

MODEMS

fred harris

SDR'10
Wireless Innovation Conference
and Product Exposition

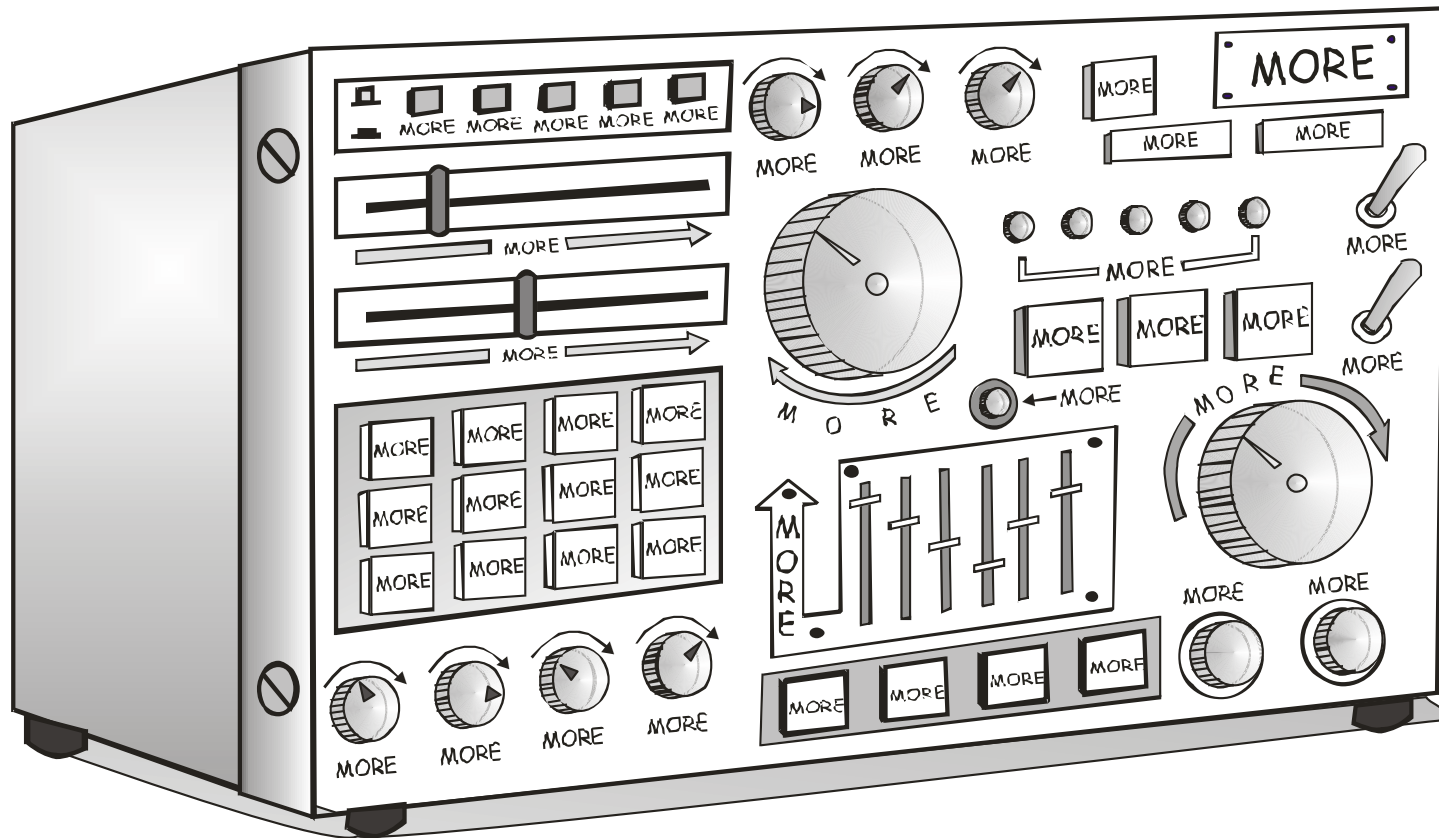
30 November - 3 December 2010



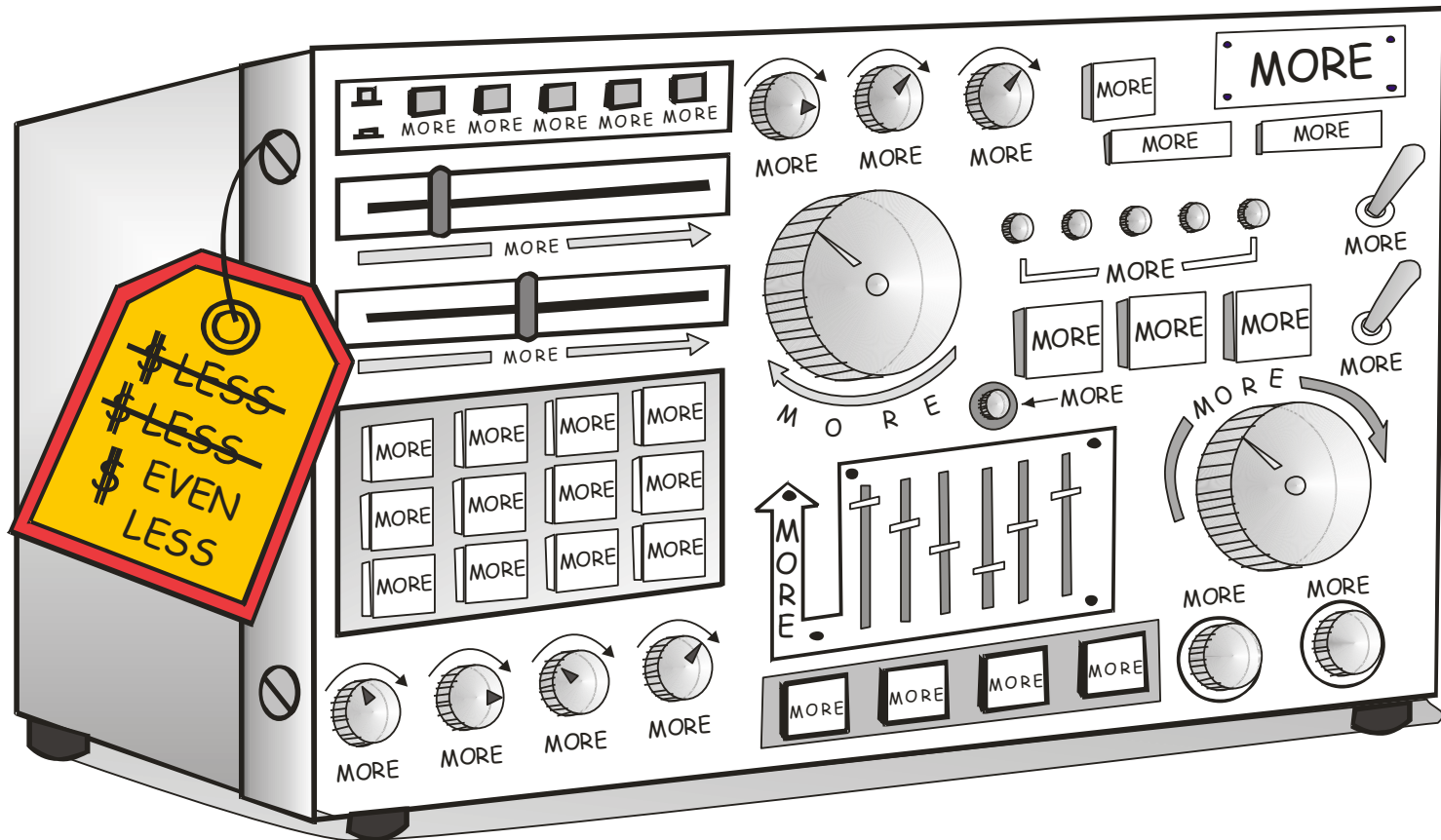
**SAN DIEGO STATE
UNIVERSITY**

College of Engineering

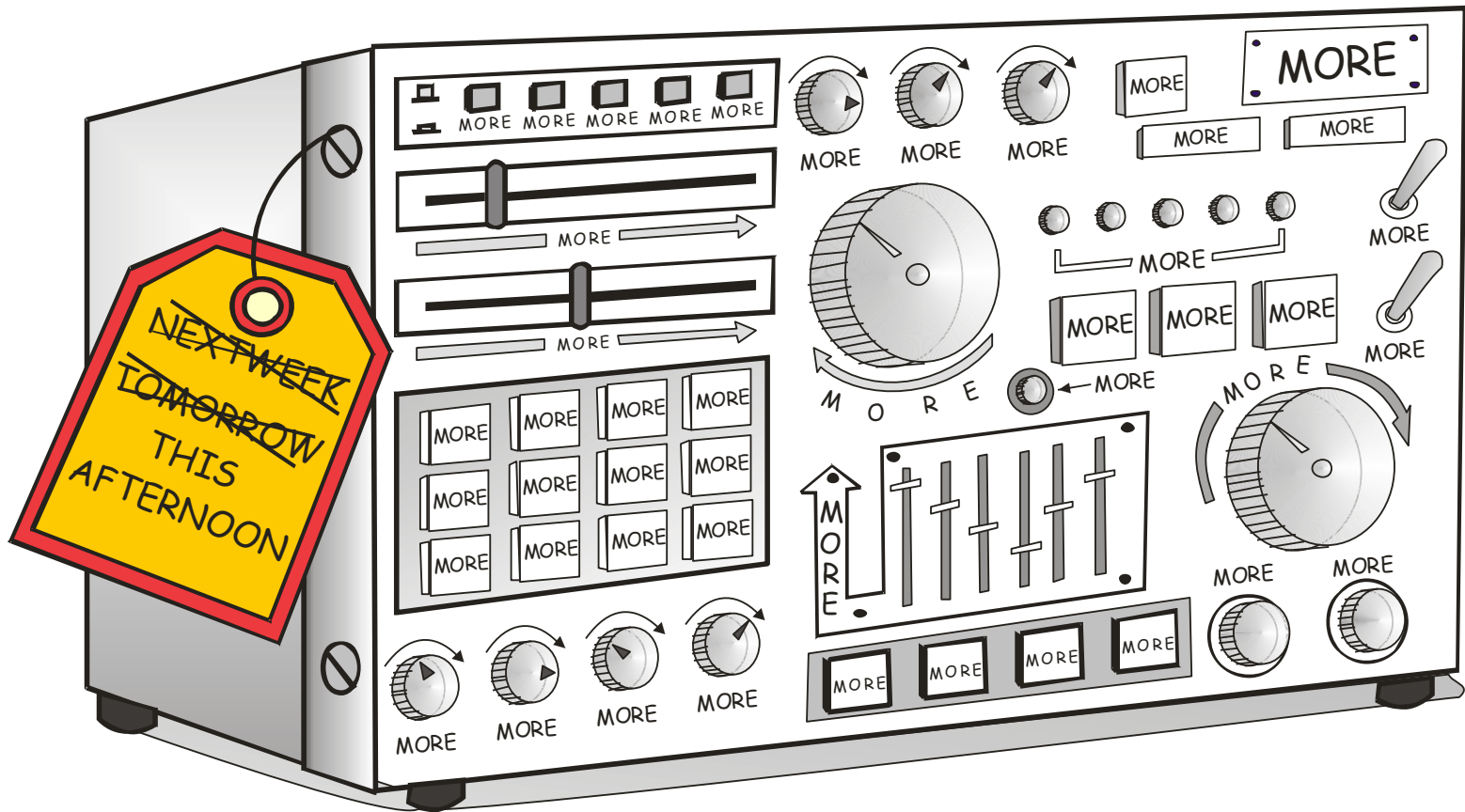
What The Customer Wants



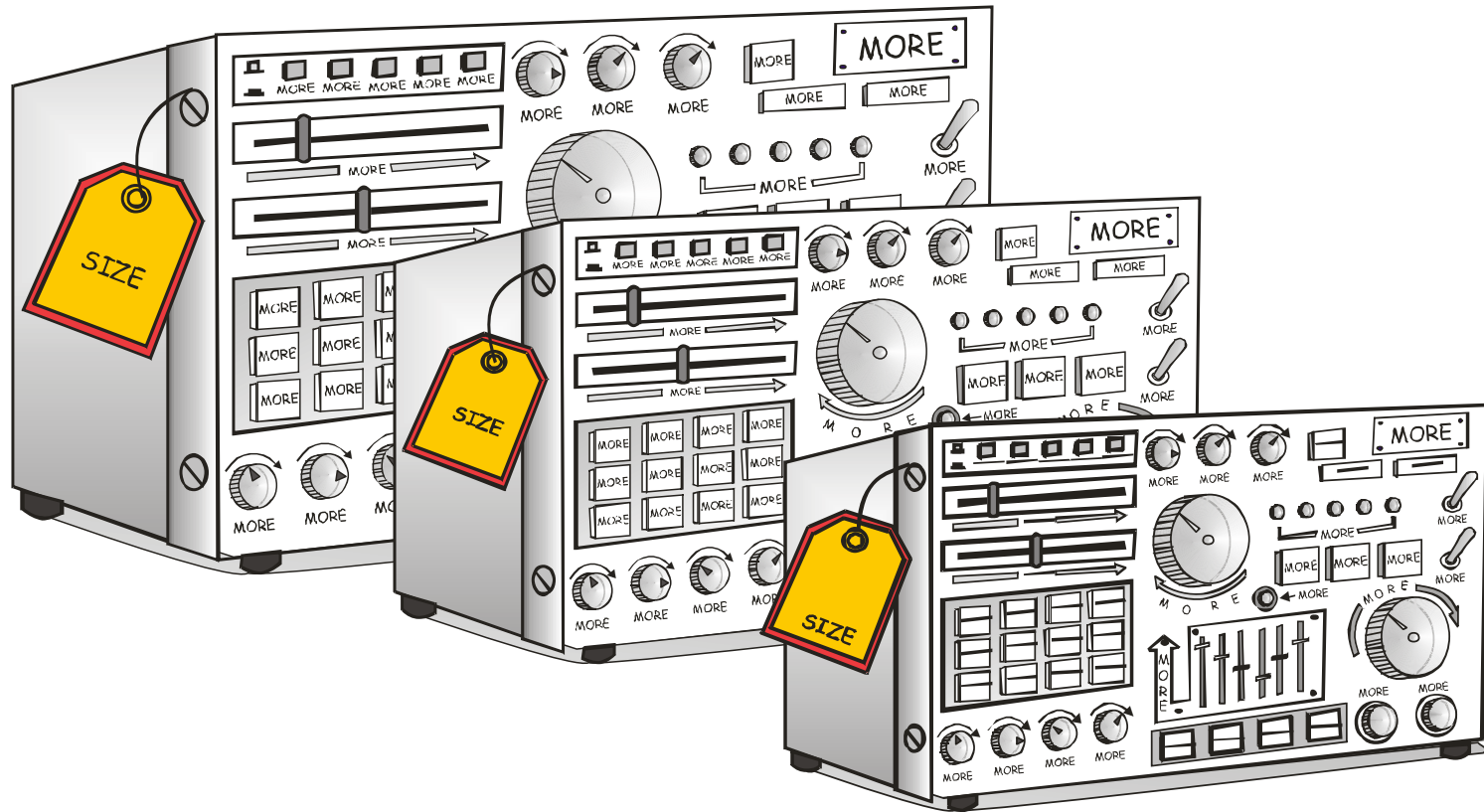
What The Customer Expects to Pay



When The Customer Wants it



What Size Customer Wants



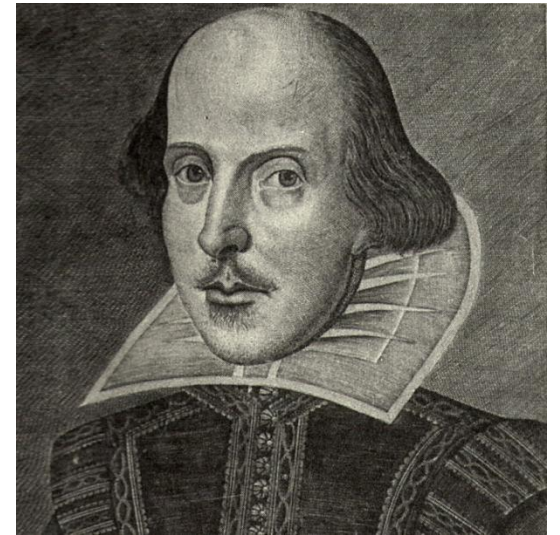
