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Non Data-Aided Carrier Tracking Techniques for Continuous-Phase Frequency-Shift Keyed Signals

35th Annual Small Satellite Conference

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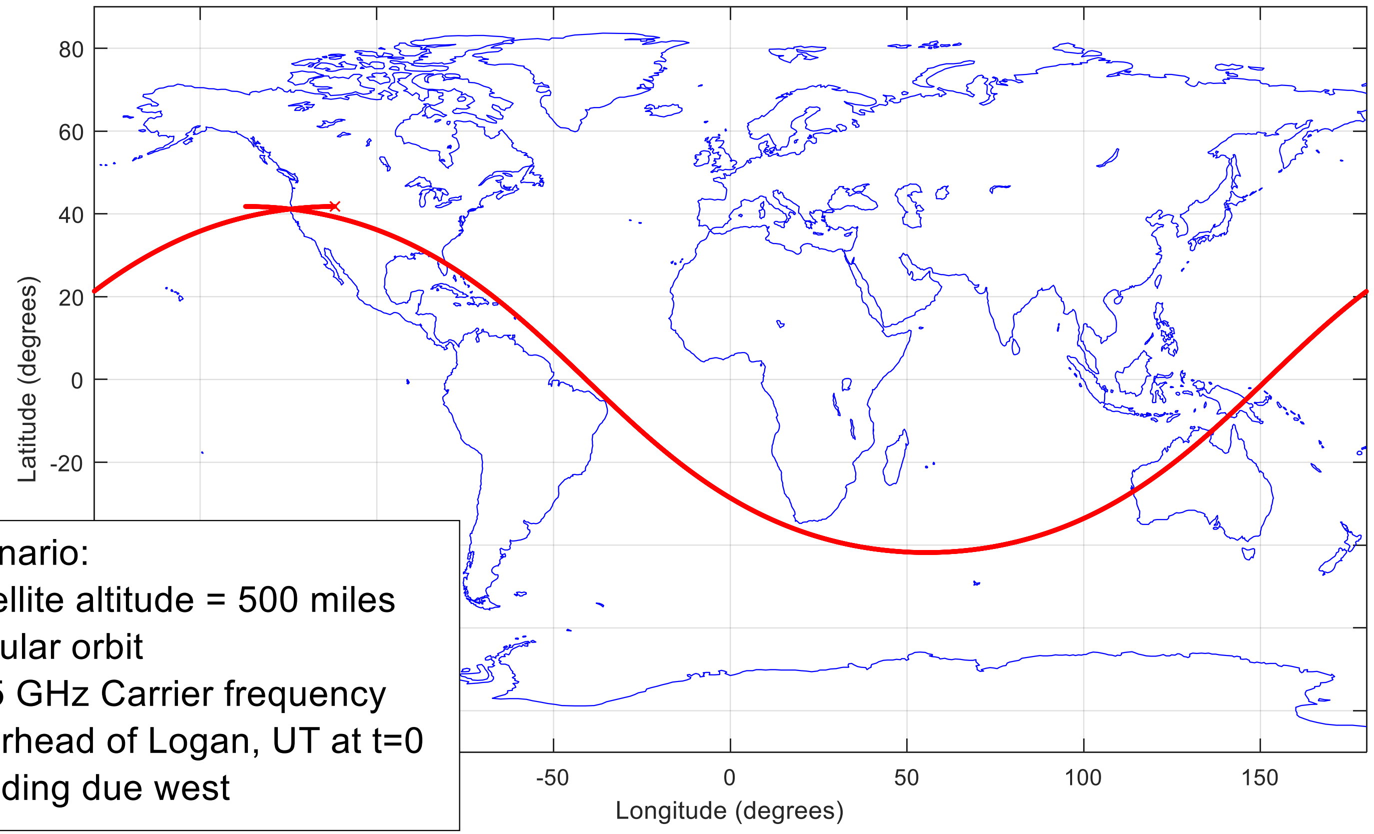
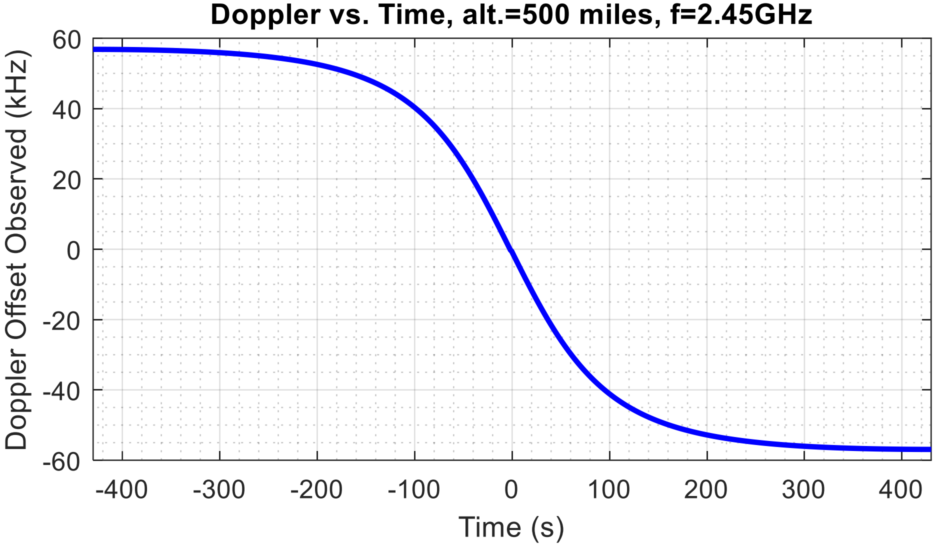
Problem: Satellite Observed Doppler vs. Time

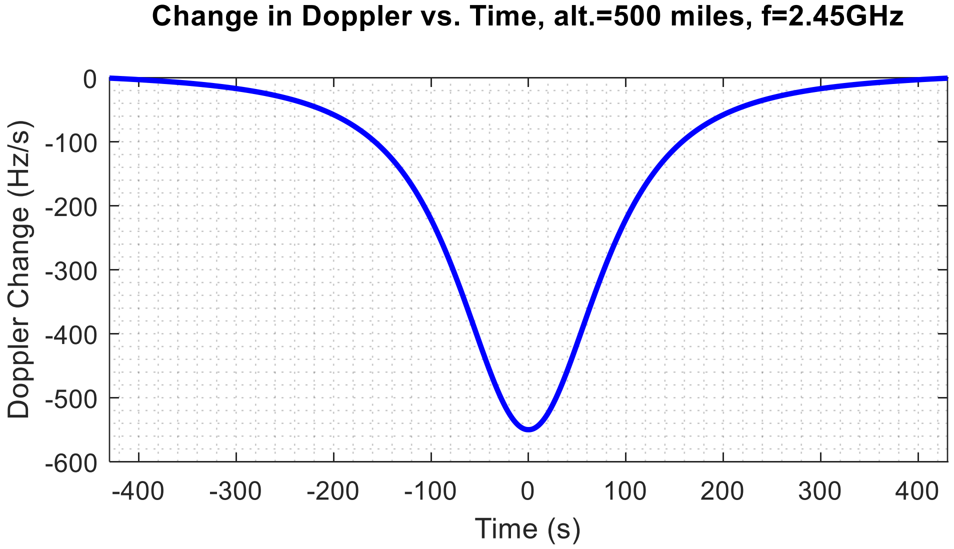
- Scenario: 500-mile altitude satellite in circular orbit flying overhead Logan, UT at t=0 heading west, 2.45 GHz carrier frequency
- Desire maximum data transfer during limited overflight time
  - 14.5 minute overflight out of 1 hour 40 minute orbit time
  - Satellite isn’t visible over same location for multiple orbits
- Doppler Changes with Time
  - Satellite’s velocity 7.45 km / s to stay in circular orbit
  - Doppler observed is proportional to component of velocity vector in direction between satellite and ground terminal
  - Peak Doppler Magnitude of 57 kHz
  - Peak rate change of -550 Hz/s
- Terrestrial radios may not have been designed to handle large Doppler frequency offsets
- Desire techniques for detecting and tracking time-varying Doppler without demodulating the signal

Doppler vs. Time During Satellite Overflight



Scenario:
Satellite altitude = 500 miles
Circular orbit
2.45 GHz Carrier frequency
Overhead of Logan, UT at t=0
Heading due west





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Band Edge Filters Review

- Optimum band edge filters have frequency response that is the frequency derivative of the matched filter frequency response
- Easy to implement for PSK signals
  - Single matched filter in receiver, symbols are chosen based on measured amplitude or phase
  - Single prototype band edge filter frequency translated to band edges to make upper and lower band edge filters
- More complicated for CPFSK signals
  - In general, separate matched filter for each possible symbol
  - Symbols are tones
- Approach: Separately add all possible positive symbols (tones) and all possible negative symbols (tones), multiply each by –j*t to take derivative in with respect to frequency
  - Complexity of CPFSK signal affects band edge filter design

Band Edge Filters for Binary CPFSK

- Maximize energy of received signal with respect to frequency offset
  - Achieved by making frequency response equal to derivative of matched filter frequency response
- Positive band edge filter is -j*t*$g_{pos}(t)$, where $g_{pos}(t)$ is matched filter for positive frequency symbol(s)
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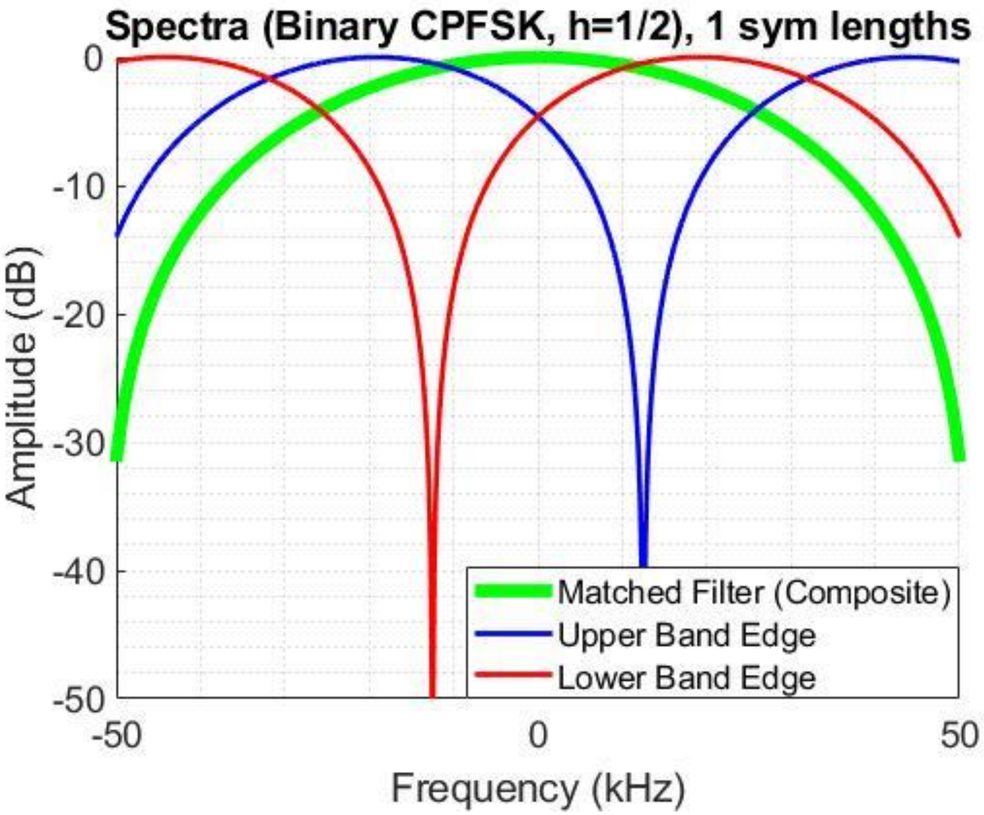
  - Tones at -12.5 kHz, +12.5 kHz



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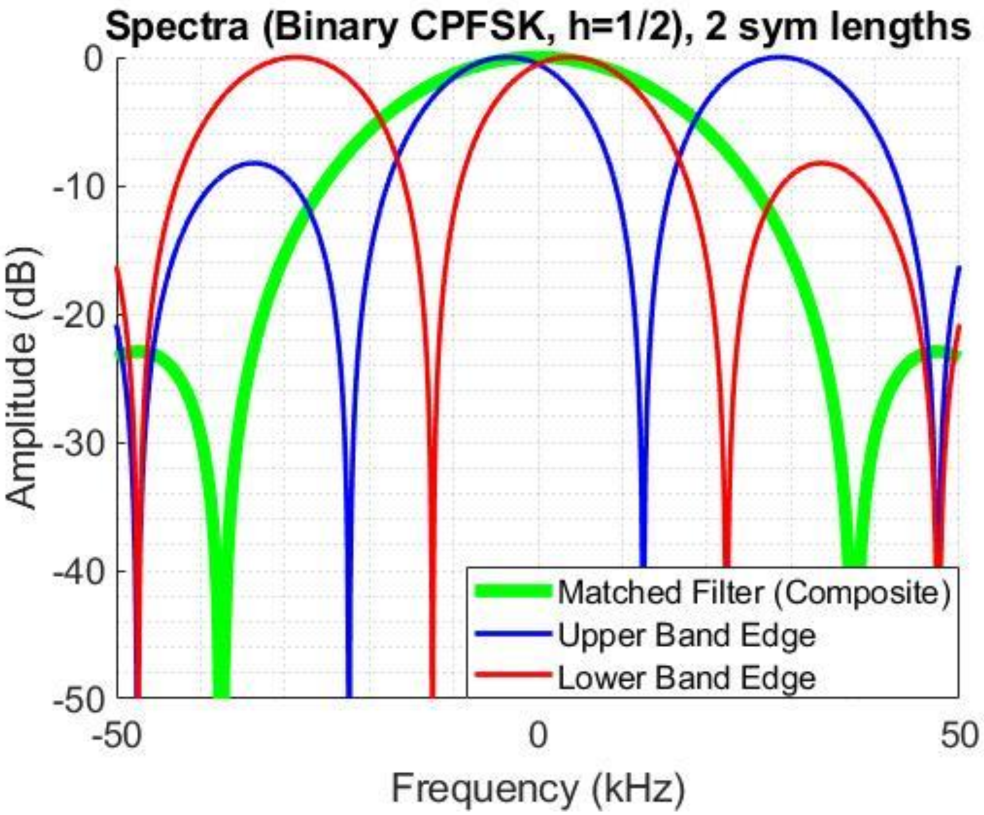

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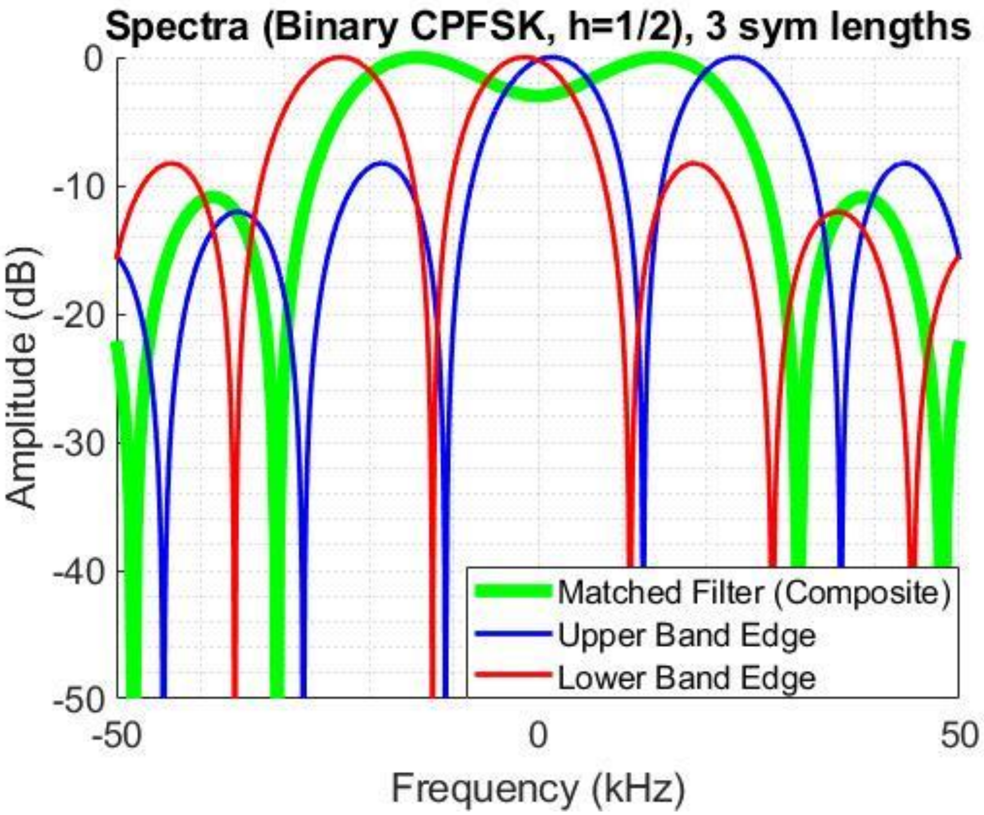

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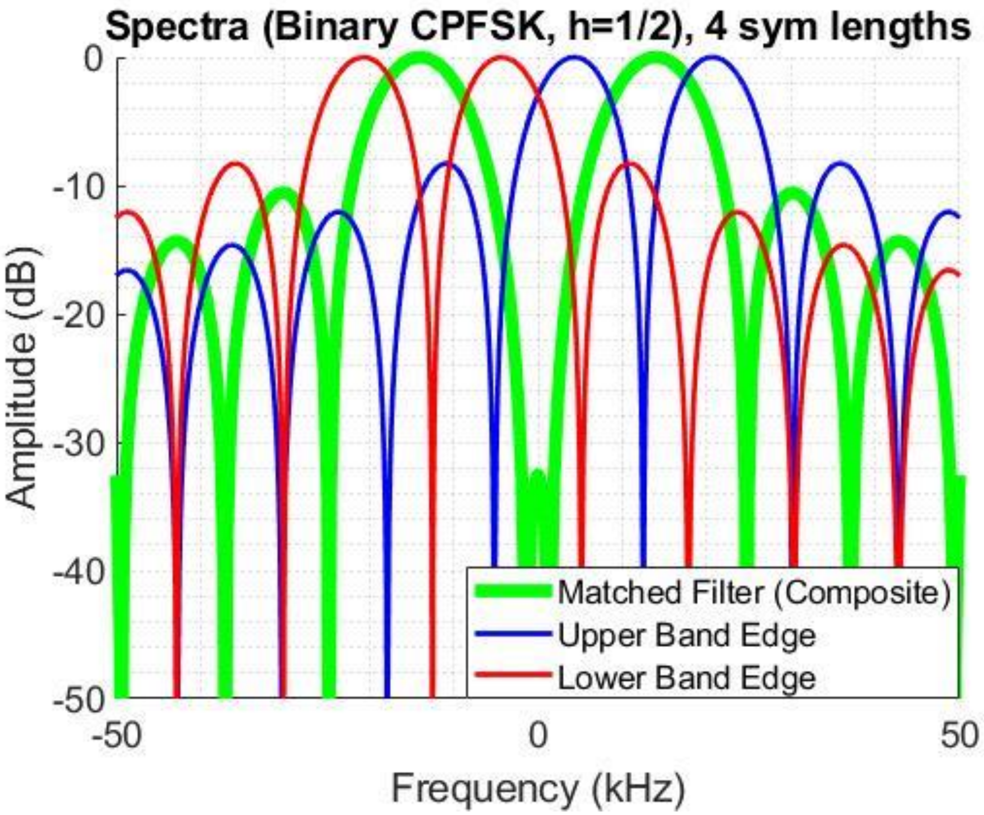

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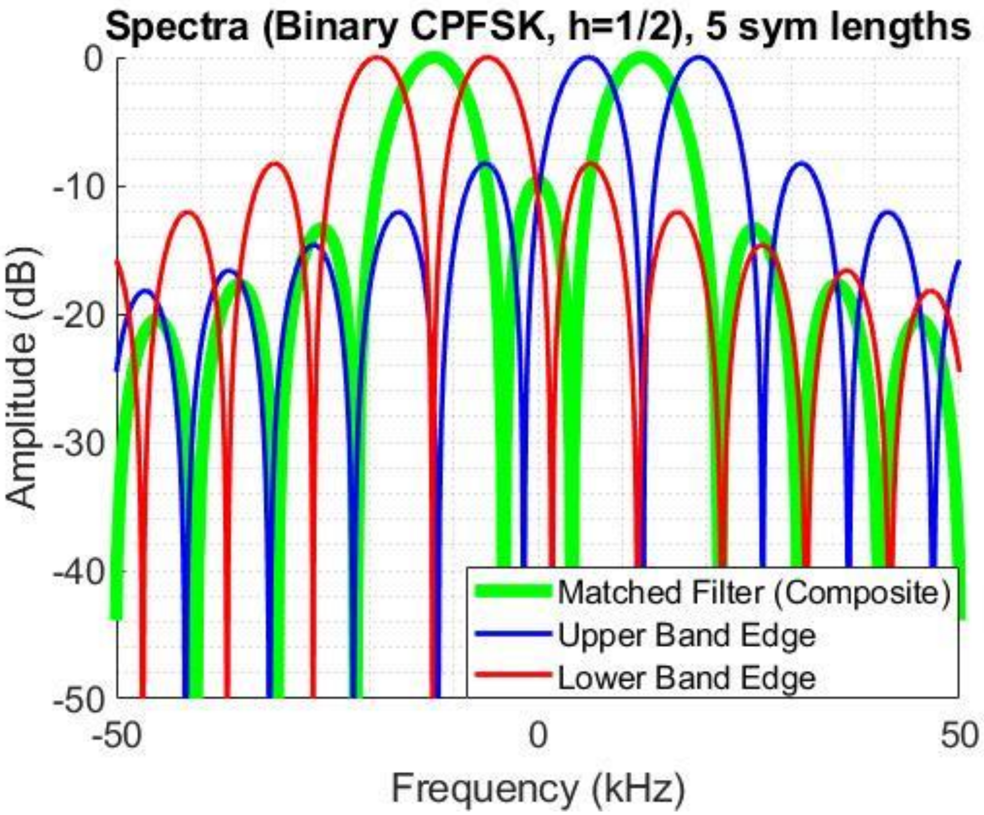

