CONTINUOUS PHASE MODULATION (CPM)

PREAMBLES, DOPPLER ESTIMATES AND OPTIMAL RECEIVERS

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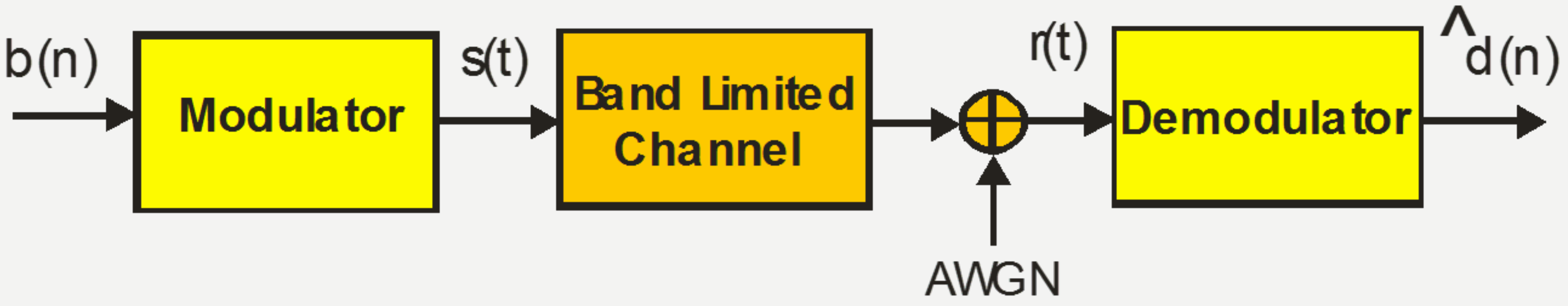
DIGITAL MODULATION



$s(t) = R(t) \cdot \cos(\omega_c t + \phi(t))$: Amplitude and Phase Modulated Carrier

$= R(\mathrm{t}) \cdot \cos(\phi(t)) \cdot \cos(\omega_c t) - R(\mathrm{t}) \cdot \sin(\phi(t)) \cdot \sin(\omega_c t)$

$= I(t) \cdot \cos(\omega_c t) - Q(t)\sin(\omega_c t)$

$\mathrm{s(t)} = \mathrm{Re}\{R(t)\,\mathrm{e}^{j\phi(t)}\, e^{j\omega_c t}\}$: Polar Complex form with Baseband Modulation

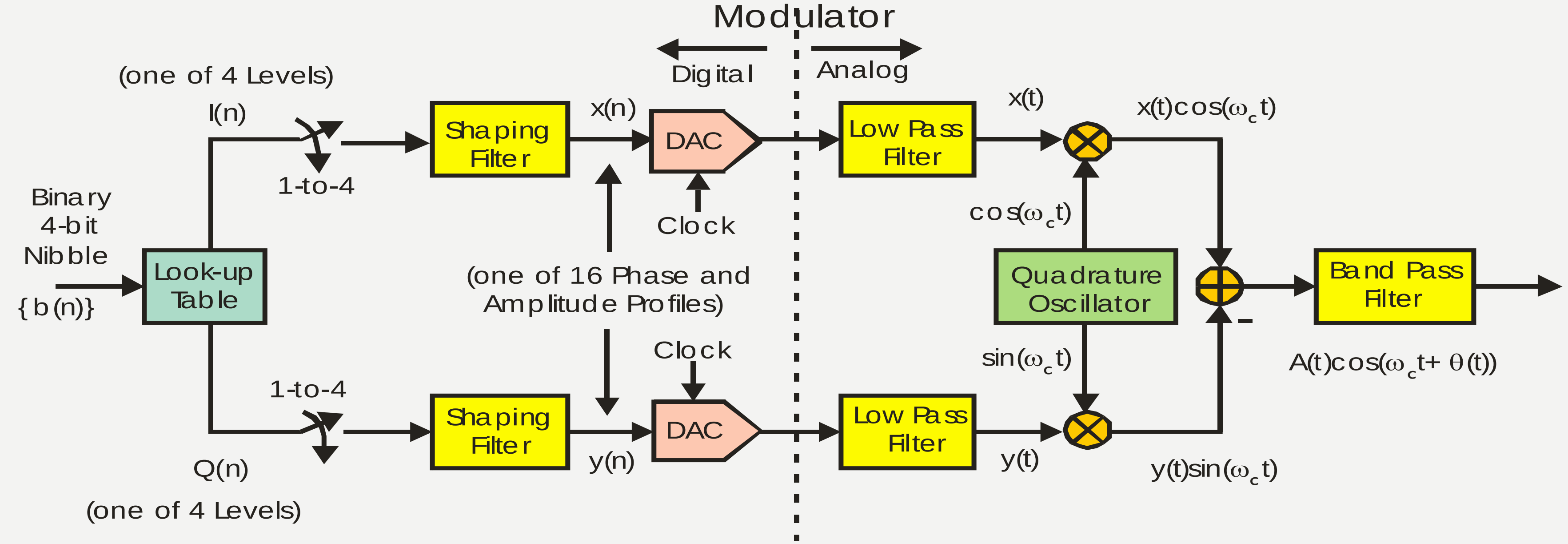
$R(t)\,\mathrm{e}^{j\phi(t)} = \sum_k I_k g_k(t - kT)$: Digital Baseband Modulation,

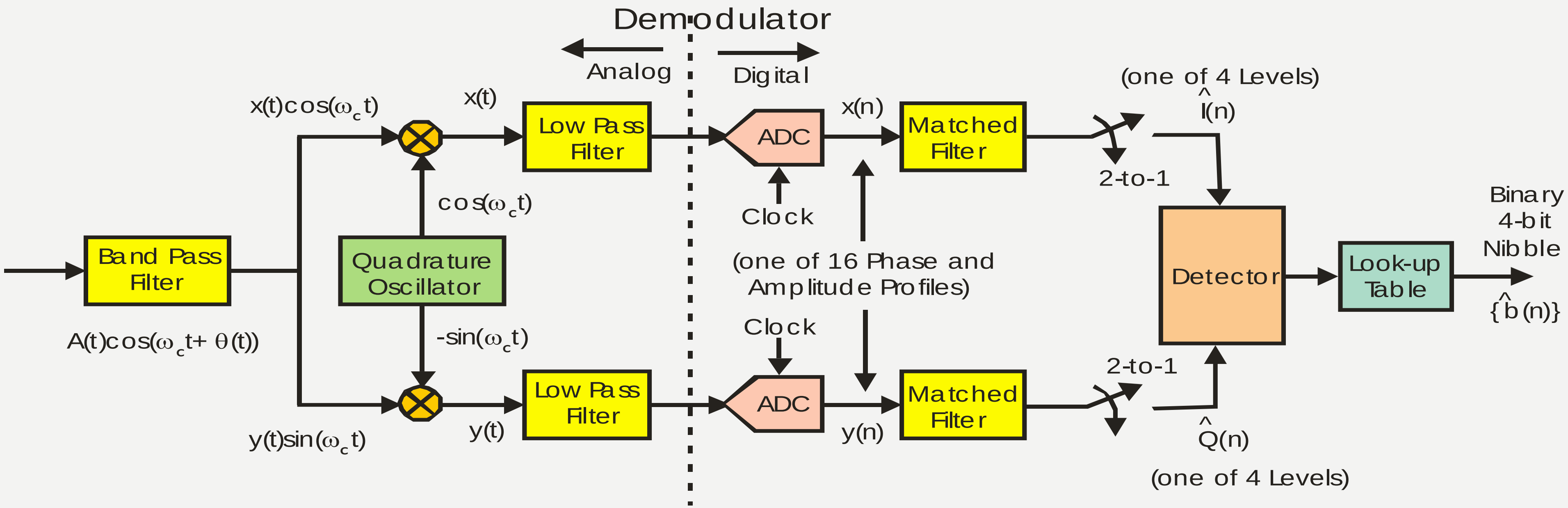
Sum of Scaled Offset Waveshapes

I_k : one of 2^M Complex Amplitudes from Finite Look-up Table

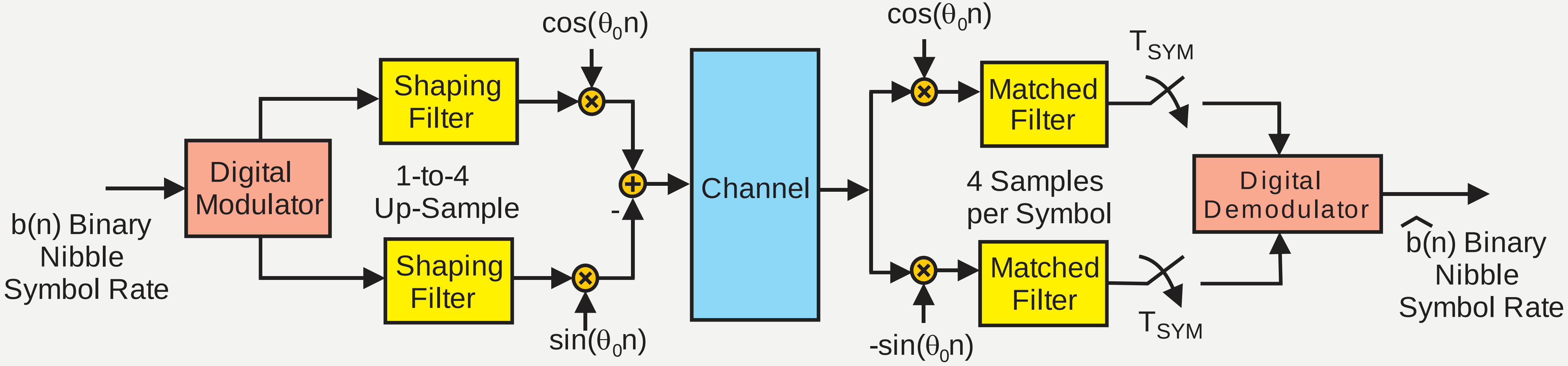
g_k : one of 2^Q Waveshapes from Finite List

SHAPING FILTER AND MATCHED FILTER IN MODULATOR AND DEMODULATOR

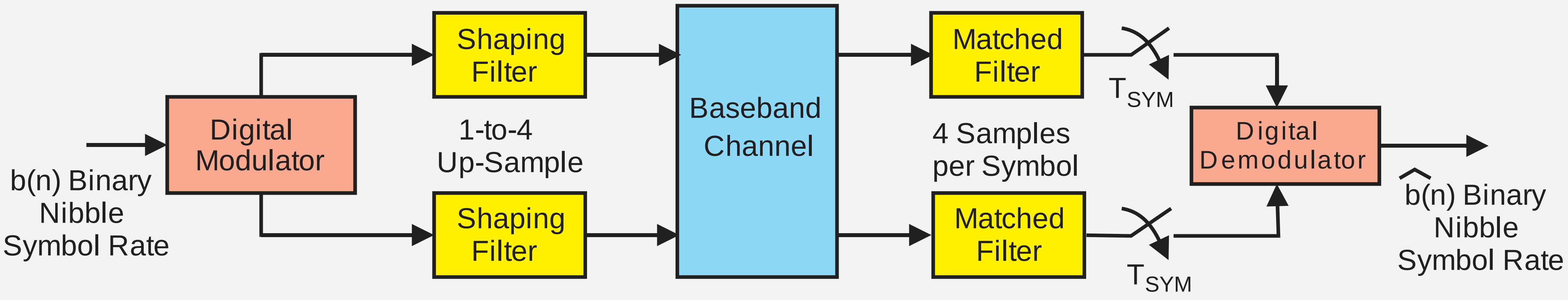




REAL, CARRIER CENTERED MODEL OF MODULATOR AND DEMODULATOR



Complex, Baseband Model of Modulator and Demodulator



VARIOUS QAM MODULATION CLASSES

- Linear Memoryless Modulation
  - Pulse Amplitude Modulation (PAM)
  - Phase Shift Keying (PSK)
  - Quadrature Phase Shift Keying (QPSK)
  - Quadrature Amplitude Modulation (QAM)
- Linear Modulation with Memory
  - Offset QPSK (O-QPSK)
  - π/4-QPSK (pi/4-QPSK)
- Non Linear Modulation with Memory
  - Continuous Phase FSK (CPFSK)
  - Minimum-Shift Keying (MSK)
  - Gaussian MSK (GMSK)
  - Continuous-Phase Modulation (CPM)
  - Shaped Binary Phase Shift Keying (SBPSK)

“Practical Digital Wireless Signals, Cambridge University Press, Earl McCune

6.1 Signals and characteristics

The newest fundamental signal type to join the DWC pantheon is phase-shift keying (PSK). The reason for PSK’s relatively tardy entry is easy to understand, however. As will be seen in detail later in the signal quality required for successful generation is quite high, and the amount of information required for successful reception of a PSK signal is the greatest of these fundamental signal types. In the early decades of DWC this type of signal quality was beyond the state of the art, so ASK and FSK were used. As time and technology progressed, achieving the required signal quality became possible – and PSK began to be used.

Author’s dilemma

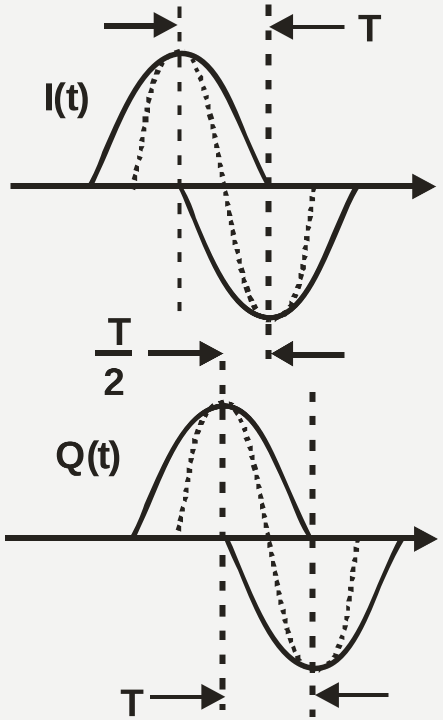
In the logical signal progression being followed so far, one might expect that this discussion on PSK will focus on a Digital Wireless Communication signal type that strictly modulates the signal phase parameter, just as ASK only modulates the amplitude parameter and FSK only modulates the frequency parameter. Indeed, this type of signal is possible, practical, and useful. Yet for a number of reasons this form of PSK, which we shall refer to here as “pure-PSK”, is almost never used. What the great majority of signal designers call PSK is actually a special case of QAM (quadrature amplitude modulation).

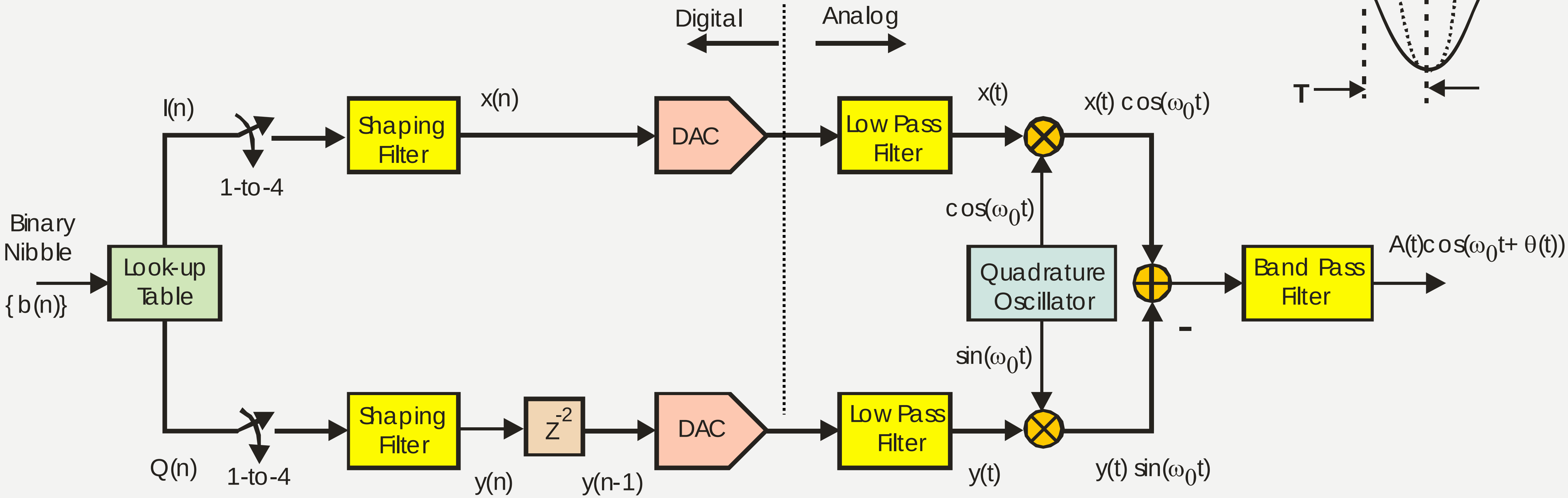
In the remainder of this text we shall refer to this form as “conventional-PSK”. Therefore, the main difference between pure- and conventional PSK is that pure-PSK is restricted to being a constant envelope signal by operating a one-dimensional phase-only modulation process directly from the PSK states, while conventional-PSK is not restricted in this way. Both forms of PSK are discussed in this chapter. Interleaved discussions address each type of PSK as appropriate in the context.

OFFSET-QPSK MODULATOR

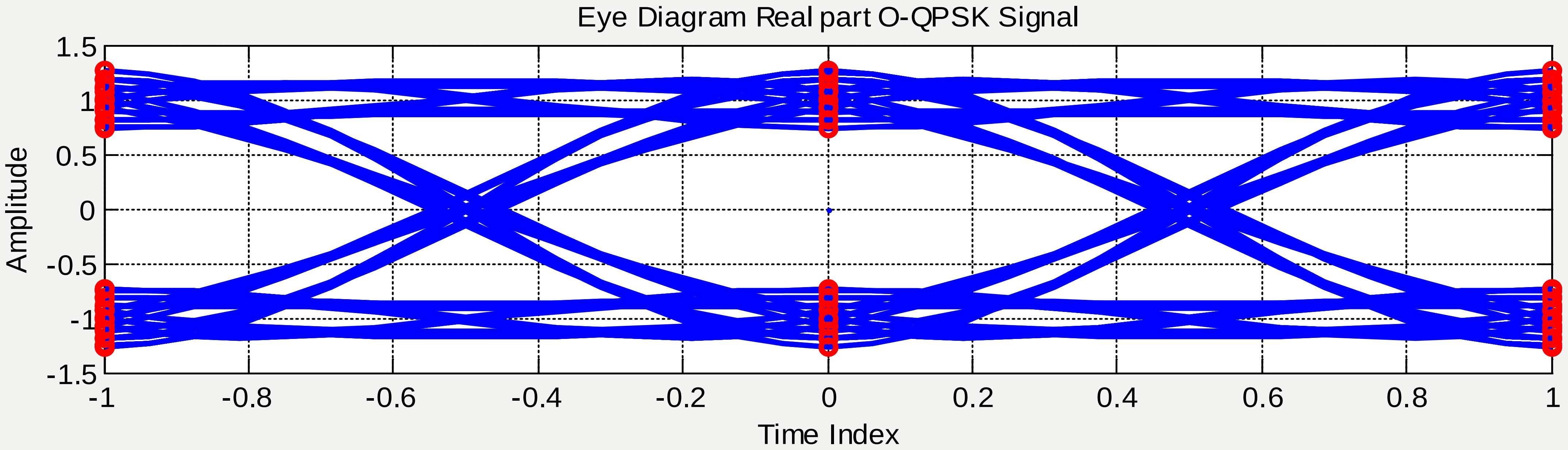
QPSK Signals: T Second Spacing Of Successive Symbols