Why Digital Communications?

But Let Your Communications Be
Yea, Yea: Nay, Nay:

For What So Ever is More Than
These Cometh of Evil.

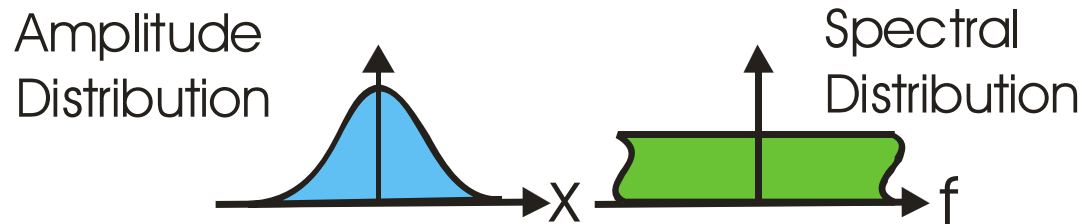
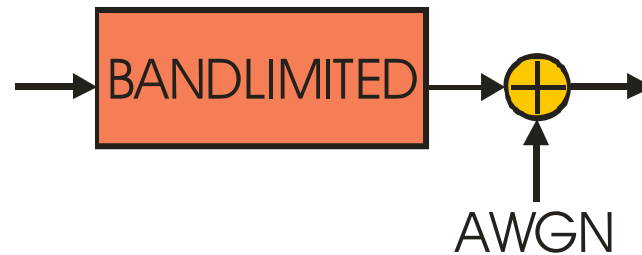
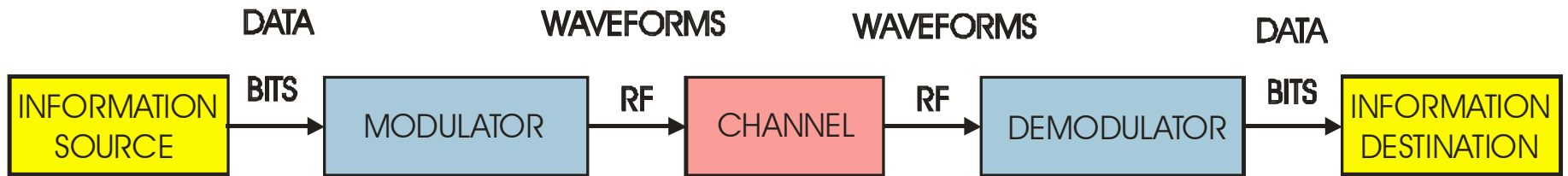
Sermon on the Mount,
Matthew, Ch. 5, verse. 37

To Paraphrase
the Great Bard

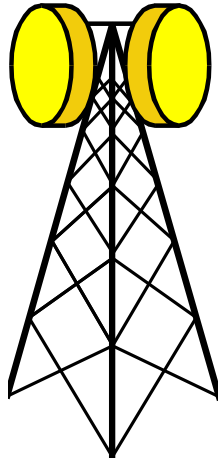
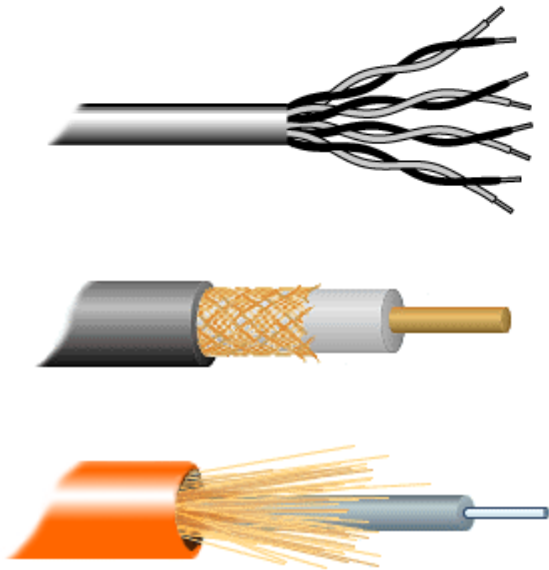
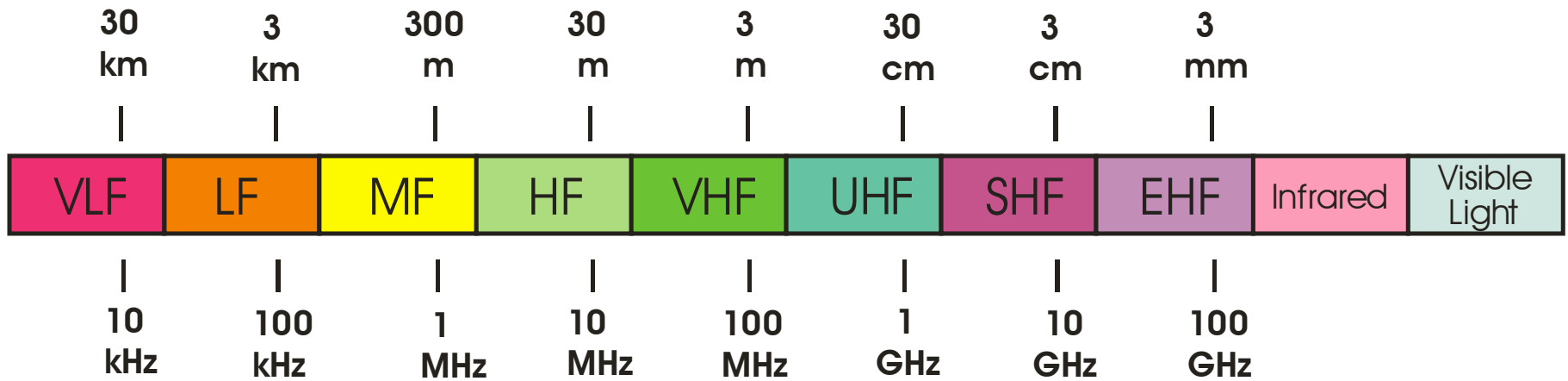