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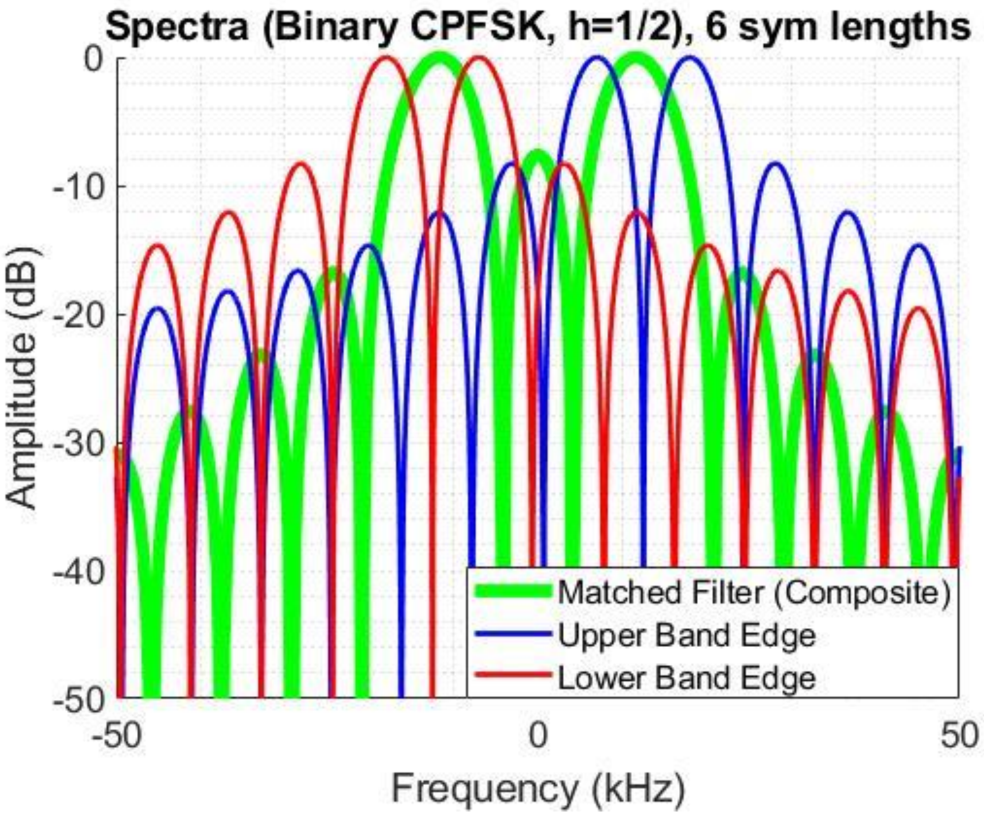

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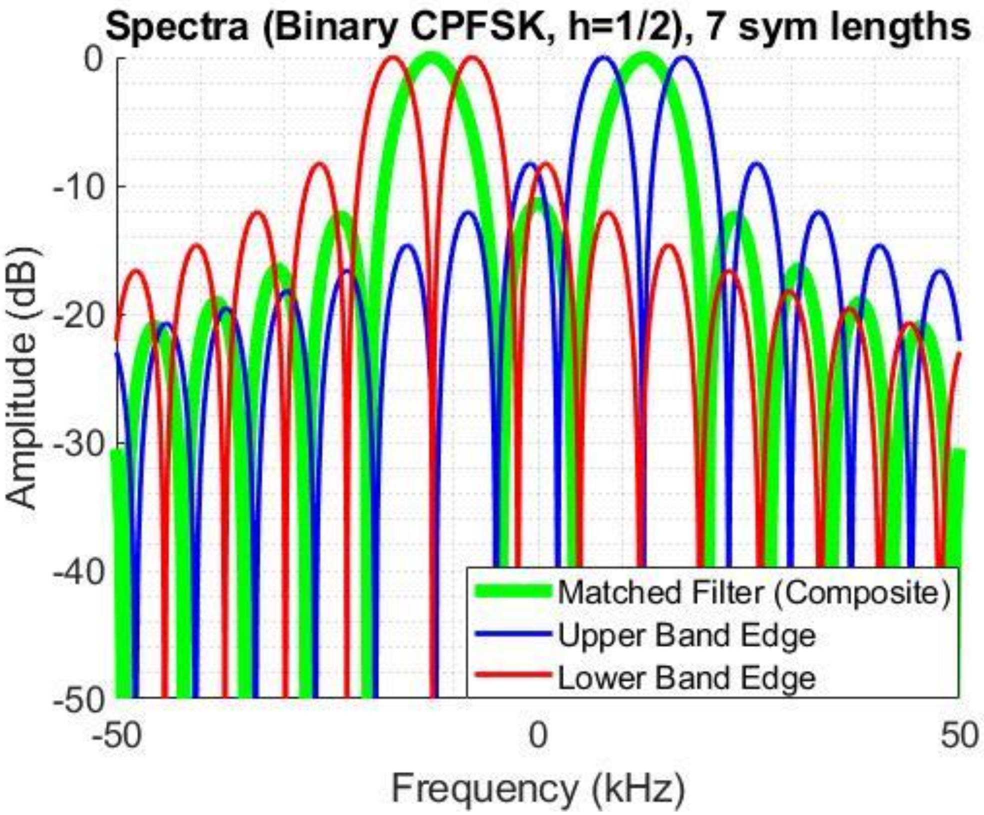

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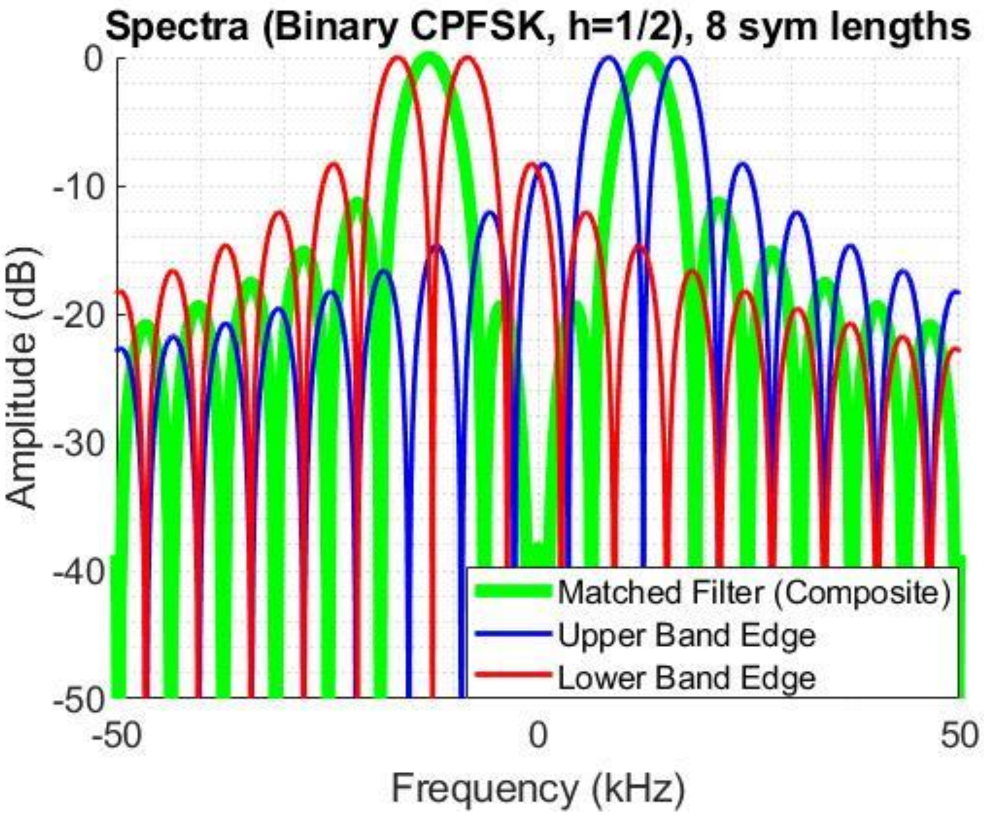

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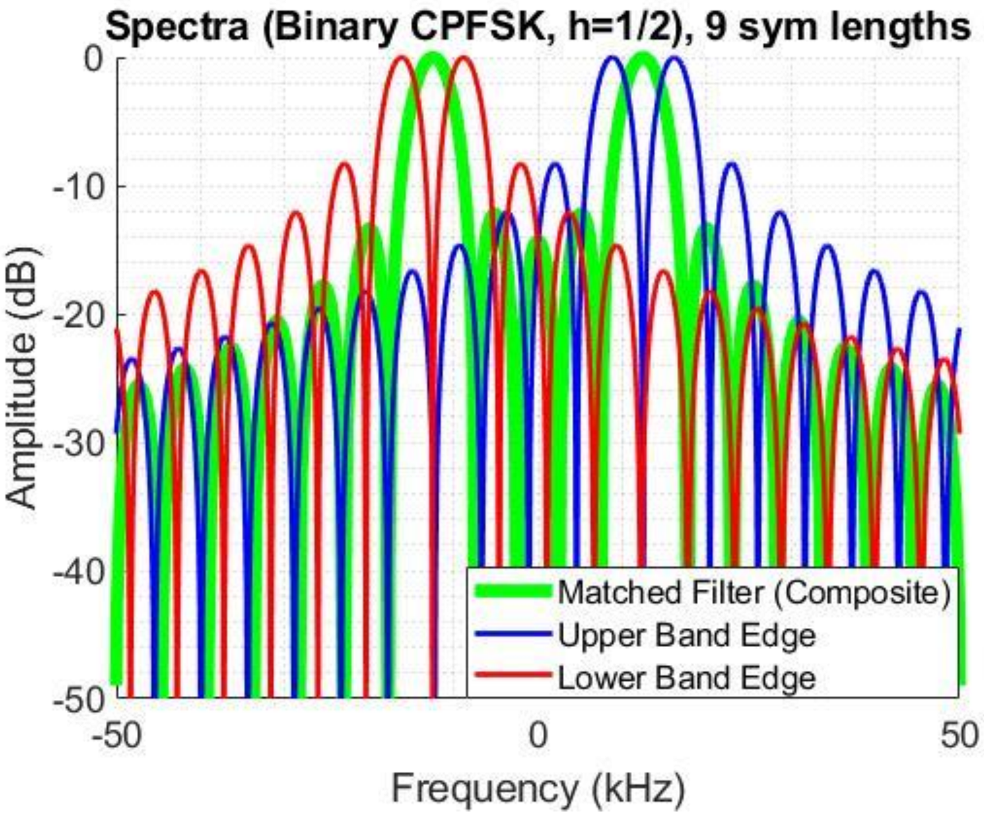

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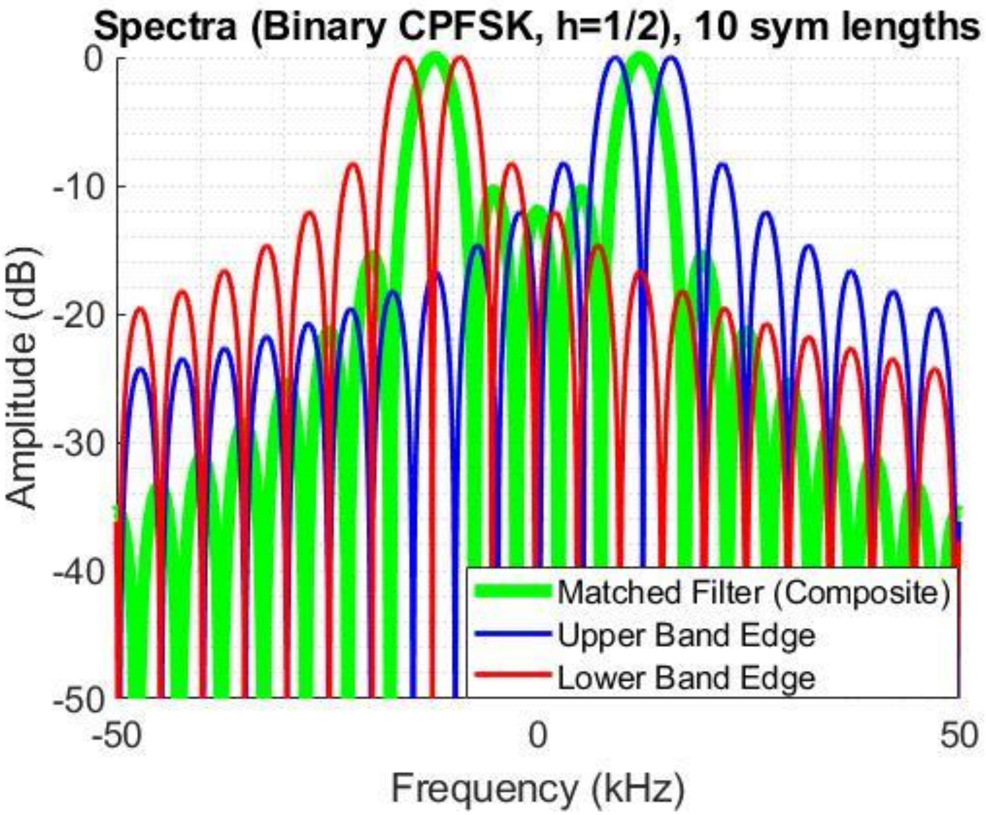

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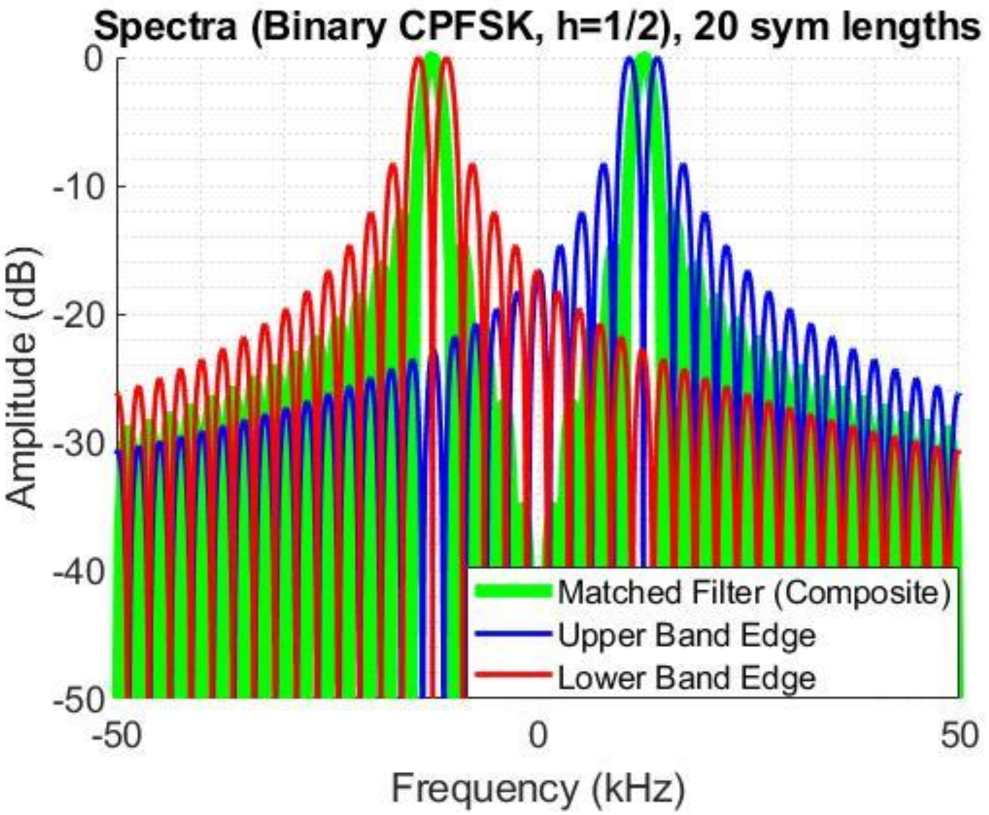

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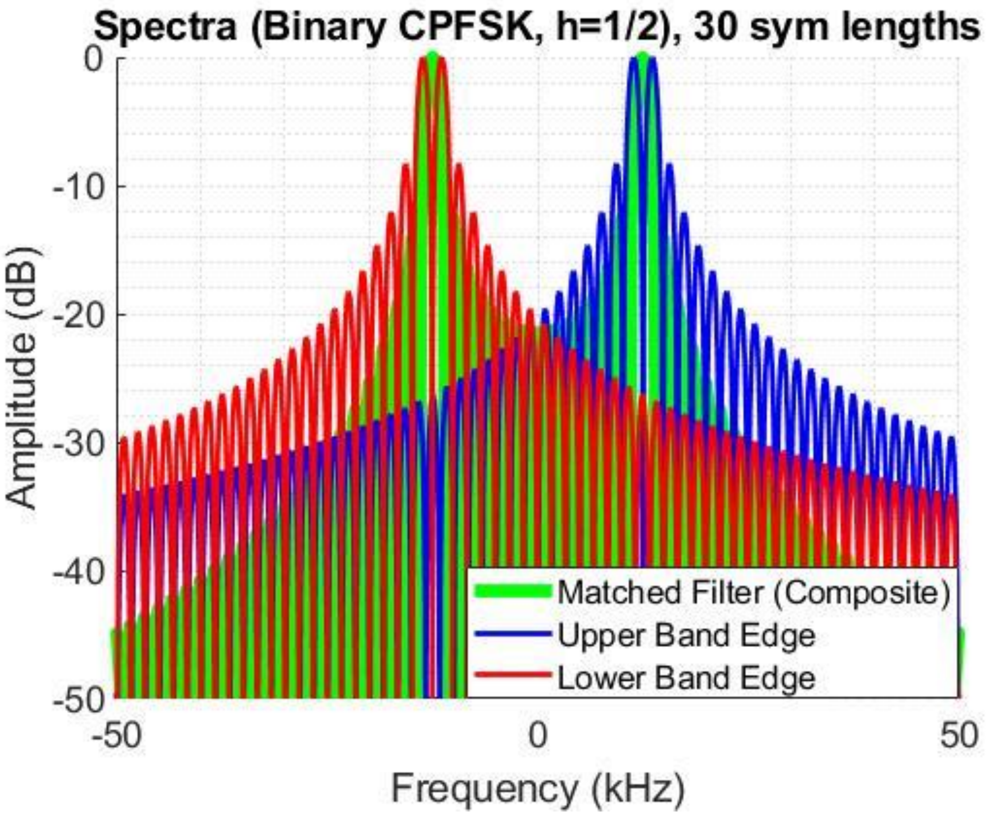

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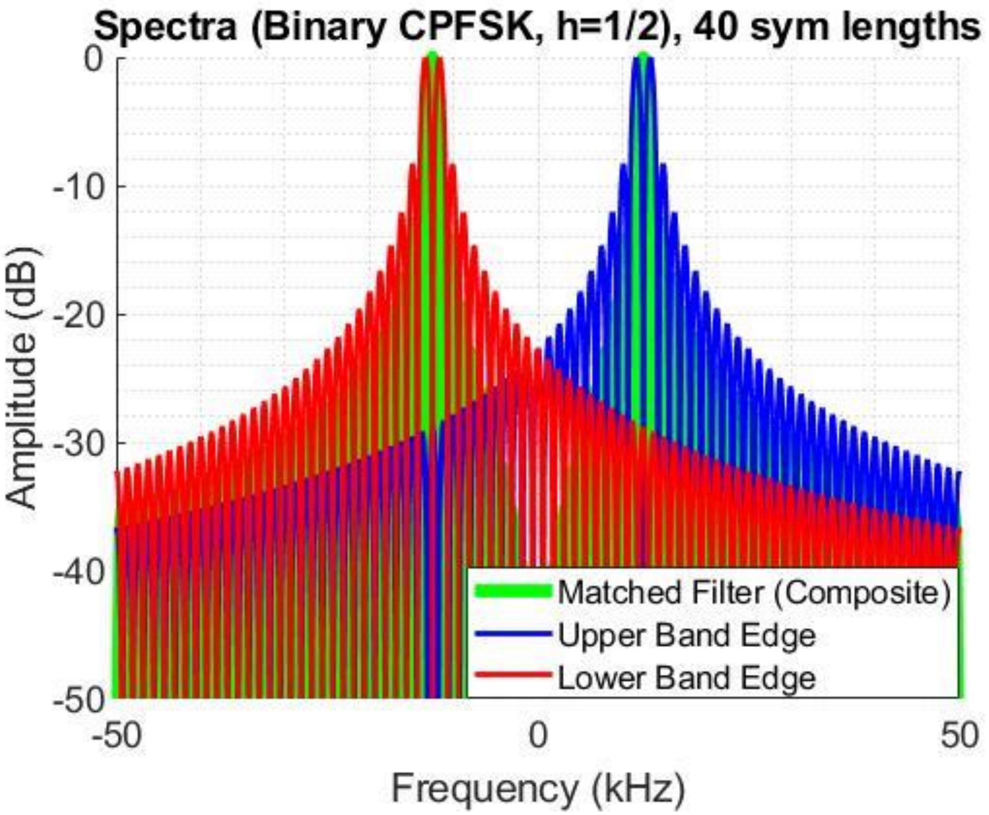

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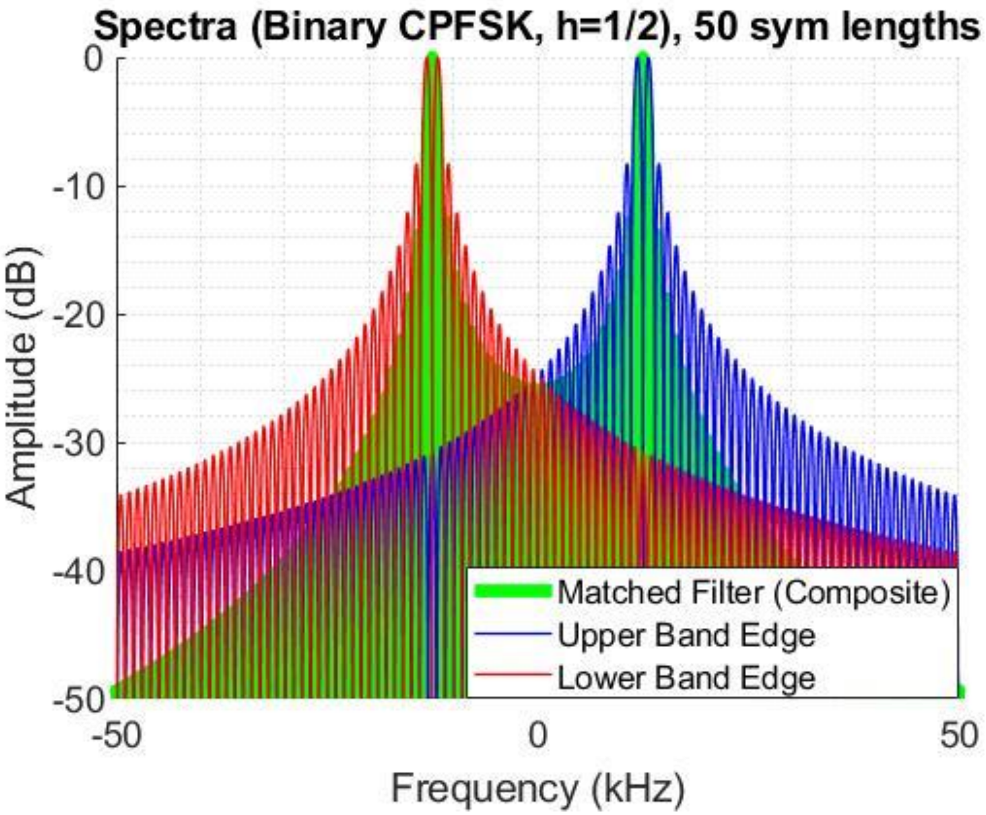