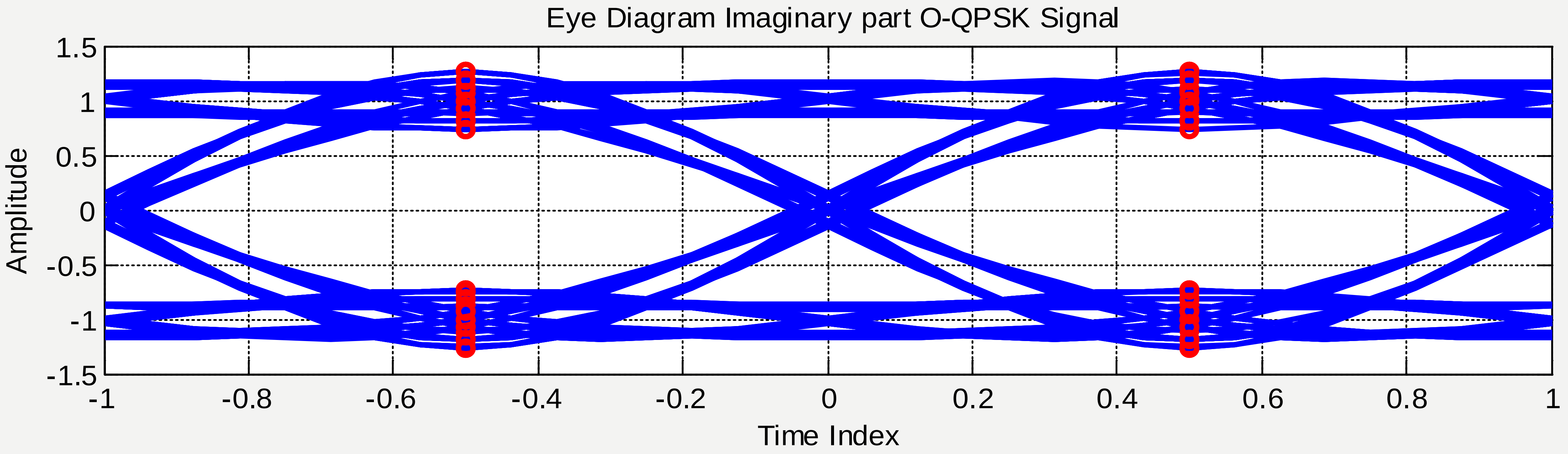
O-QPSK Signals: T/2 Second Spacing Of In-Phase & Quadrature Symbols



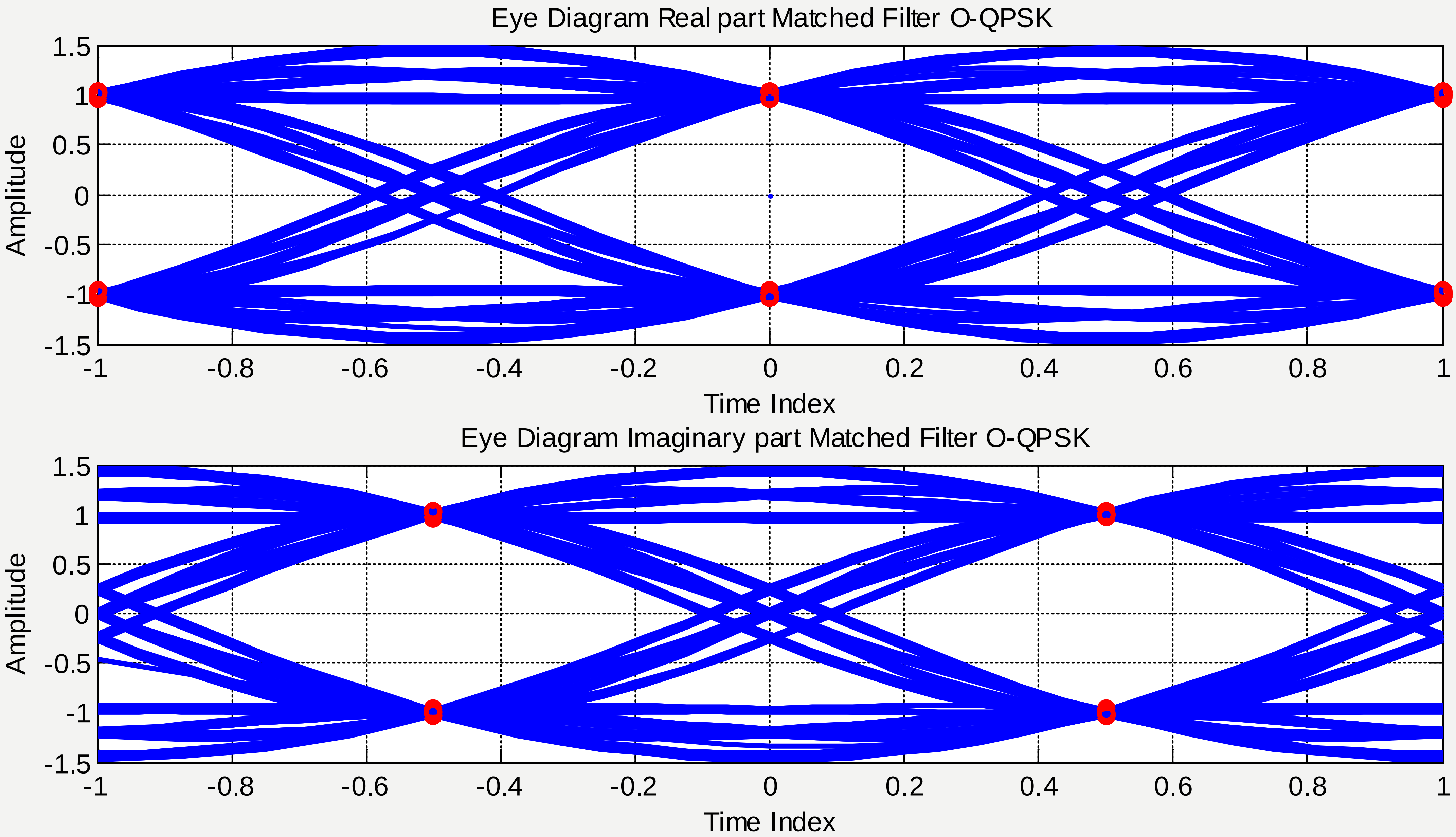


Modulator Eye Diagrams O-QPSK

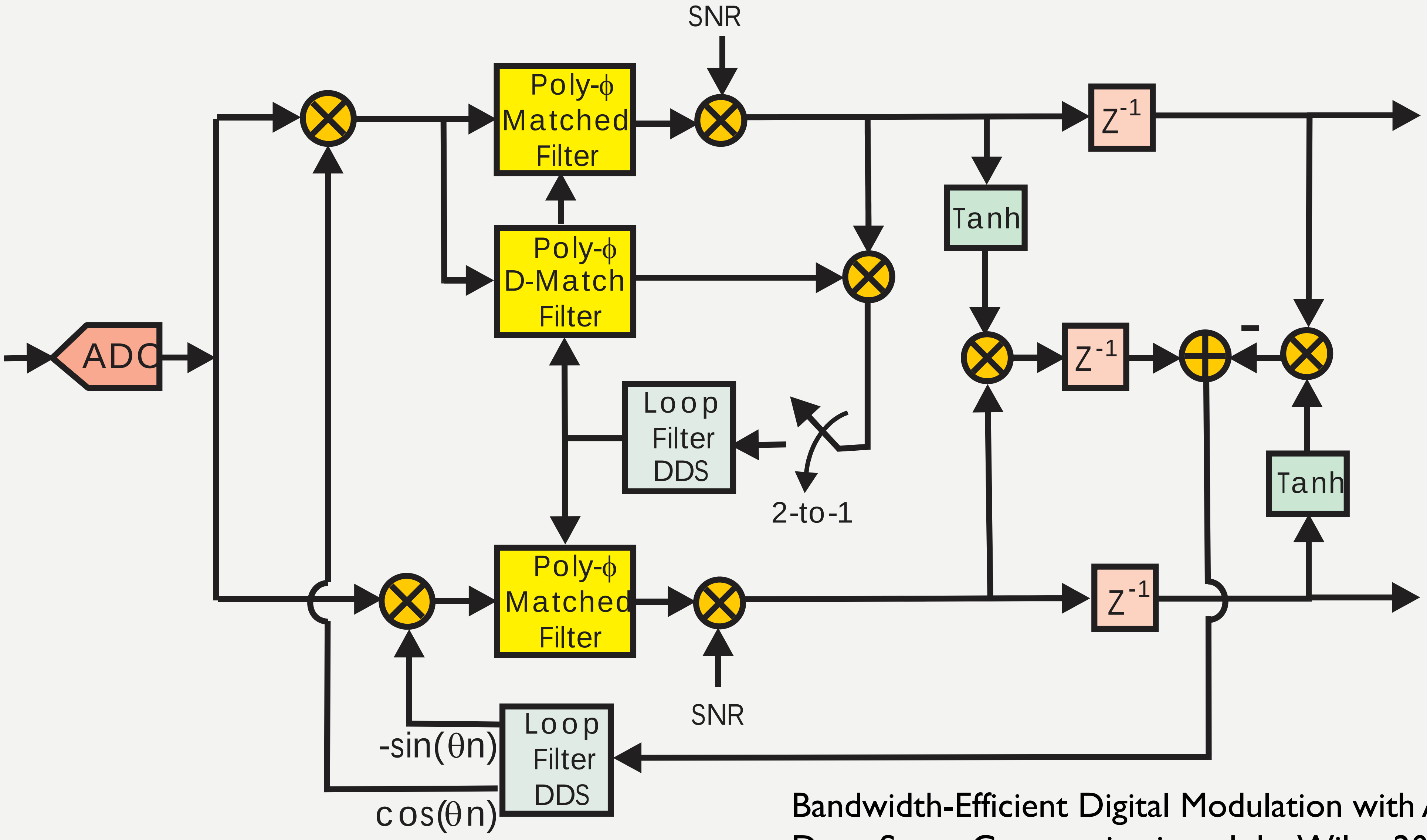




Demodulator Eye Diagrams O-QPSK



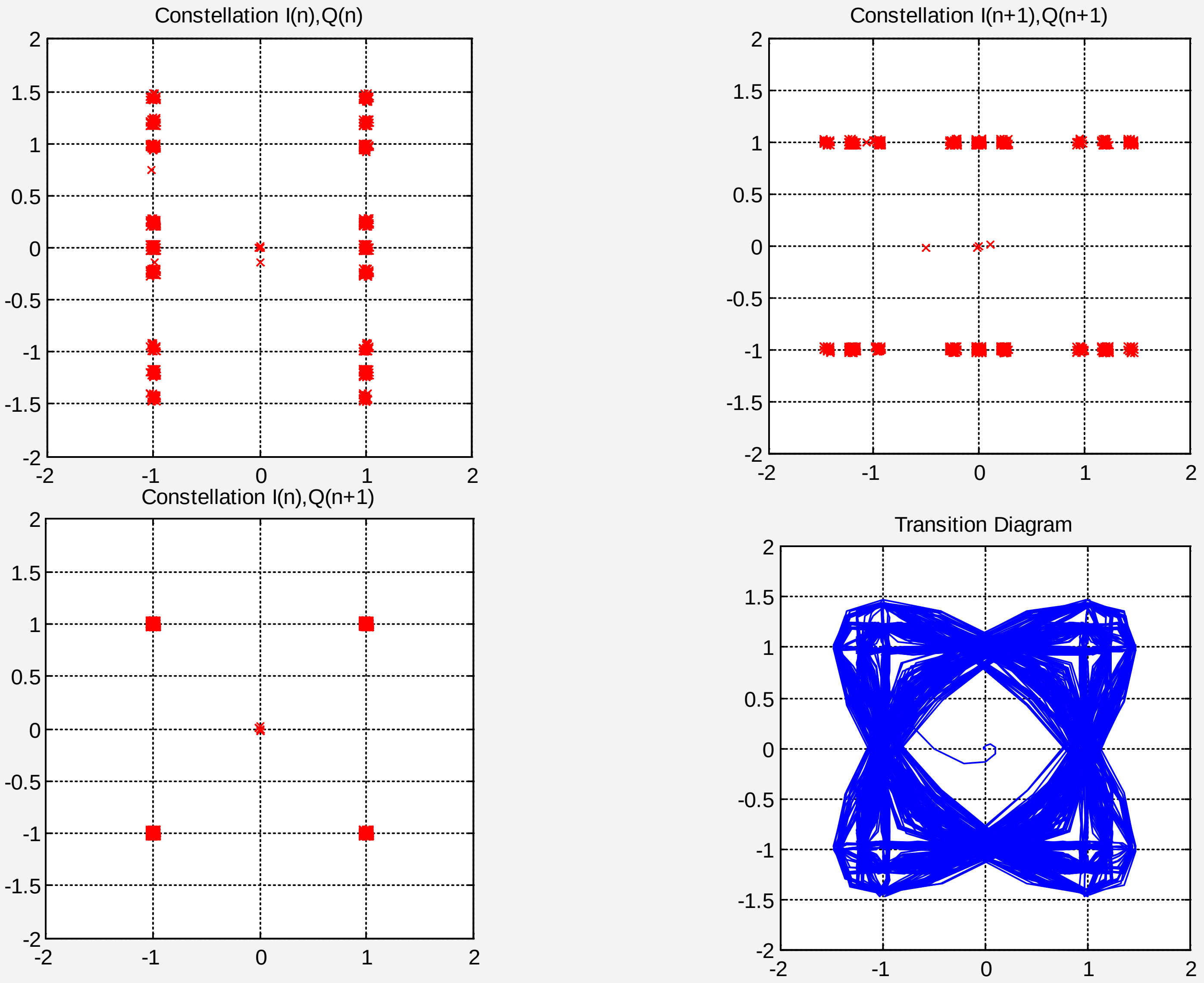
OQPSK COUPLED TIMING-CARRIER LOOPS



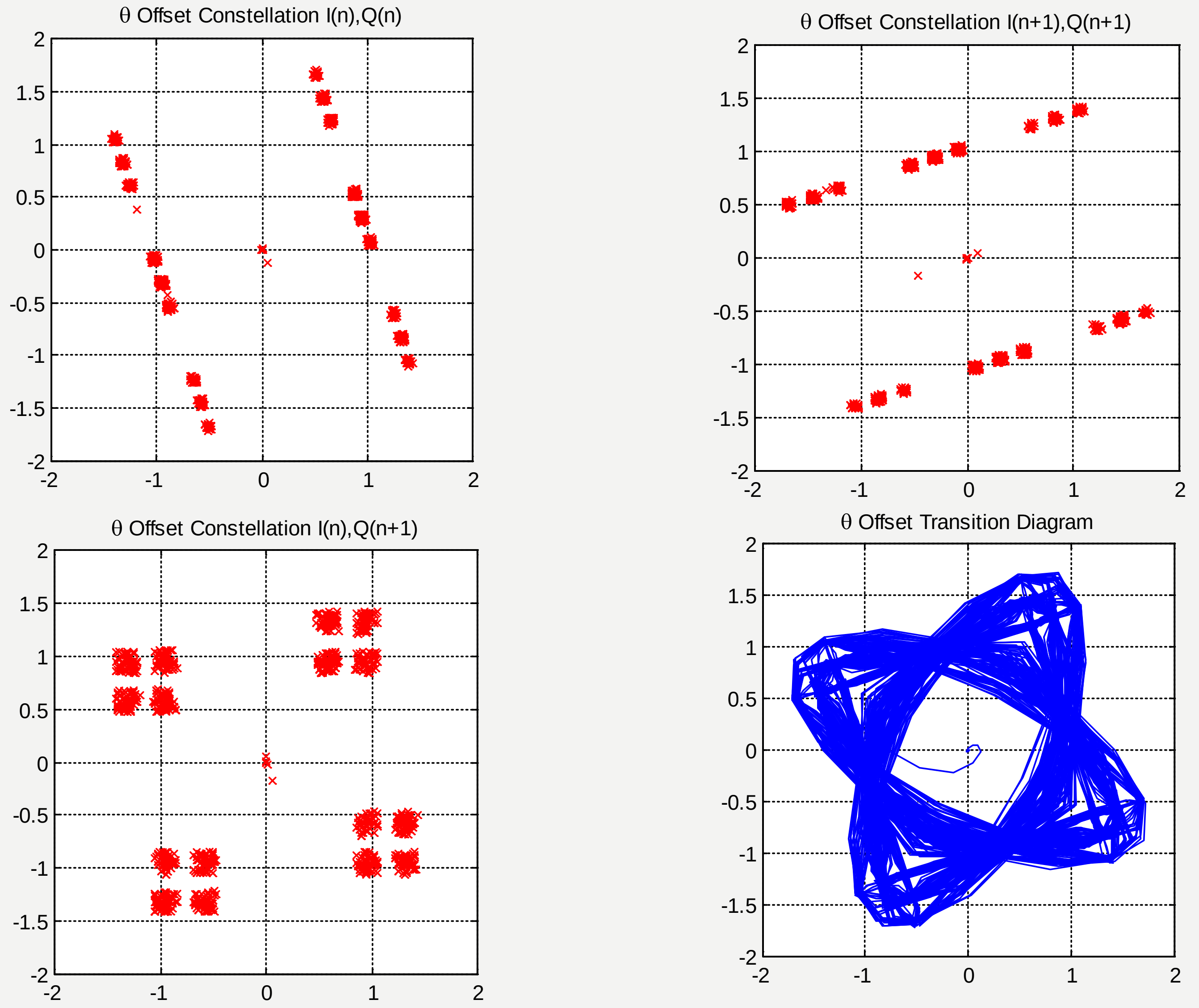
Bandwidth-Efficient Digital Modulation with Application to Deep Space Communications, John Wiley, 2003

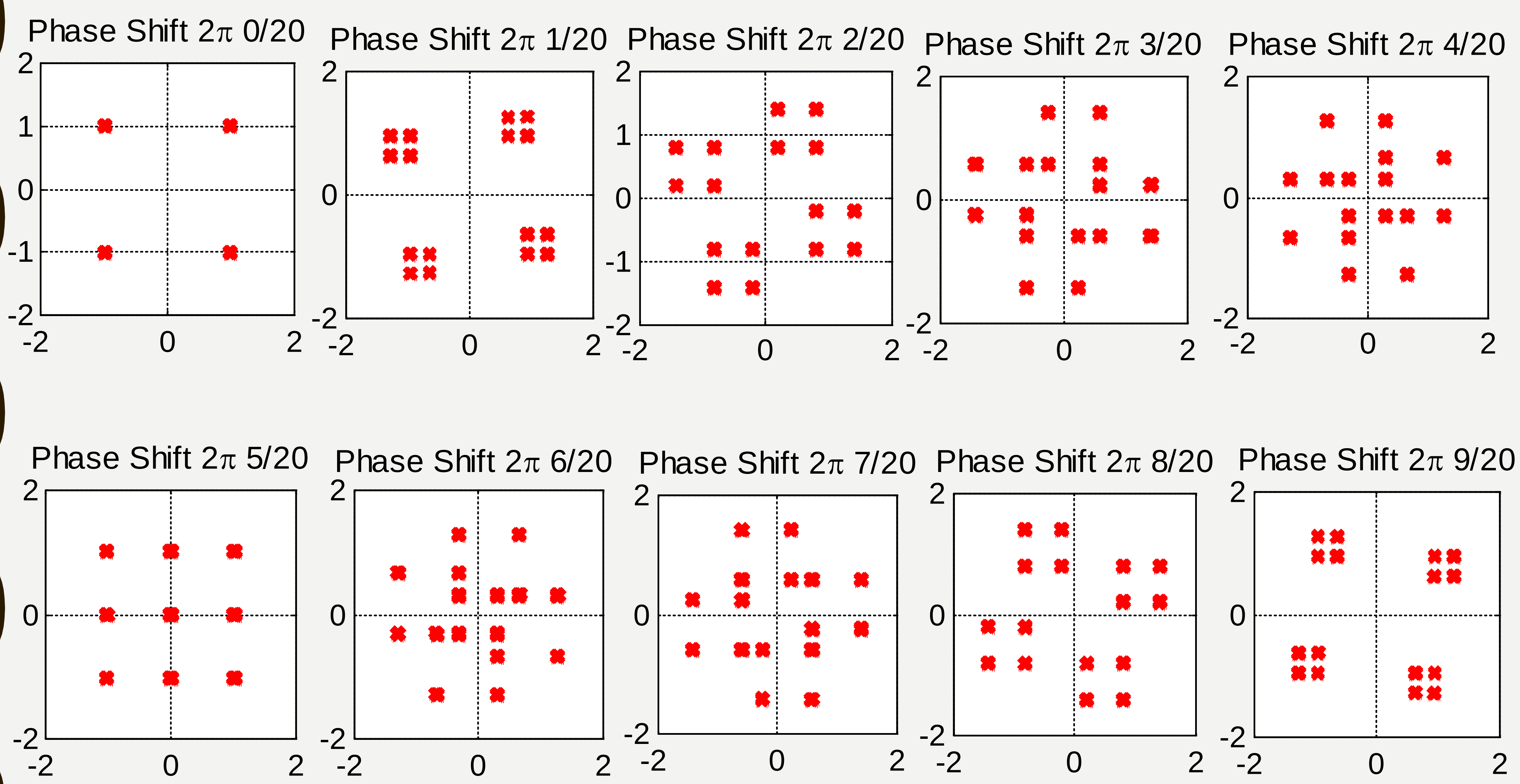
Carrier Synchronization of Offset Quadrature Phase-Shift Keying, Marv Simon, JPL TMO-report 42-133, 15-may 1998