The World is an Analog Stage
In Which Digital
Plays A Bit Part

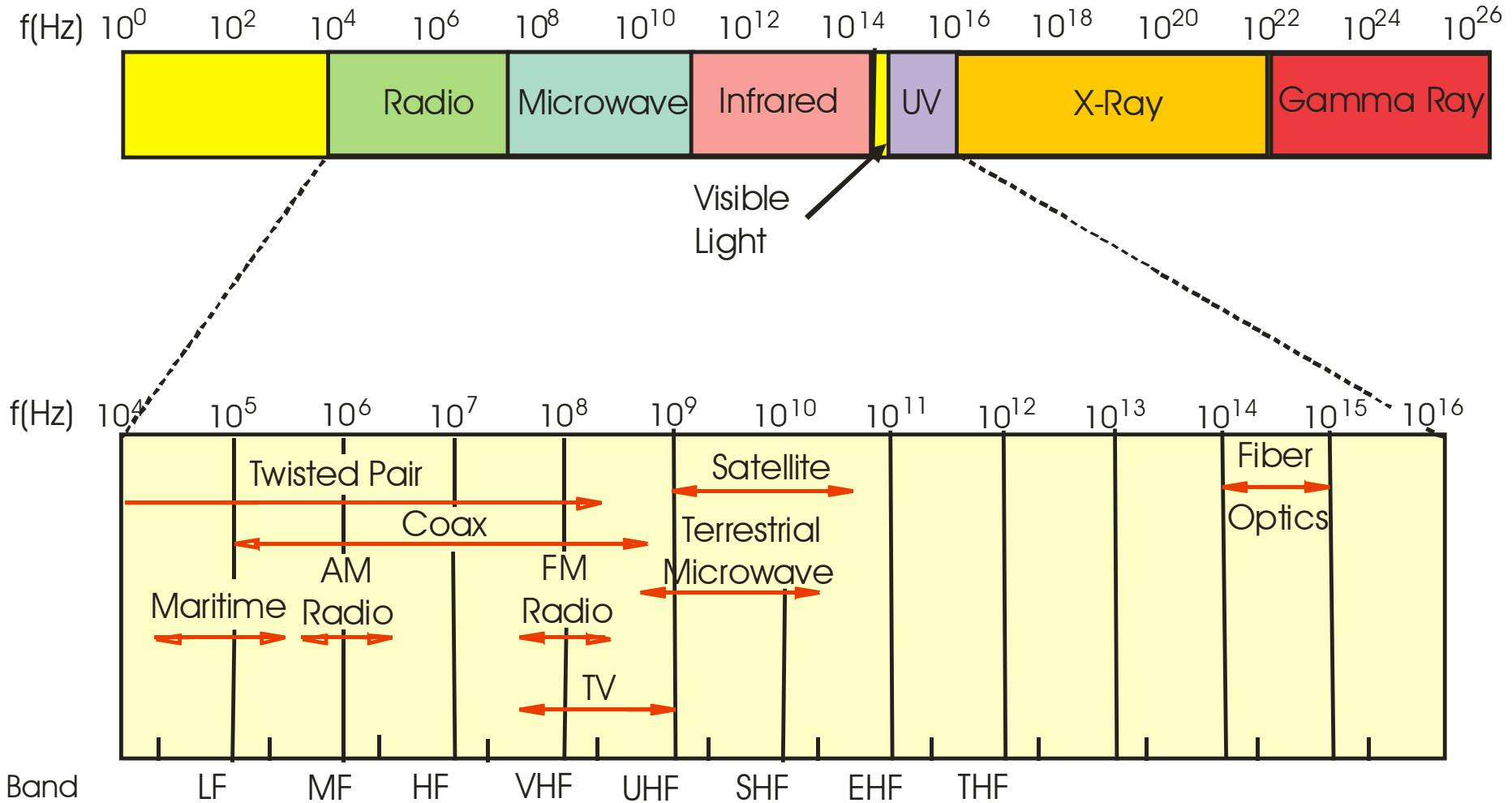
The Basic Communication System



The Radio Channel Frequency Band



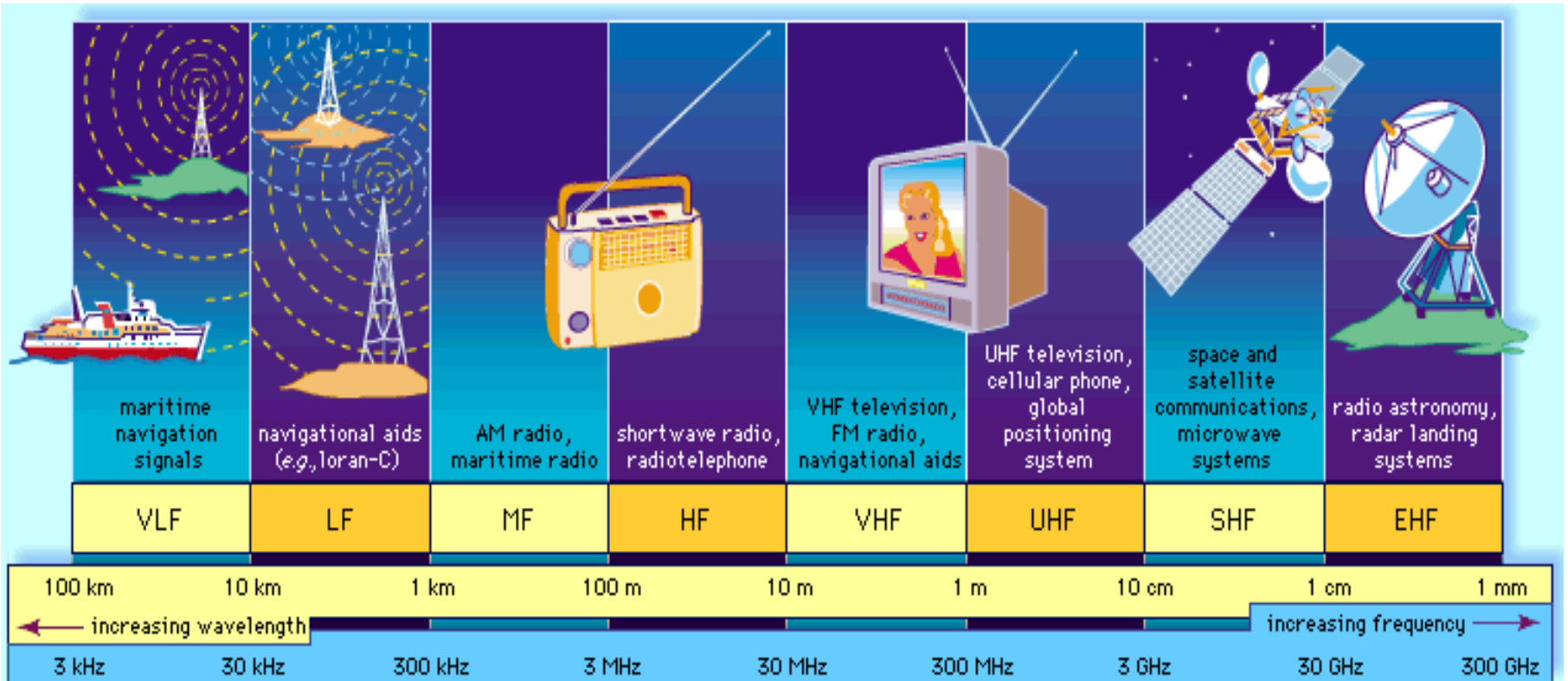
The Electromagnetic Spectrum



Spectral Utilization

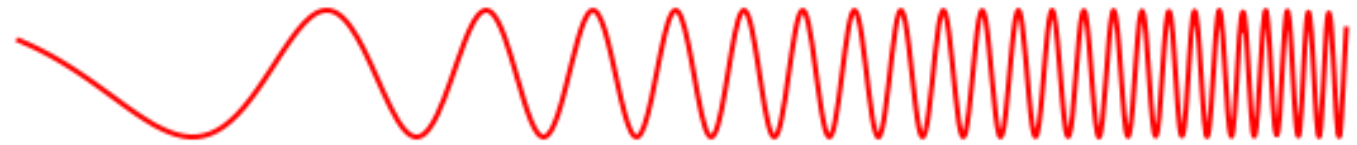
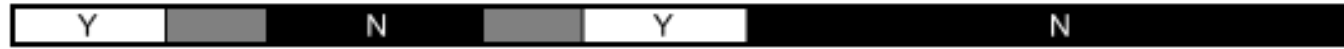
<i>Band</i>	<i>Frequency</i>	<i>Wavelength</i>	<i>Some Uses</i>
VLF	3 - 30 kHz	100 km - 10 km	Long range navigation and marine radio
LF	30 - 300 kHz	10 km - 1 km	Aeronautical and marine navigation
MF	300 kHz - 3 MHz	1 km - 100 m	AM radio and radio telecommunication
HF	3 - 30 MHz	100 m - 10 m	Amateur radio bands, NRC time signal
VHF	30 - 300 MHz	10 m - 1 m	TV, FM, cordless phones, air traffic control
UHF	300 MHz - 3 GHz	1 m - 10 cm	UHFTV, satellite, air traffic radar, etc
SHF	3 - 30 GHz	10 cm - 1 cm	Mostly satellite TV and other satellites
EHF	30 - 300 GHz	1 cm - 1 mm	Remote sensing and other satellites

Radio Spectrum



Radio Spectrum Wavelength

Penetrates Earth's Atmosphere?



Radiation Type
Wavelength (m)

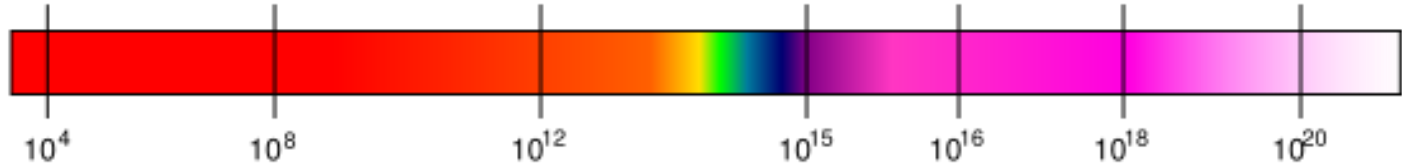
Radio 10^3	Microwave 10^{-2}	Infrared 10^{-5}	Visible 0.5×10^{-6}	Ultraviolet 10^{-8}	X-ray 10^{-10}	Gamma ray 10^{-12}
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Approximate Scale
of Wavelength

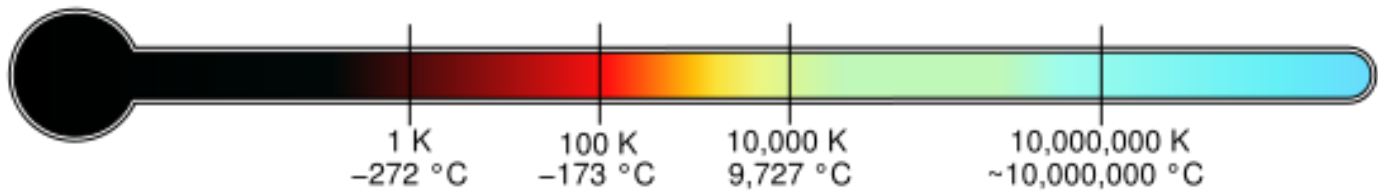


Buildings Humans Butterflies Needle Point Protozoans Molecules Atoms Atomic Nuclei

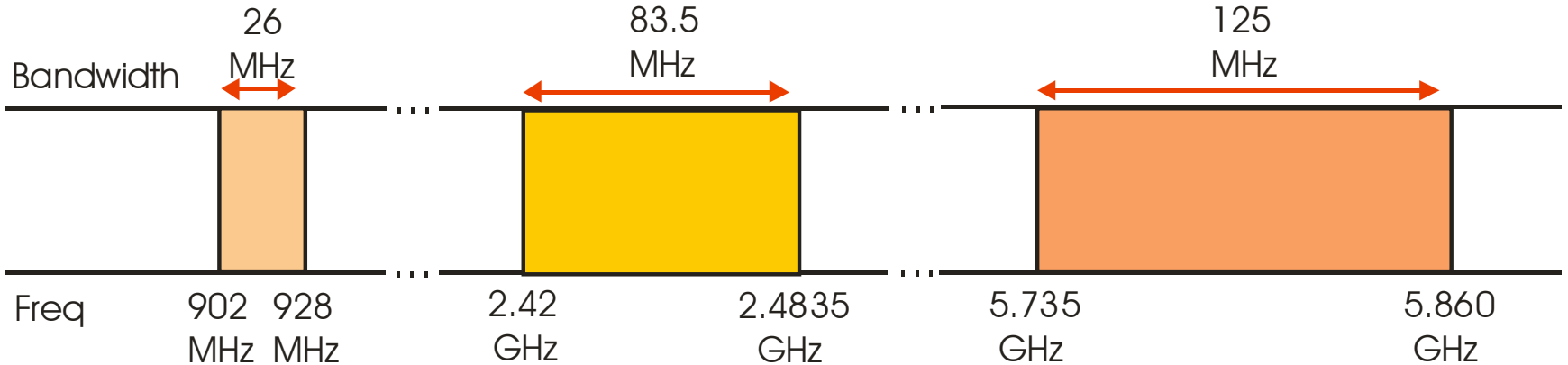
Frequency (Hz)



Temperature of objects at which this radiation is the most intense wavelength emitted

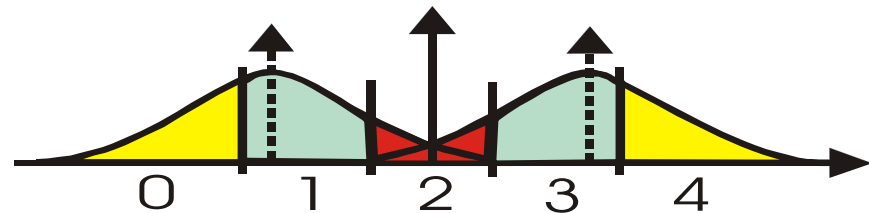
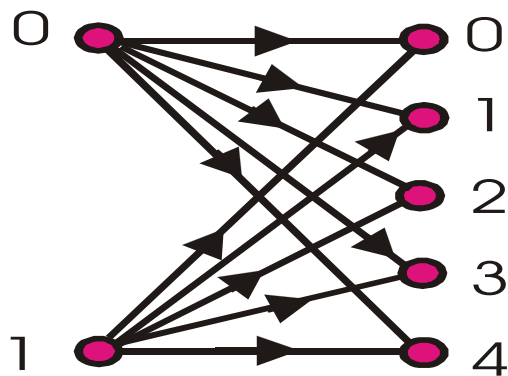
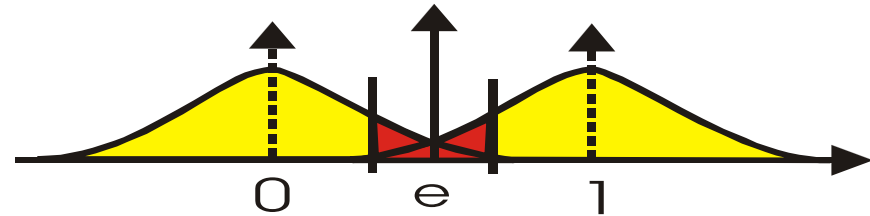
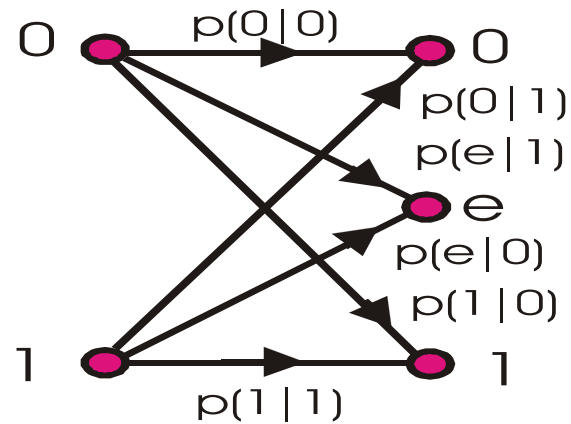
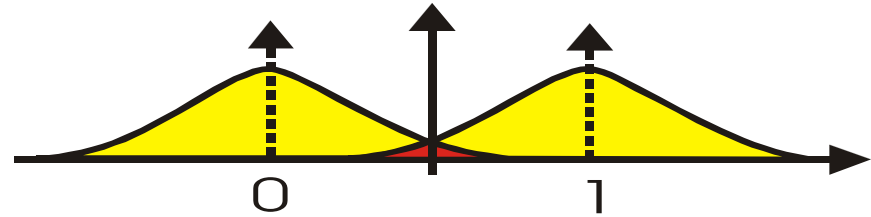
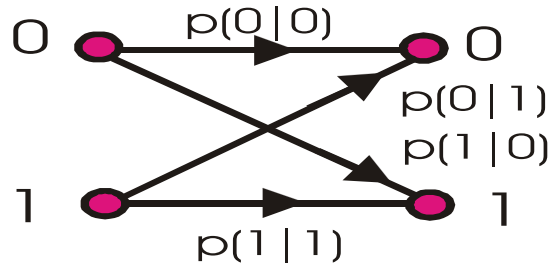