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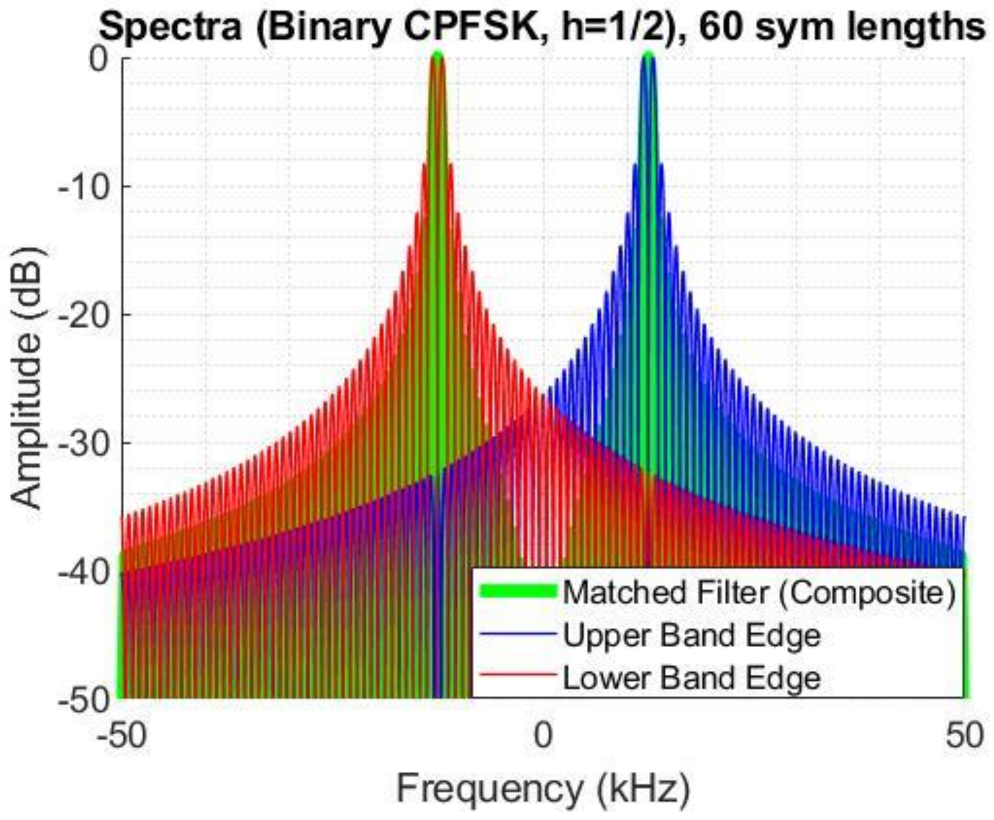

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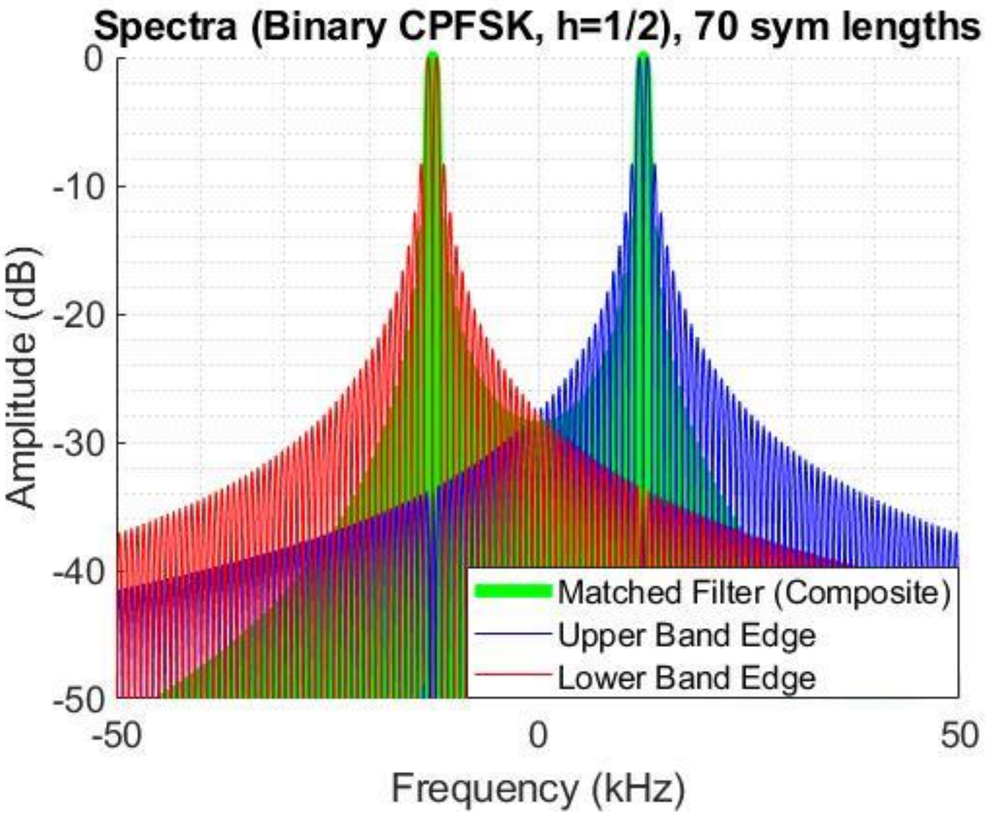

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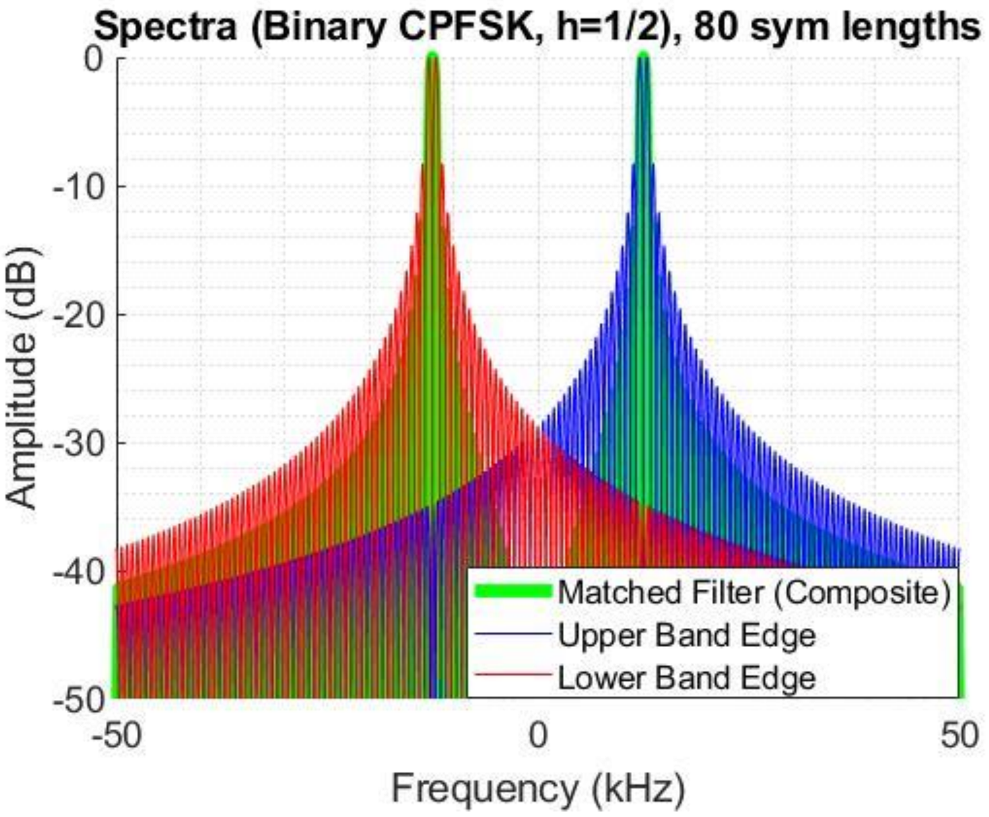

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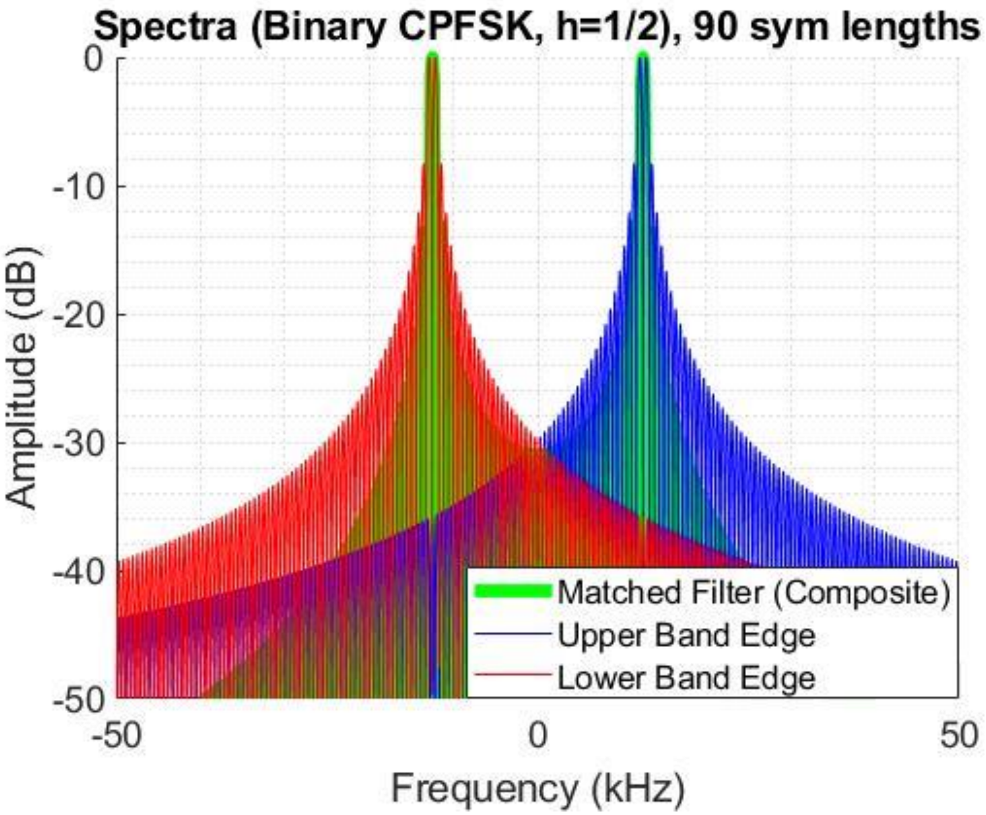

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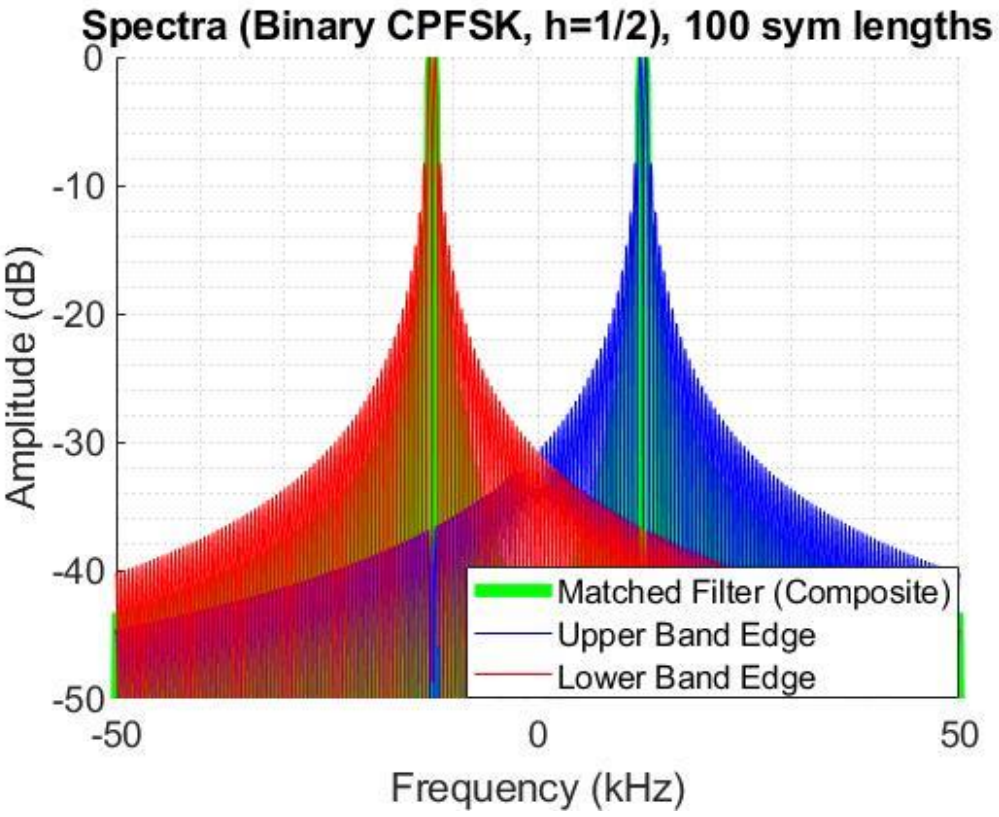

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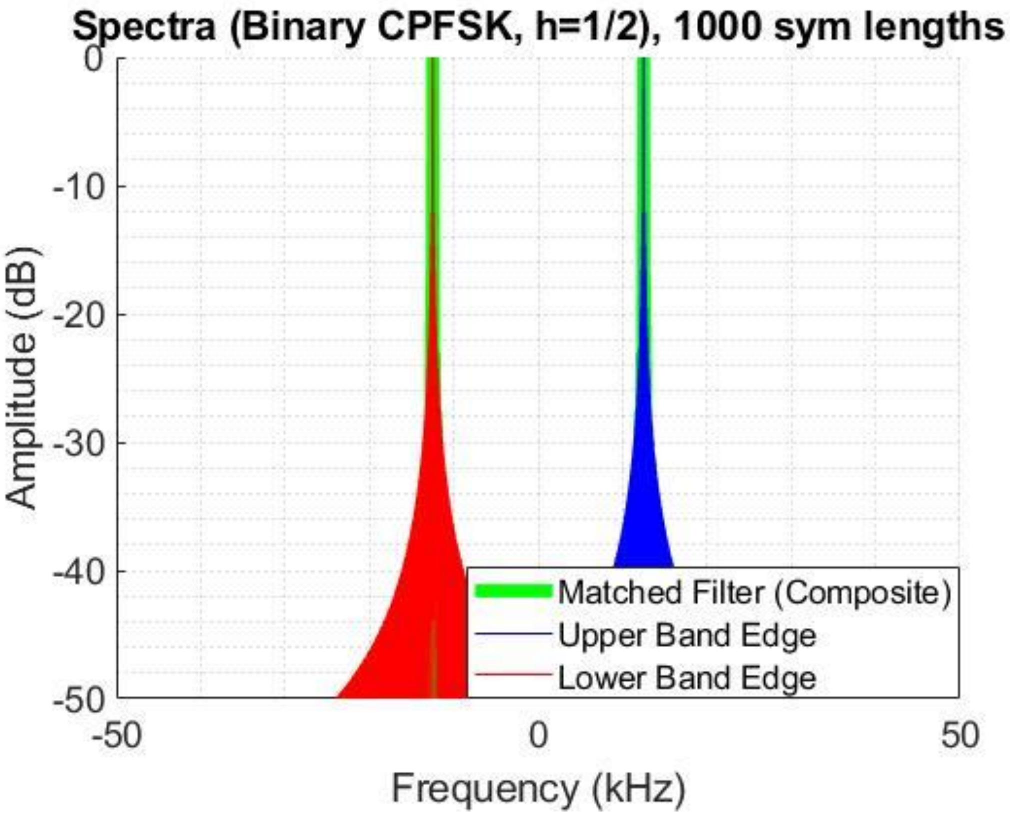
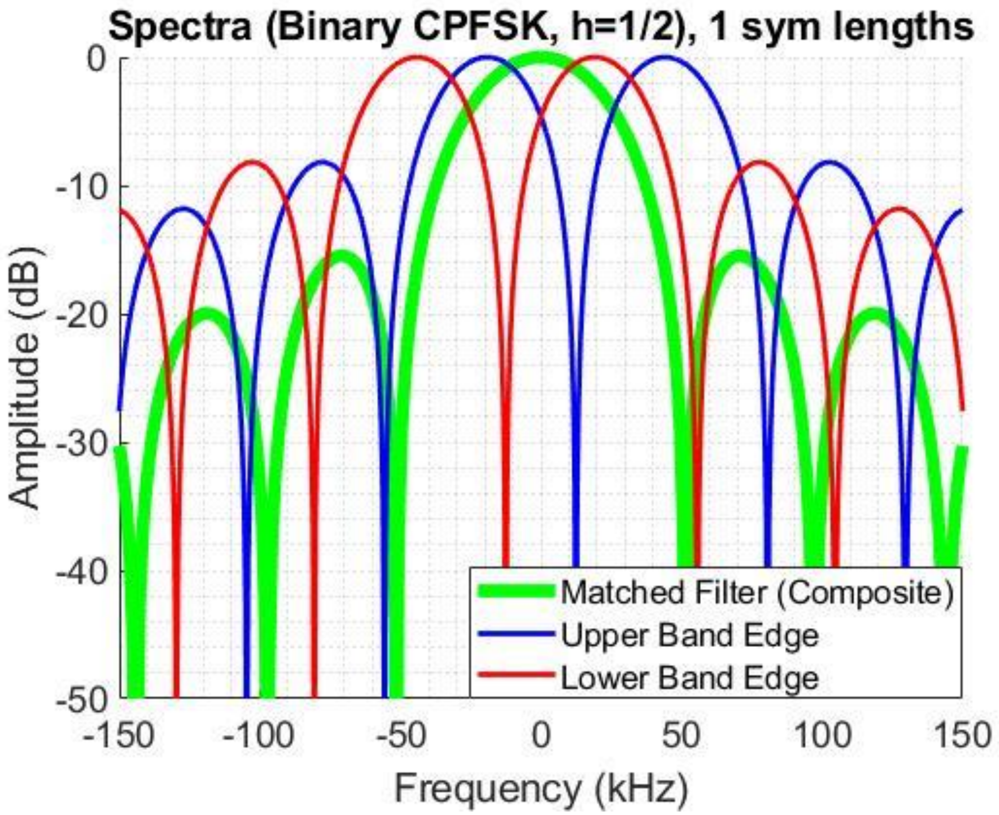
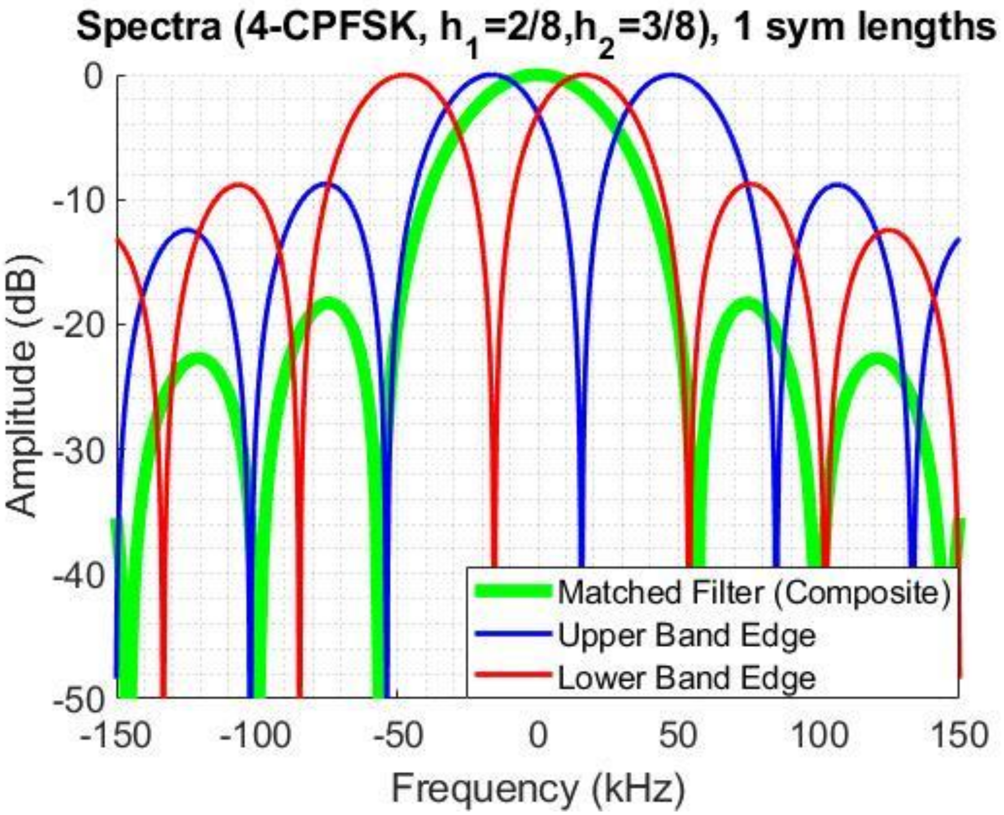


Band Edge Filters Binary CPFSK vs. 4-ary CPFSK with Alternating Modulation Index (2/8, 3/8)