OQPSK CONSTELLATIONS

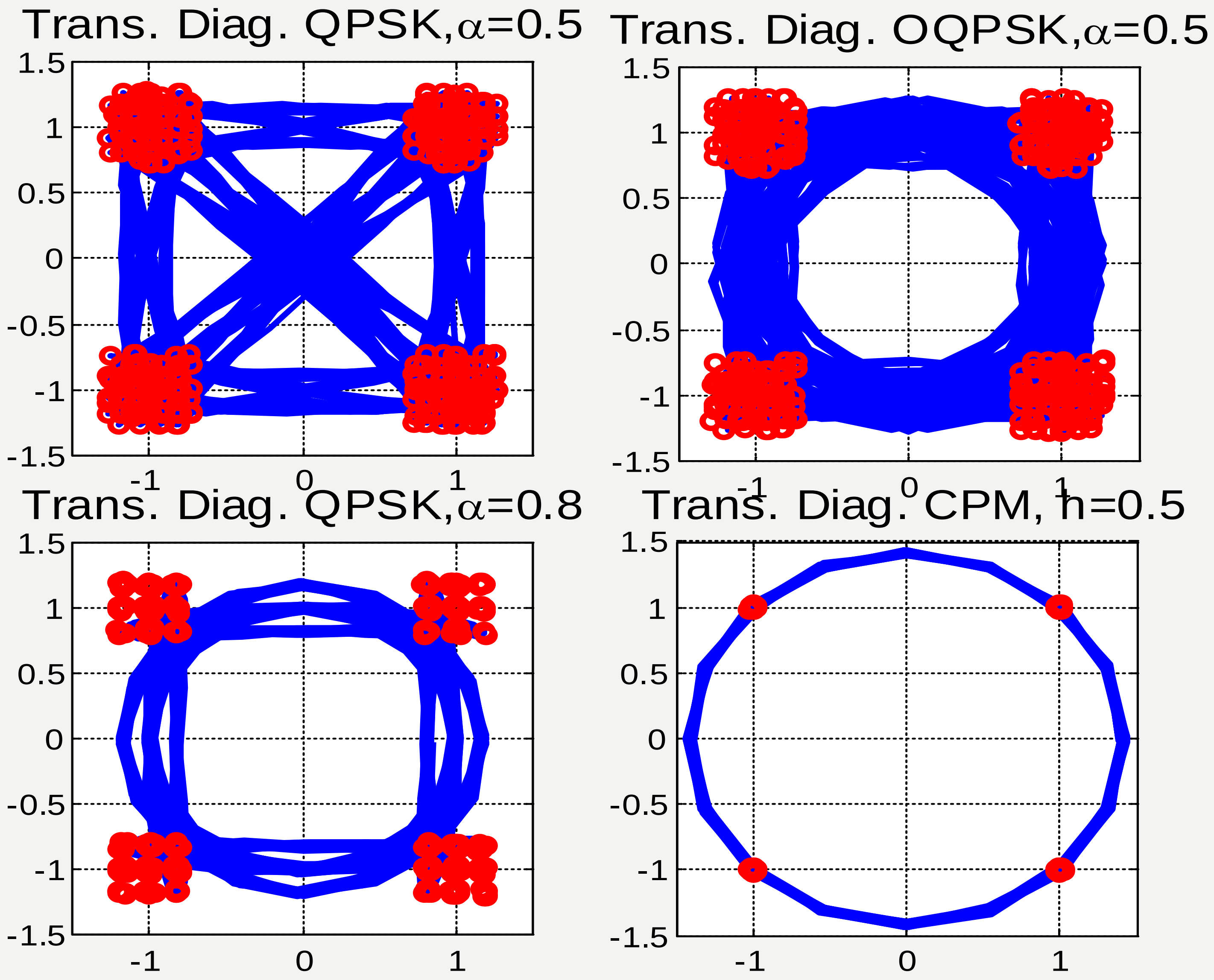


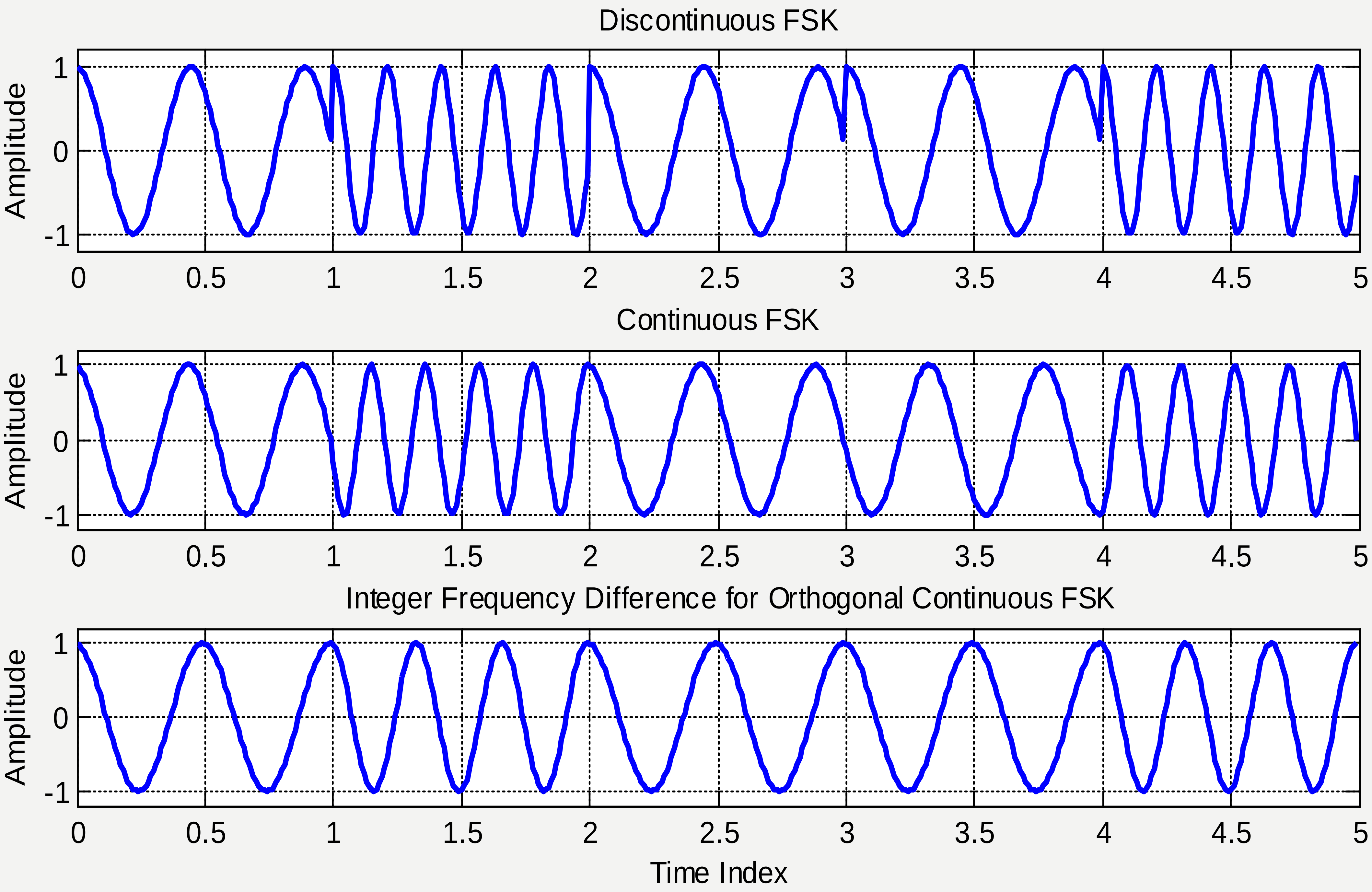
PHASE OFFSET OQPSK CONSTELLATIONS



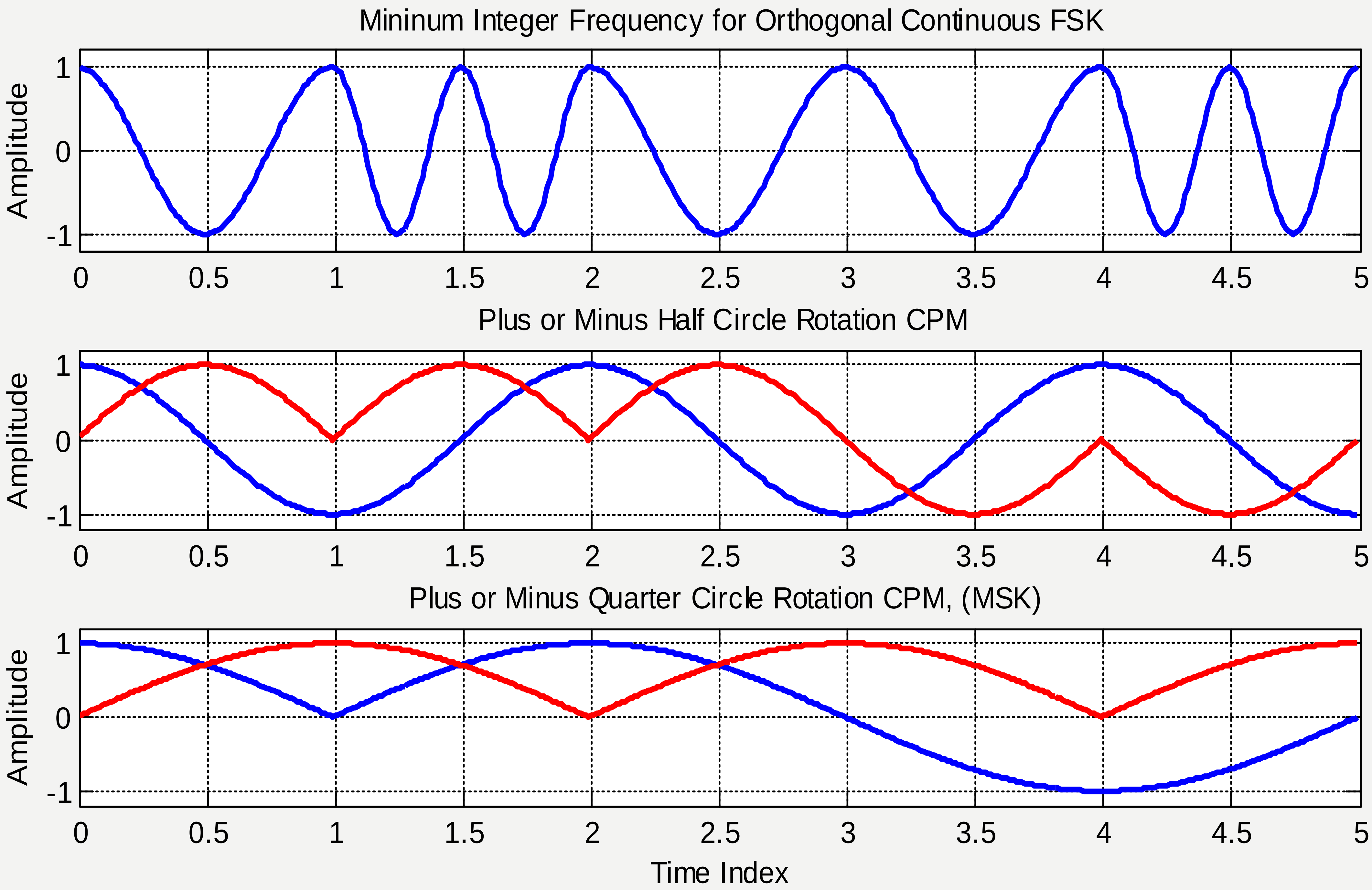

Phase Shift 2π 0/20
Phase Shift 2π 1/20
Phase Shift 2π 2/20
Phase Shift 2π 3/20
Phase Shift 2π 4/20
Phase Shift 2π 5/20
Phase Shift 2π 6/20
Phase Shift 2π 7/20
Phase Shift 2π 8/20
Phase Shift 2π 9/20

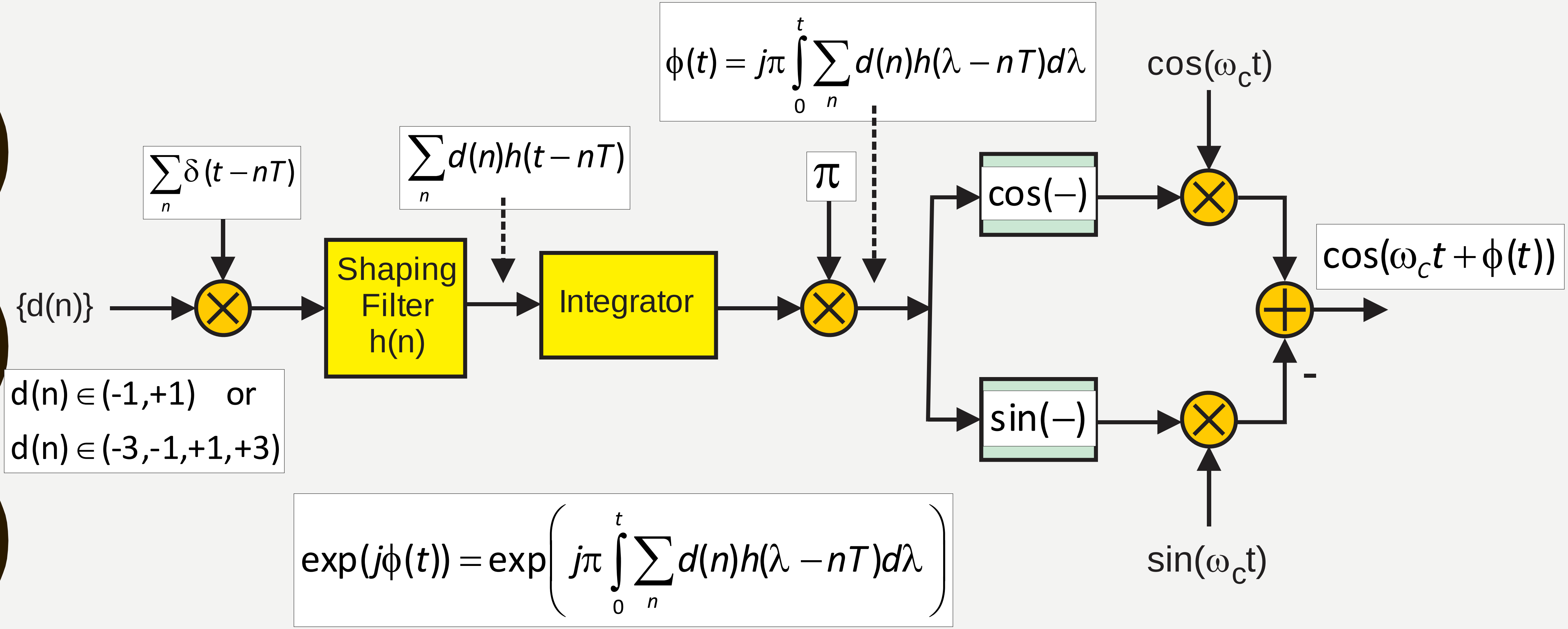
TRANSITIONS: QPSK, OFFSET QPSK, CPM



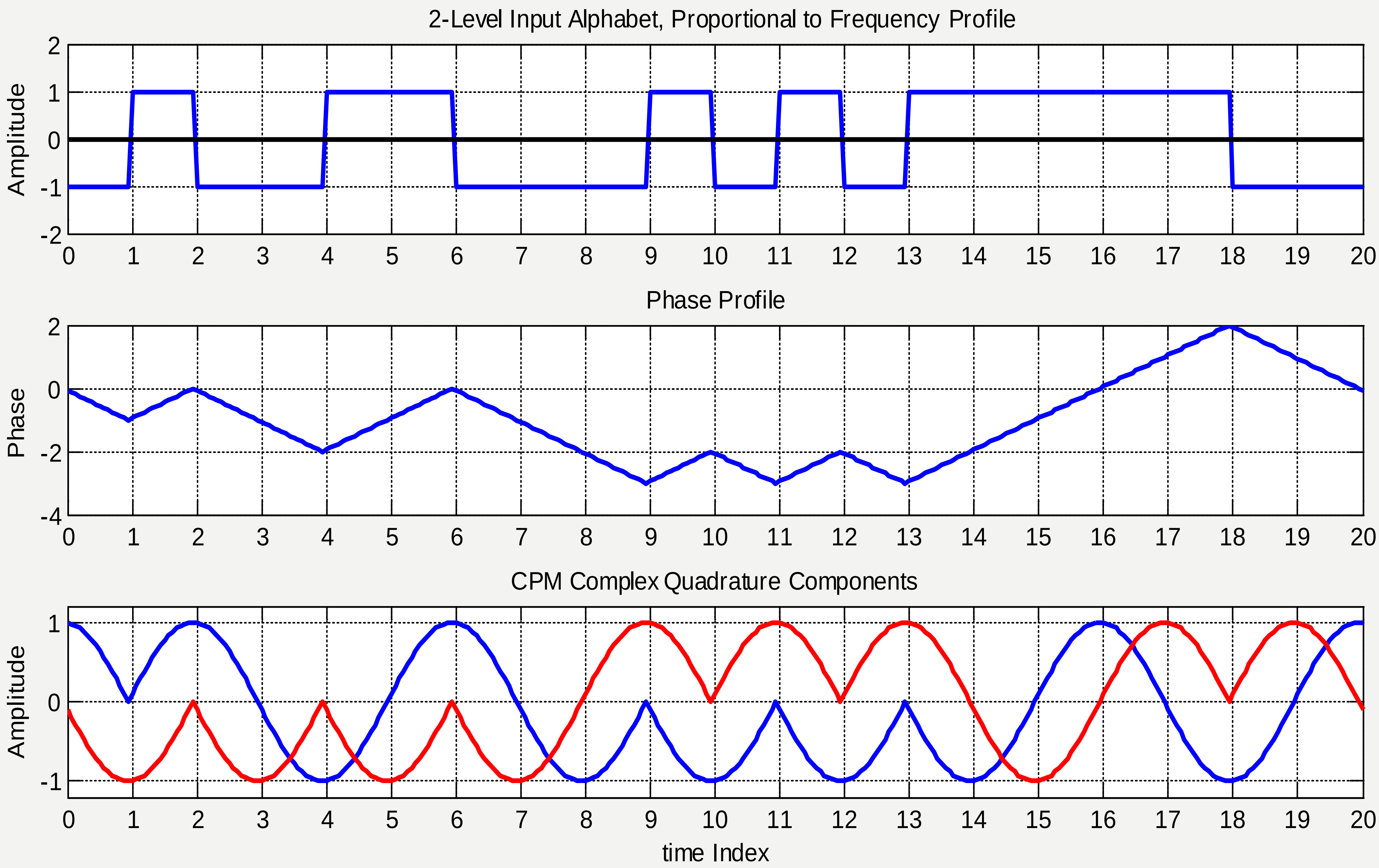


Discontinuous FSK
Amplitude
1
0
-1
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Continuous FSK
Amplitude
1
0
-1
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Integer Frequency Difference for Orthogonal Continuous FSK
Amplitude
1
0
-1
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time Index