Parts of the Electromagnetic Spectrum

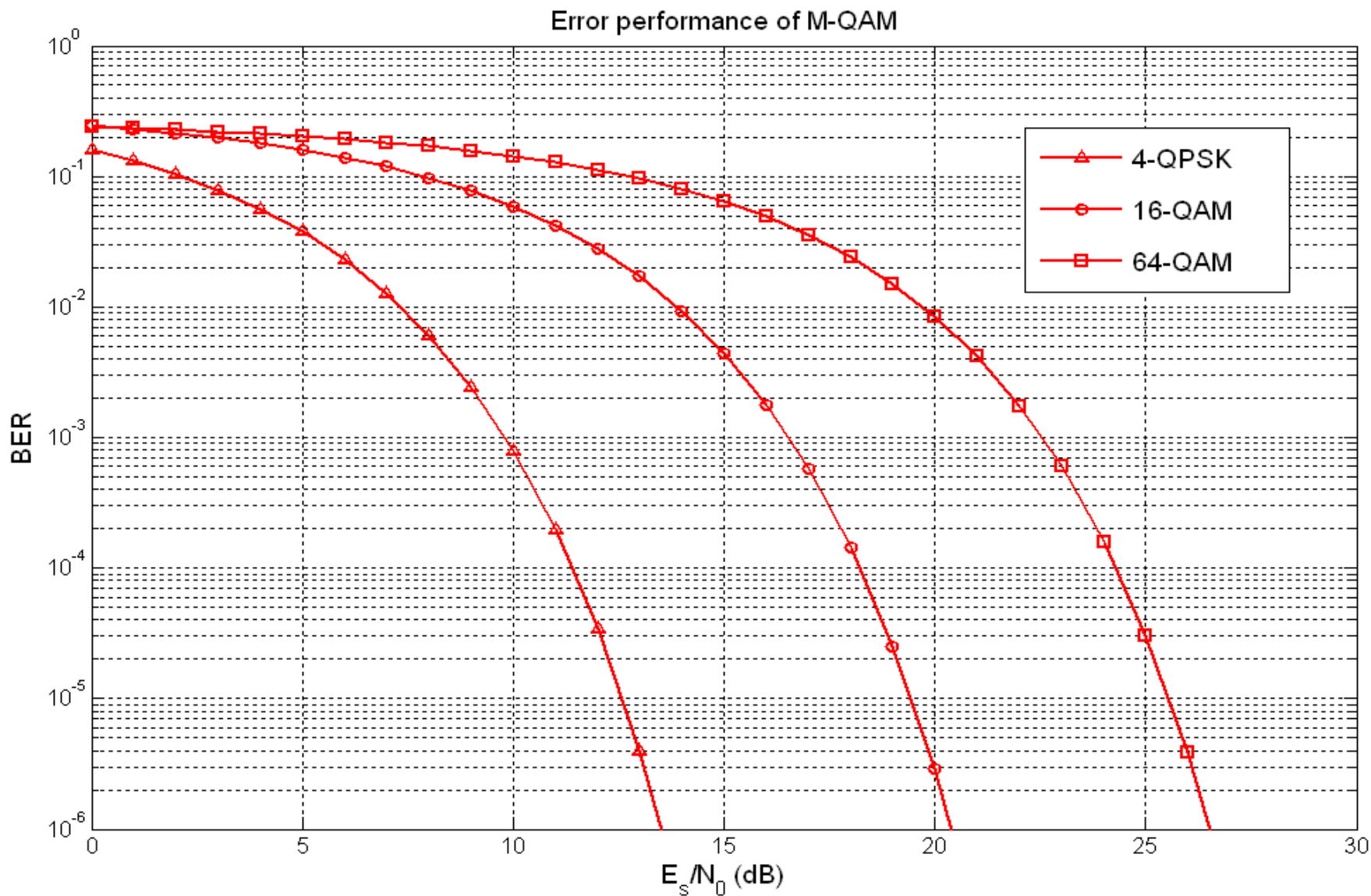


The ISM bands in the United States.

Cross-Over Probabilities



E_s/N_0 Required for Specified BER



QPSK, 16-QAM, & 64-QAM Constellations for 10^{-5} BER

BER = 10^{-5}

$E_S/N_0 = 12.49$ dB

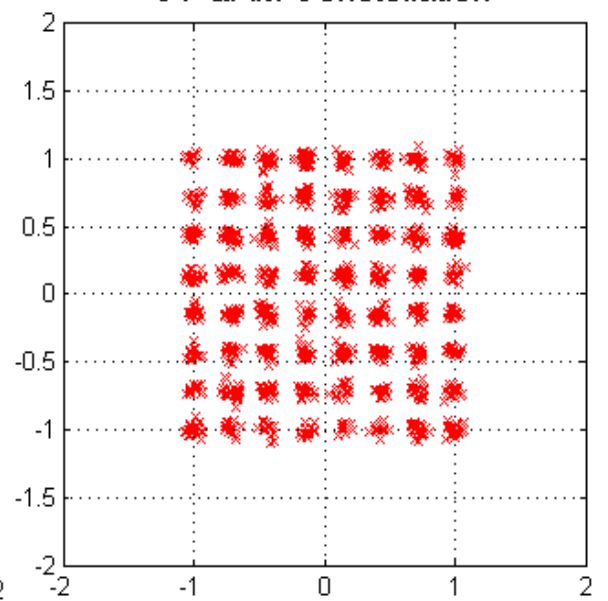
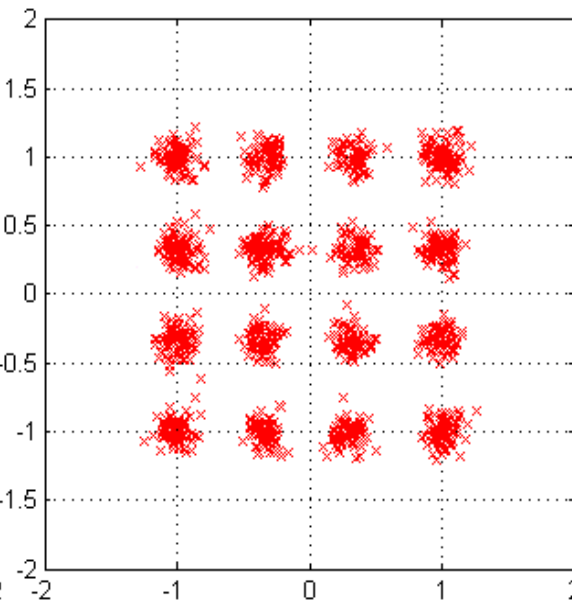
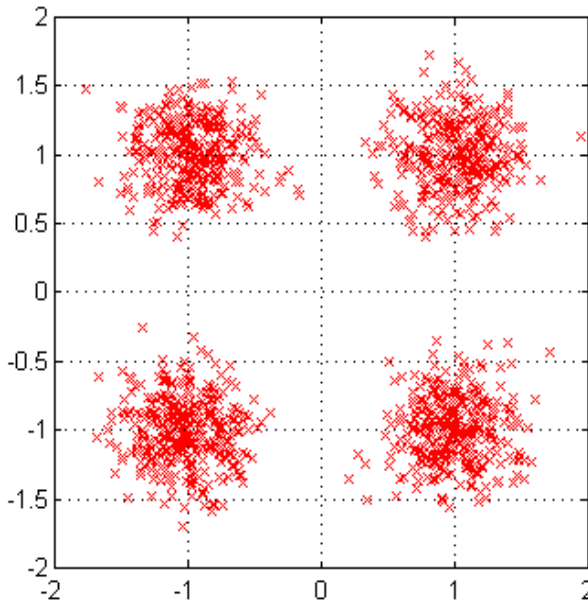
$E_S/N_0 = 19.50$ dB

$E_S/N_0 = 25.50$ dB

QPSK Constellation

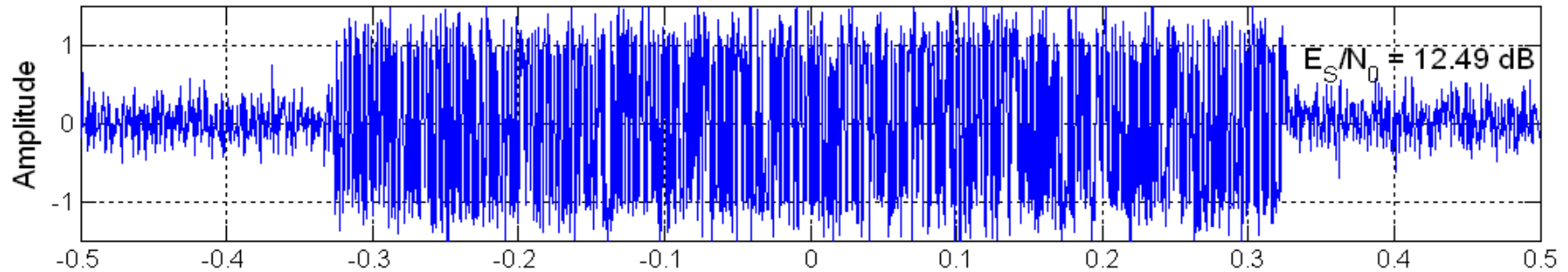
16-QAM Constellation

64-QAM Constellation

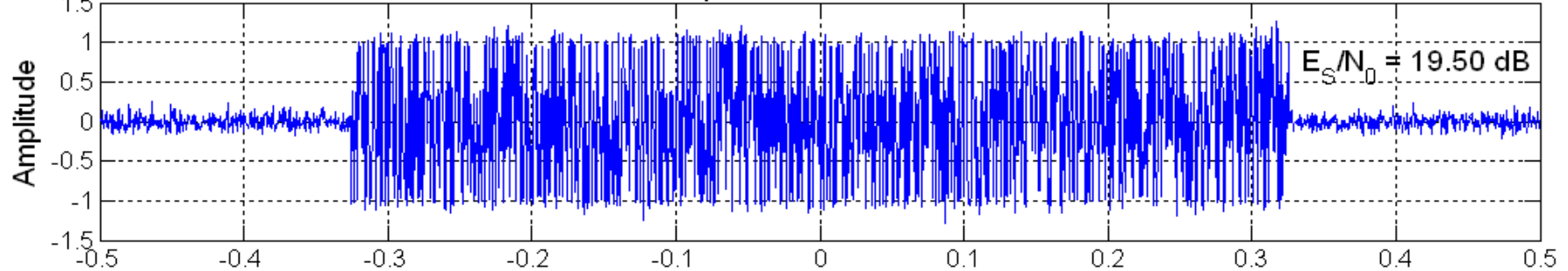


Spectral Levels of Signal and Noise for QPSK, 16-QAM, & 64-QAM for 10^{-5} BER

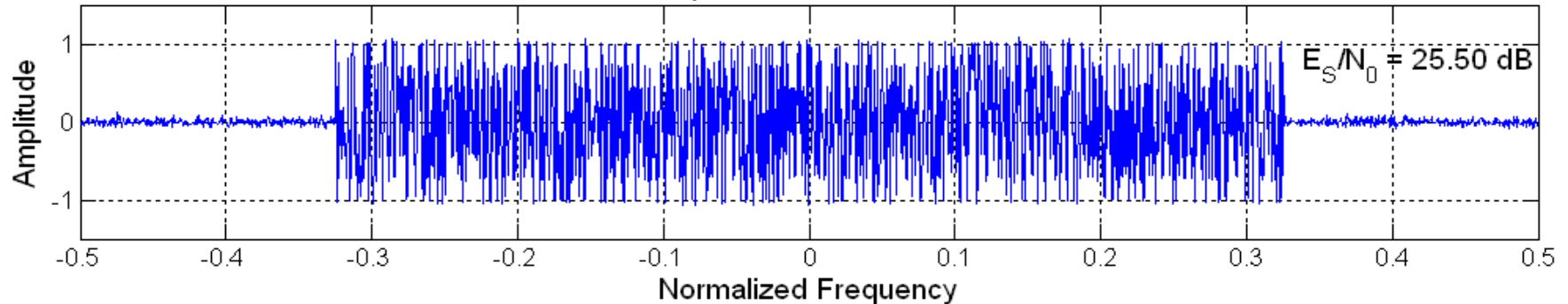
Real Part of Spectrum QPSK Constellation