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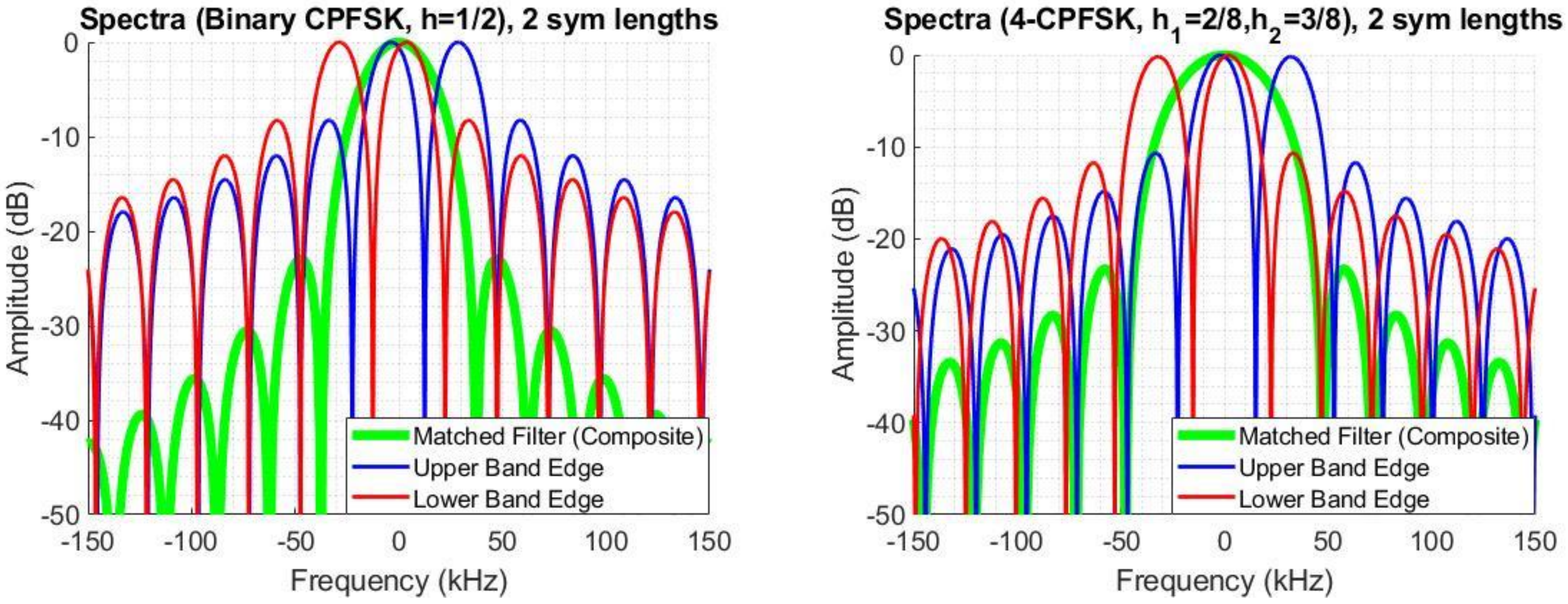

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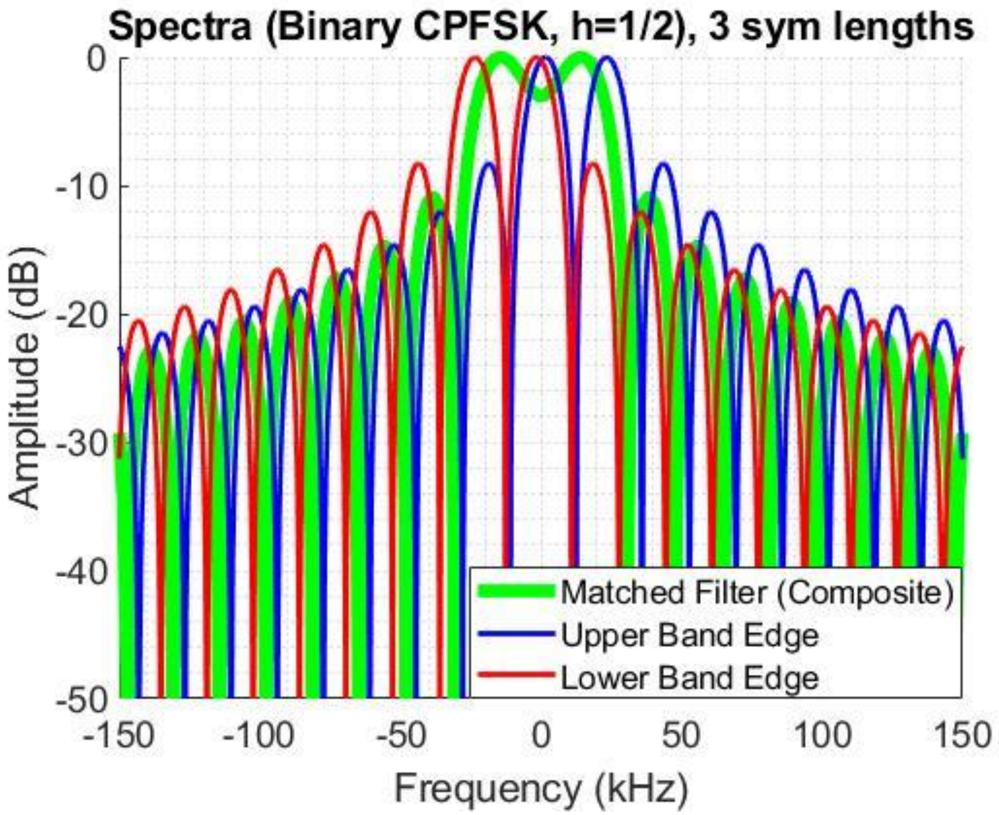

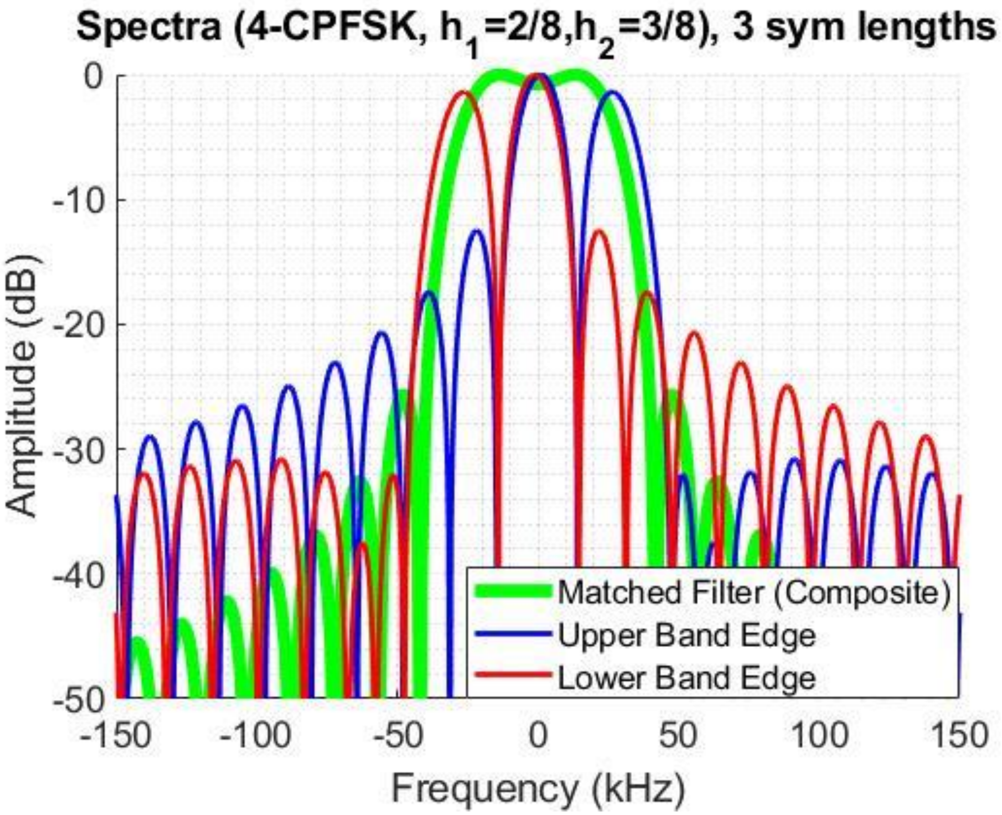

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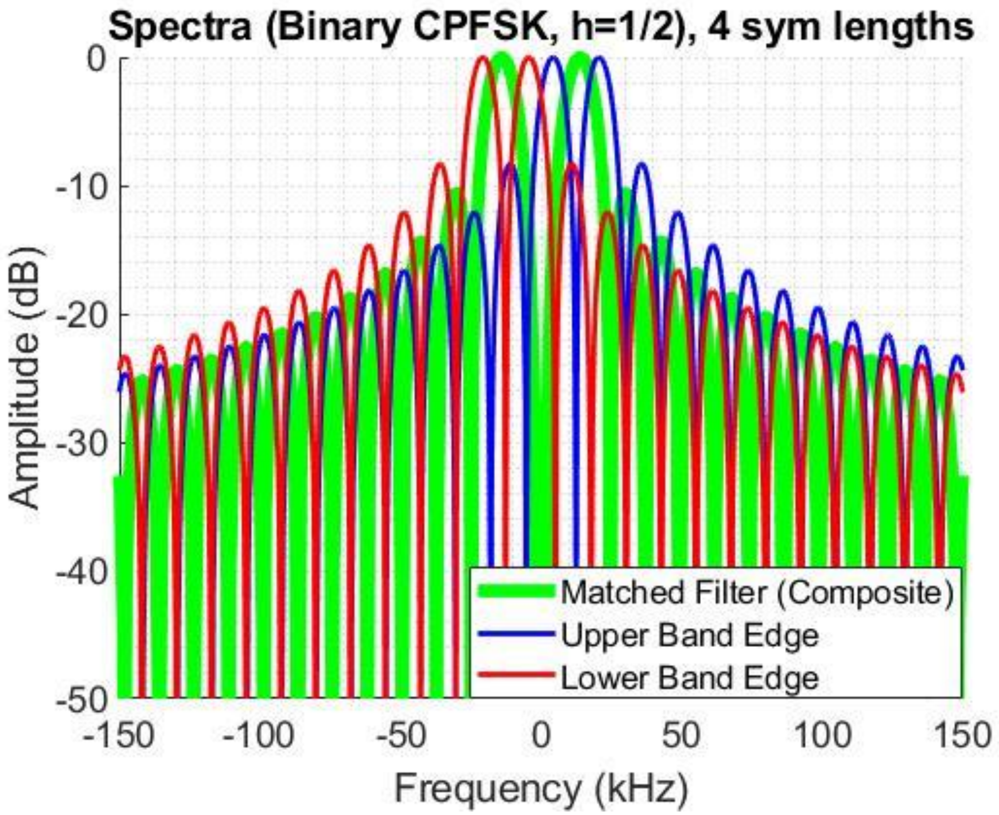

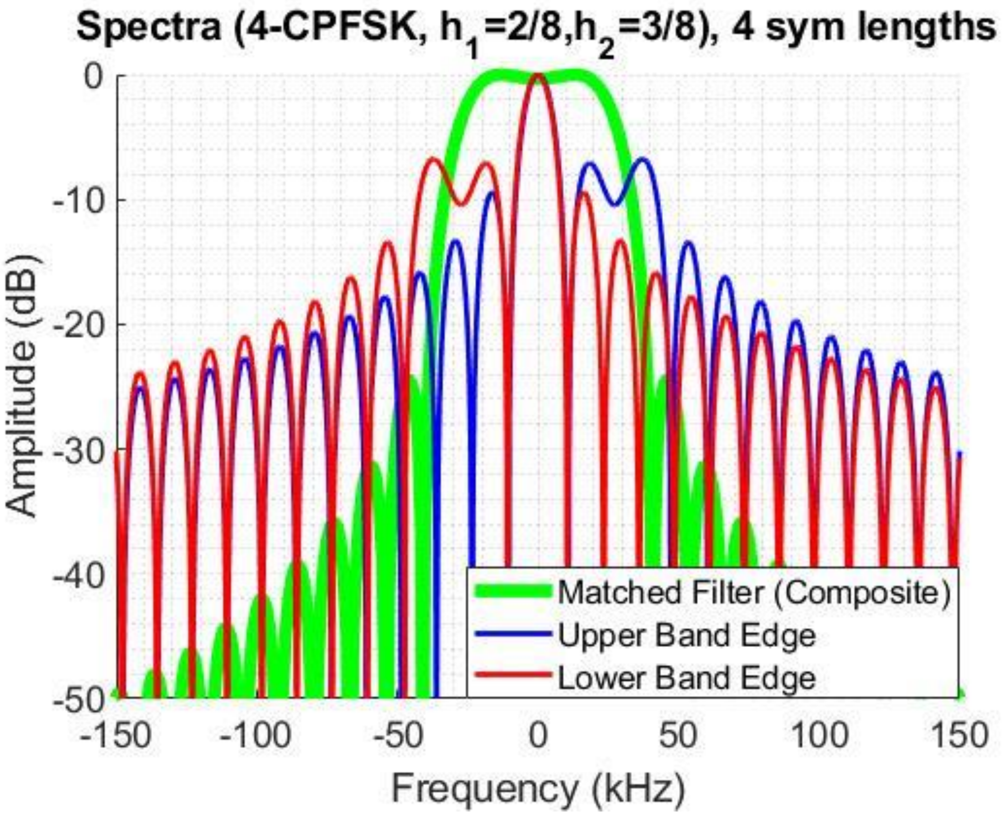

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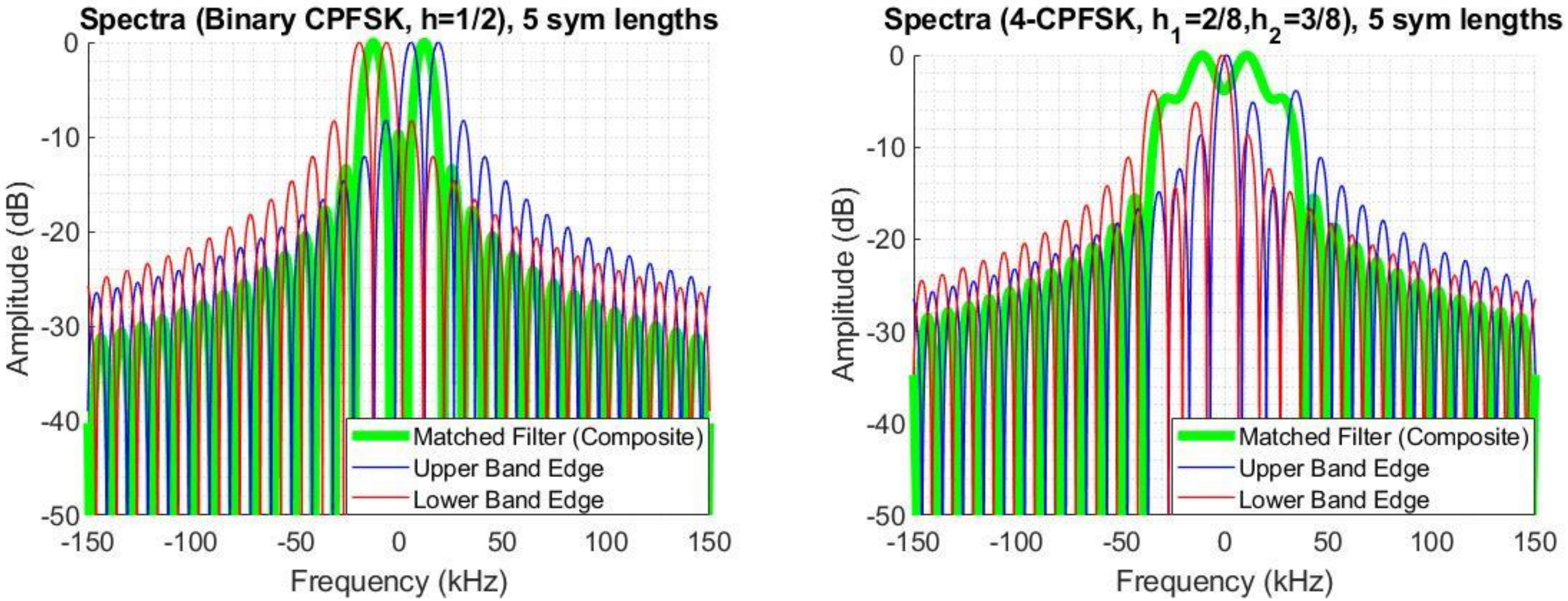

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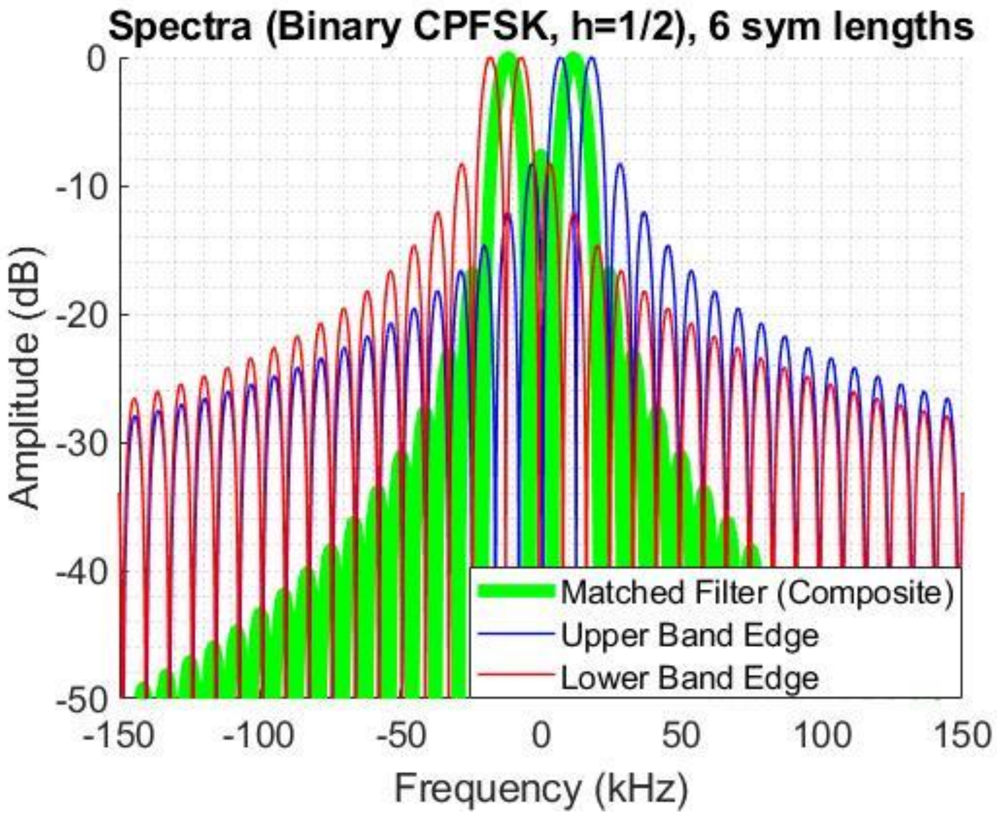

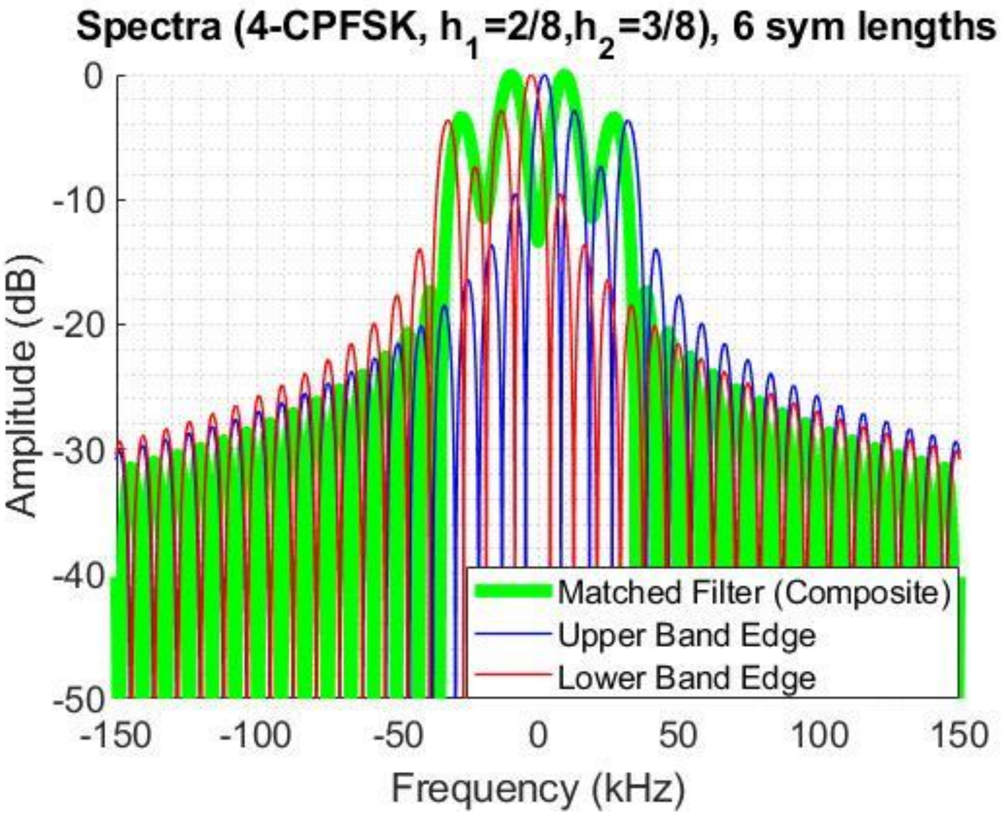

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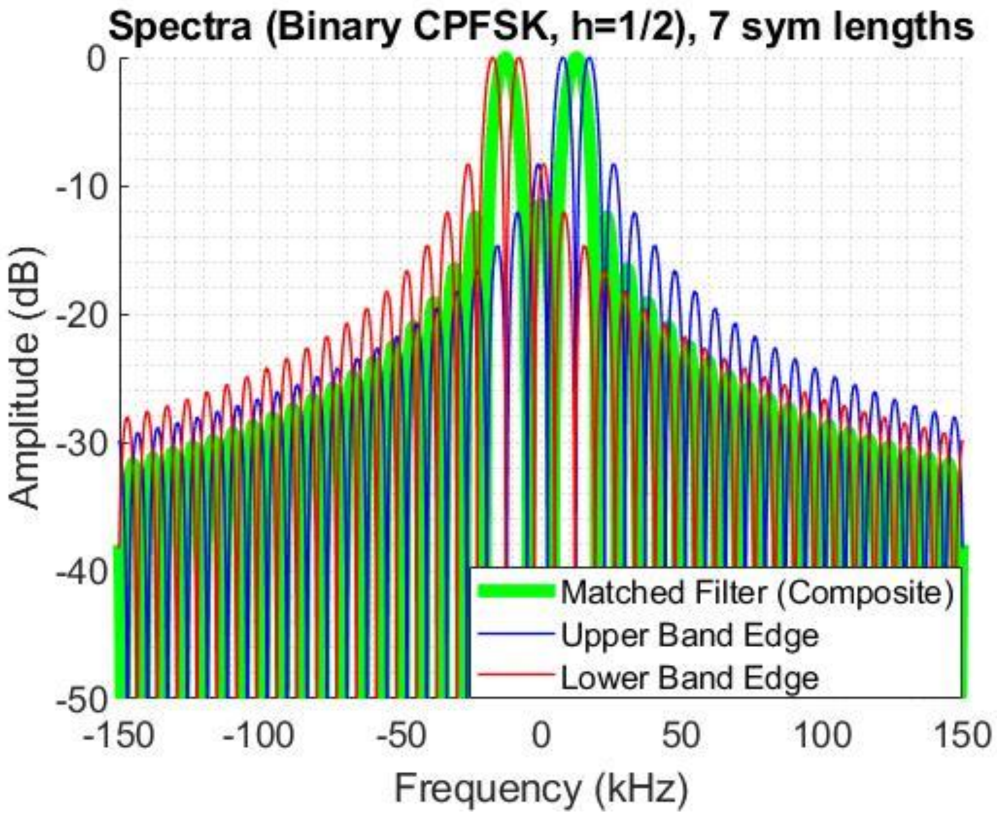