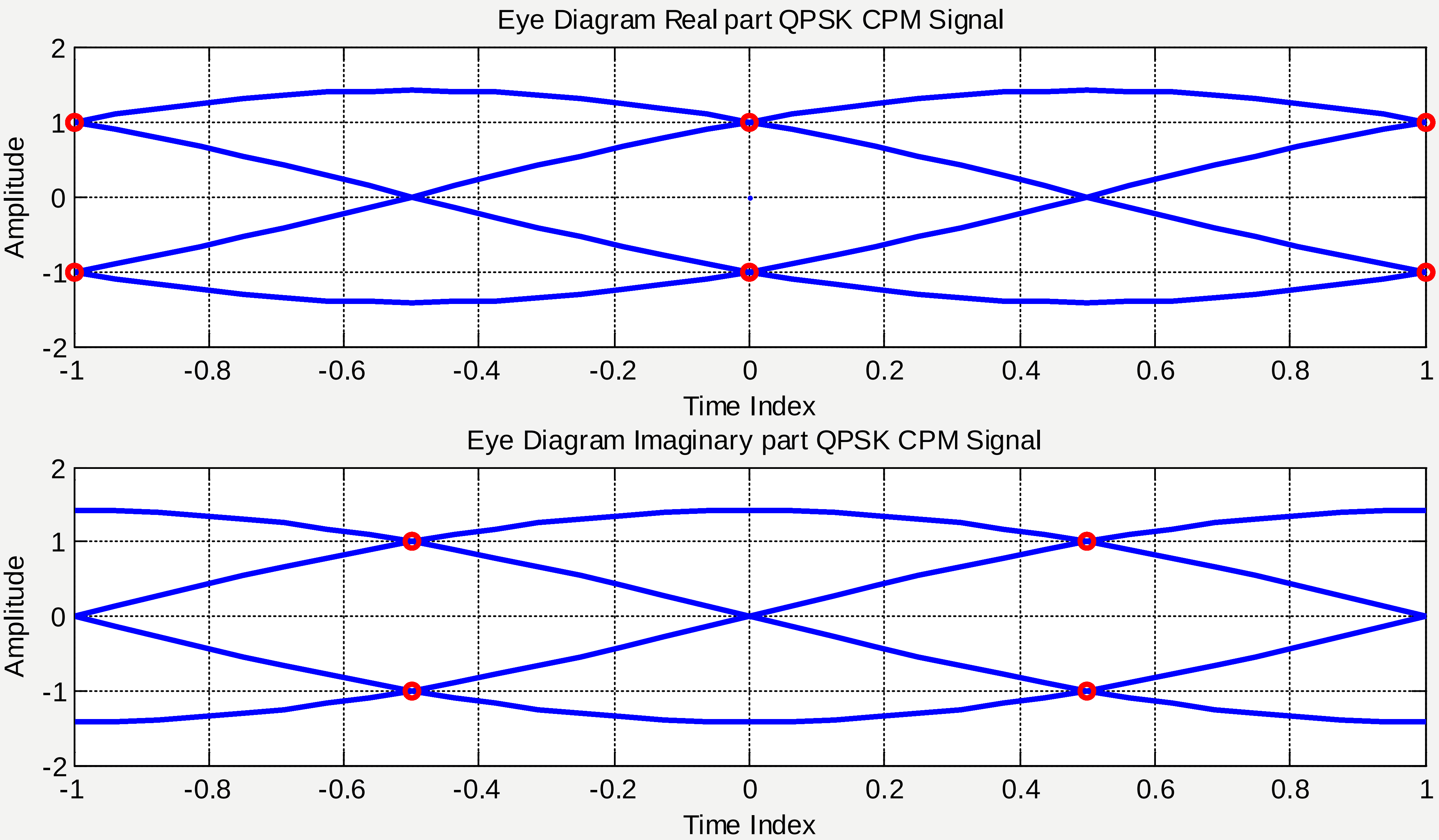

Mininum Integer Frequency for Orthogonal Continuous FSK
Amplitude
1
0
-1
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Plus or Minus Half Circle Rotation CPM
Amplitude
1
0
-1
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Plus or Minus Quarter Circle Rotation CPM, (MSK)
Amplitude
1
0
-1
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time Index



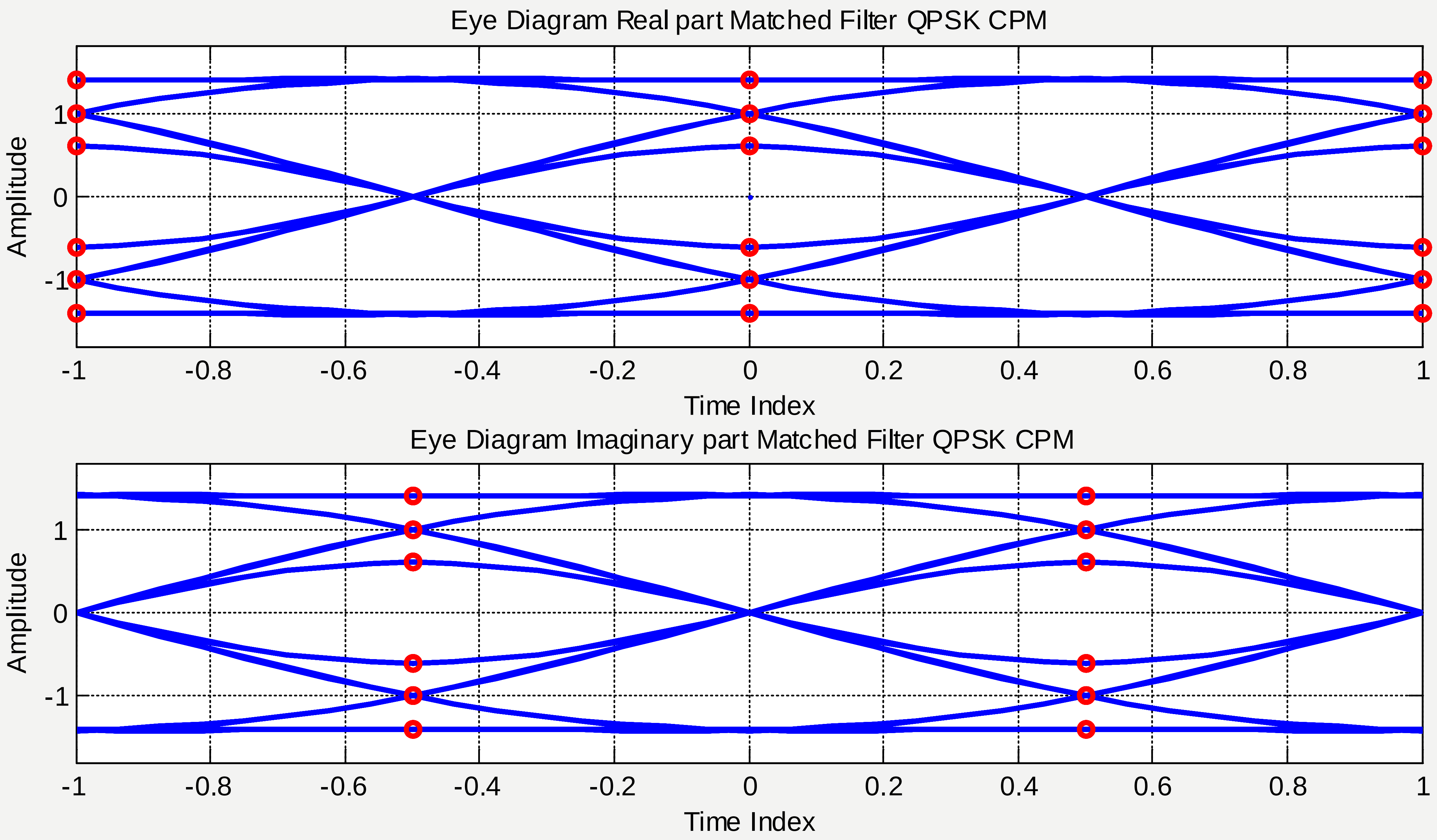
{d(n)}
$\sum_n \delta(t-nT)$
Shaping Filter h(n)
$\sum_n d(n)h(t-nT)$
Integrator
$\phi(t) = j\pi \int_0^t \sum_n d(n)h(\lambda - nT)d\lambda$
π
cos(–)
sin(–)
$\cos(\omega_c t)$
$\sin(\omega_c t)$
-
$\cos(\omega_c t + \phi(t))$
d(n) ∈ (-1,+1) or
d(n) ∈ (-3,-1,+1,+3)
$\exp(j\phi(t)) = \exp\left(j\pi \int_0^t \sum_n d(n)h(\lambda - nT)d\lambda\right)$


2-Level Input Alphabet, Proportional to Frequency Profile
Amplitude
Phase Profile
Phase
CPM Complex Quadrature Components
Amplitude
time Index

Modulator Eye Diagrams CPM

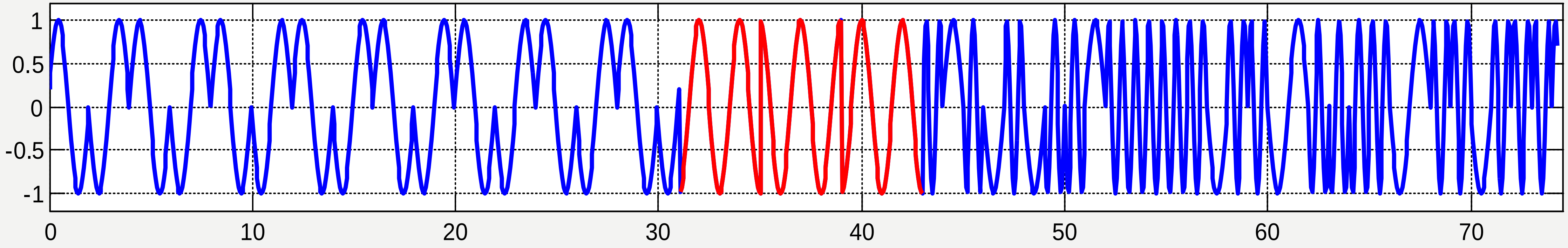


Demodulator Eye Diagrams CPM



Typical (stylized) CPM Signal Structure

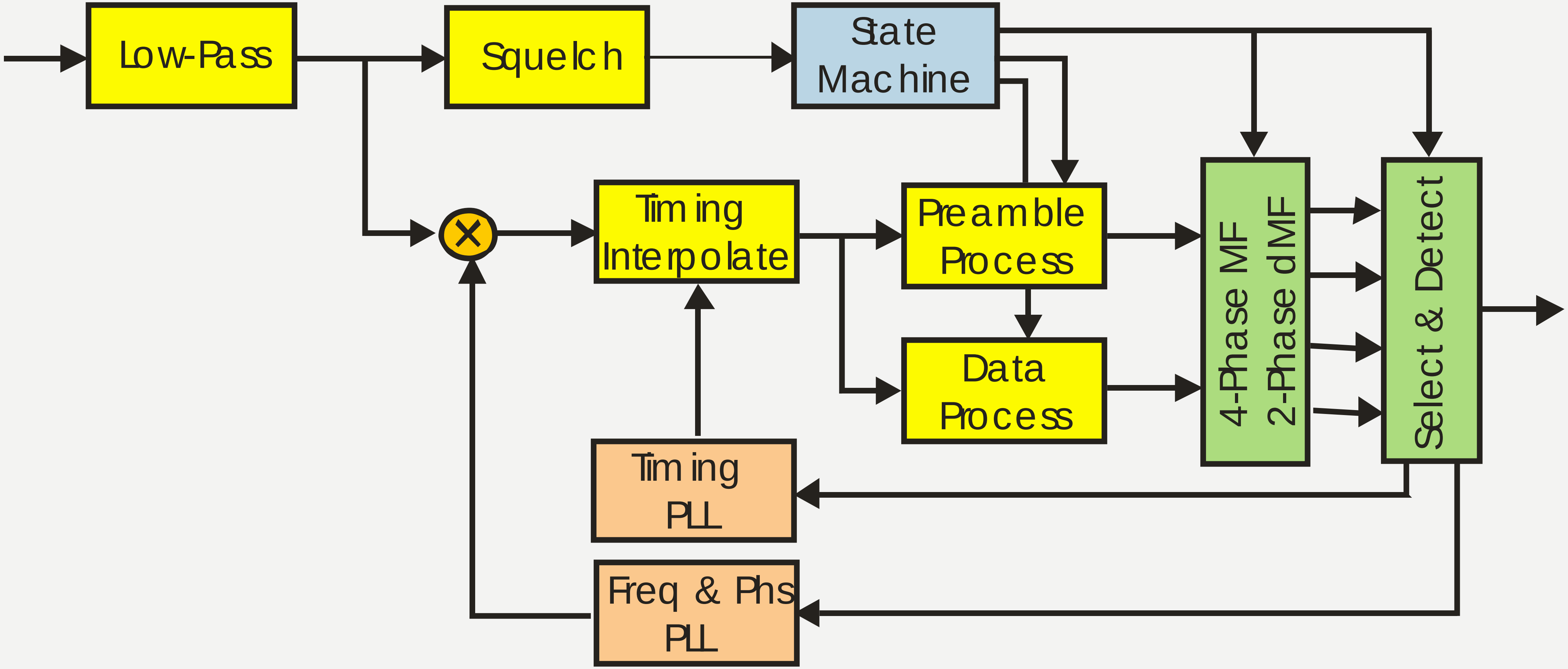
Preamble | Start of Message | Random Data Payload



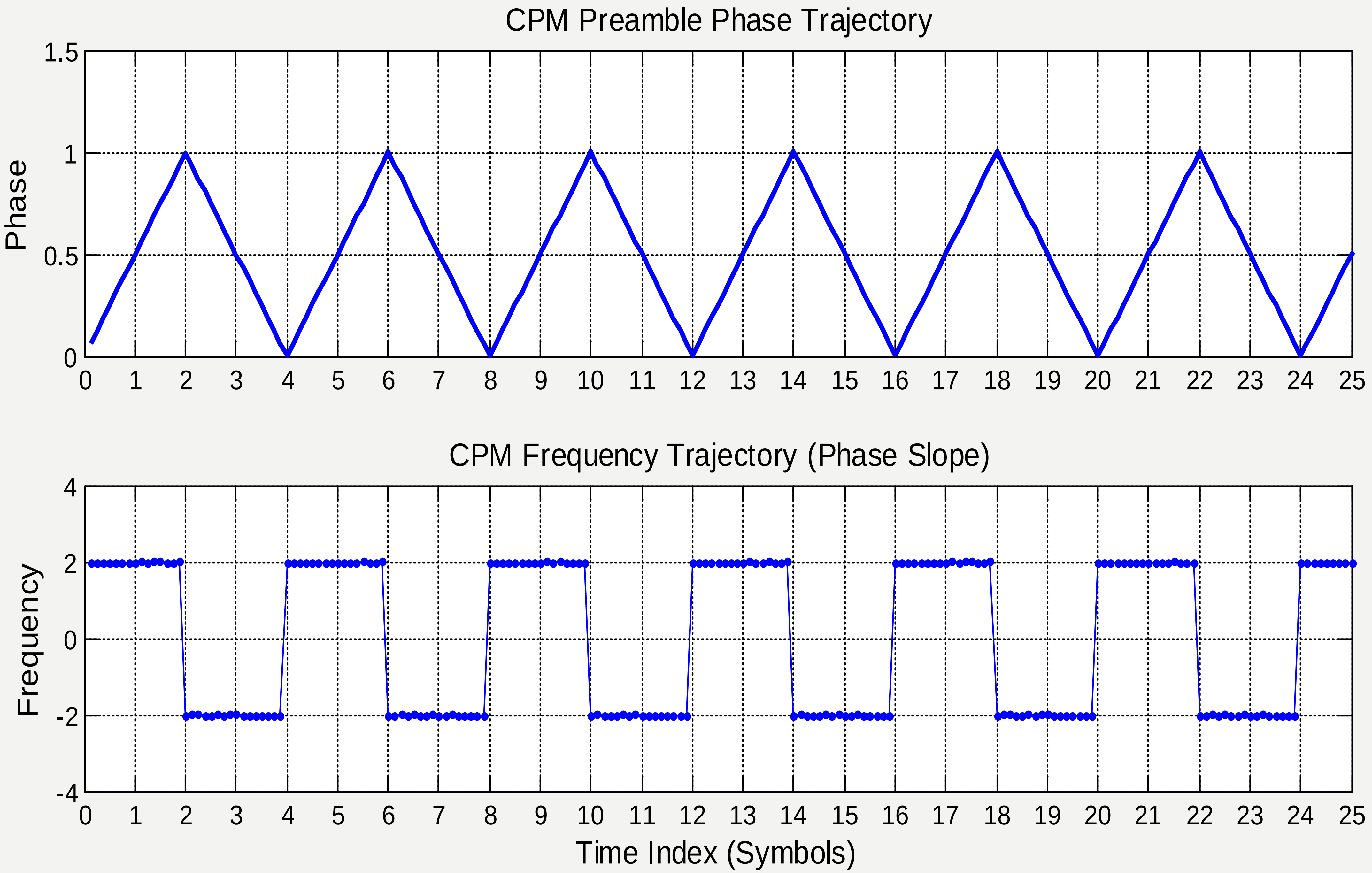
Perform Squelch Detection
Detect and Remove Doppler
Perform AGC
Matched Filter Preamble
Perform Timing Synch

Detect SOM
Inform State Machine
Enable All Matched Filters
Enable Comparisons of
Matched Filter Outputs
Engage Phase PLL

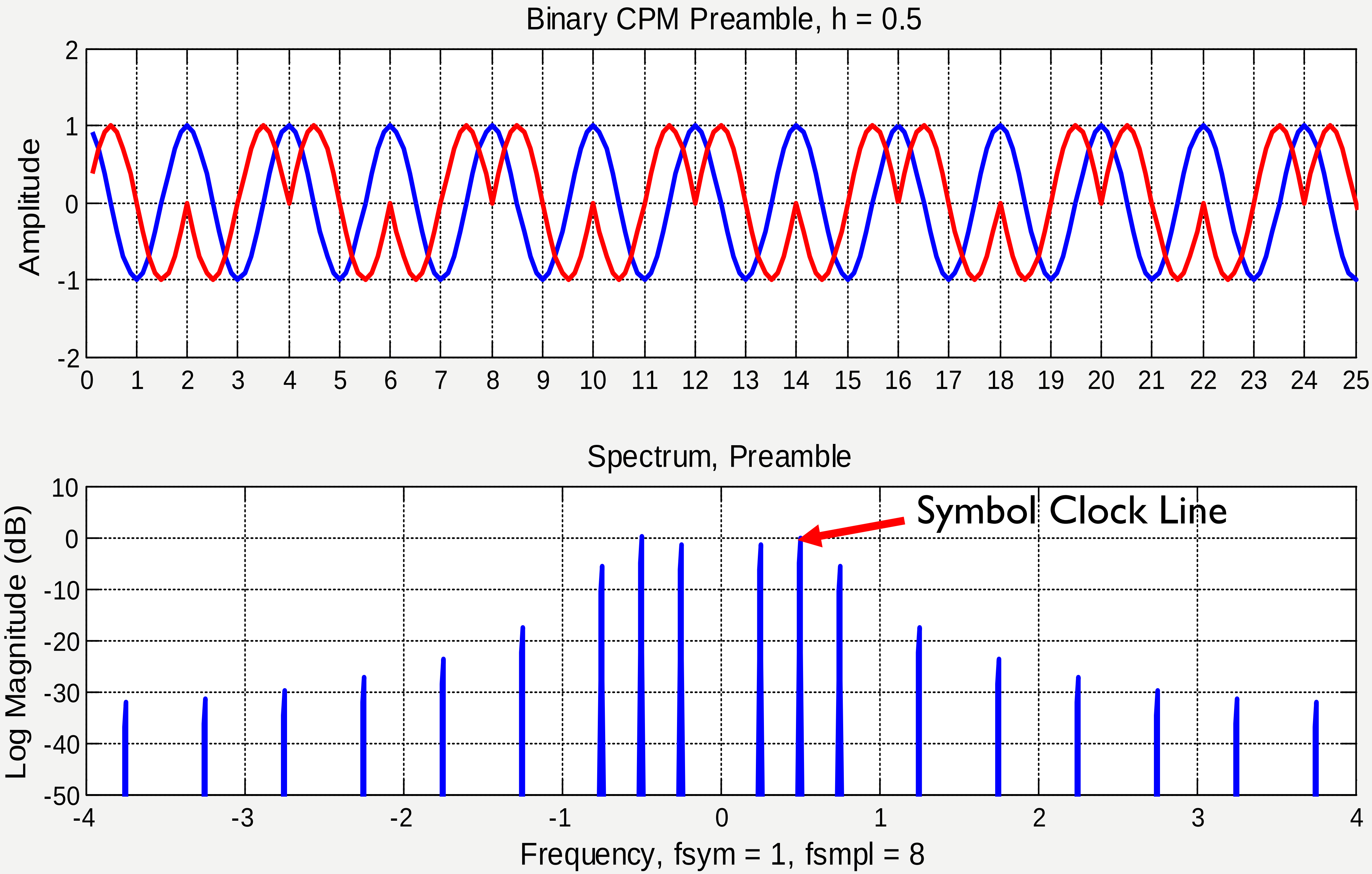
Operate Timing PLL
Operate Phase PLL
Operate AGC Loop
Operate all Matched Filters
Compare MF Outputs and
Select Largest Output
Detect Signal of Selected MF