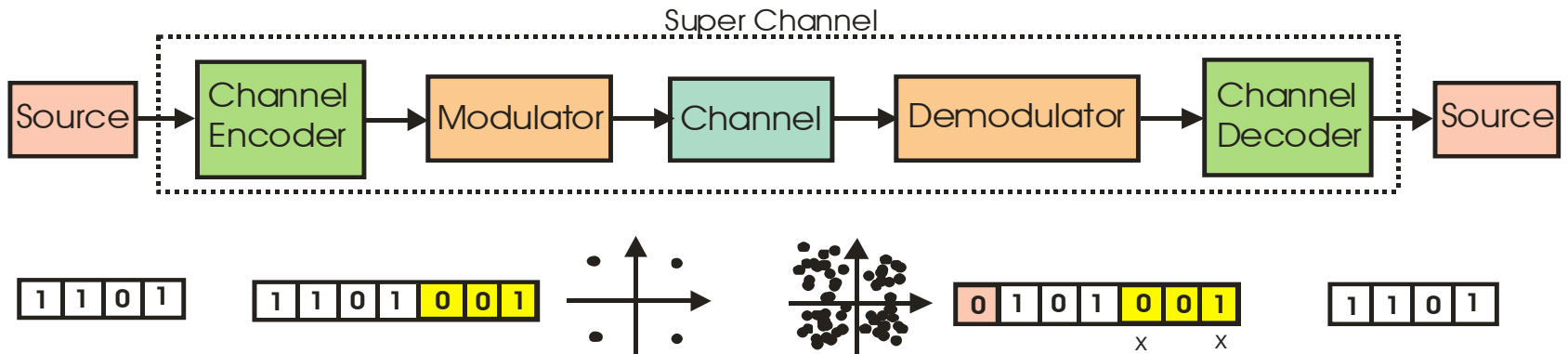
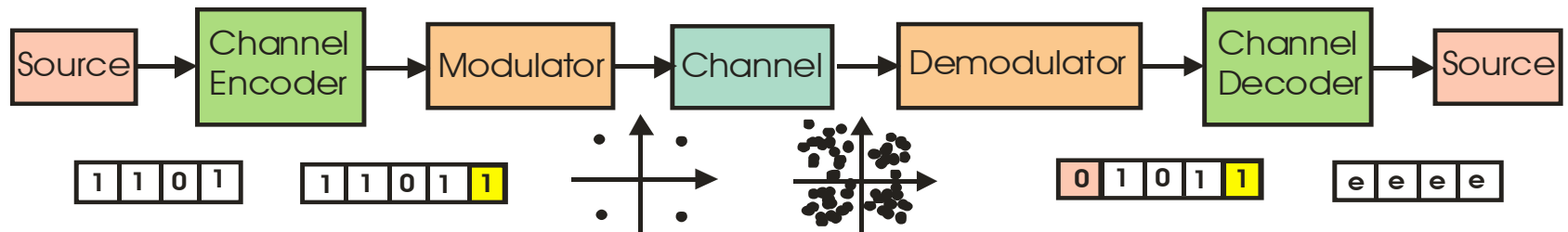
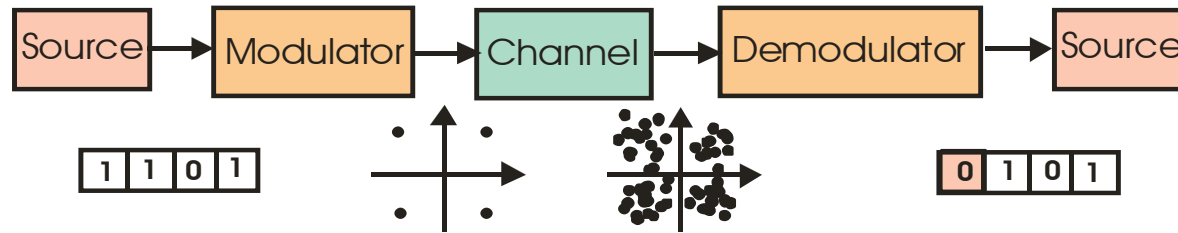
Real Part of Spectrum 16-QAM Constellation



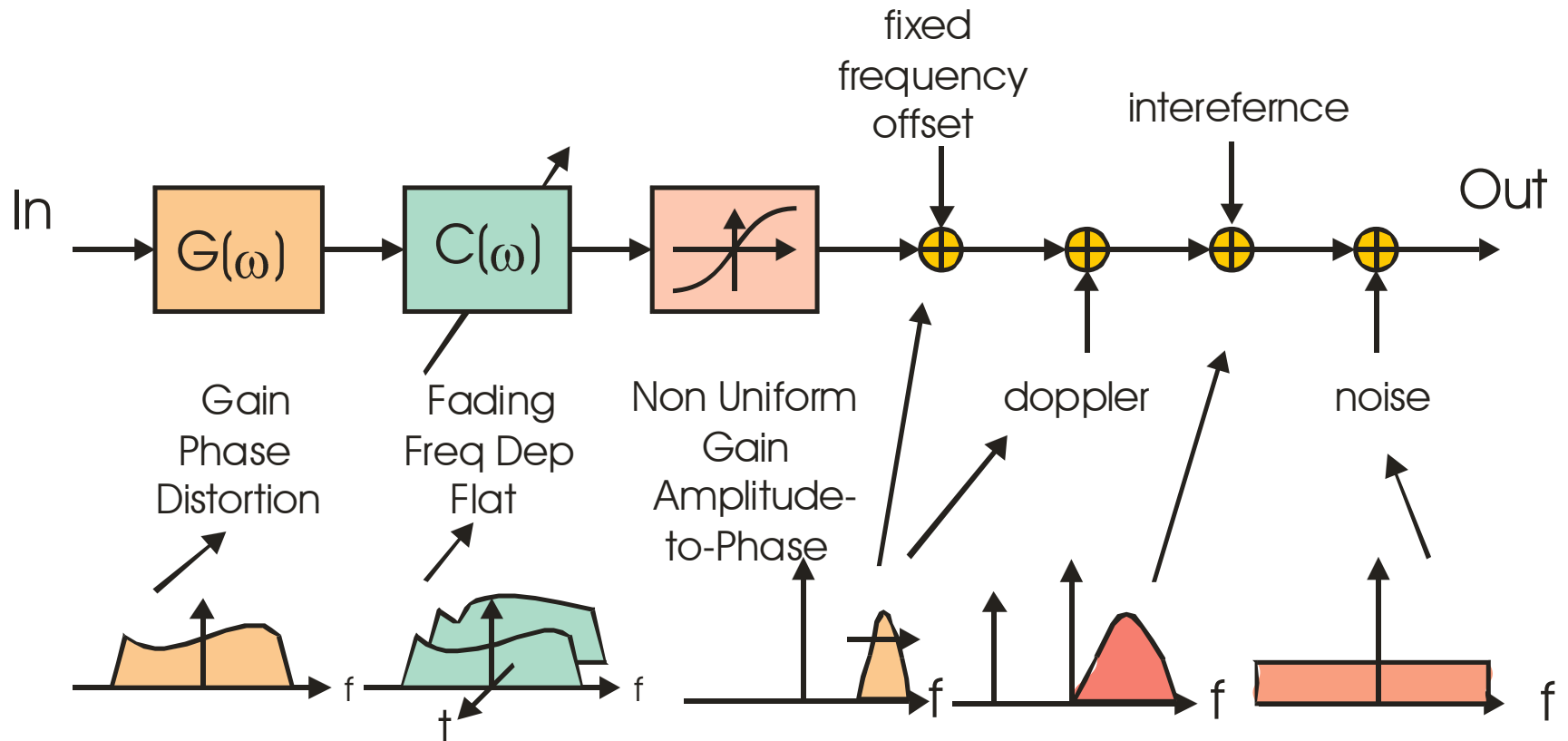
Real Part of Spectrum 64-QAM Constellation



Channel Coding: Add Structured Redundancy



Other Channel Impairments



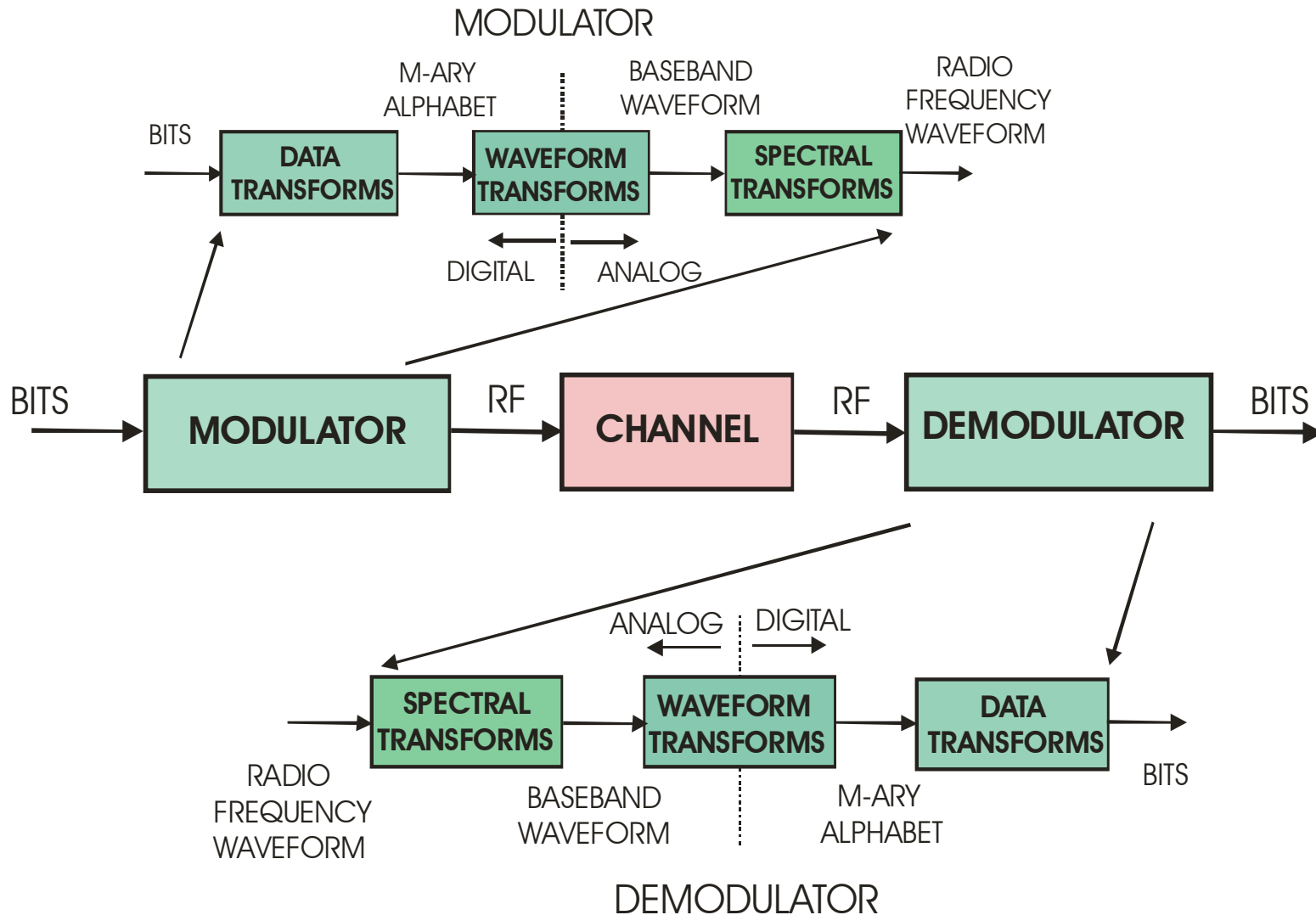
Modern Physical Layer Modem Recipe:

Add these Ingredients, Stir, Bake for 20 Minutes at 300°.
Let Cool! Enjoy your Modem!

- First Tier Processing: Modulation and Demodulation
 - Shaping Filters
 - Spectral Translation
 - Signal Conversion
- Second Tier Processing: Parameter Estimation
 - Carrier Frequency and Phase Synchronization
 - Timing Frequency and Phase Synchronization
 - Automatic Gain Control
 - SNR Estimate
- Third Tier Processing: Channel and Hardware (Dirty RF)
 - Equalization
 - I-Q Balance
 - DC-Cancel
 - Peak-to-Average Ratio Control
 - Predistortion
 - Interference Suppression
 - Intrusion Suppression
 - Diversity



Modulator and Demodulator



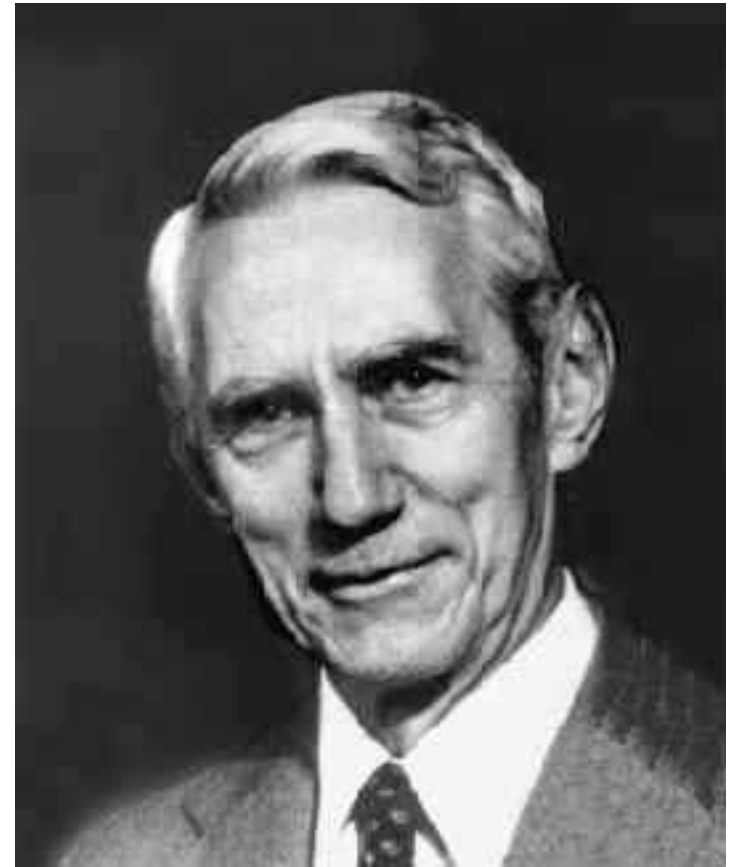
Claude Shannon

Information is measurable.