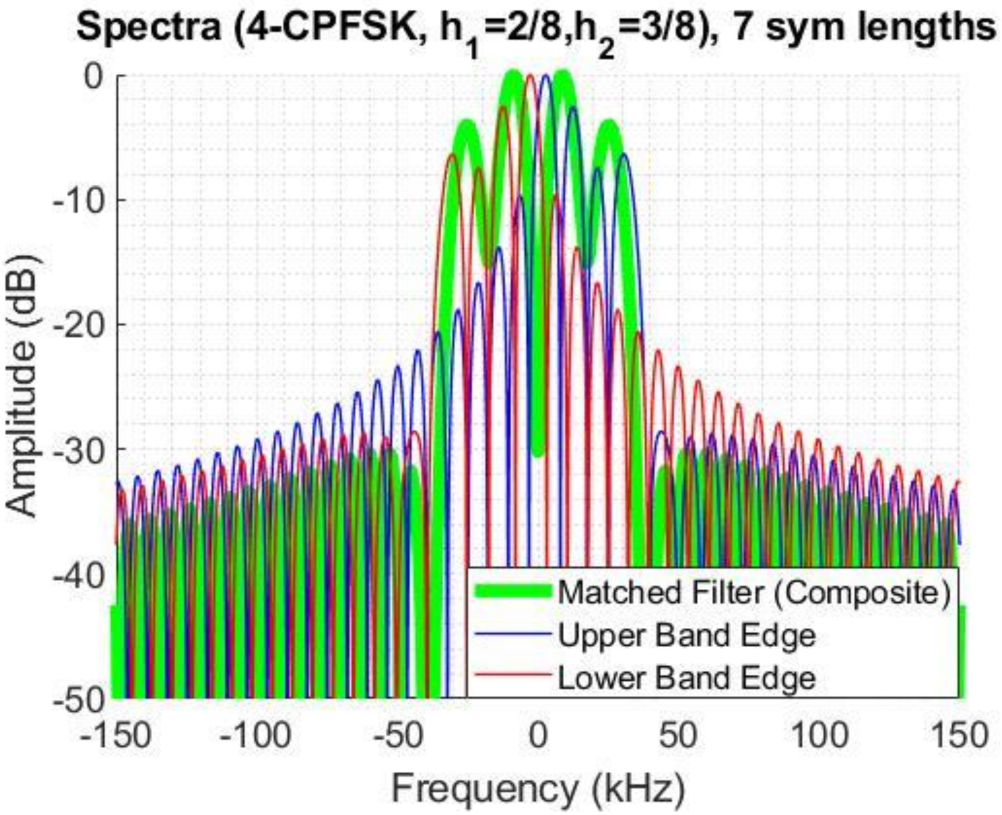

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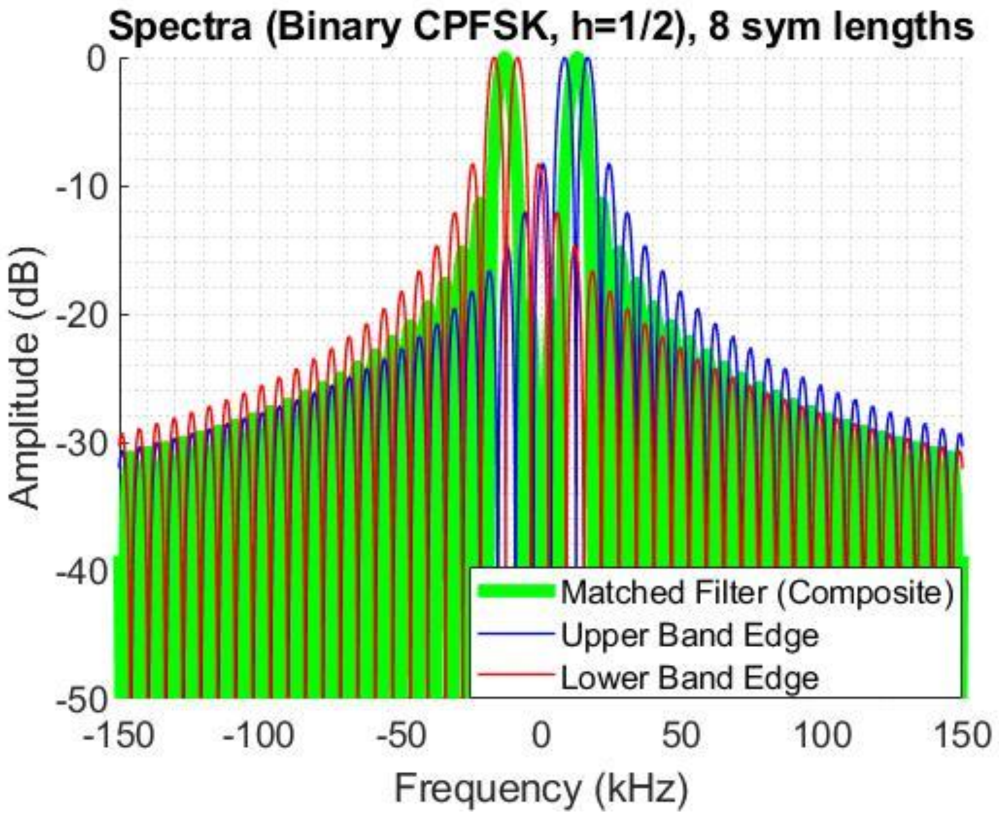

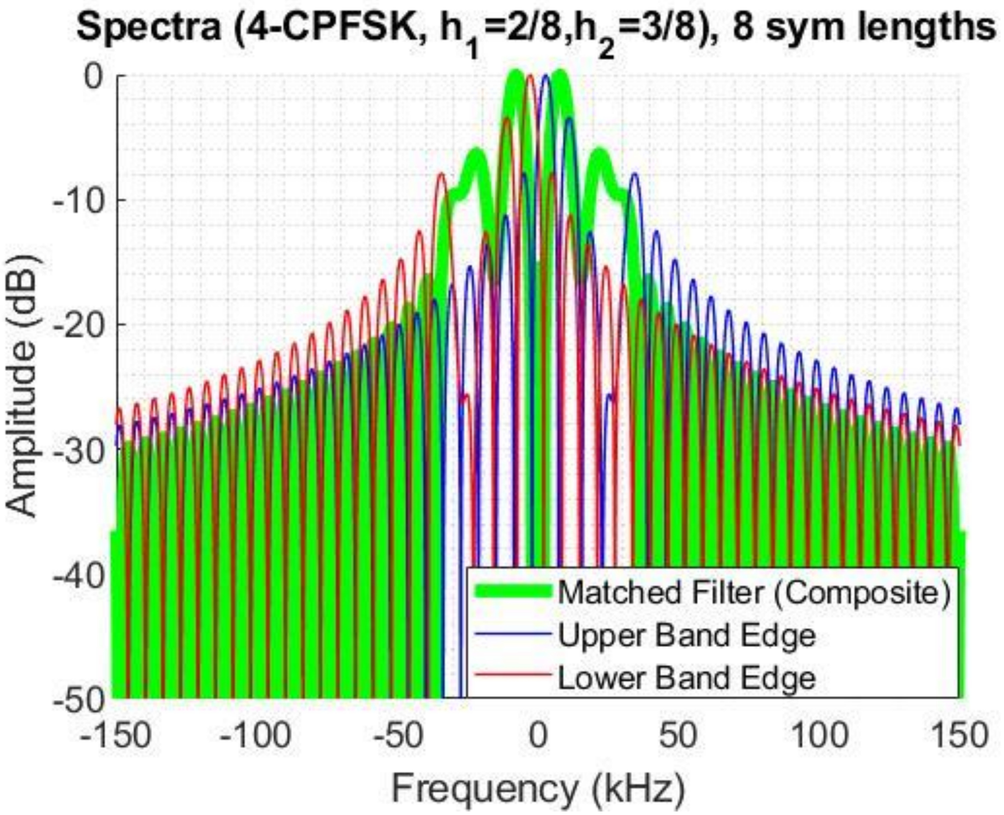

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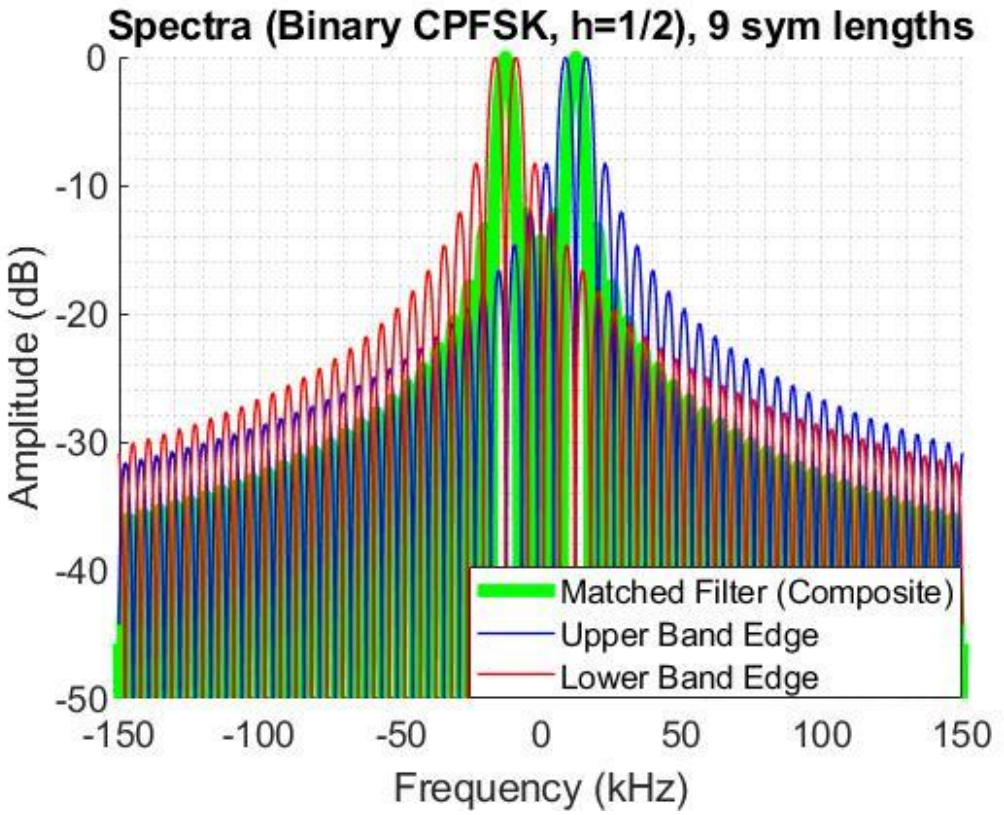

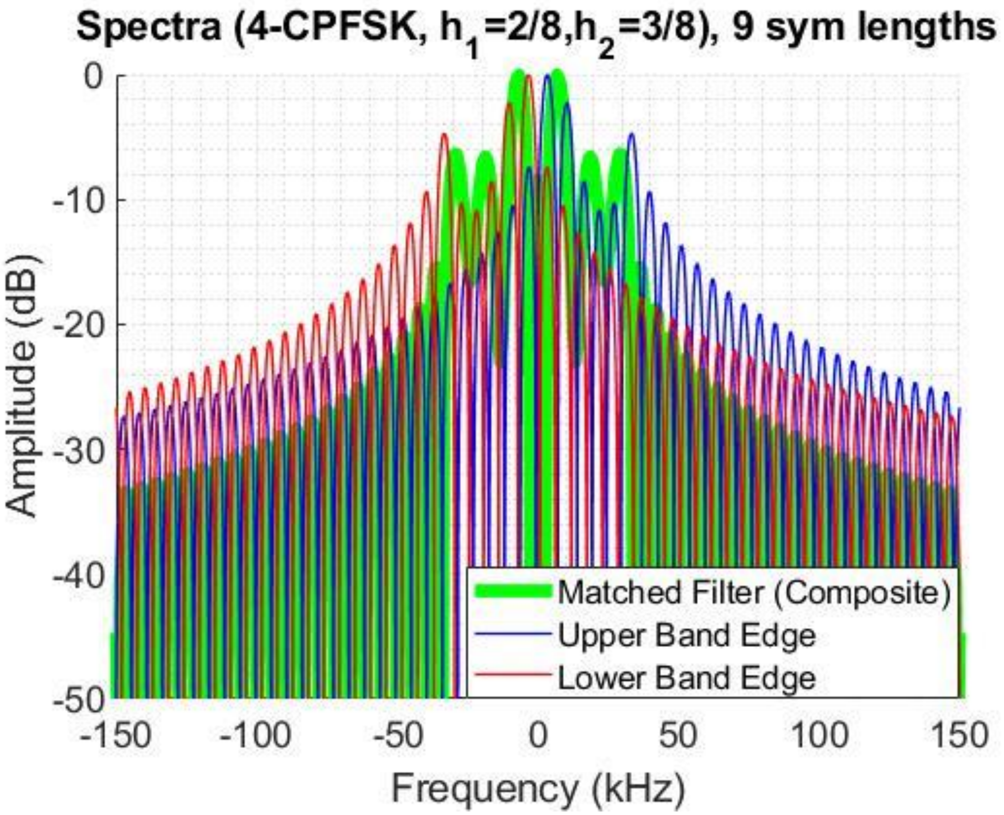

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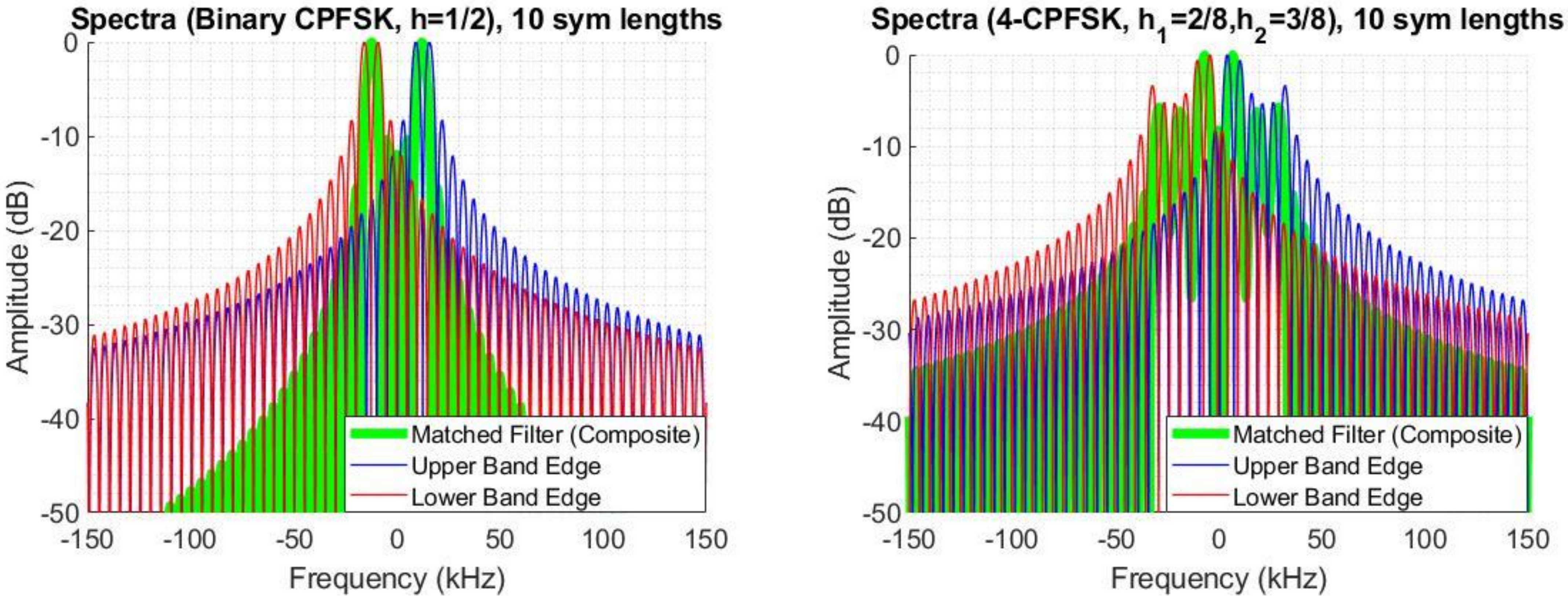

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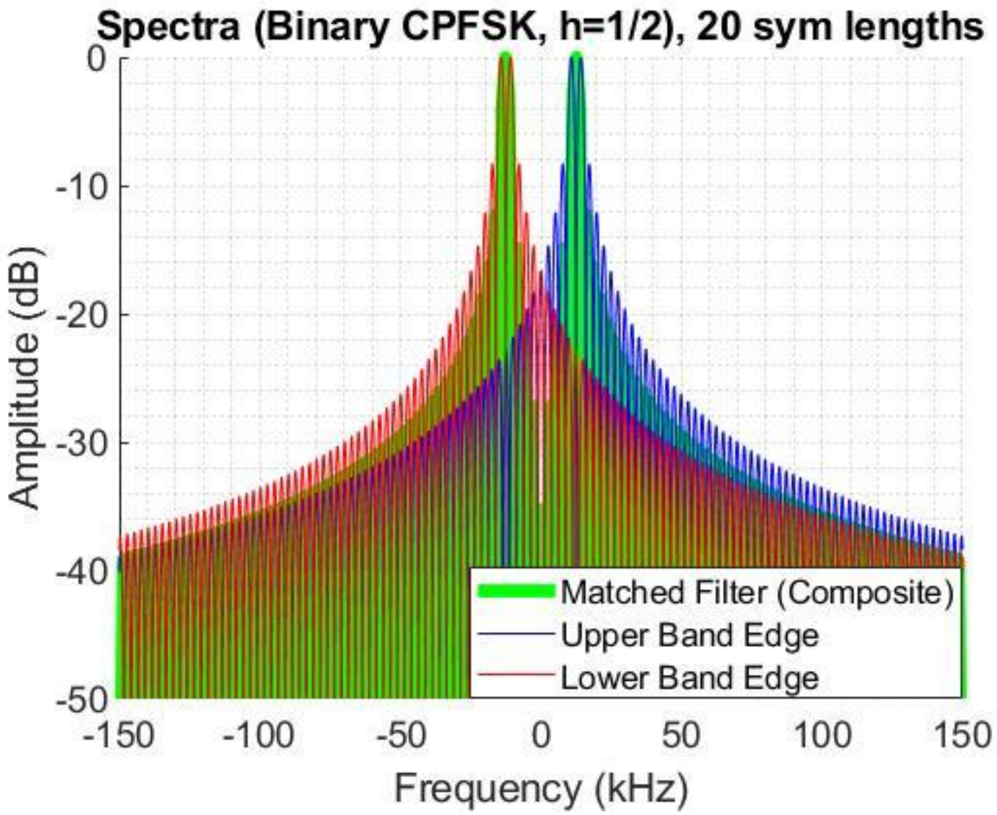

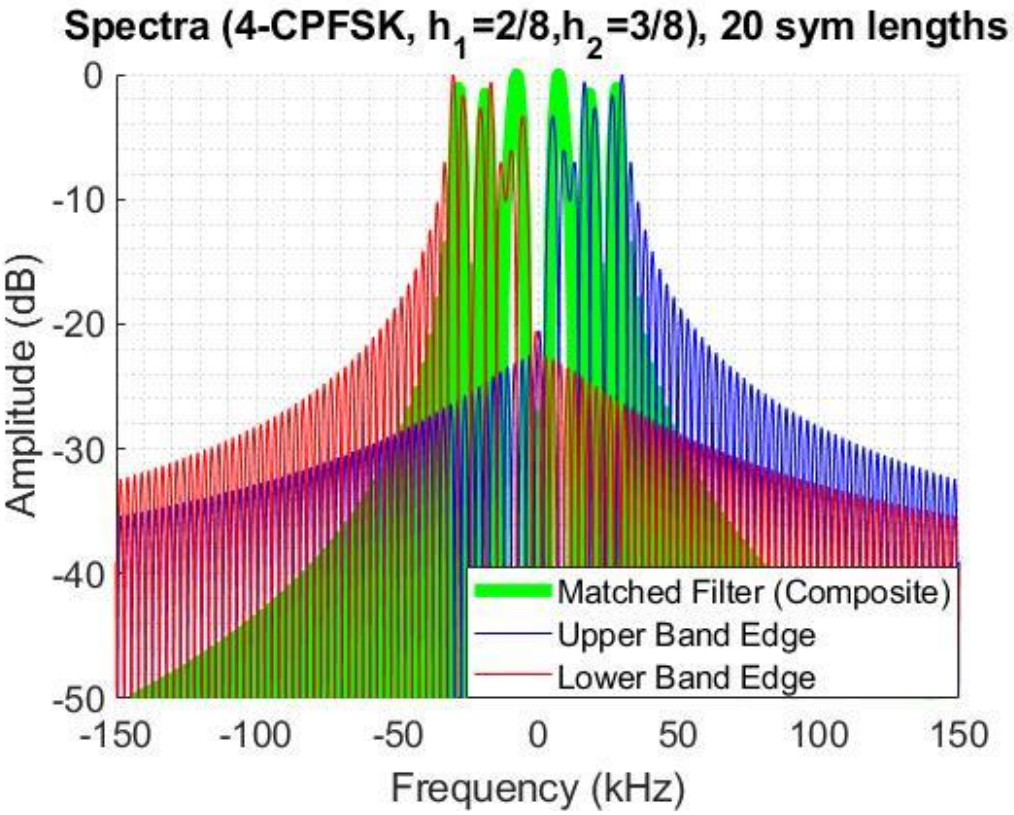

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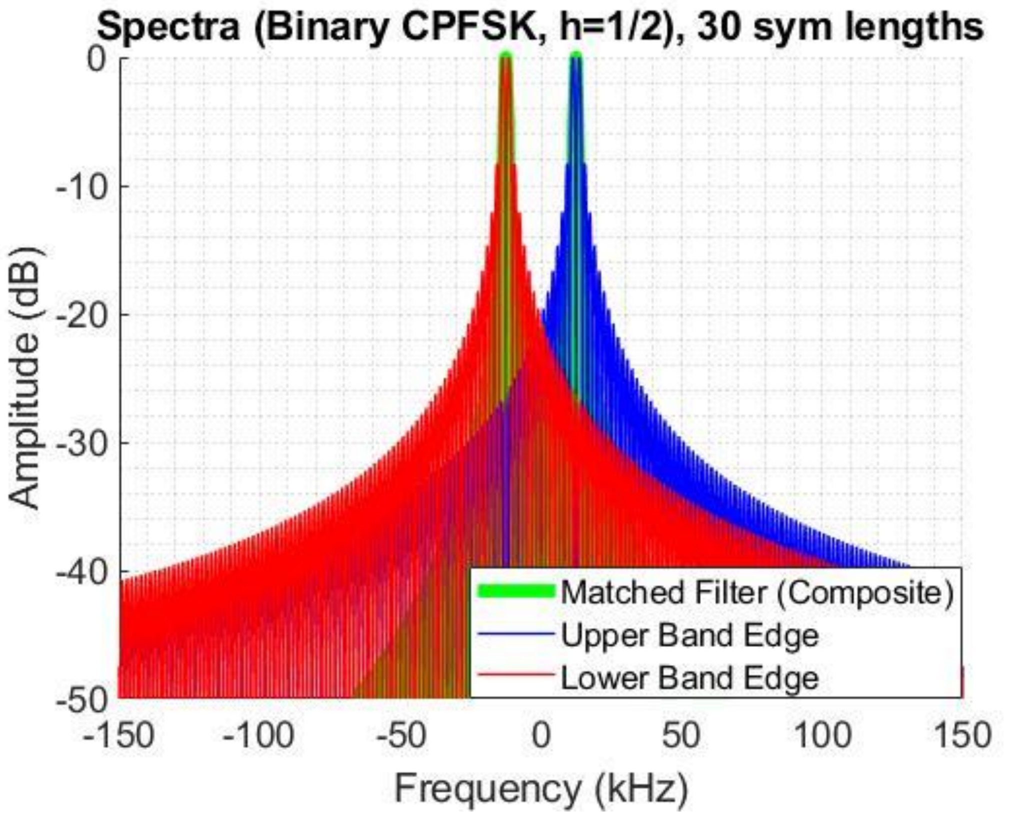