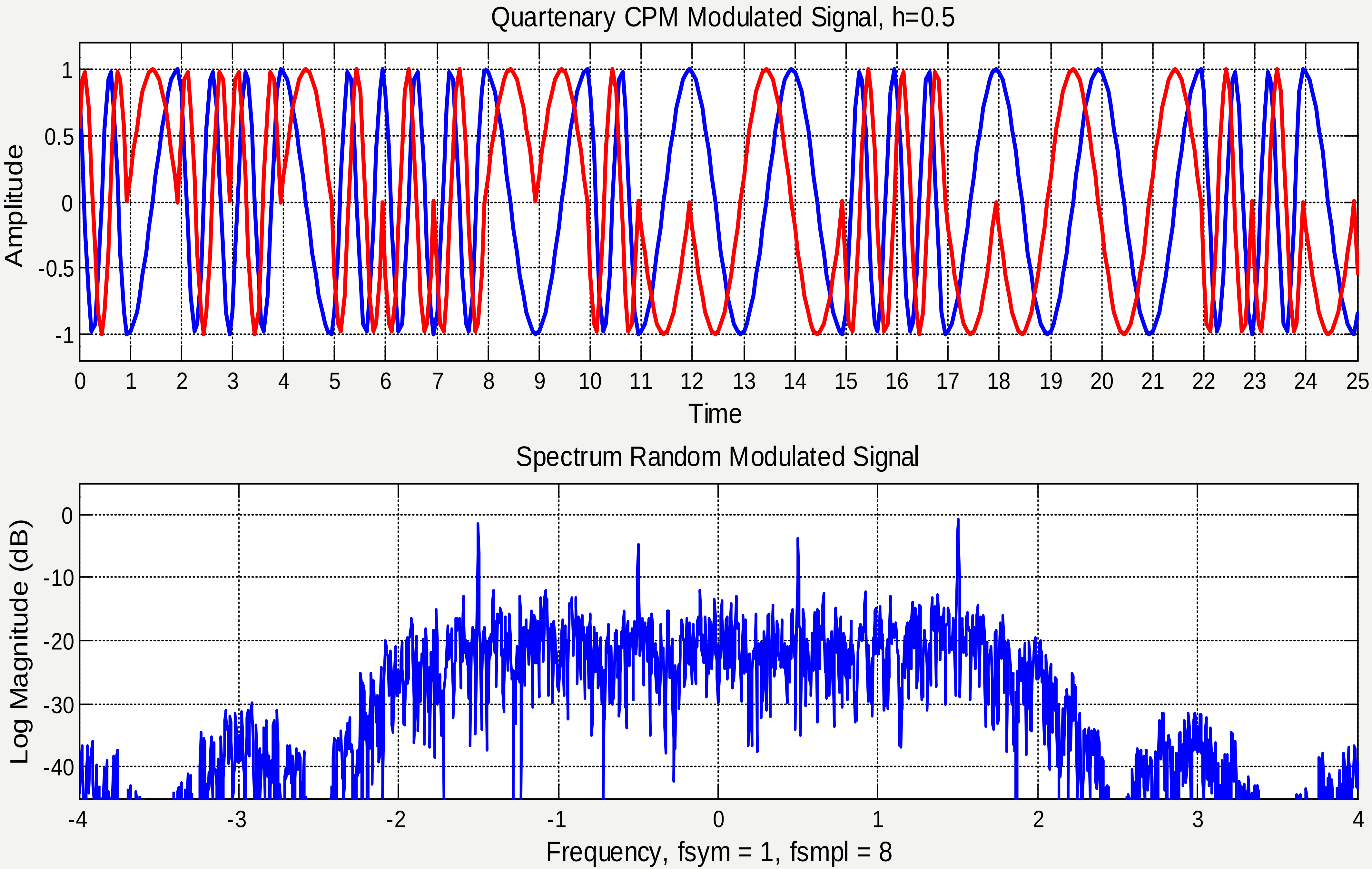
Low-Pass
Squelch
State Machine
Timing Interpolate
Preamble Process
Data Process
4-Phase MF
2-Phase dMF
Select & Detect
Timing PLL
Freq & Phs PLL



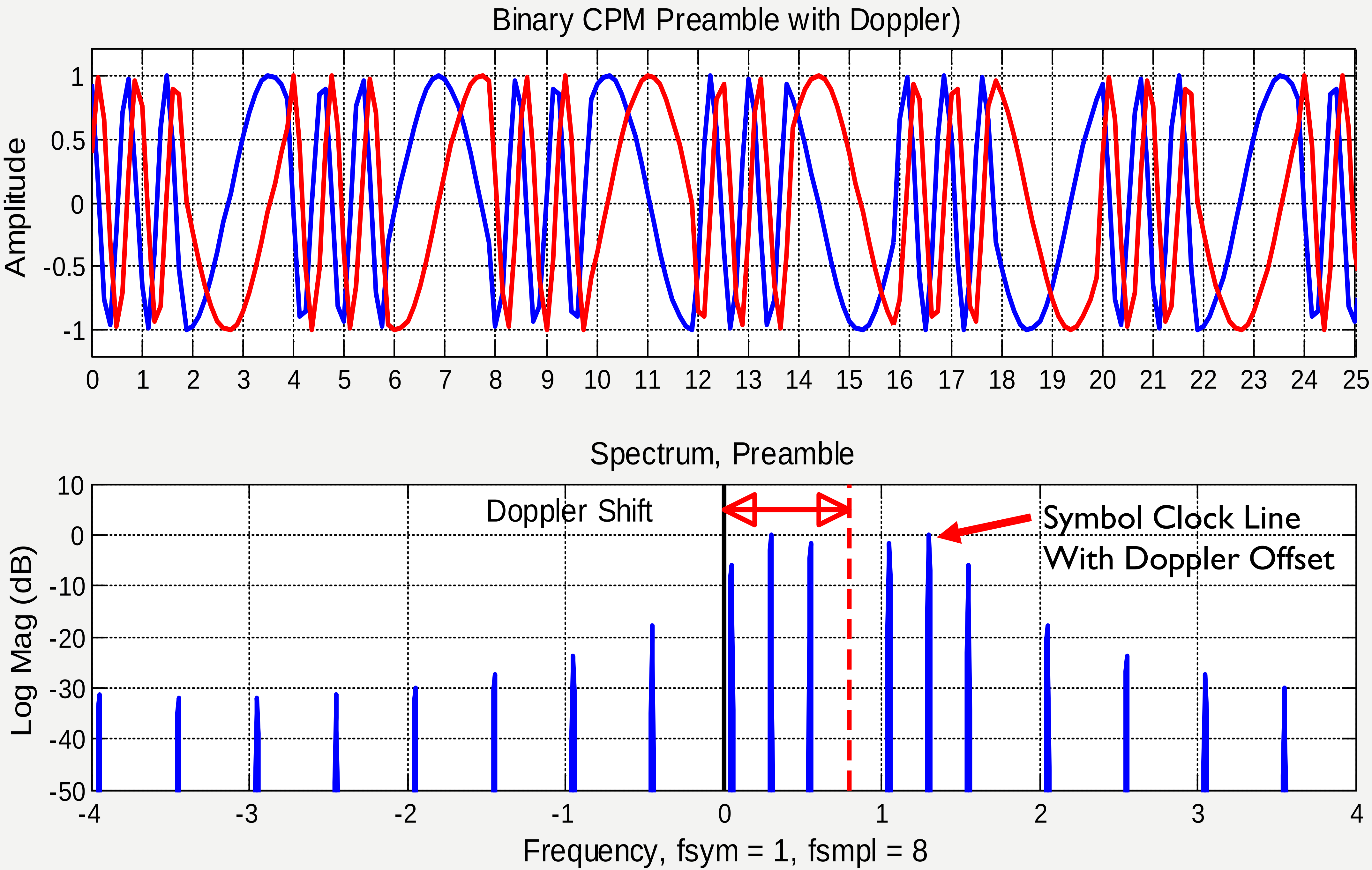
CPM Preamble Phase Trajectory
Phase
1.5
1
0.5
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
CPM Frequency Trajectory (Phase Slope)
Frequency
4
2
0
-2
-4
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
Time Index (Symbols)



Binary CPM Preamble, h = 0.5
Amplitude
2
1
0
-1
-2
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
Spectrum, Preamble
Symbol Clock Line
Log Magnitude (dB)
10
0
-10
-20
-30
-40
-50
-4 -3 -2 -1 0 1 2 3 4
Frequency, fsym = 1, fsmpl = 8



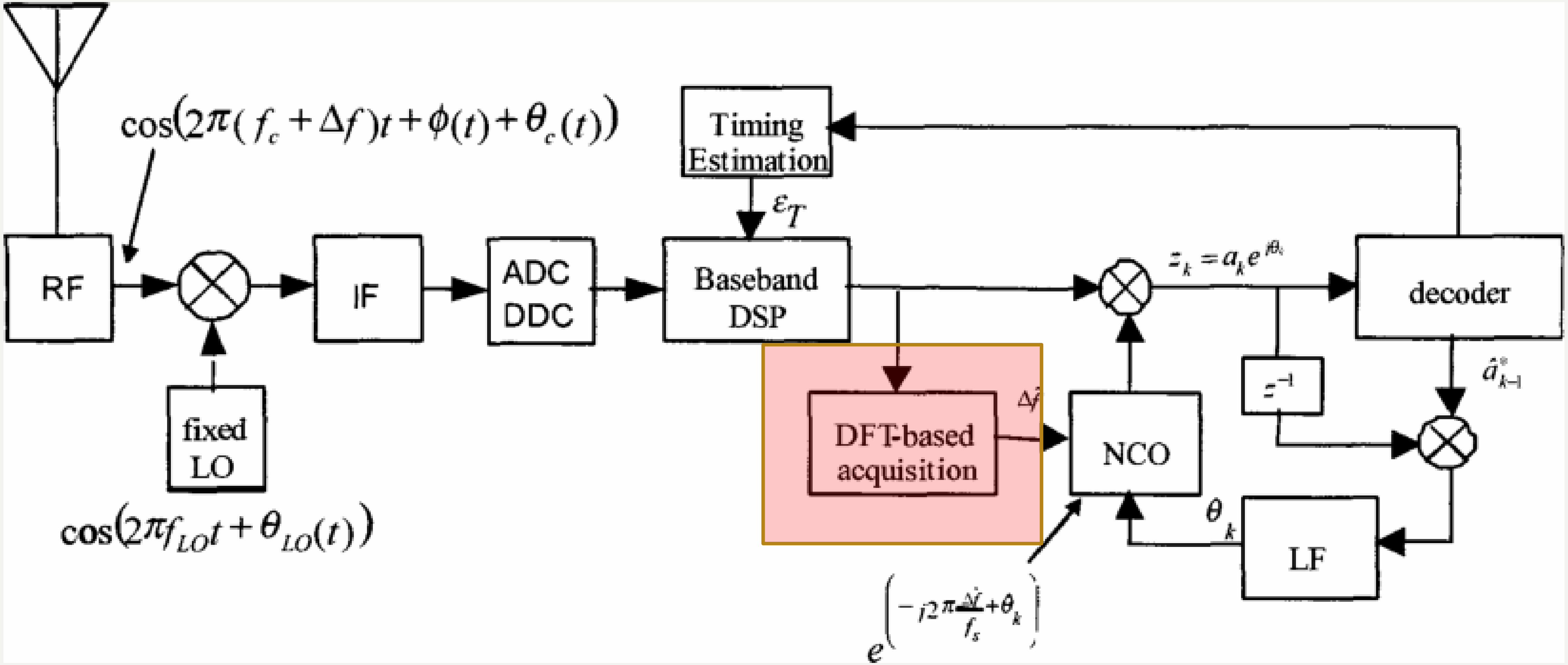
Quartenary CPM Modulated Signal, h=0.5
Amplitude
Time
Spectrum Random Modulated Signal
Log Magnitude (dB)
Frequency, fsym = 1, fsmpl = 8



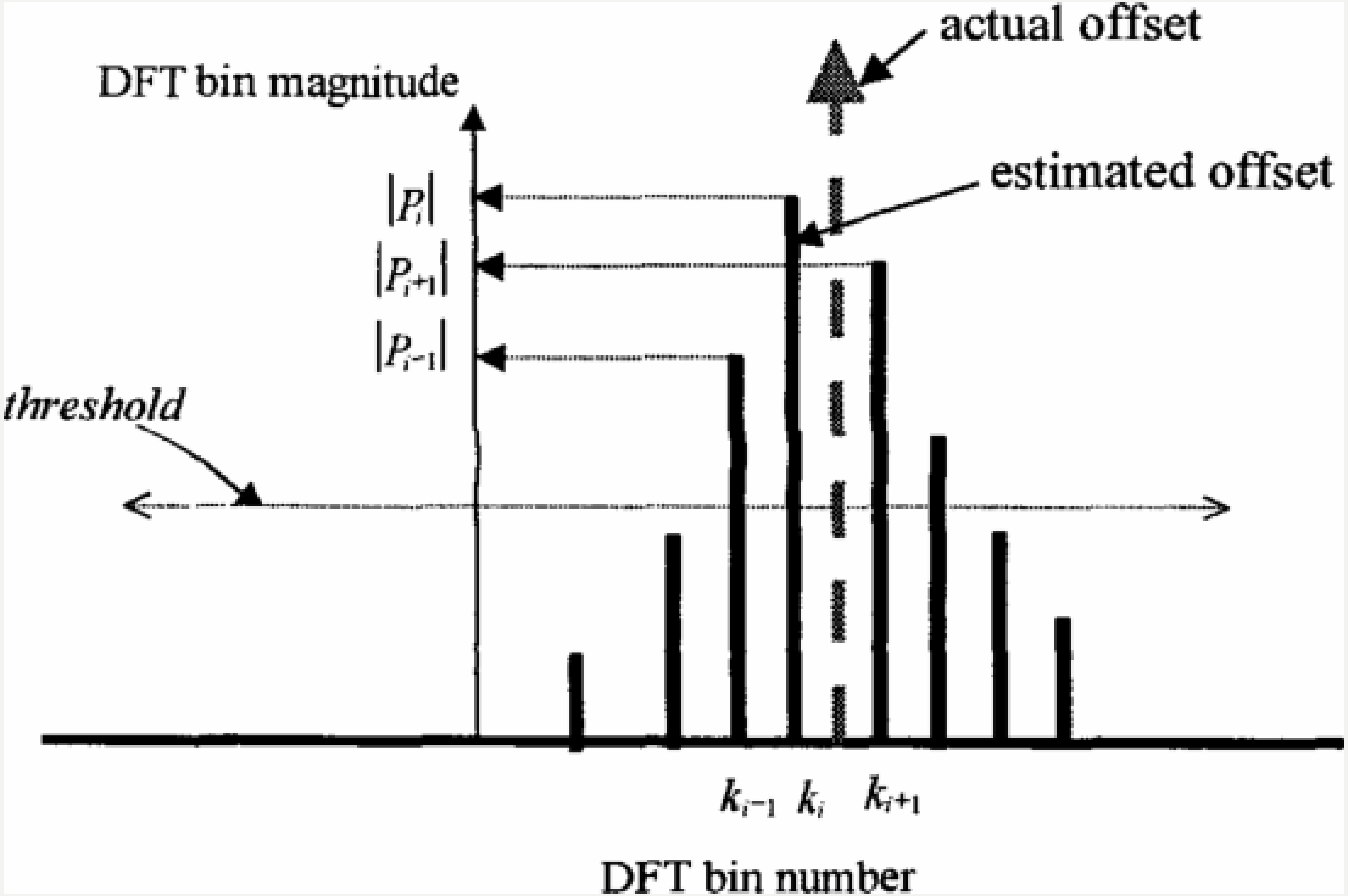
Binary CPM Preamble with Doppler)
Amplitude
1
0.5
0
-0.5
-1
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
Spectrum, Preamble
Doppler Shift
Symbol Clock Line
With Doppler Offset
Log Mag (dB)
10
0
-10
-20
-30
-40
-50
-4 -3 -2 -1 0 1 2 3 4
Frequency, fsym = 1, fsmpl = 8

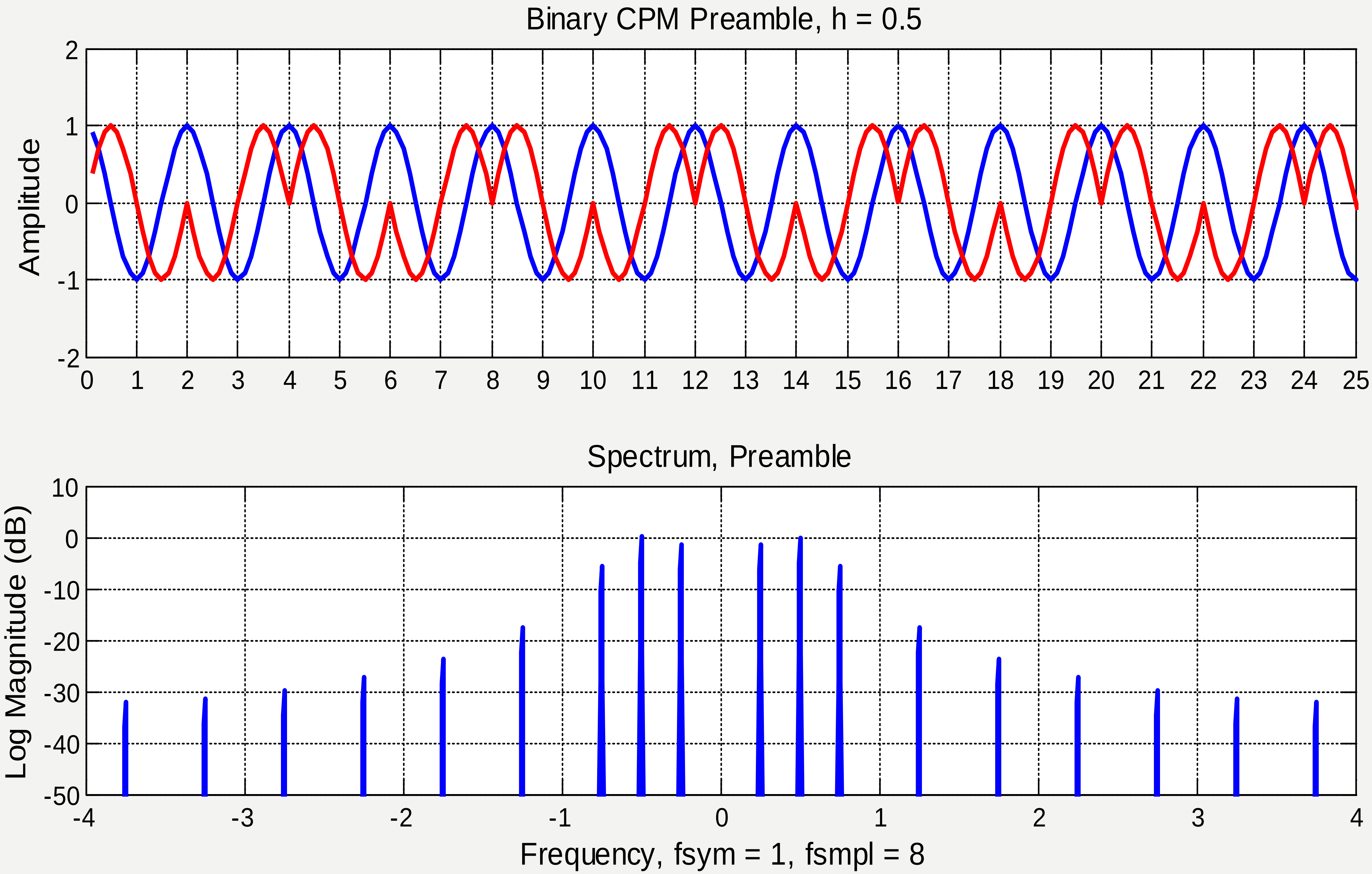
Techniques for Acquiring and Tracking MIL-STD-181B Signals

Milcom 7-10 October 2002, Anaheim CA., Mohammed K. Nezami, PhD, Raytheon, Saint Petersburg, FL.