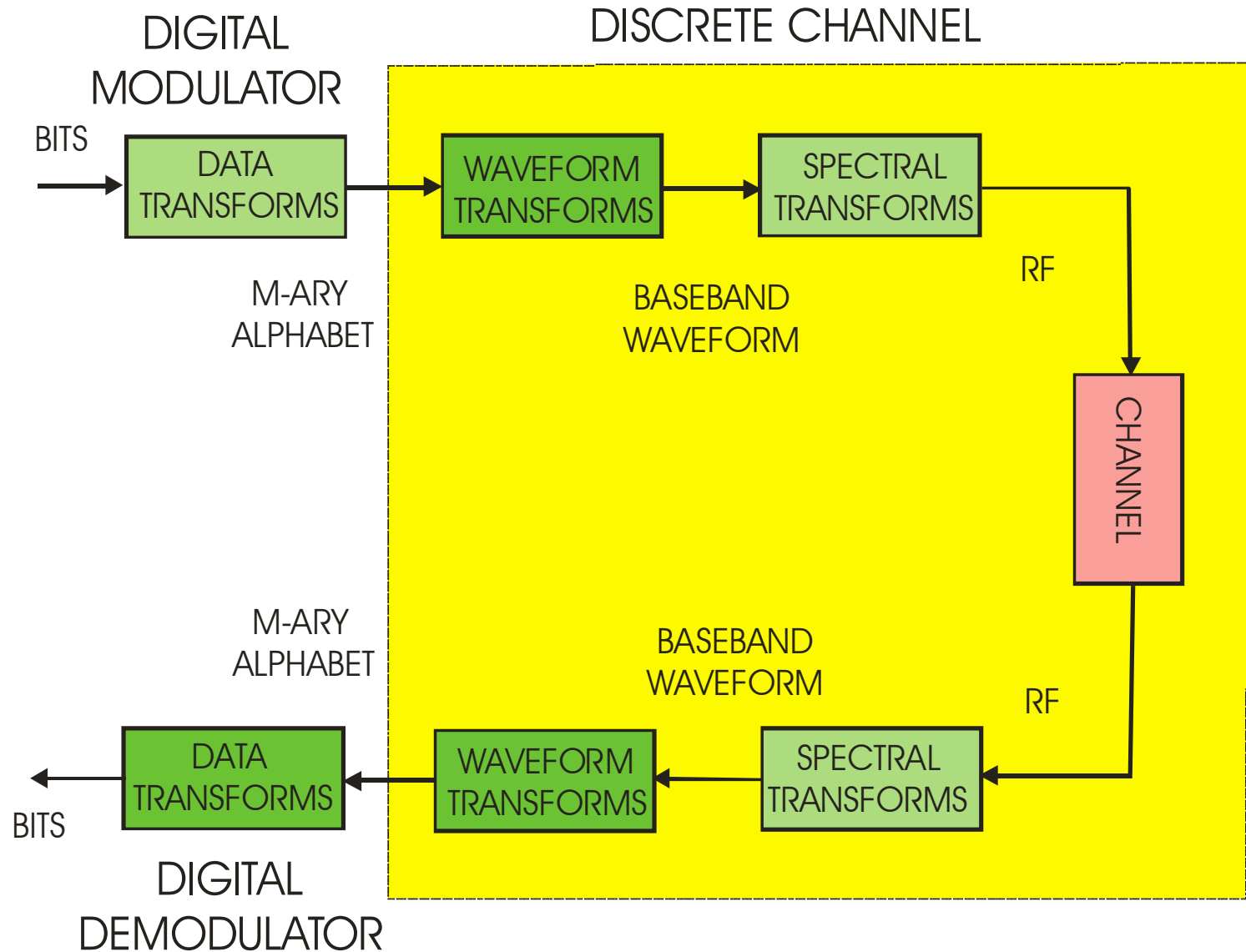
Noise Does not Limit Fidelity.

'The world has only 10
kinds of people.

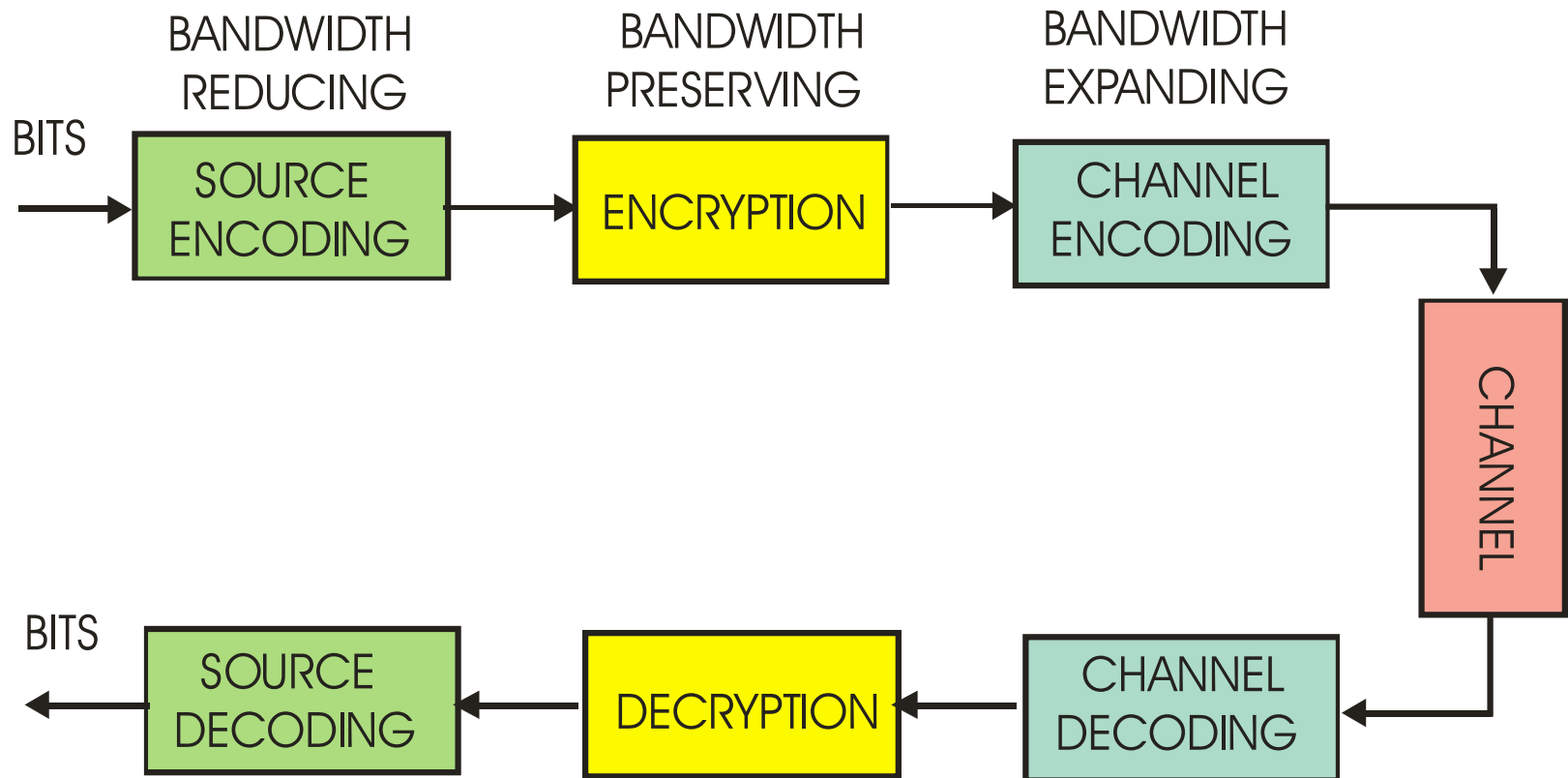
Those who get binary,
and those who don't.'



Shannon's Communication System



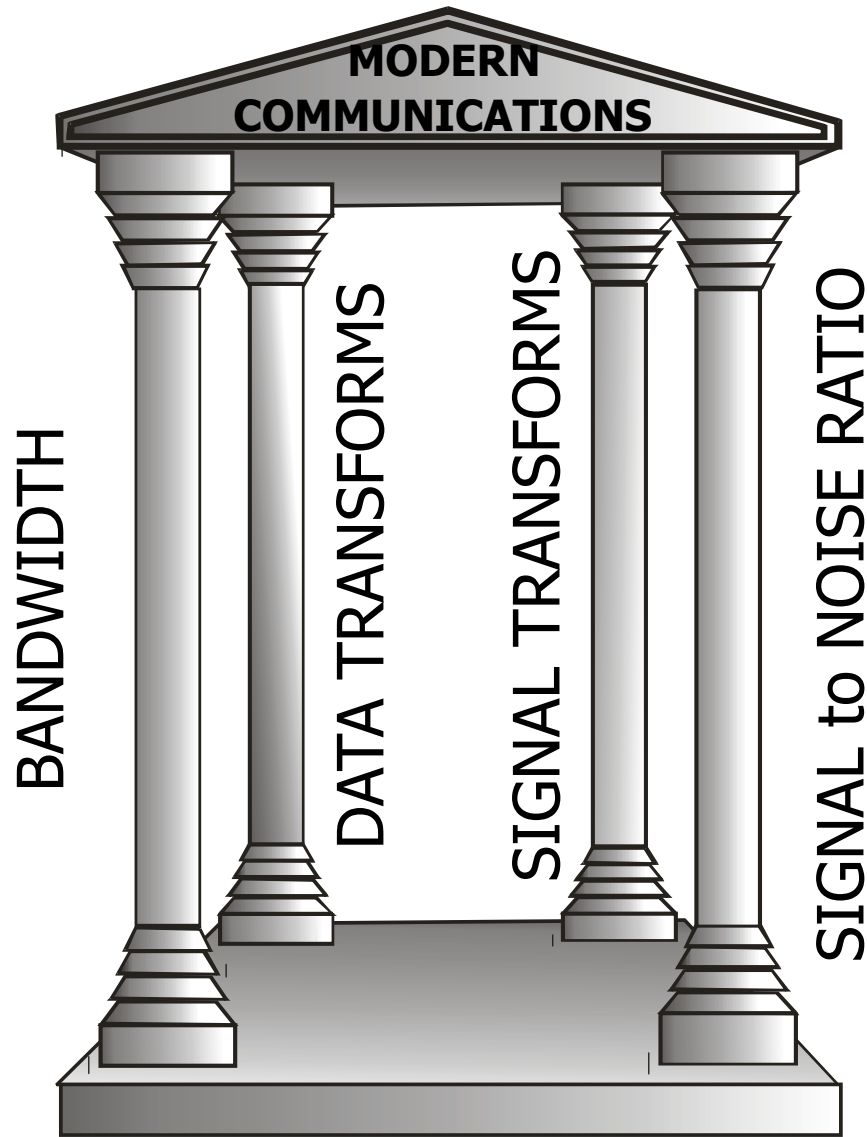
Shannon's Model



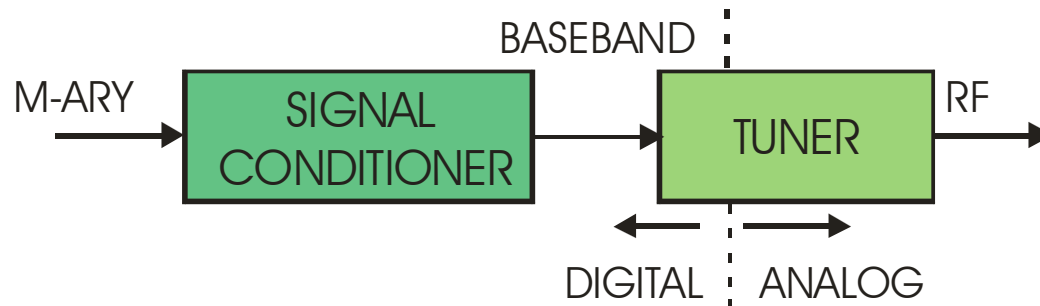
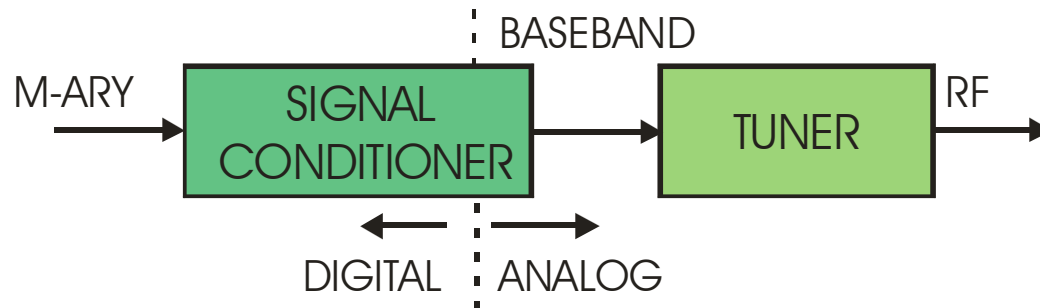
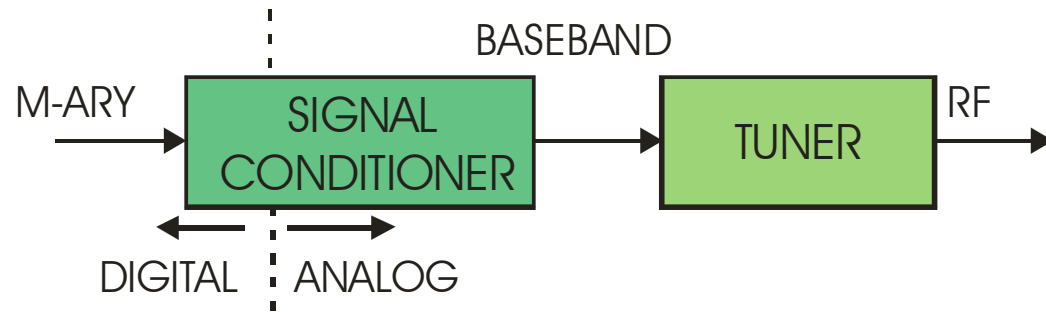
Shannon's Legacy

- ❖ Communication System Resources
 - Bandwidth
 - Signal to Noise Ratio
 - Memory and Computations
- ❖ A Communication System needs a *Computer* in Modulator and Demodulator!
- ❖ We have a *Computer* on Board!
- ❖ We can use it to do some other Heavy Lifting!