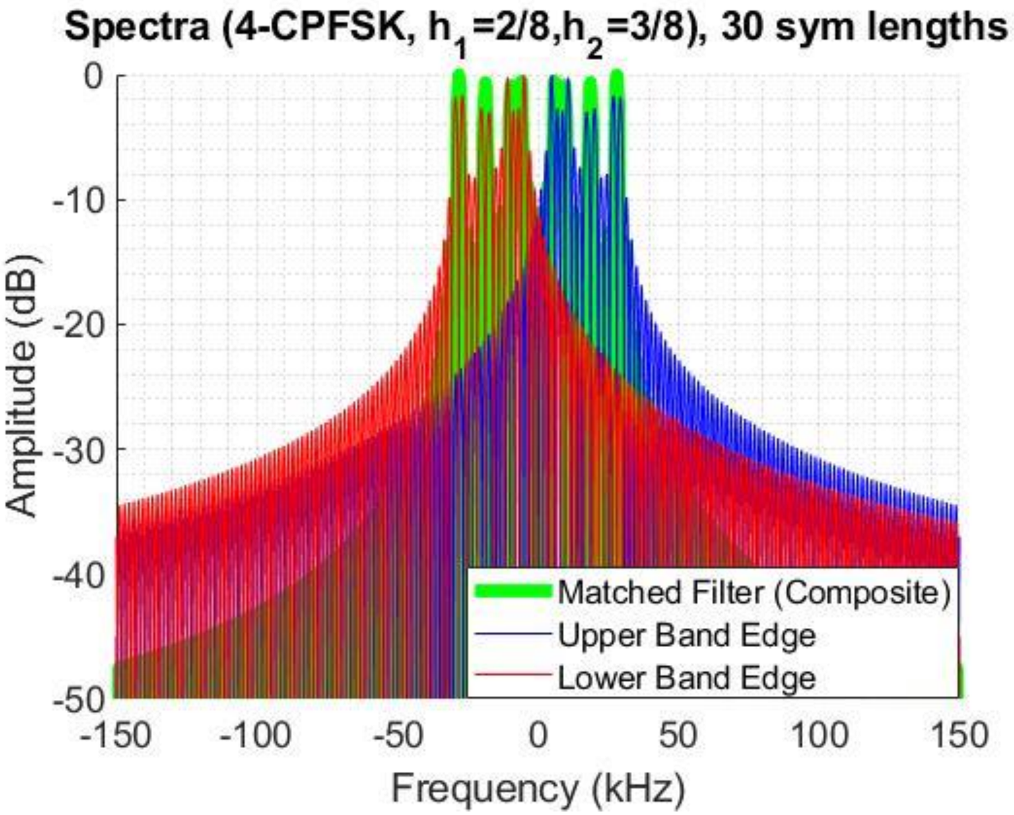

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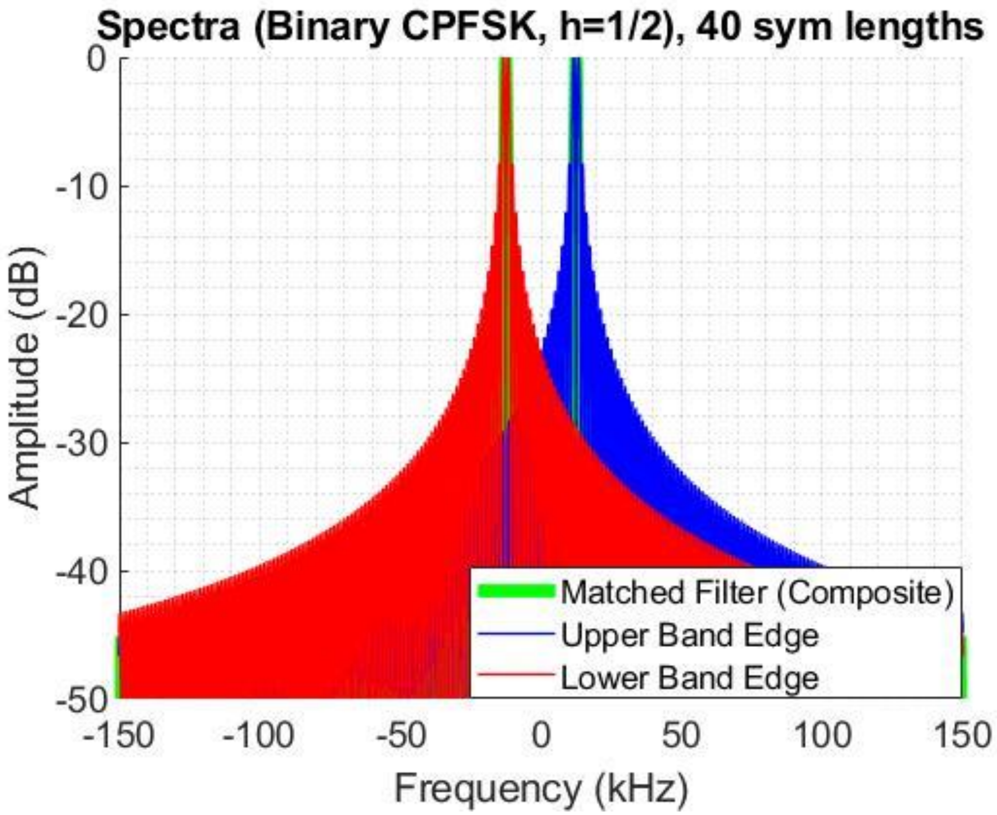

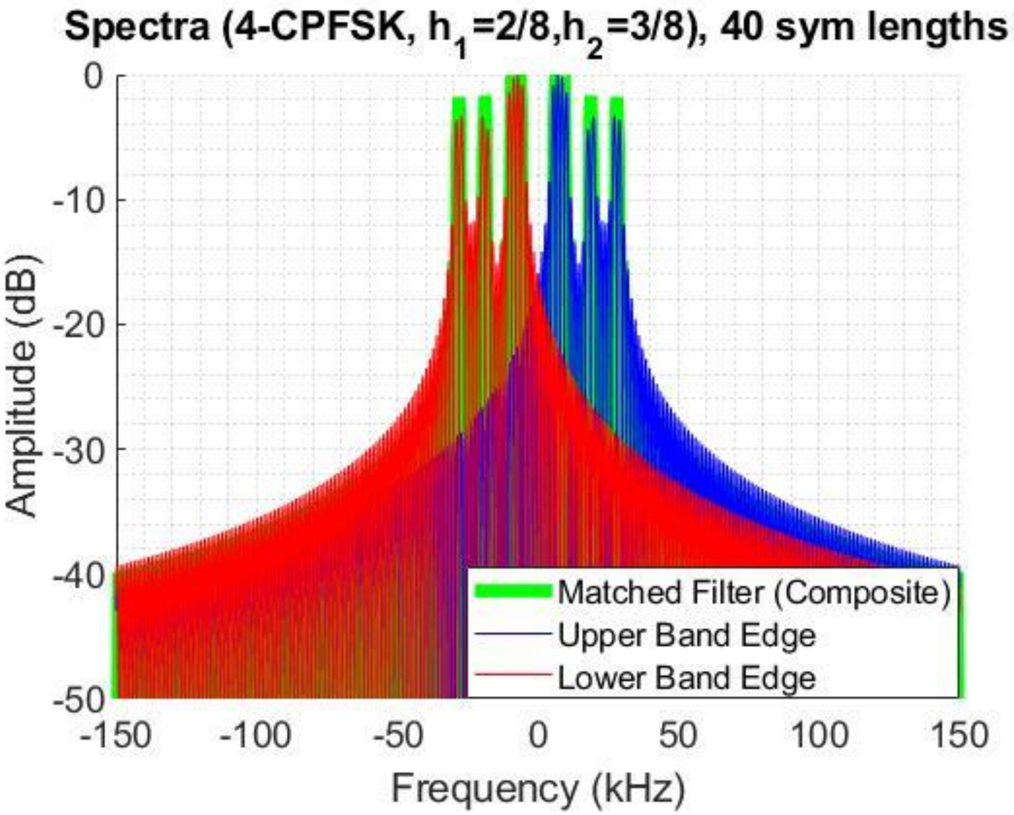

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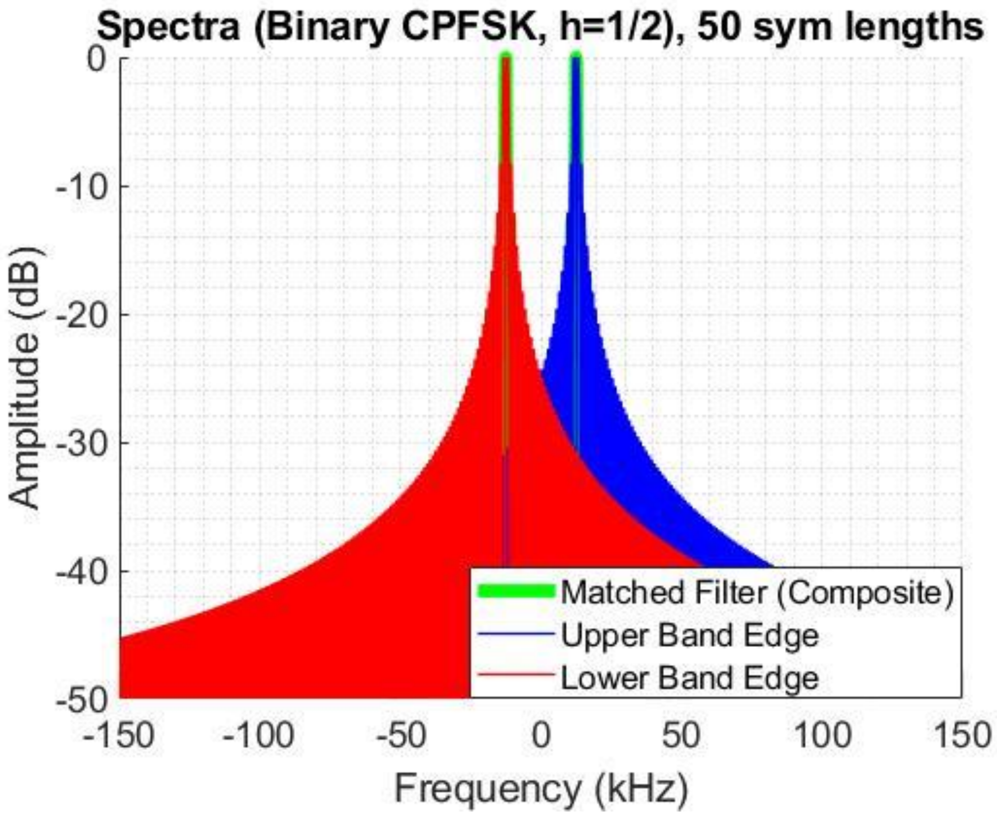

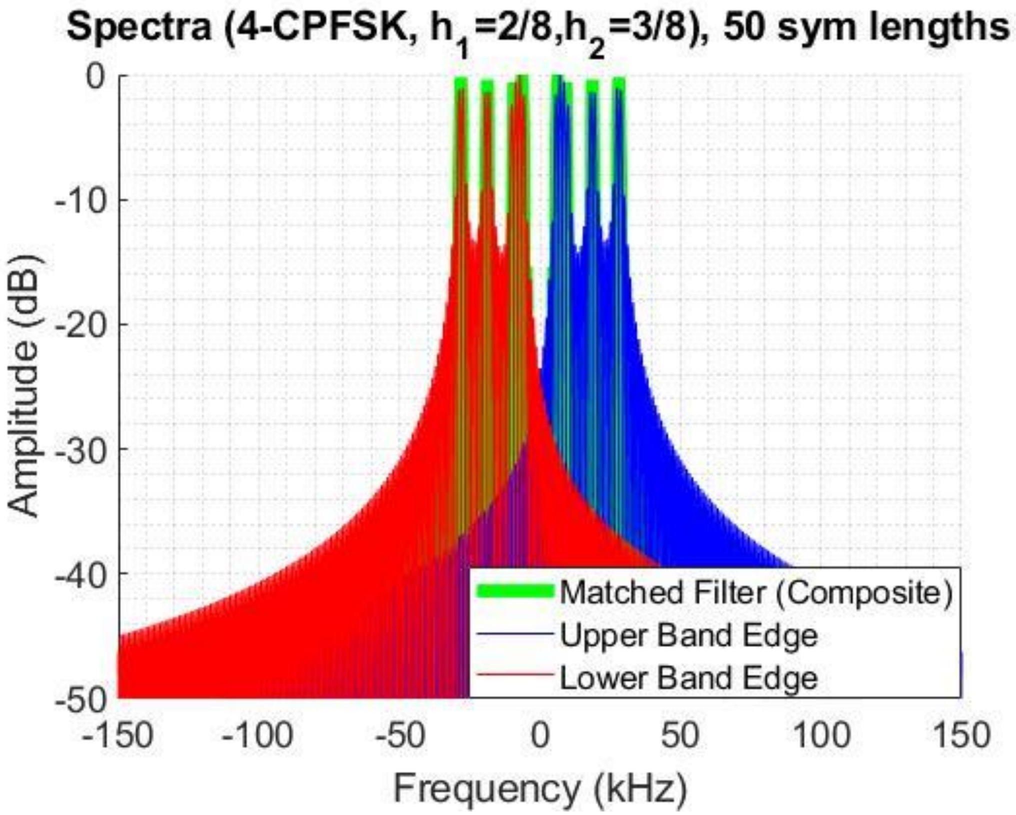

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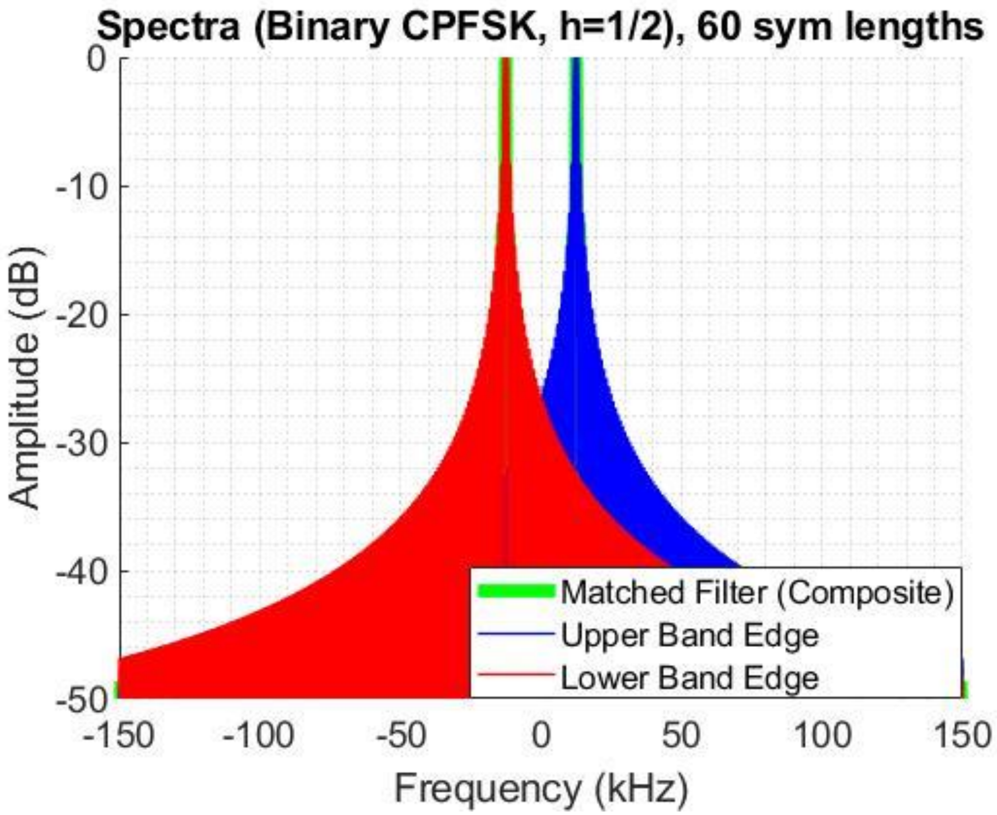

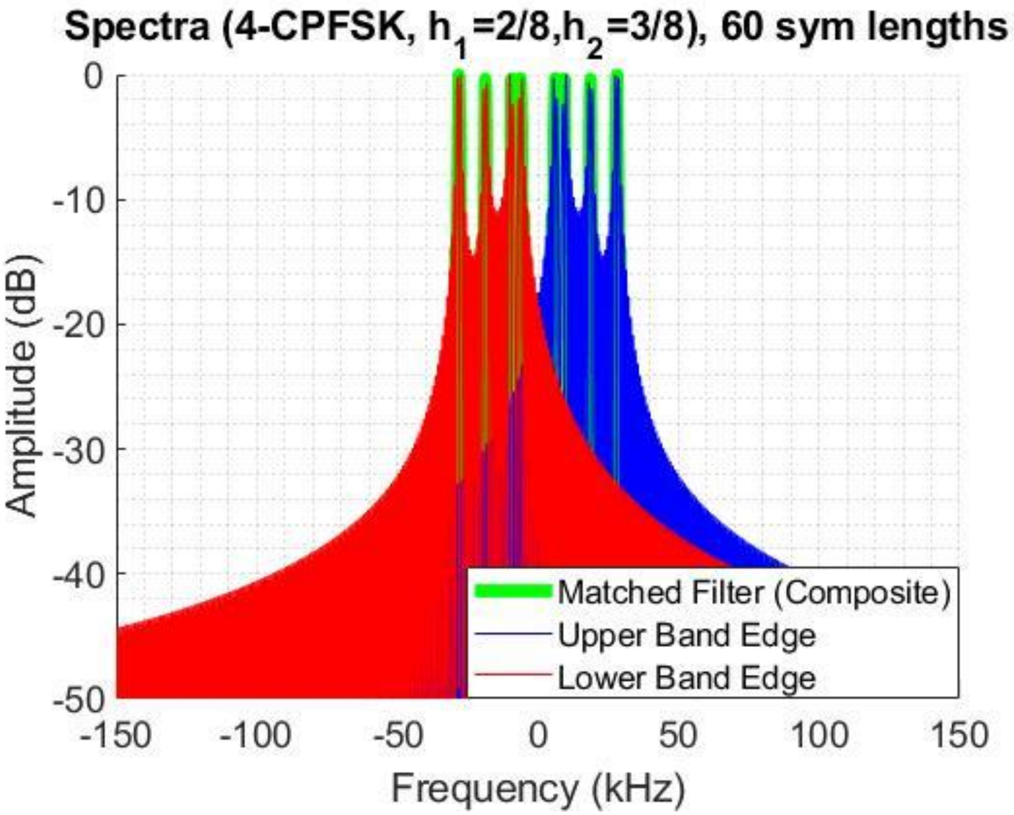

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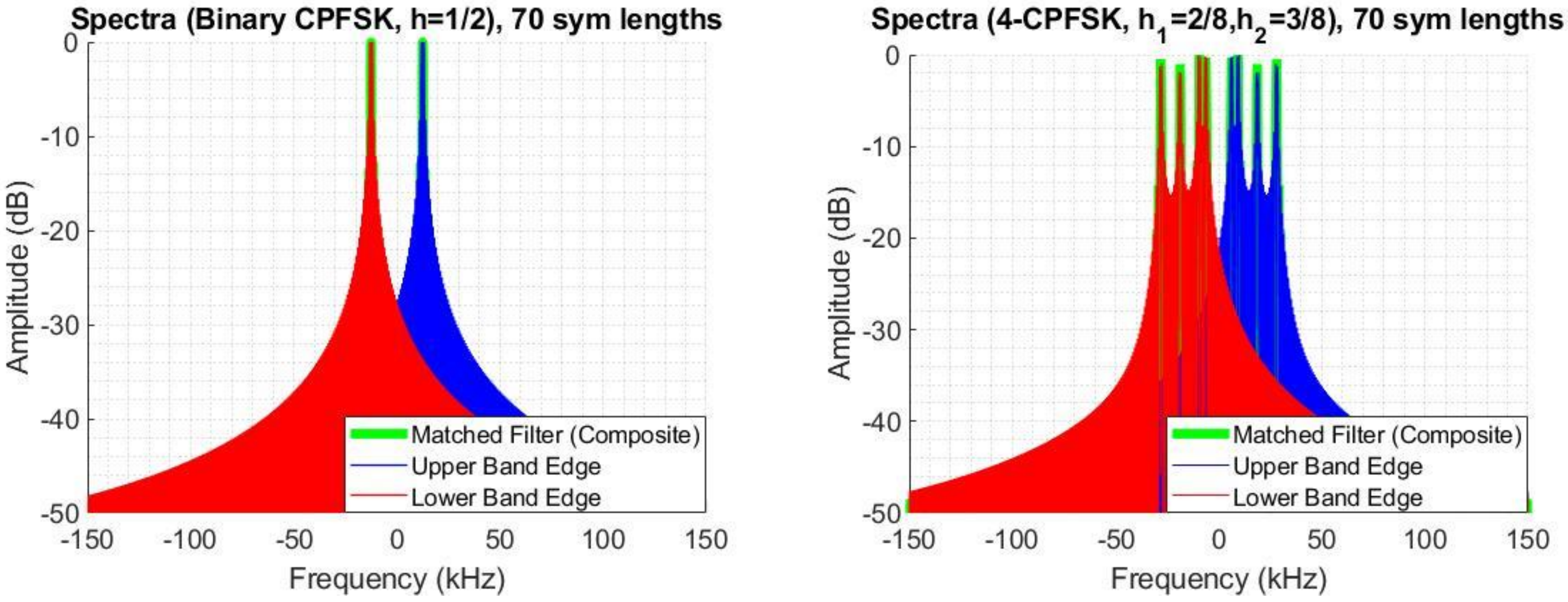