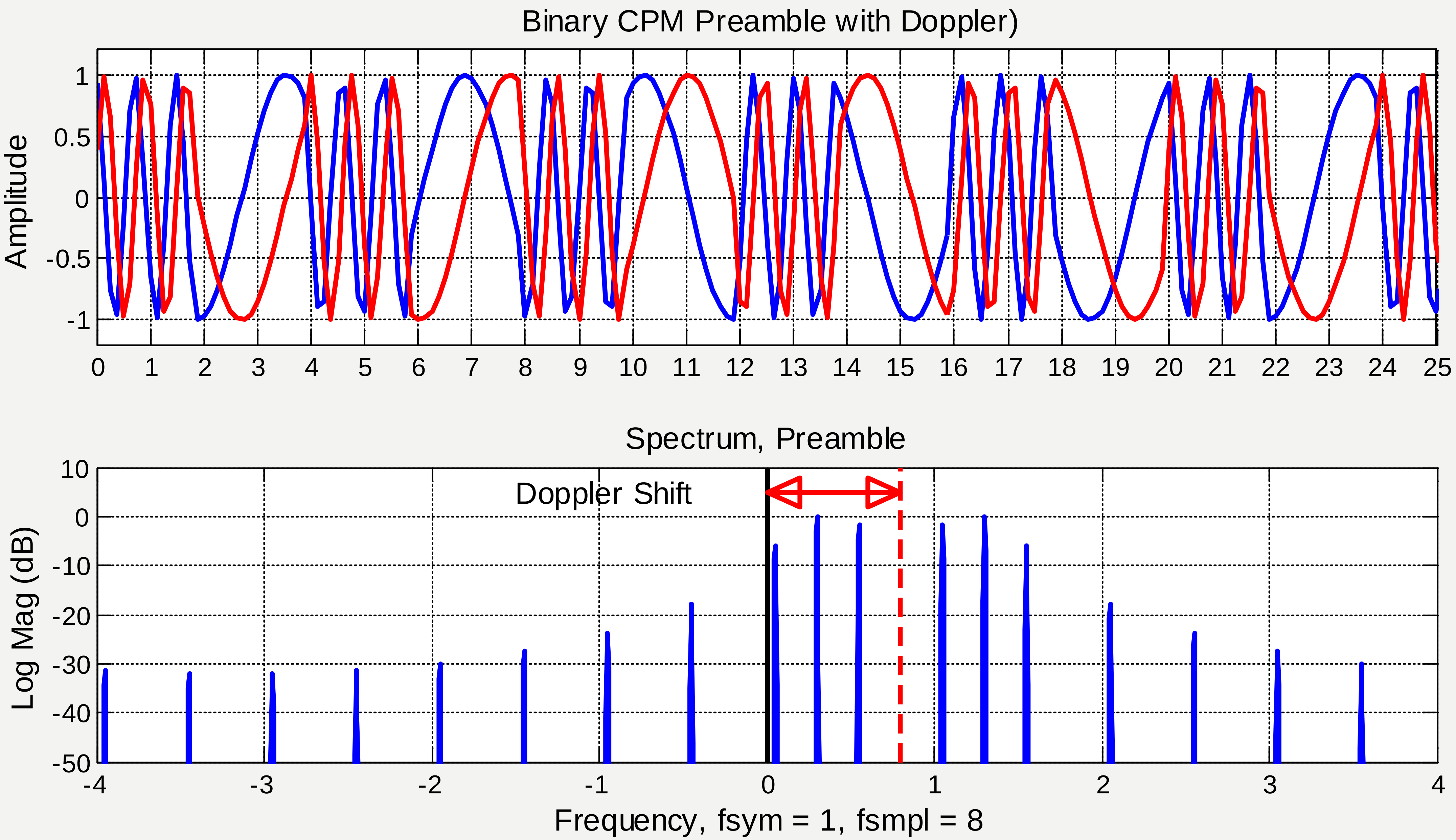


Estimate Spectral Center of Mass, and Direct DDS to shift Spectrum by the estimated Offset.





Binary CPM Preamble, h = 0.5
Amplitude
2
1
0
-1
-2
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
Spectrum, Preamble
Log Magnitude (dB)
10
0
-10
-20
-30
-40
-50
-4 -3 -2 -1 0 1 2 3 4
Frequency, fsym = 1, fsmpl = 8



Binary CPM Preamble with Doppler)
Amplitude
1
0.5
0
-0.5
-1
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
Spectrum, Preamble
Doppler Shift
Log Mag (dB)
10
0
-10
-20
-30
-40
-50
-4 -3 -2 -1 0 1 2 3 4
Frequency, fsym = 1, fsmpl = 8

$$s(\mathrm{n}) = \mathrm{e}^{j\theta_{prmbl}n}\,\mathrm{e}^{j\theta_{dplr}n} \; :$$

$$\mathrm{n} = 0 : \mathrm{N}-1$$

$$s(\mathrm{n}+N) = \mathrm{e}^{-j\theta_{prmbl}n}\,\mathrm{e}^{j\theta_{dplr}n} \; :$$

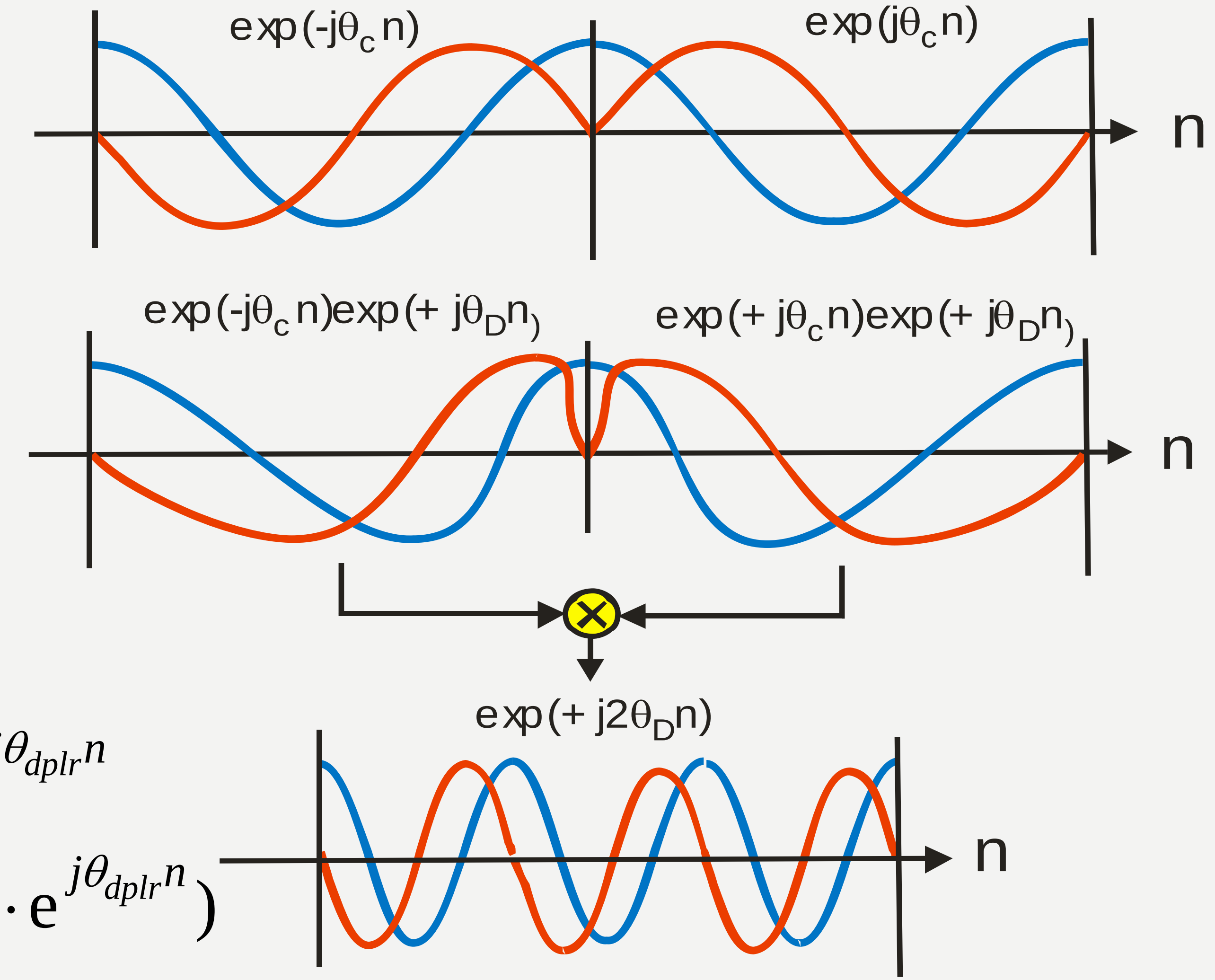
$$\mathrm{n} = 0 : N-1$$

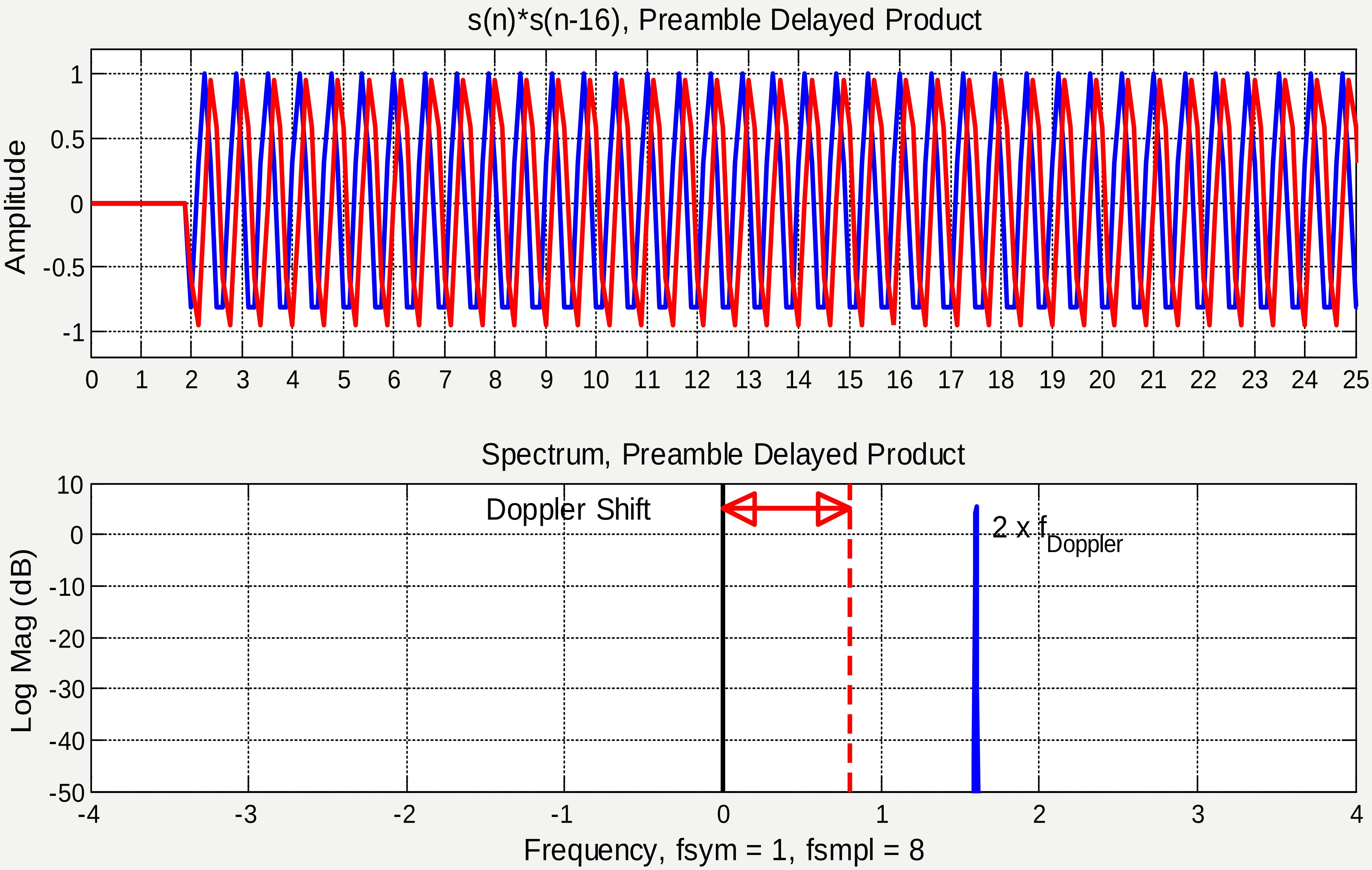
$$p(n) = s(n)\cdot s(n+N)$$

$$= \mathrm{e}^{+j\theta_{prmbl}n}\,\mathrm{e}^{j\theta_{dplr}n}\cdot\mathrm{e}^{-j\theta_{prmbl}n}\,\mathrm{e}^{j\theta_{dplr}n}$$

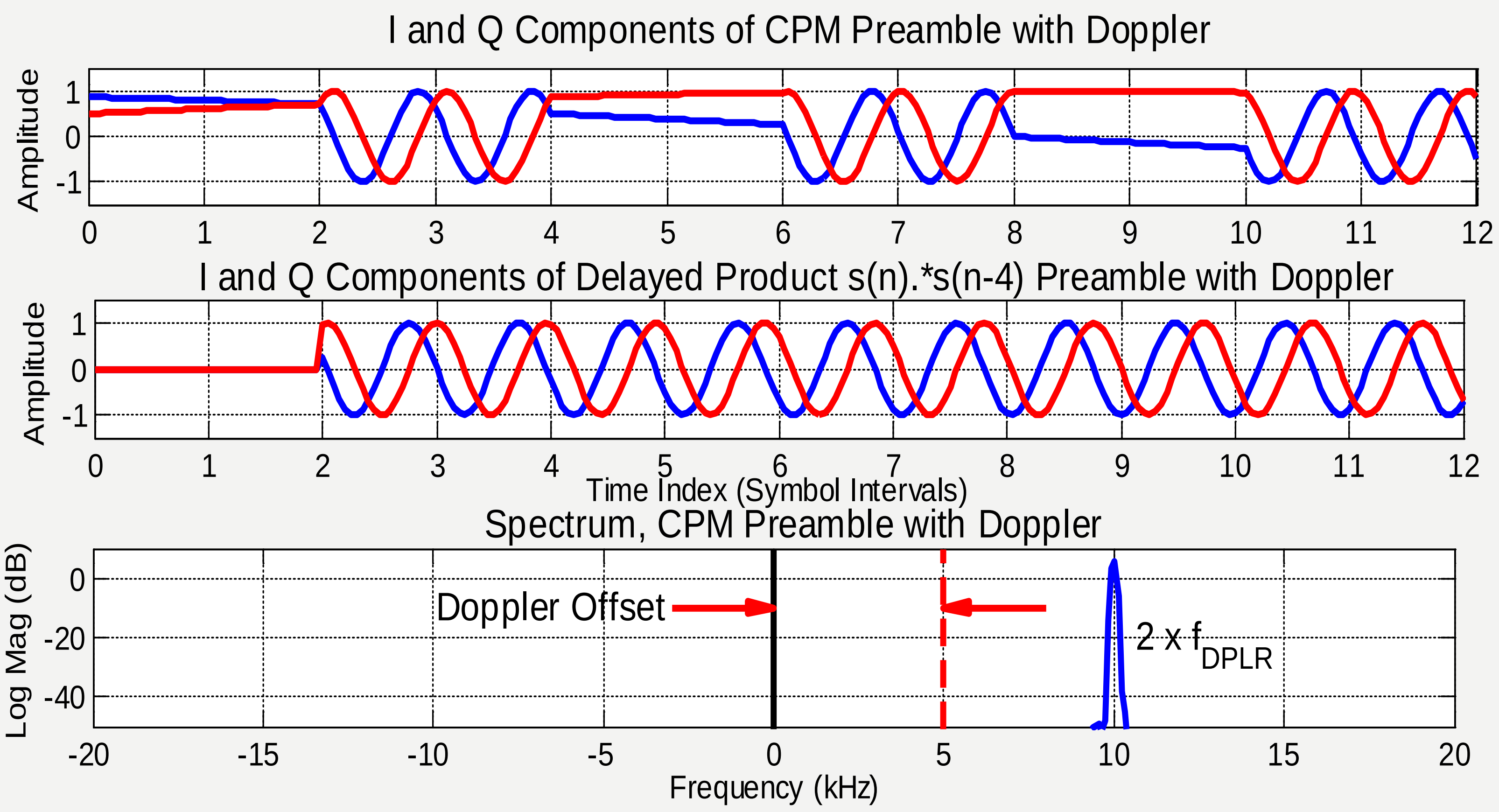
$$= (\mathrm{e}^{+j\theta_{prmbl}n}\cdot\mathrm{e}^{-j\theta_{prmbl}n})(\mathrm{e}^{j\theta_{dplr}n}\cdot\mathrm{e}^{j\theta_{dplr}n})$$

$$= \mathrm{e}^{\mathrm{j}2\theta_{dplr}n}$$




s(n)*s(n-16), Preamble Delayed Product
Amplitude
1
0.5
0
-0.5
-1
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25
Spectrum, Preamble Delayed Product
Doppler Shift
2 x f Doppler
Log Mag (dB)
10
0
-10
-20
-30
-40
-50
-4 -3 -2 -1 0 1 2 3 4
Frequency, fsym = 1, fsmpl = 8

Top Subplot. Doppler Distorted Tones in Successive Preamble Intervals Center Subplot, Product of Successive Conjugate Symbol Intervals Forms Complex Tone at Twice Doppler Frequency. Third Subplot Spectrum of Doppler Tone Formed.