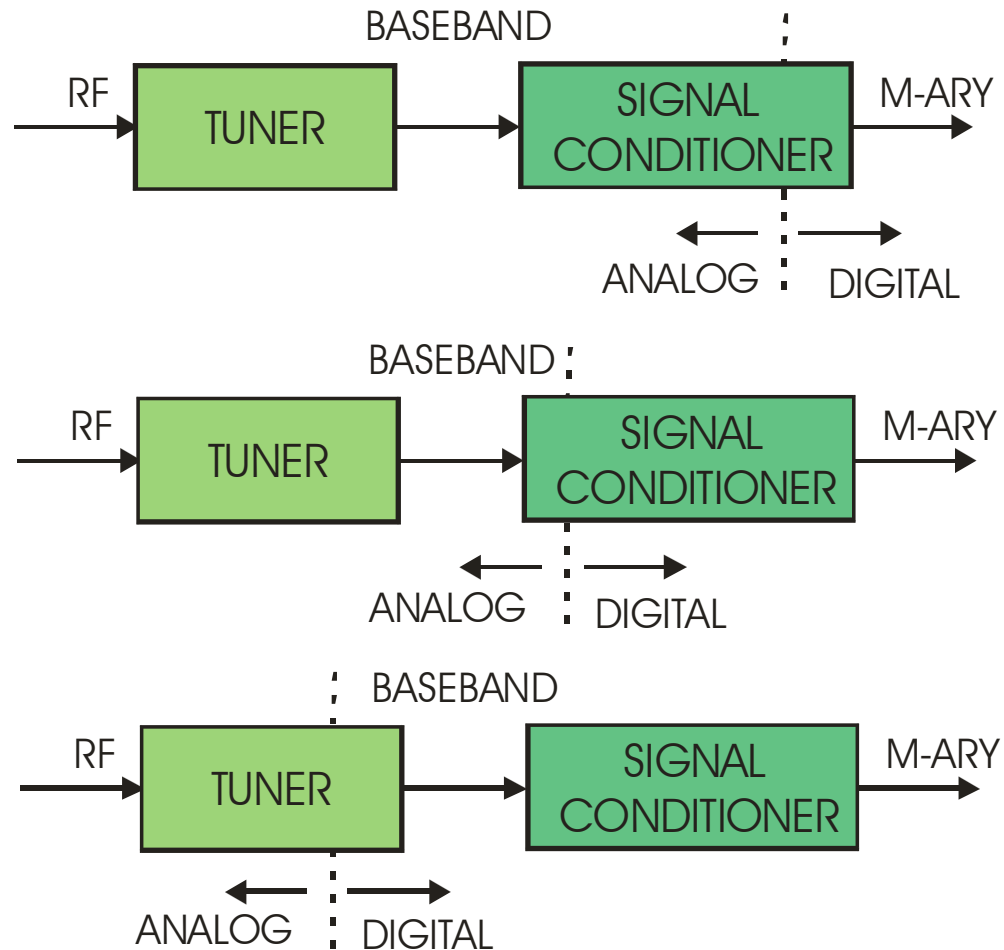
Four Pillars of Modern Communications



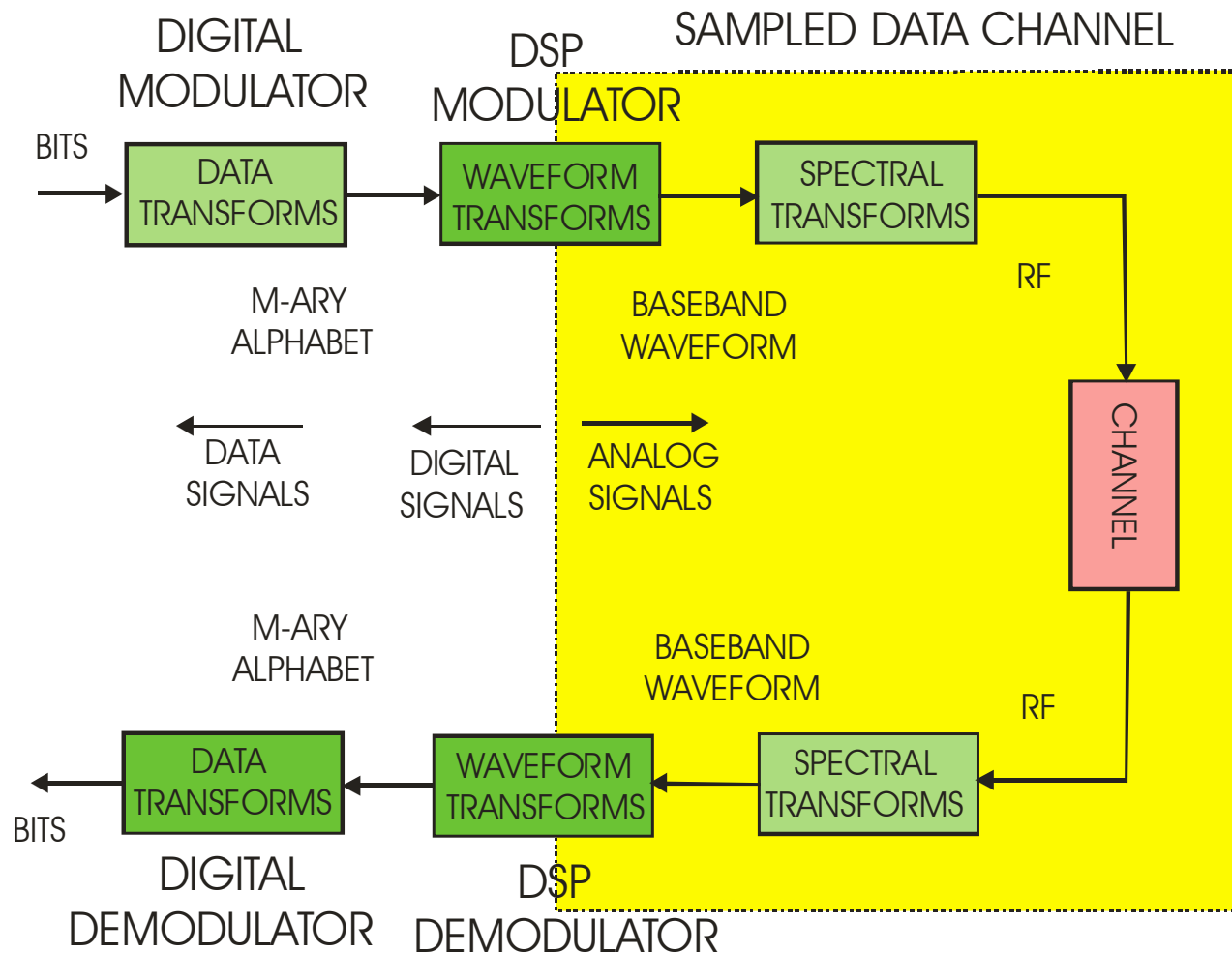
The Modulator Digital to Analog Interface Moves Towards the RF



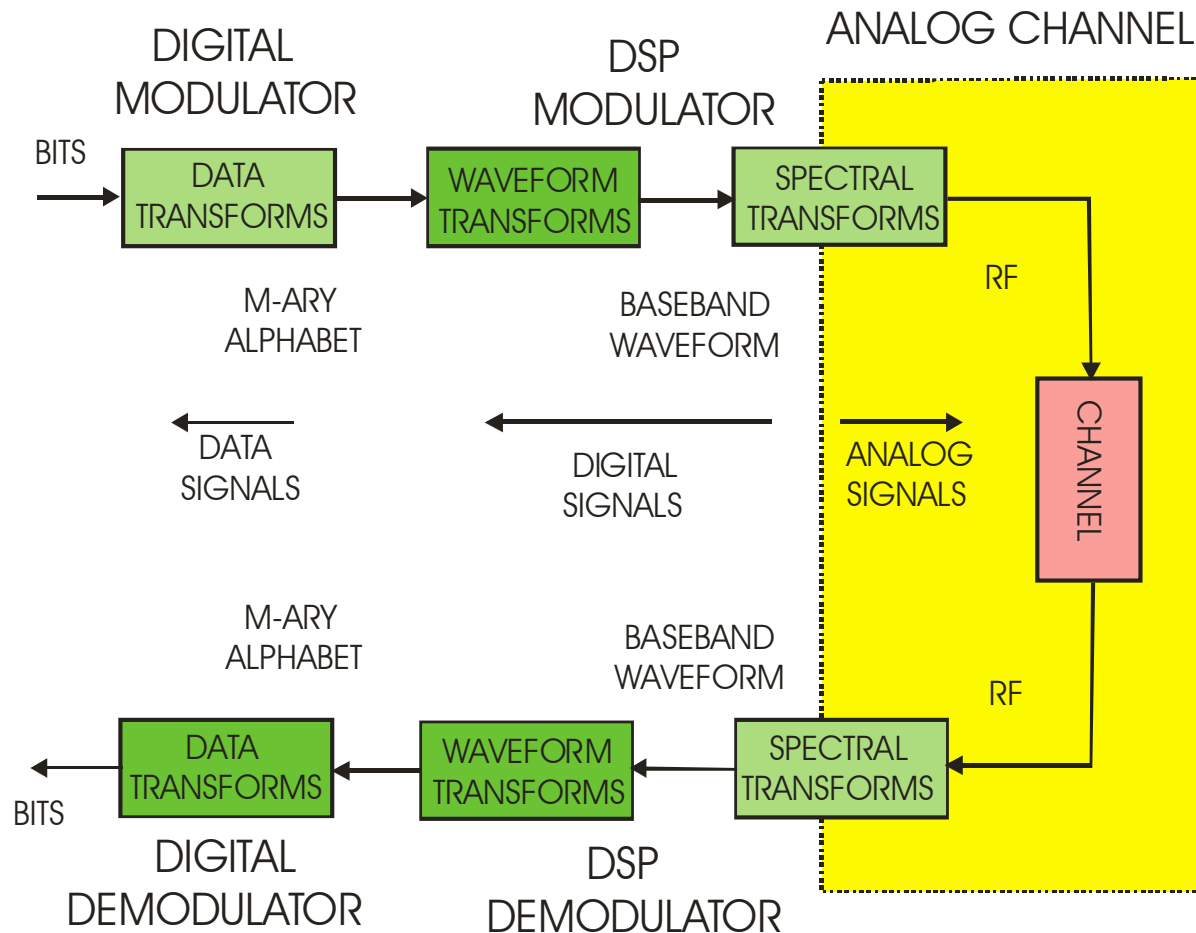
The Demodulator Analog to Digital Interface Moves Towards the RF