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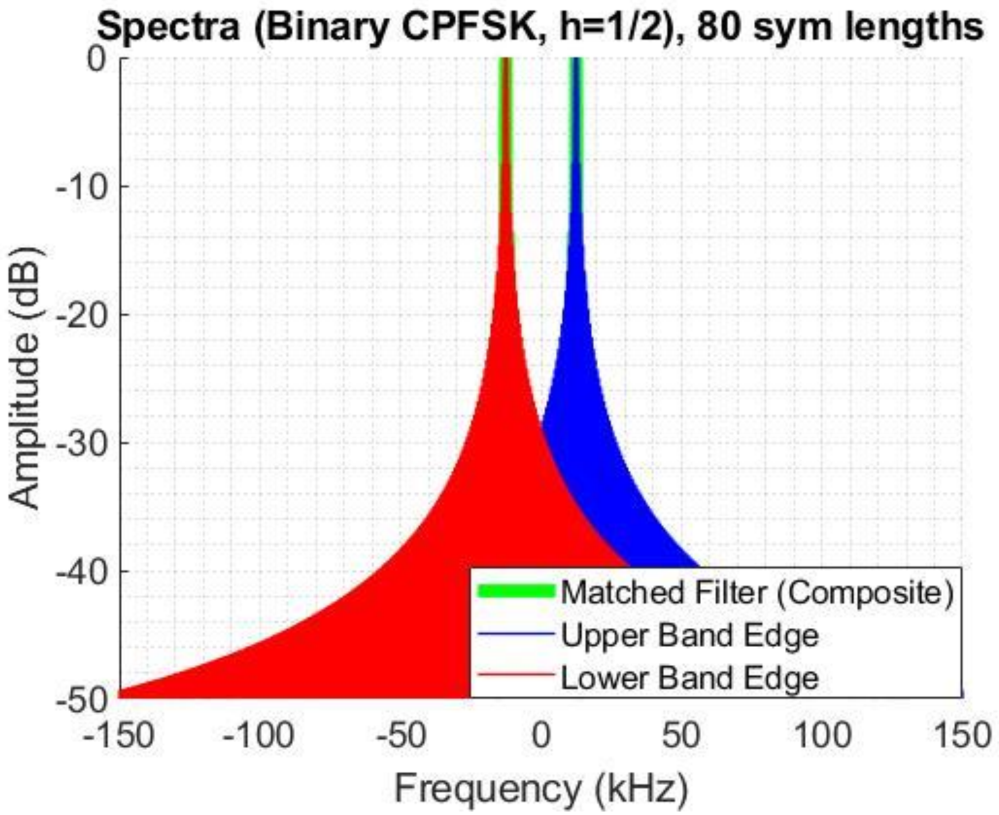

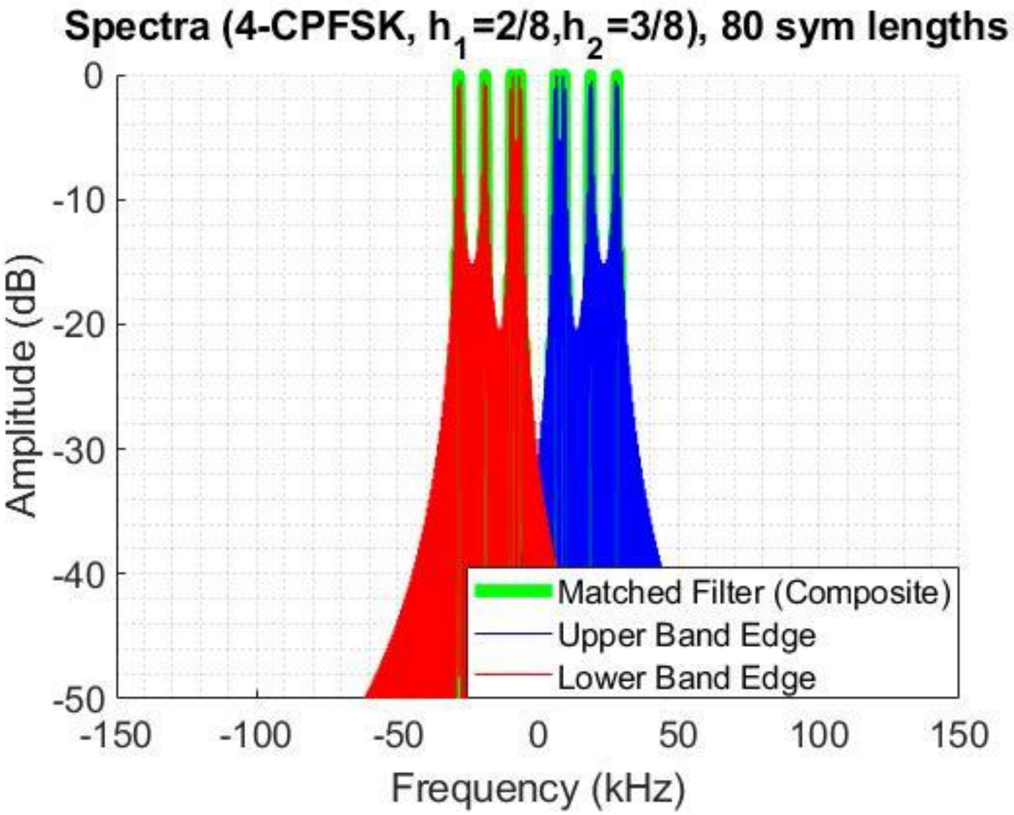

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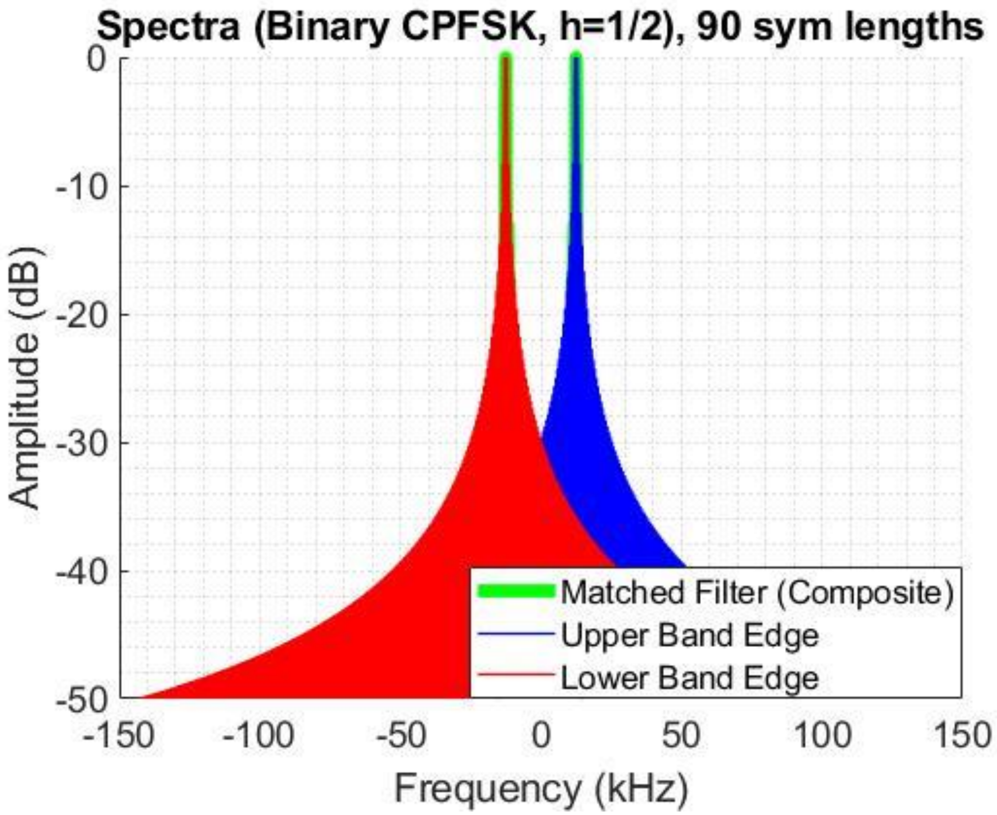

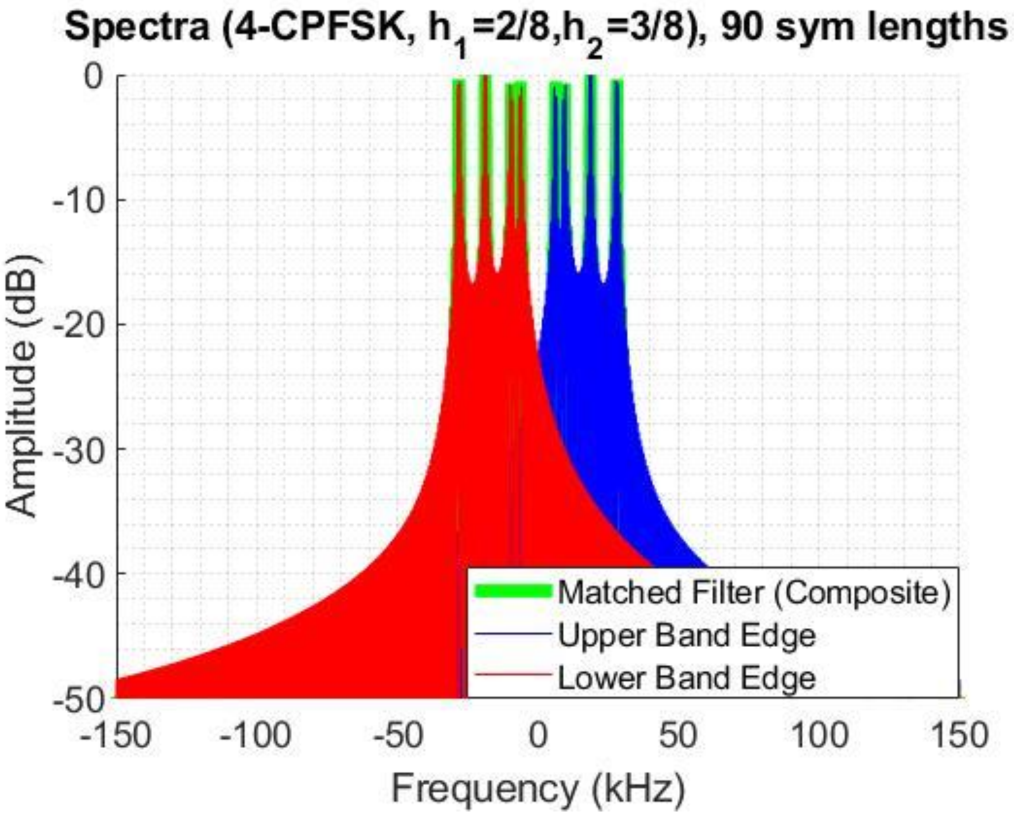

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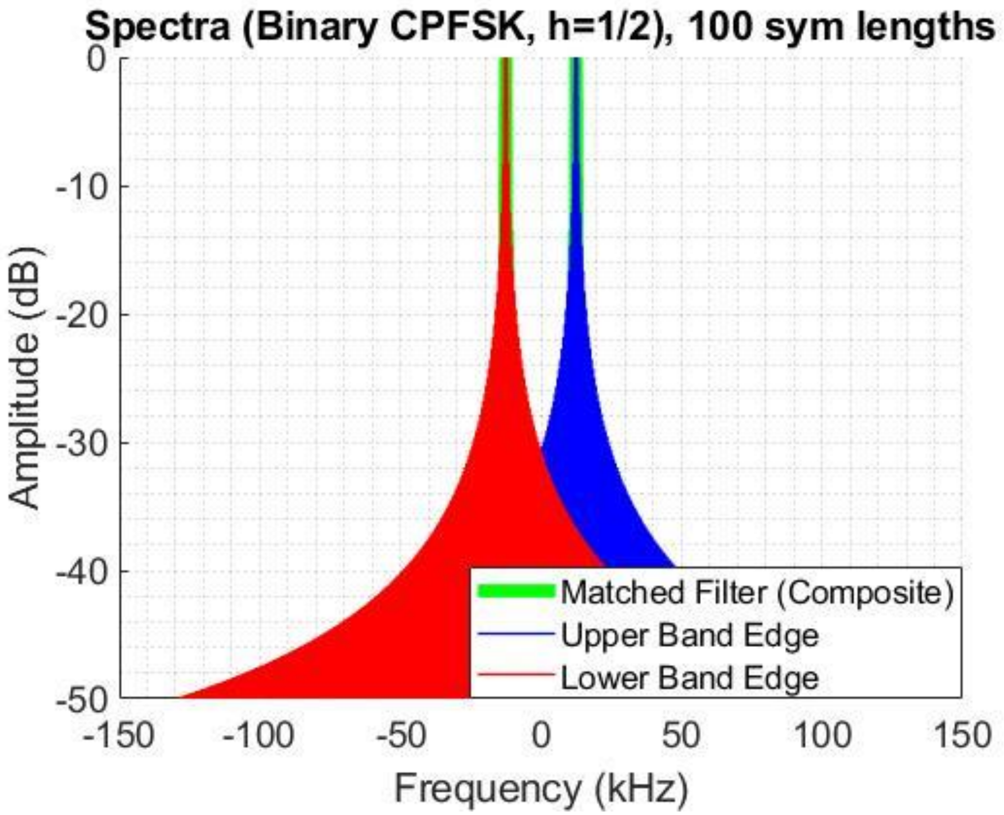

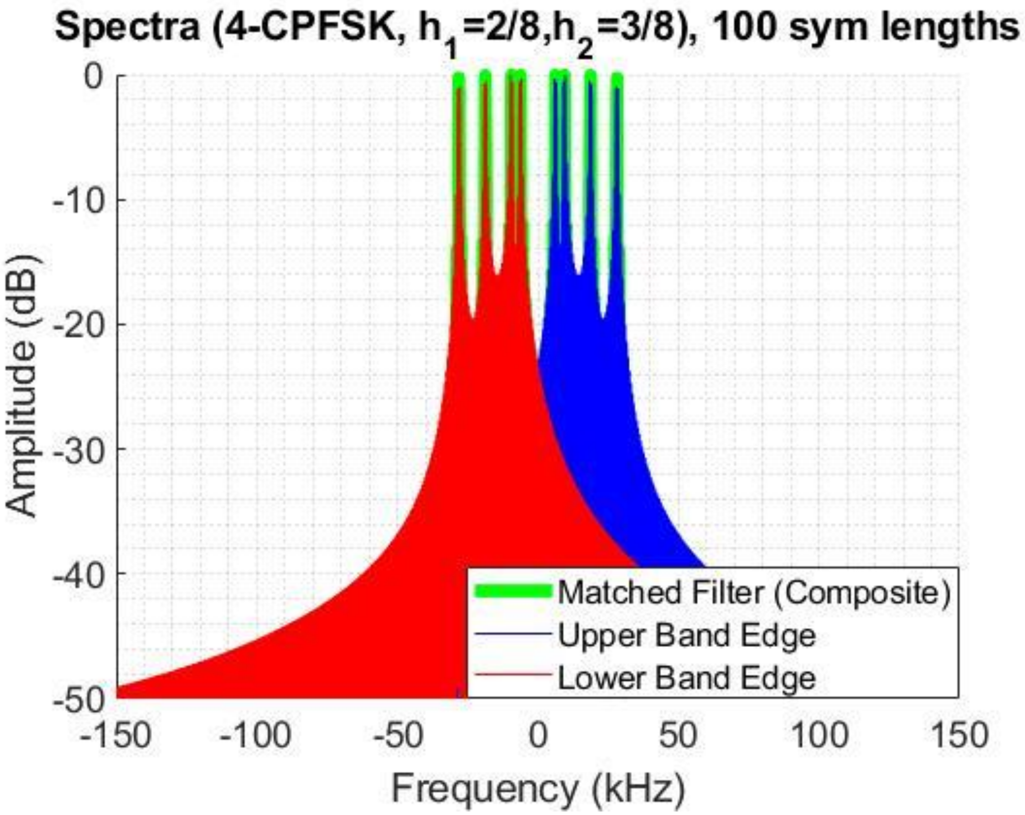

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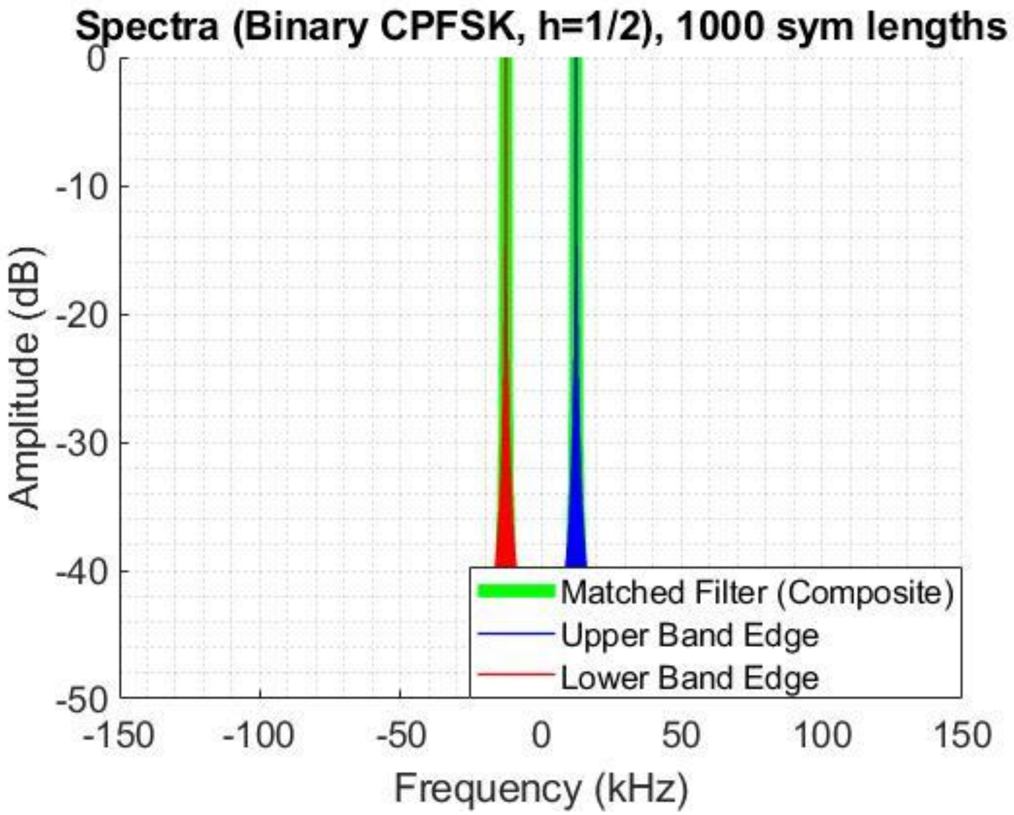