four *Modulation Complex Envelopes, N−Samples per Symbol*

$h1a=\exp(+j\frac{\pi}{2N}(0:N-1))$: *Positive Rotation, Quarter Cycle*

$h1b=\exp(-j\frac{\pi}{2N}(0:N-1))$: *Negative Rotation, Quarter cycle*

$h2a=\exp(+j\frac{\pi}{N}(0:N-1))$: *Positive Rotation, Half Cycle*

$h2b=\exp(-j\frac{\pi}{N}(0:N-1))$: *Negative Rotation, Half cycle*

four Matched Filter Complex Envelopes, N−Samples per Symbol

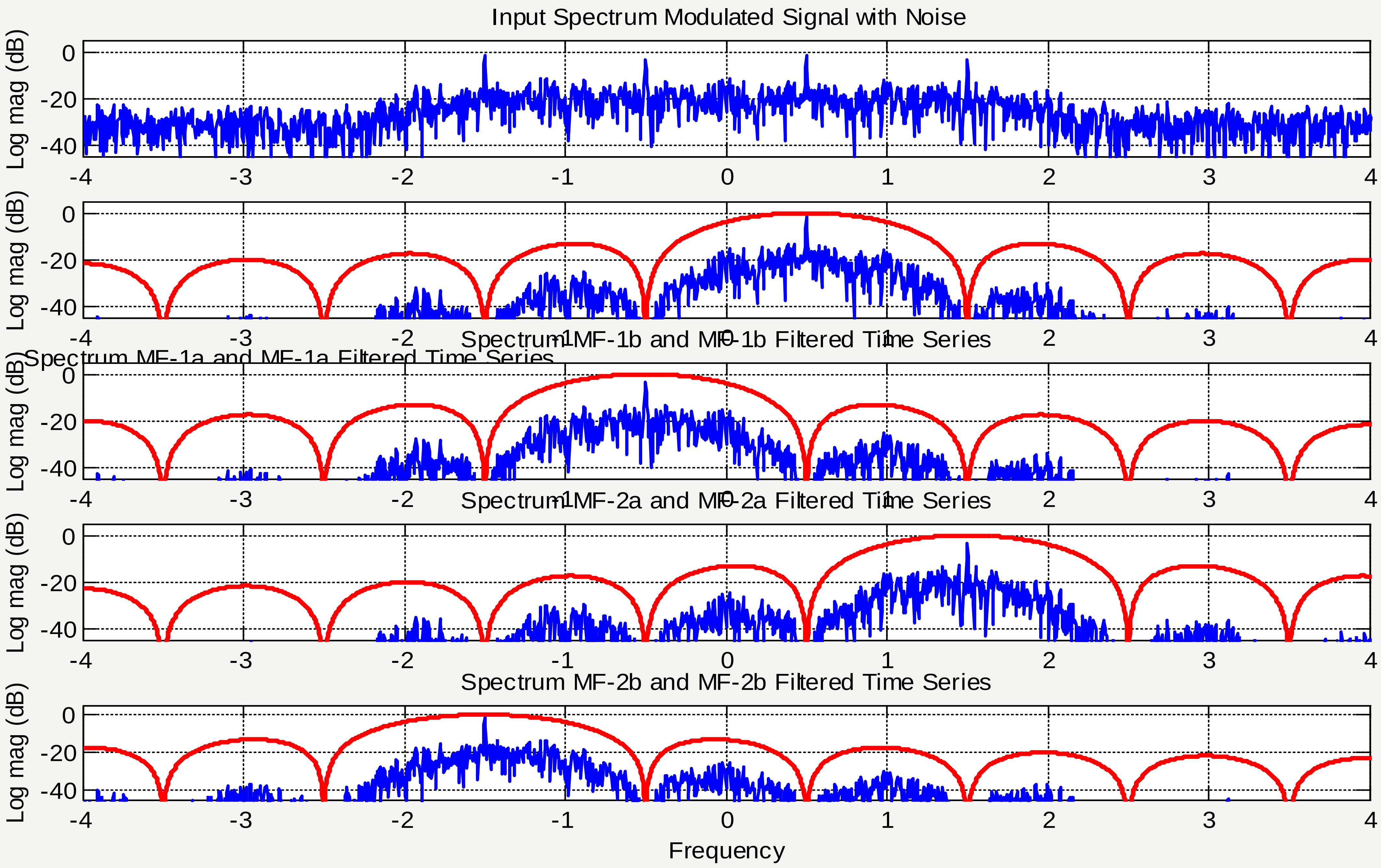
Time Reversed and Complex Conjugate

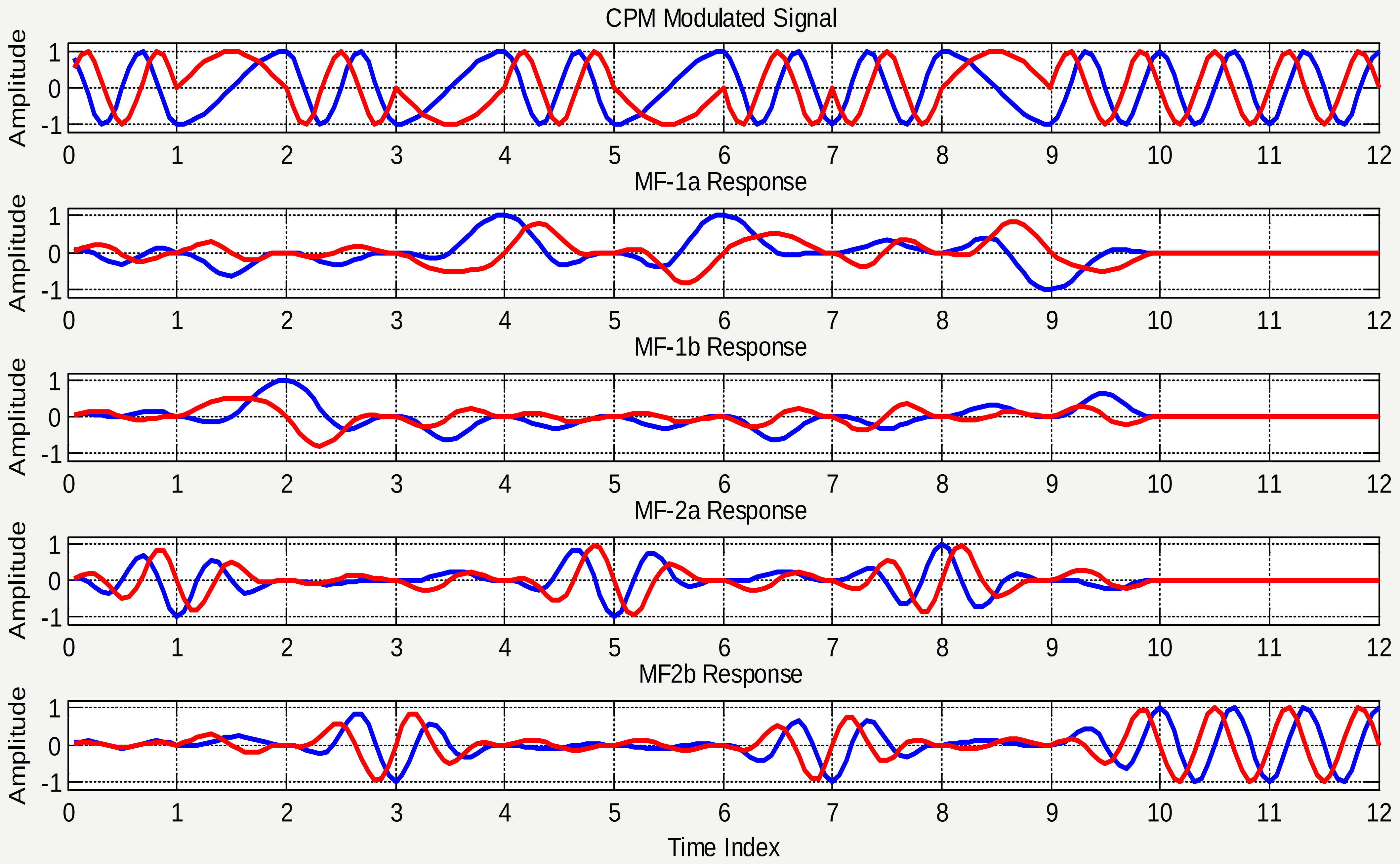
$MF1a=\exp(-j\frac{\pi}{2N}(N-1:-1:0))$: *Positive Rotation, Quarter Cycle*

$MF1b=\exp(+j\frac{\pi}{2N}(N-1:-1:0))$: *Negative Rotation, Quarter cycle*

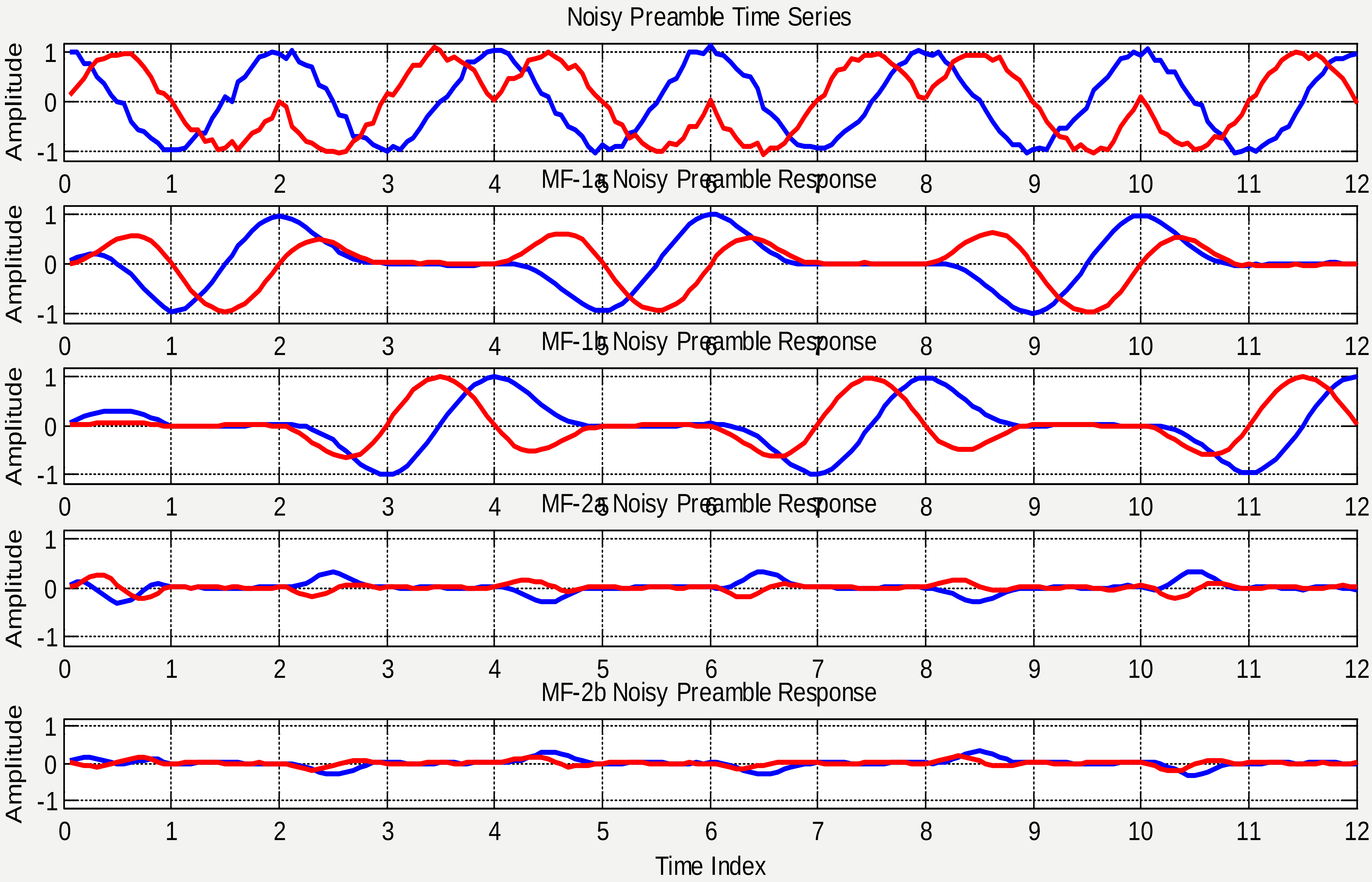
$MF2a=\exp(-j\frac{\pi}{N}(N-1:-1:0))$: *Positive Rotation, Half Cycle*

$MF2b=\exp(+j\frac{\pi}{N}(N-1:-1:0))$: *Negative Rotation, Half cycle*

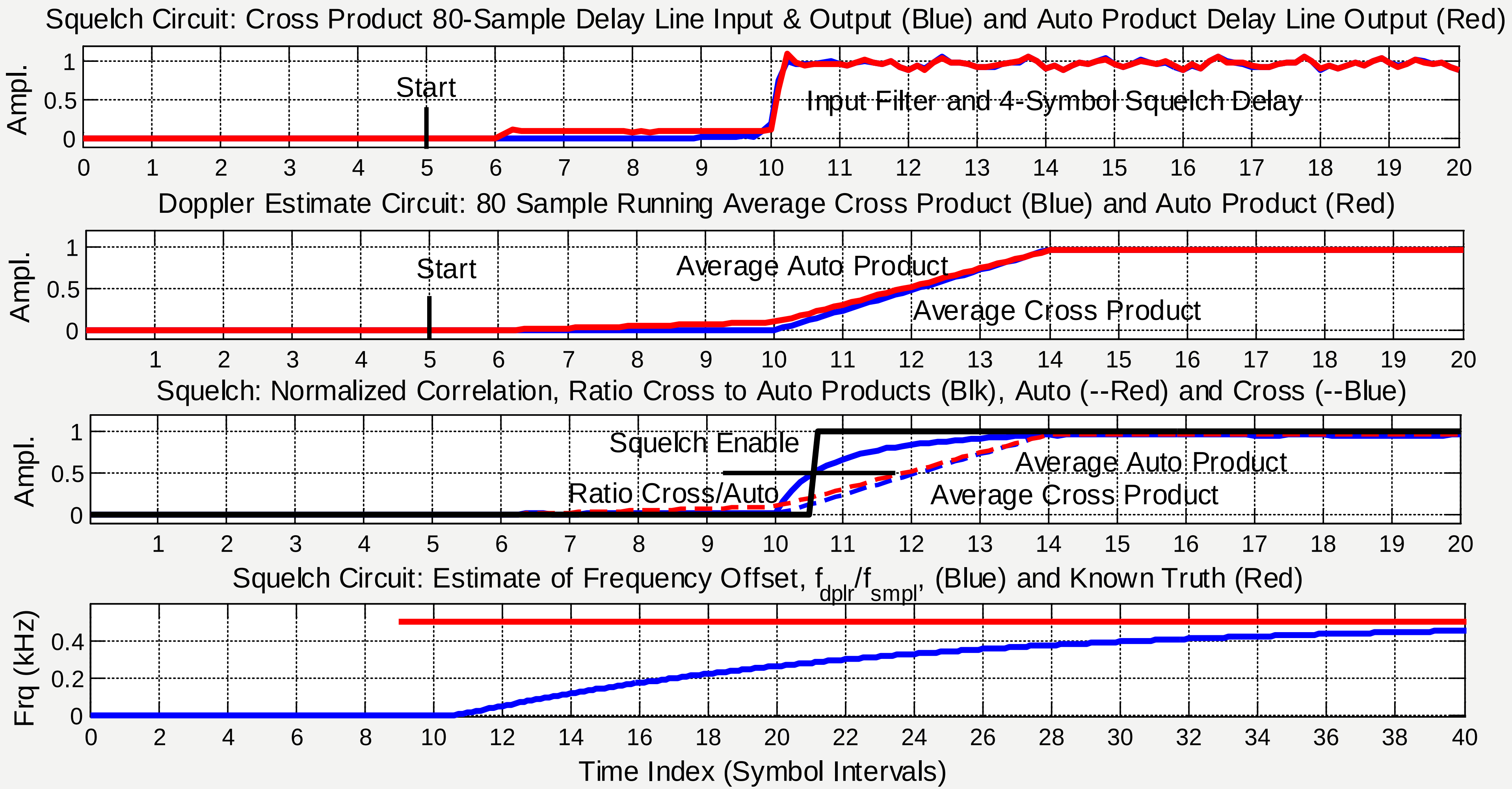

Input Spectrum Modulated Signal with Noise
Spectrum MF-1a and MF-1a Filtered Time Series
Spectrum MF-1b and MF-1b Filtered Time Series
Spectrum MF-2a and MF-2a Filtered Time Series
Spectrum MF-2b and MF-2b Filtered Time Series
Log mag (dB)
Frequency
0
-20
-40
-4
-3
-2
-1
0
1
2
3
4



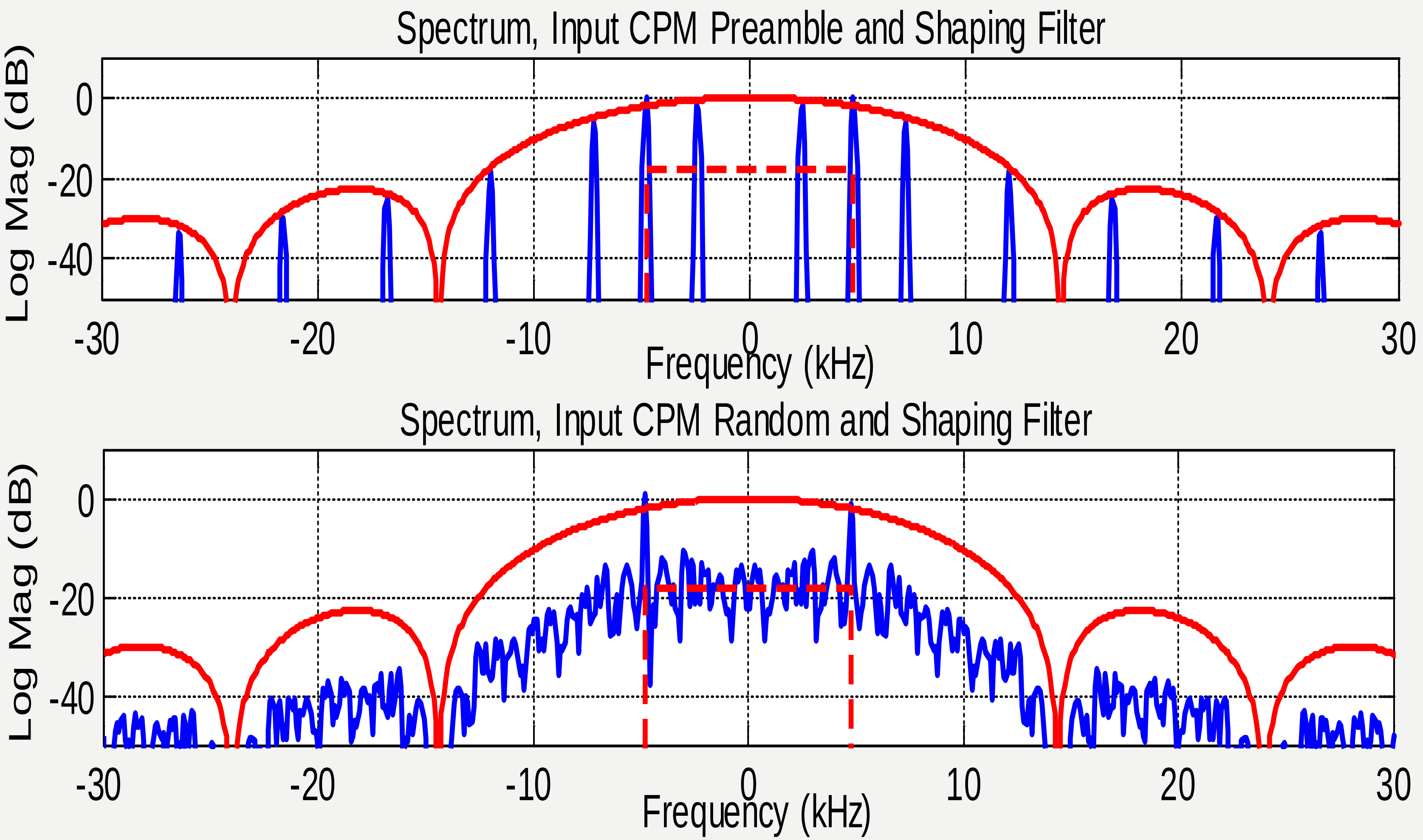
CPM Modulated Signal
MF-1a Response
MF-1b Response
MF-2a Response
MF2b Response
Amplitude
Time Index


Noisy Preamble Time Series
MF-1a Noisy Preamble Response
MF-1b Noisy Preamble Response
MF-2a Noisy Preamble Response
MF-2b Noisy Preamble Response
Amplitude
Time Index

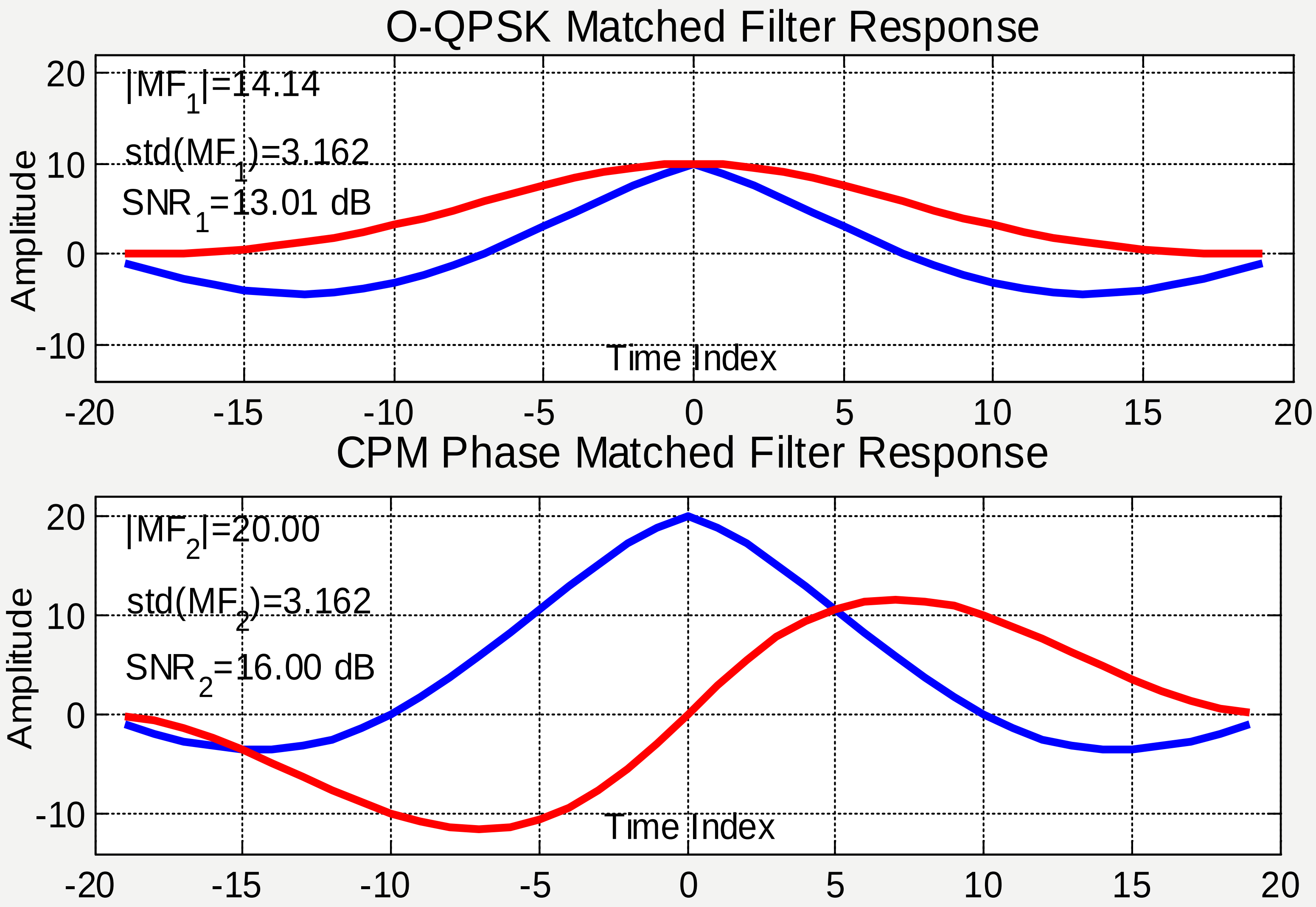
Squelch Network, Auto and 4-Symbol Delayed Conjugate Cross Product and Auto and Cross Correlation Normalized Correlation and Threshold Crossing, 2-Symbol Delayed Product, and 0.3 kHz Doppler Frequency Estimate.



