desired part of the spectrum and had suppressed the undesired spectral components near the band edges. Finally the bottom subplot shows the 96 sample time series formed by the IFFT of the weighted spectrum of the center subplot. The 3-to-1 down-sampled samples of the time series, shown as stemmed samples, are the demodulated samples of the shaped SC-OFDM modulation-demodulation sequence.

Figure 9 shows, in the upper two subplots, the position specific real and imaginary constellation points from 100 SQRT Nyquist shaped SQRT SC-OFDM modulated symbols that have been passed through the 32 channel synthesis filter bank and then through the 32 channel analysis filter bank. The channel chosen for demodulation example was channel -5 of figures 6 and 7. This channel was selected because both adjacent channels in the channelizer were occupied and we wanted to illustrate that the channelizer successfully isolates the desired channel from the adjacent channel spectra as well as the adjacent channel aliased spectra. The bottom subplot shows the conventional constellation diagram from all 32 position points and from all 100 OFDM symbols.

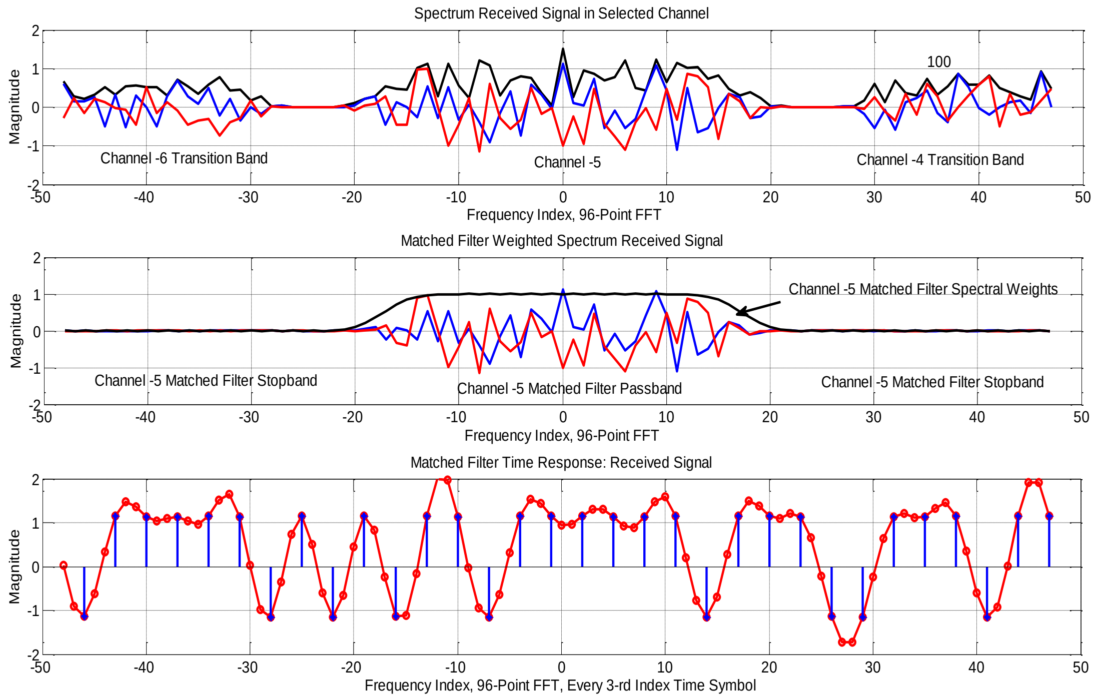


Figure 8. Upper Subplot: Spectrum of 96 Samples of Time Series from Channelizer Channel -5. Center Segment Contains Spectrum form Channel -5, Edge Segments Contains Spectral Contributions from Channels -6 and -4. Center Subplot: Spectrum after Spectral Weights of SQRT Nyquist Matched Filter, Passed Desired Spectral Region, Suppressed Undesired Spectral Regions. Bottom Subplot 96 Time Samples from 96 point IFFT of SC-OFDM weighted Spectrum. Every Third Sample is Demodulated Shaped SC-OFDM signal.