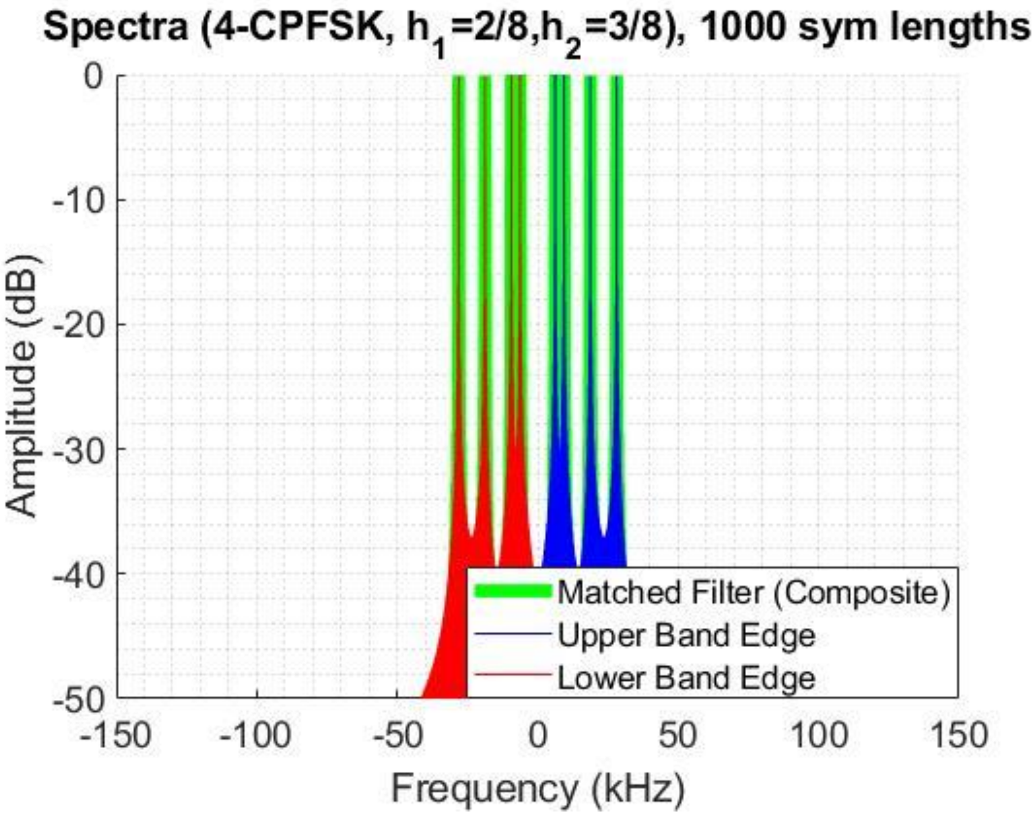

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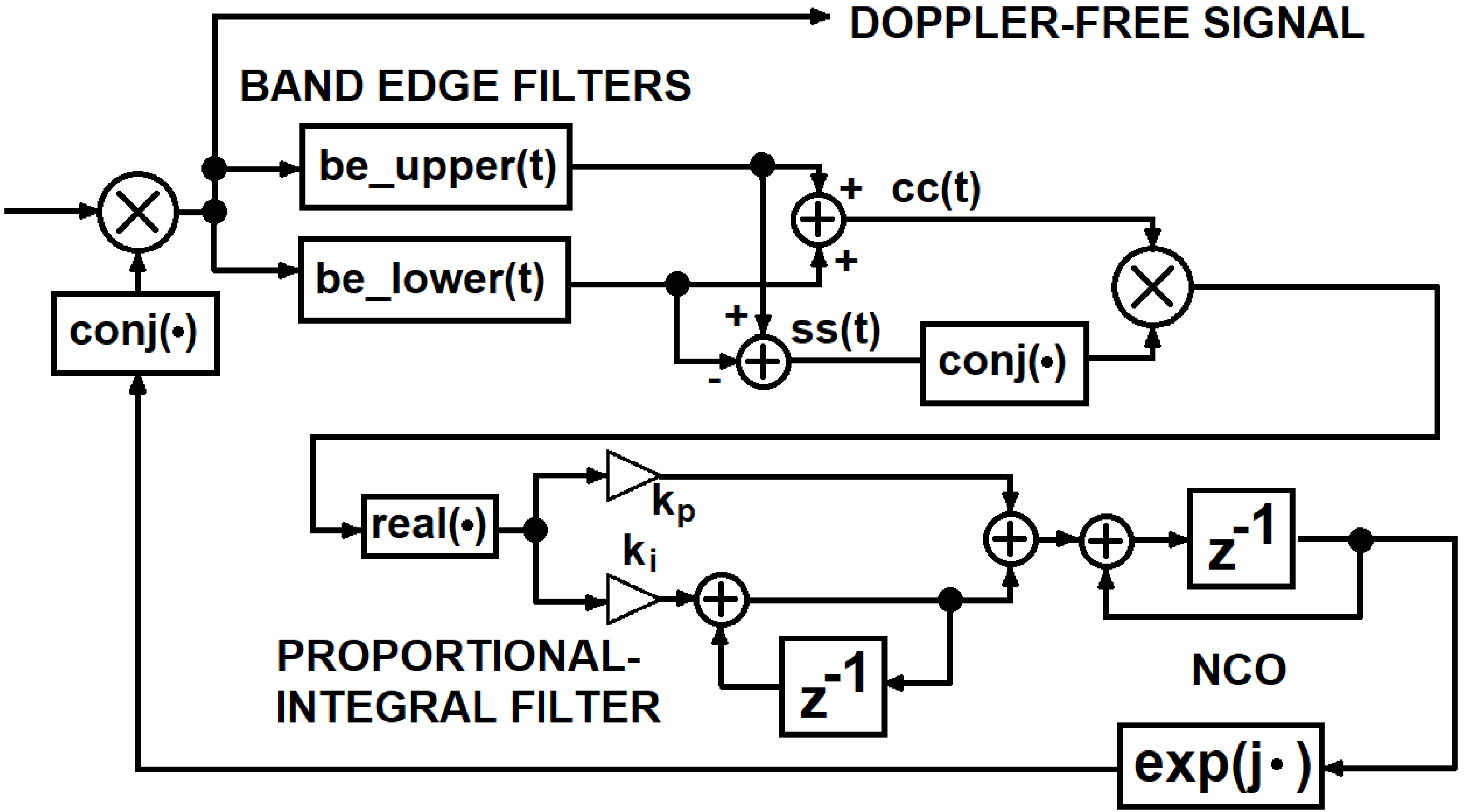
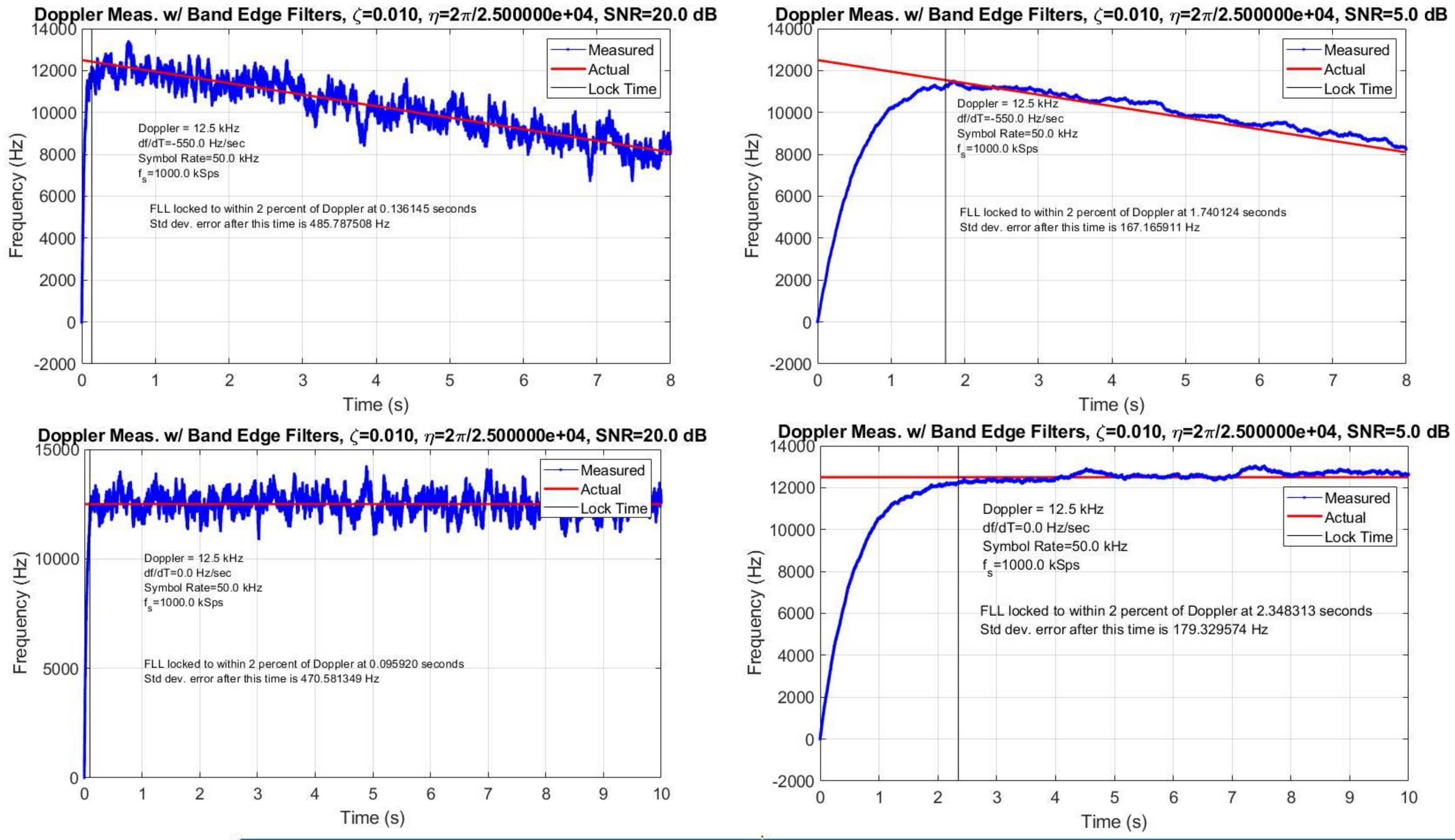
Band Edge Filter FLL Structure



Performance of Band Edge FLL

4-ary FSK Mod. Rate 50 kHz
1 MS/s Sample Rate
Changing modulation index
$h_1 = 2/8$, $h_2 = 3/8$
Initial Doppler = 12.5 kHz
Doppler change =
-550 Hz/s on top
0 Hz/ s on botton
SNR = 20 dB on left
= 5 dB on right

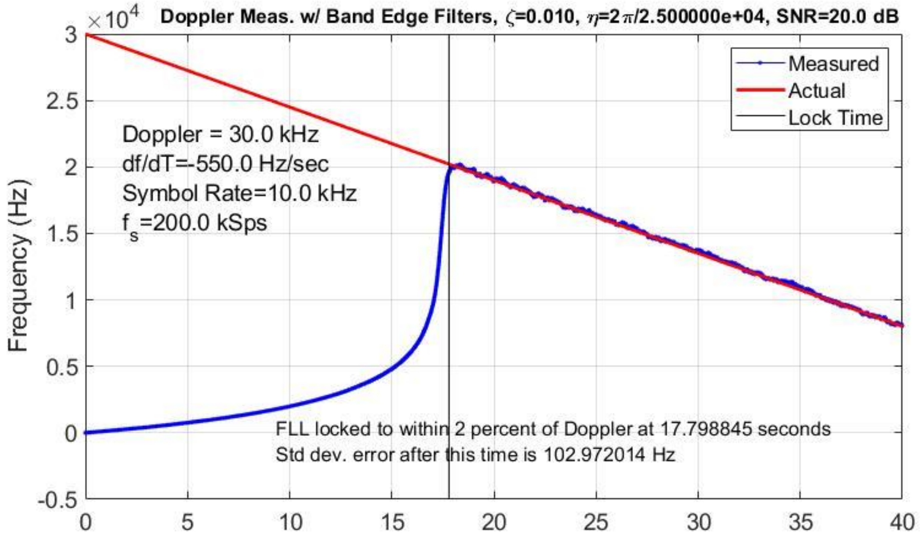


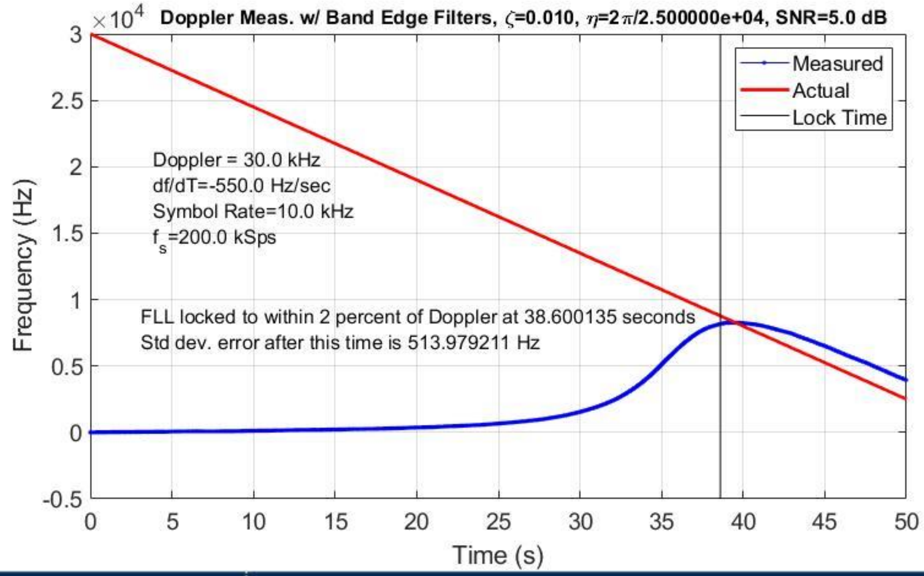
Why does the error magnitude after lock "improve" for lower SNR?

- The signal of interest has frequency changes as part of its design.
- If a long run of the same symbol occurs, the signal of interest will appear to be a tone (if the modulation index is constant). However, the FLL will try to "correct" this tone all the way to zero Hz.
- In a Phase Shift Keyed signal, a long sequence of constant symbols looks like a constant voltage. FLL "corrects" this all the way to zero as it should.
- The CPFSK FLL depends on fact that different symbols are equally likely to occur, so the "average" measured frequency offset should be correct.

Problem with Band Edge FLL when Doppler Exceeds Modulation Bandwidth

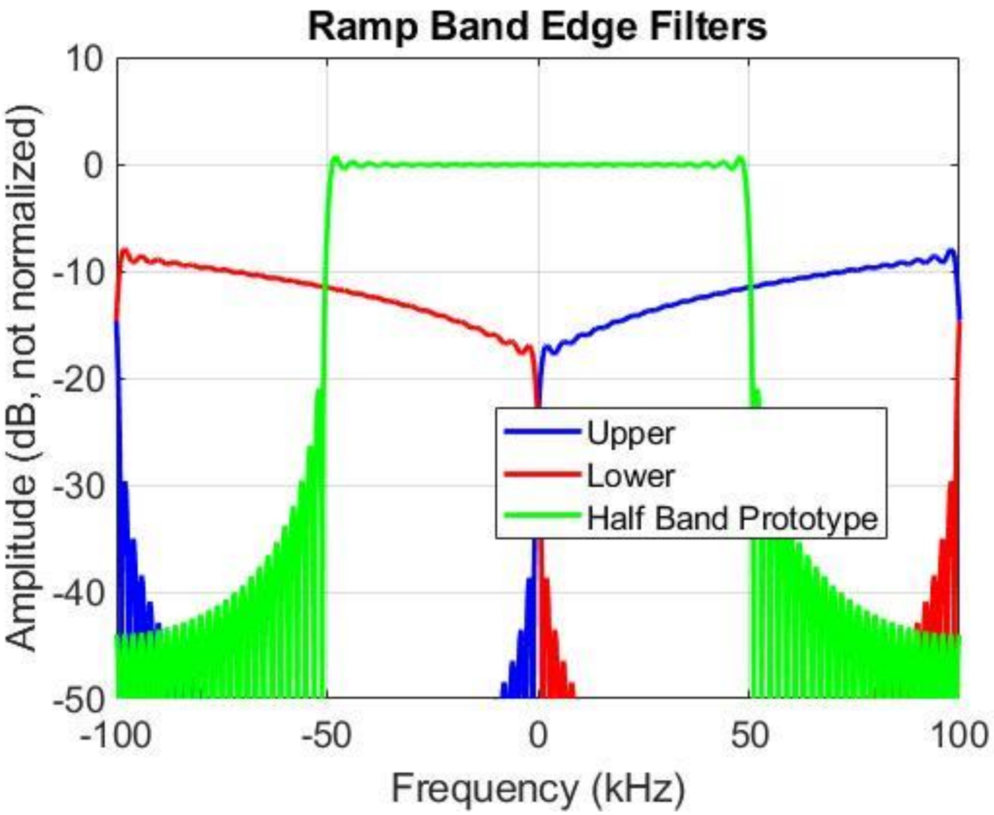
- 4-ary CPFSK (h_1=2/8, h_2=3/8) 10 kHz modulation rate
- 200 kS/s sample rate (20 samples/sym)
- Initial Doppler = 30 kHz
- Doppler change = -550 Hz/s
- SNR = 20 dB (top)
  = 5 dB (bottom)
- Band edge filters receive very little energy, preventing FLL from functioning properly
- This time, the lower SNR curve has a higher error magnitude even though it is smoother.





Fixing Problem with Ramp Half Band Filters

- Calculate a time series equal to the inverse Fourier Transform of abs(f/f_s), where f_s is the sample rate, f extends from $-f_s/2$ to $+f_s/2$
- Truncate it to 50 coefficients
- Create a half-band filter with 101 coefficients
- Frequency translate to $\pm f_s/4$ to make upper and lower half band filters
- Convolve time series of half band filters with time series of ramp
  - Convolution in time domain = multiplication in frequency domain
  - Ramped half band filters have 150 coefficients



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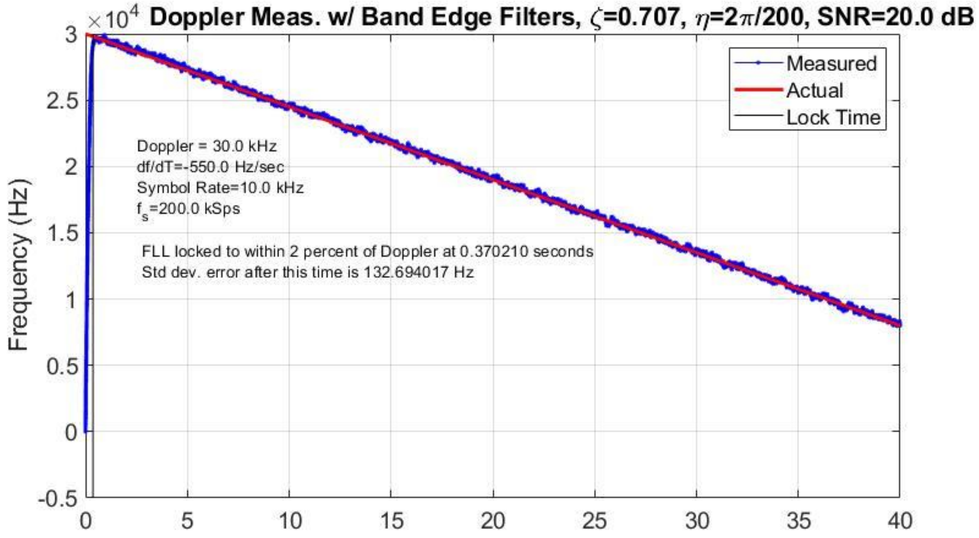
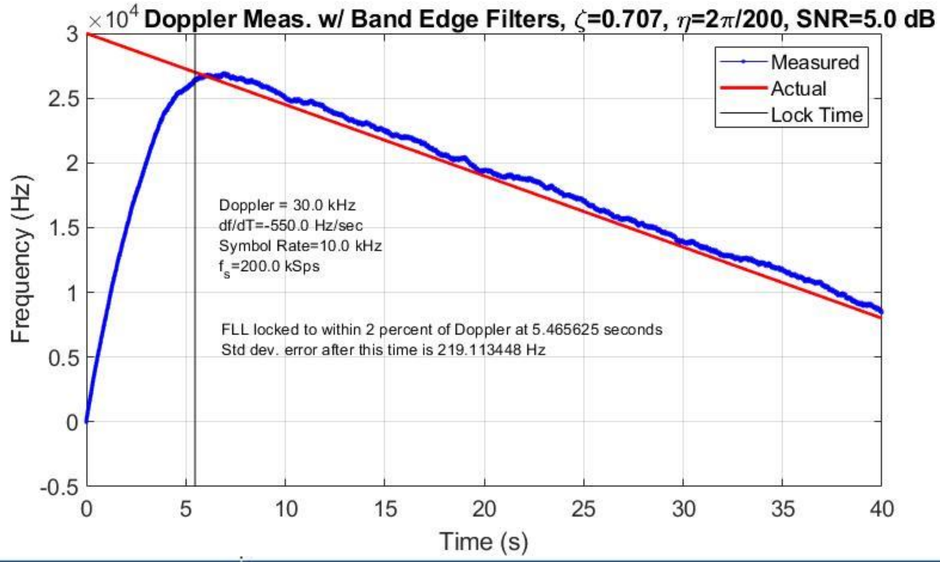
Ramp Half Band Filter FLL Performance when Doppler Exceeds Modulation Bandwidth

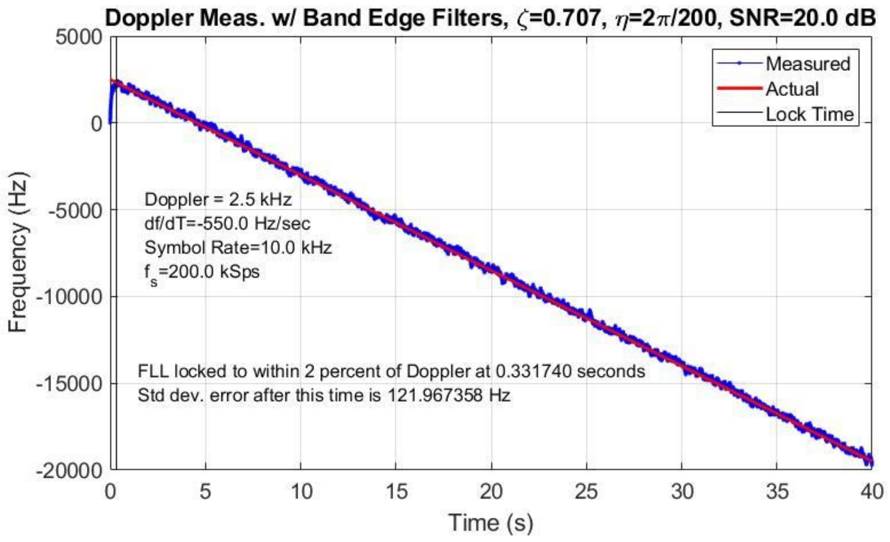
- 4-ary CPFSK (h_1=2/8, h_2=3/8)
  10 kHz modulation rate
- 200 kS/s sample rate (20 samples/sym)
- Initial Doppler = 30 kHz
- Doppler change = -550 Hz/s
- SNR = 20 dB (top)
  = 5 dB (bottom)
- Ramped Half band filters receive more energy when Doppler is larger
- Lock time significantly improves
- Lower SNR curve has more frequency error and longer lock time

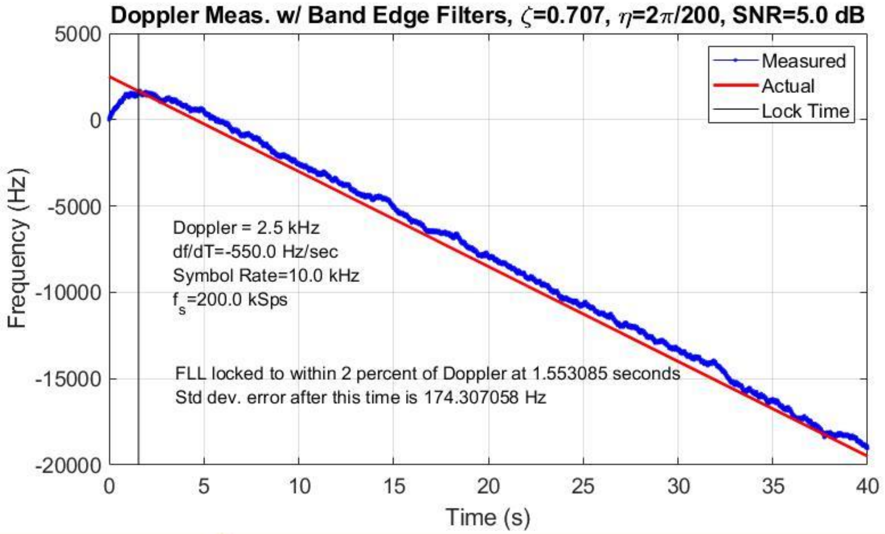




Ramp Half Band Filter FLL Performance when Doppler is Within Modulation Bandwidth

- Used same loop parameters to test time-varying Doppler with initial value within the modulation bandwidth
- 4-ary CPFSK (h_1=2/8, h_2=3/8)
  10 kHz modulation rate
- 200 kS/s sample rate (20 samples/sym)
- Initial Doppler = 2.5 kHz
- Doppler change = -550 Hz/s
- SNR = 20 dB (top)
  = 5 dB (bottom)
- Similar performance obtained for Doppler inside modulation bandwidth and outside modulation bandwidth





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Conclusions

- Create upper band edge filter out of positive frequency symbols, lower band edge filter out of negative frequency symbols
- Duration of matched filters affects bandwidth of band edge filters
- Trade-off between reaction time and frequency error after lock
  - For PSK signals, lower SNR -> slower reaction time, higher error after lock
  - For CPFSK signals, lower SNR -> slower reaction time, lower error after lock
- If maximum Doppler magnitude exceeds modulation bandwidth, use ramped band edge filters
- If CPFSK signal has preamble which can be used for initial estimate of Doppler, estimate should be fed to FLL in order to shorten lock time
  - Lower the loop bandwidth to get smoother error curve

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