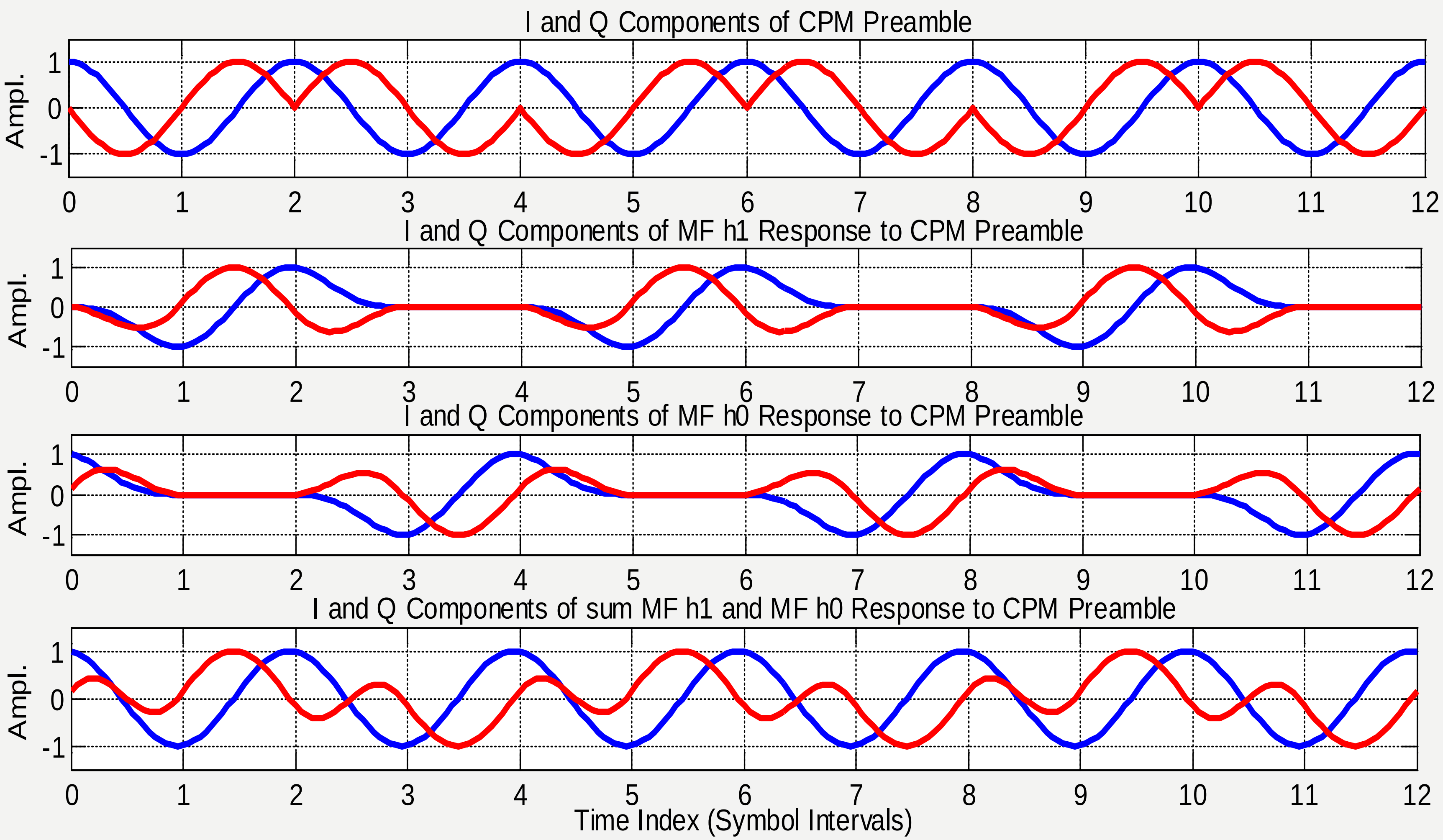
Upper Subplot: Spectra of Periodic Preamble and of Half Sinewave Shaping Filter
Lower Subplot: Spectra of Random CPM Data and of Half Sinewave Shaping Filter.



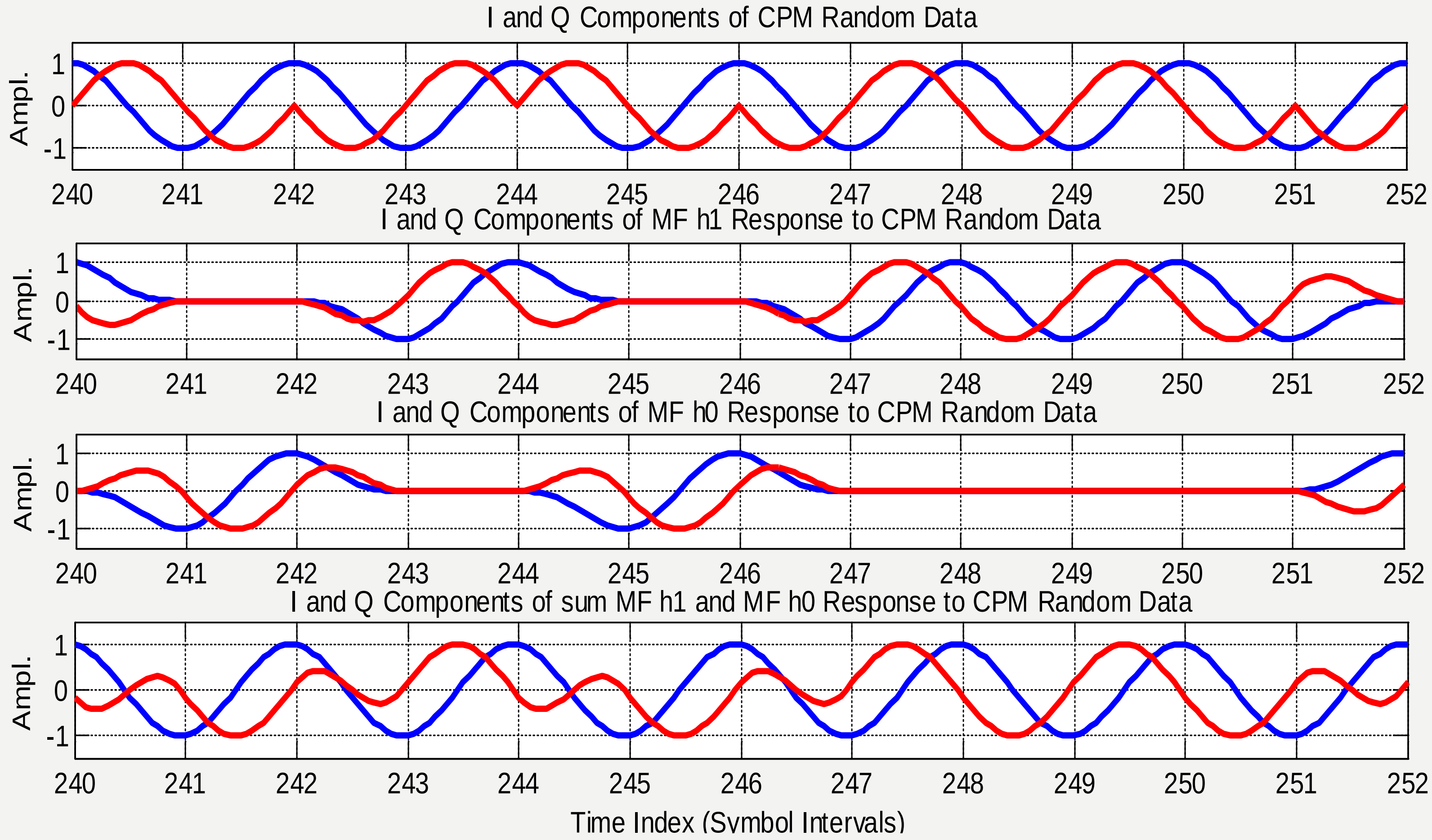
Matched Filter Response, OQPSK and CPM Process.

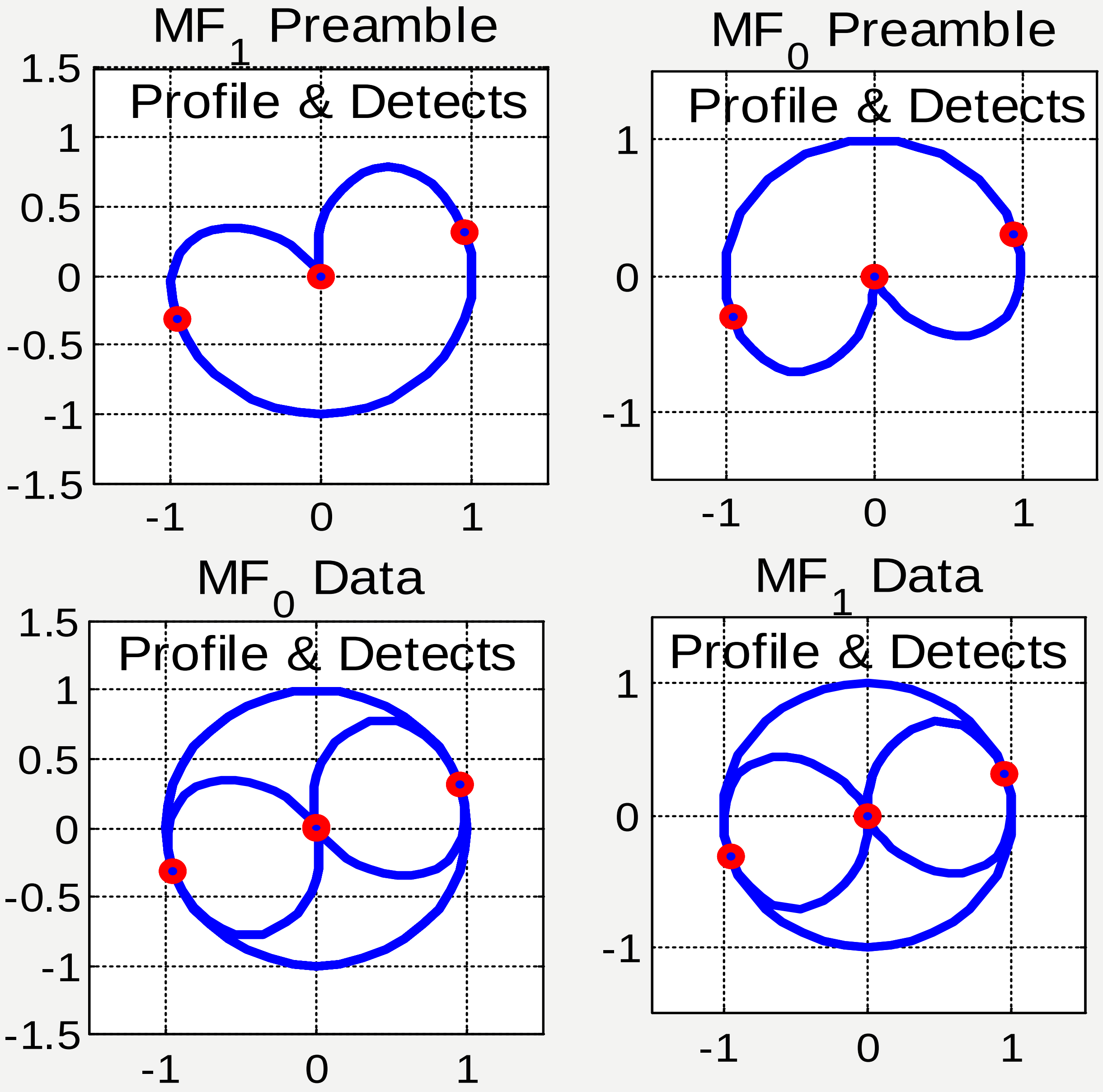


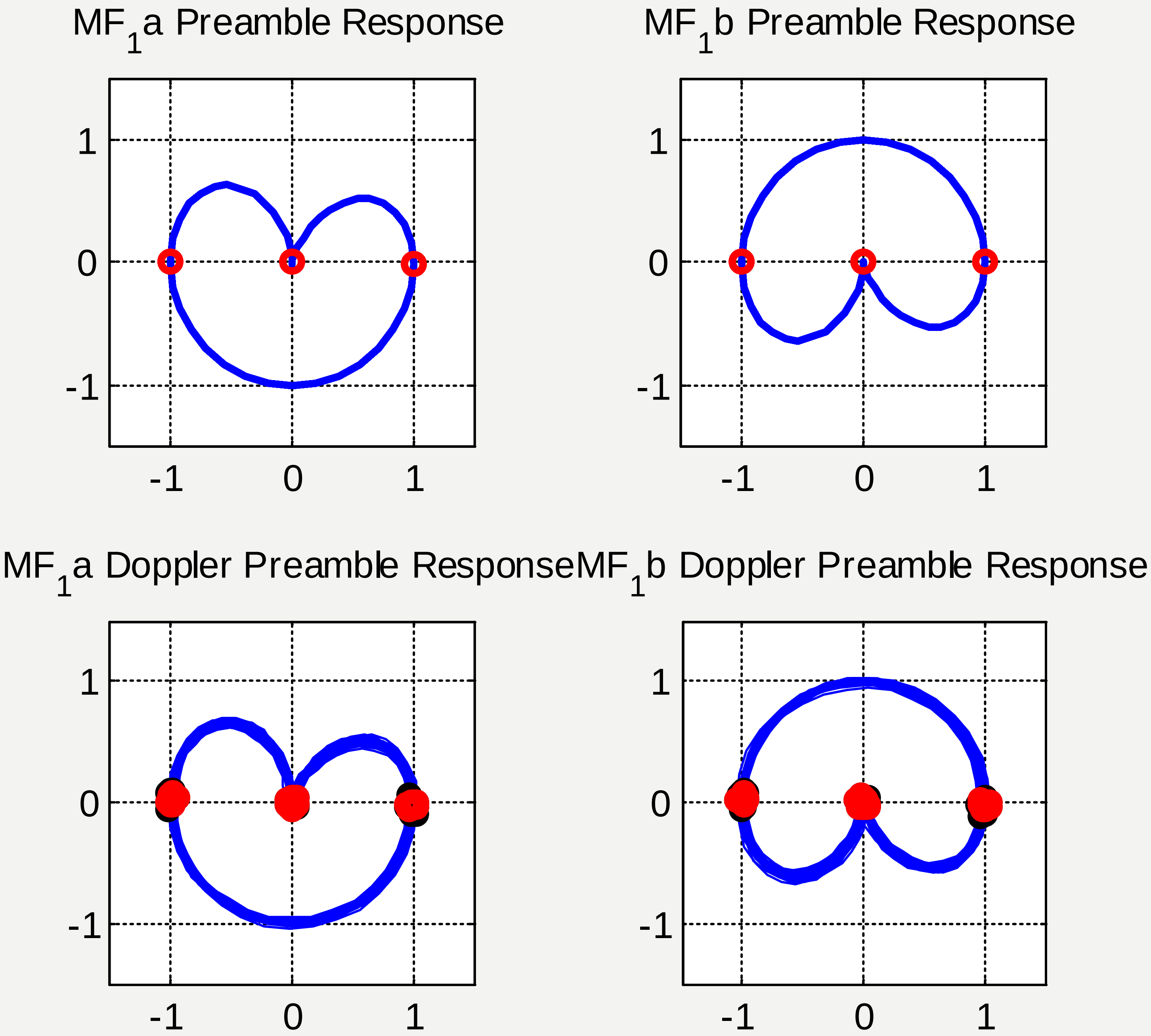
I & Q Input Signal and Two Matched Filter and the Sum of I & Q Responses of CPM Preamble Process.



I & Q Input Signal, Two Matched Filters, and the Sum of I & Q Responses of CPM Random Data Process.




MF_1 Preamble
Profile & Detects
MF_0 Preamble
Profile & Detects
MF_0 Data
Profile & Detects
MF_1 Data
Profile & Detects
1.5
1
0.5
0
-0.5
-1
-1.5
-1
0
1



MF1a Preamble Response
MF1b Preamble Response
MF1a Doppler Preamble Response
MF1b Doppler Preamble Response
1
0
-1
-1
0
1

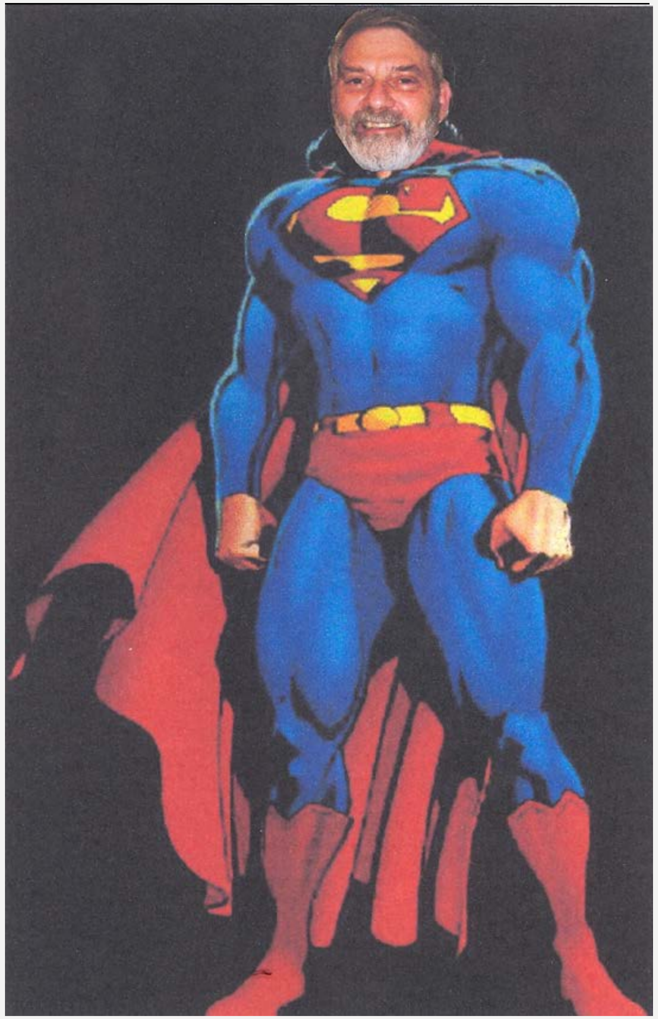
Interesting Thoughts about CPM

- Matched filter for pairs of symbols
- Preamble +1+1-1-1, can implement +1+1 filter and -1-1 filter
- Preamble +1-1-1+1, can also implement +1-1 filter and -1+1 filter

  can use them for random data as well
- Binary Random data, +1, -1: 2 matched filters
- Can form matched filters for all three-tuples: [A +1 B], and [A -1 B}.

  4 possible 3-tuple filters for each input symbol
- Quaternary Random data, +3, +1, -1, +3; 4 matched filters

  16 possible 3-tuple filters for each input symbol
- May be an alternate to trellis decoding of multi-h CPM



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Is Open For Questions