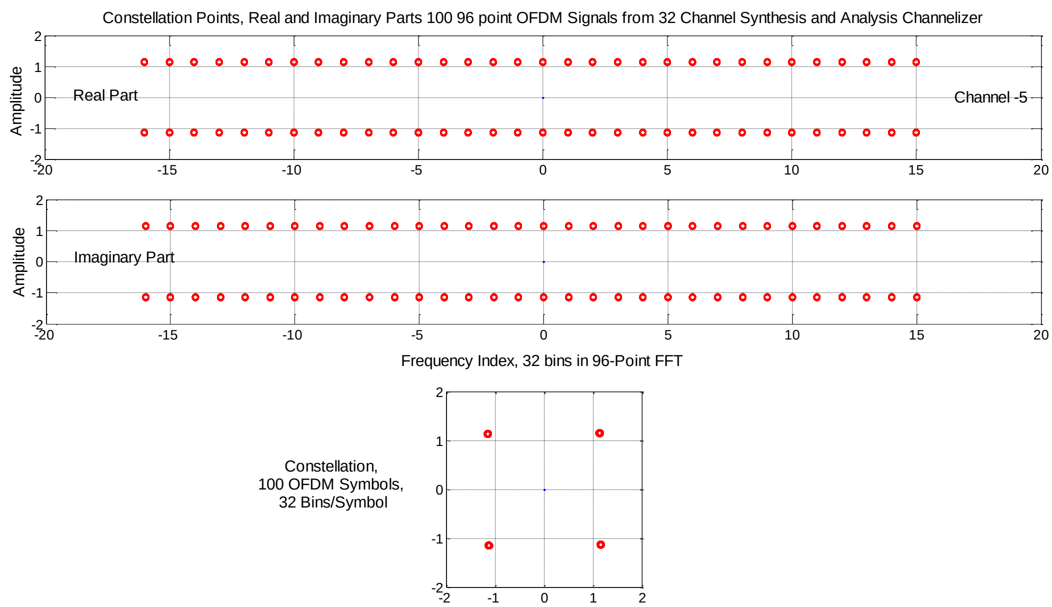


Figure 9. Upper Subplots: Real and Imaginary Components of 100 Shaped SC_OFDM Symbols Passed Through a 32-Channel Synthesis Channelizer and a 32-channel Analysis Channelizer. Selected Channel Bracketed by Occupied Channels; Analysis Channelizer and Demodulator SQRT Nyquist Spectral Weighting Terms Extracts Desired Signal and Suppresses Undesired Adjacent Signal Components. Bottom Subplot shows Constellation points for all 32 Demodulated Sample Values over the 100 Symbols.

## IV CLOSING COMMENTS

In this paper we examined use of a polyphase channelizer to separate adjacent OFDM signal bands. The adjacent bands we selected for the simulation are shaped single carrier OFDM. The shaping filters used to shape these bands are SQRT Nyquist filters with 50% excess bandwidth. We elected to use the excess as part of the channel bandwidth rather than as a guard band in conventional OFDM. The shaped SC OFDM has the added benefit of low peak to average power ratio, a desired property for the mobile transmitter.

We then presented a novel connection between the SC-OFDM up sampling sample rate and the channelizer spacing for the Channel separation and matched filter processing. In this scenario the channel filters passed the selected channel in its passband and spanned the two adjacent channels which were permitted to fold back into the span of the channel sample rate. The sample rate for each channel is 2-samples per symbol and thus the down sampled adjacent channels are seen to alias into the excess channel band afforded by the 2-to-1 excess sample rate. The novel -1-to-3 excess sample rate per channel was also shown to present precisely 2-samples time delays at final channel sam ple rate, a very small fraction of the cyclic prefix appended to the modulated signal.

## V REFERENCES

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