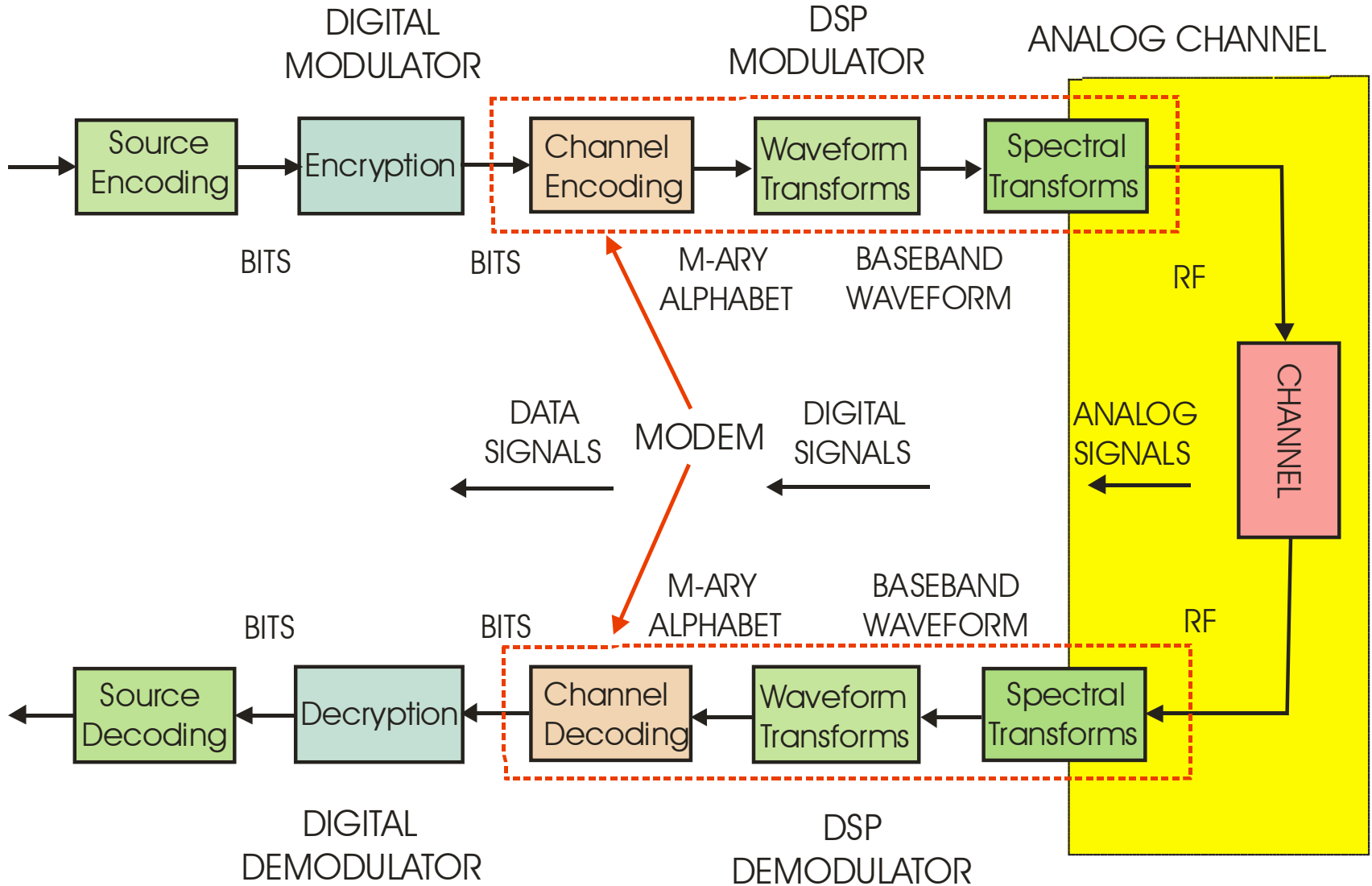
SECOND GENERATION DSP CENTRIC MODEL



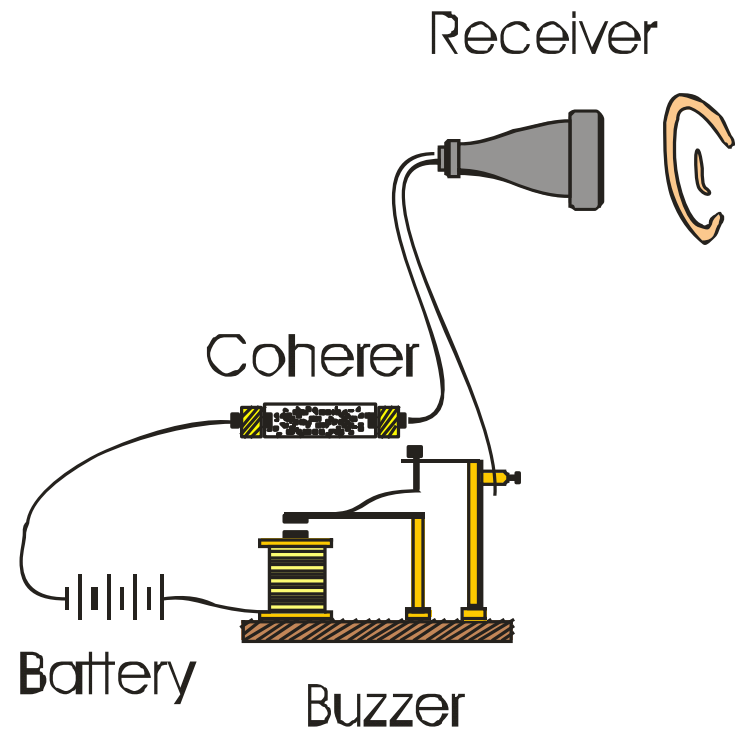
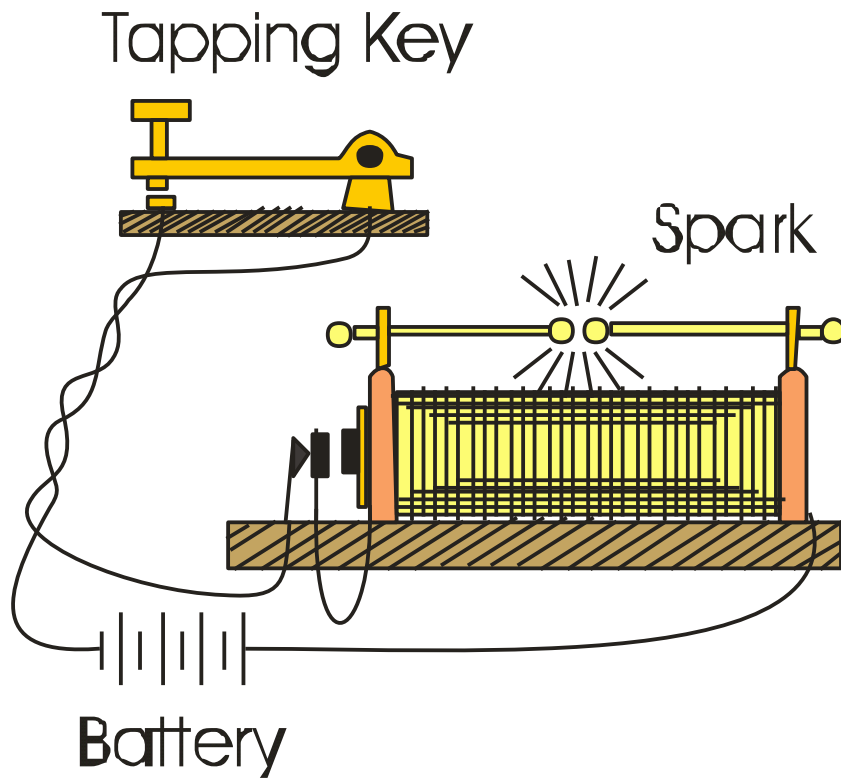
THIRD GENERATION DSP CENTRIC MODEL



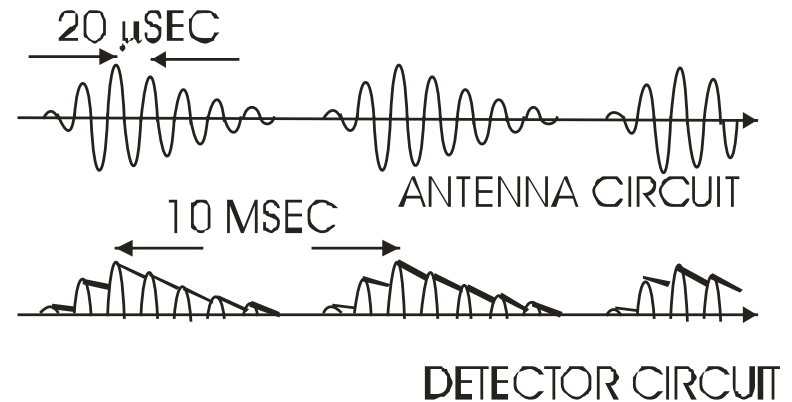
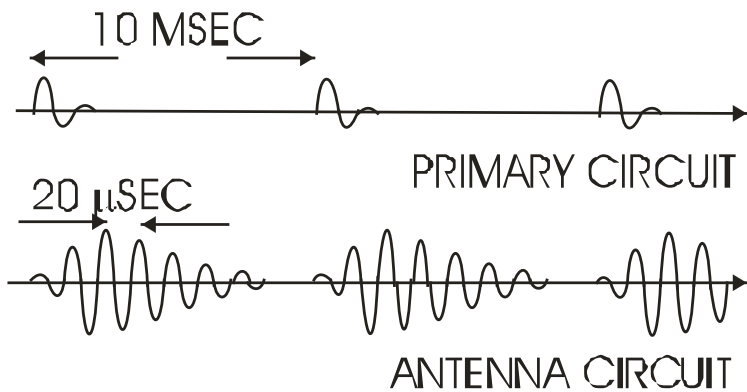
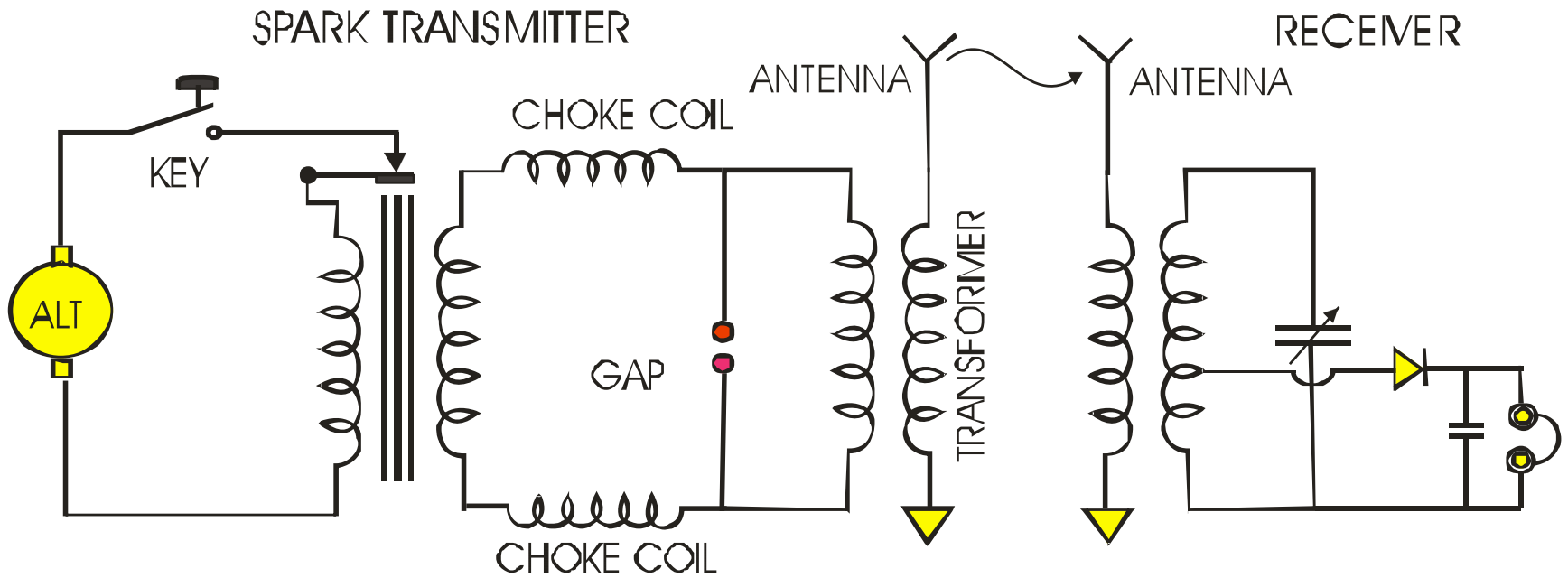
Modem: Bits In - RF Out, RF In - Bits Out



Early Radios Were Mechanical: (Many Moving Parts) Spark Transmitter and Early Receiver

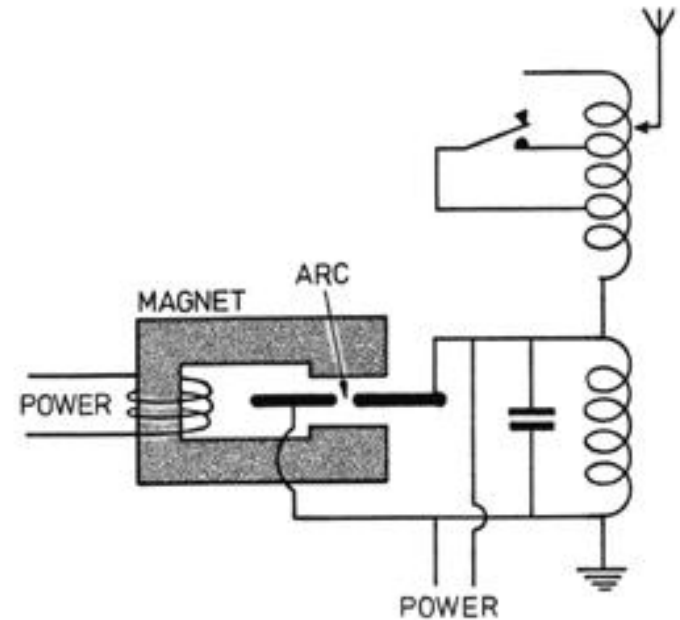
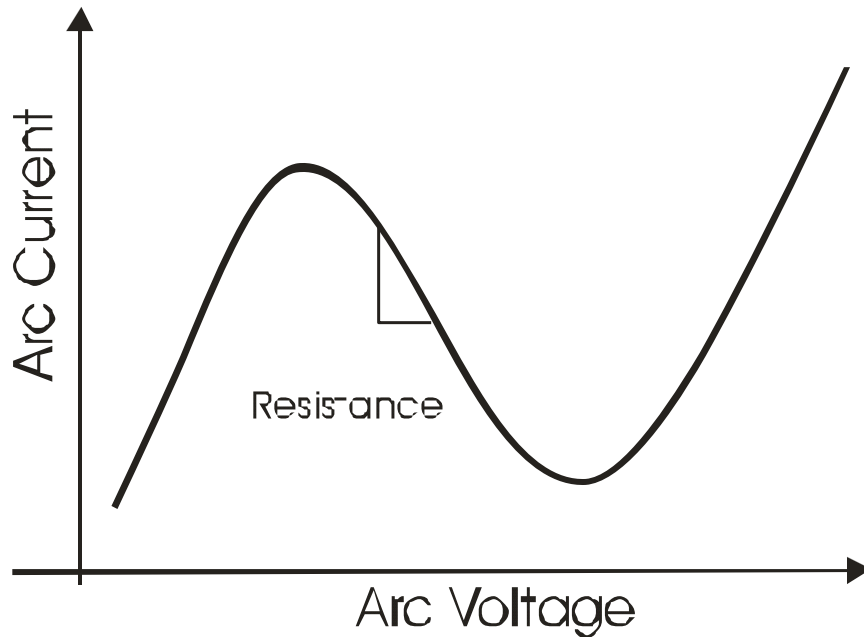


Spark Transmitter: Damped Oscillations



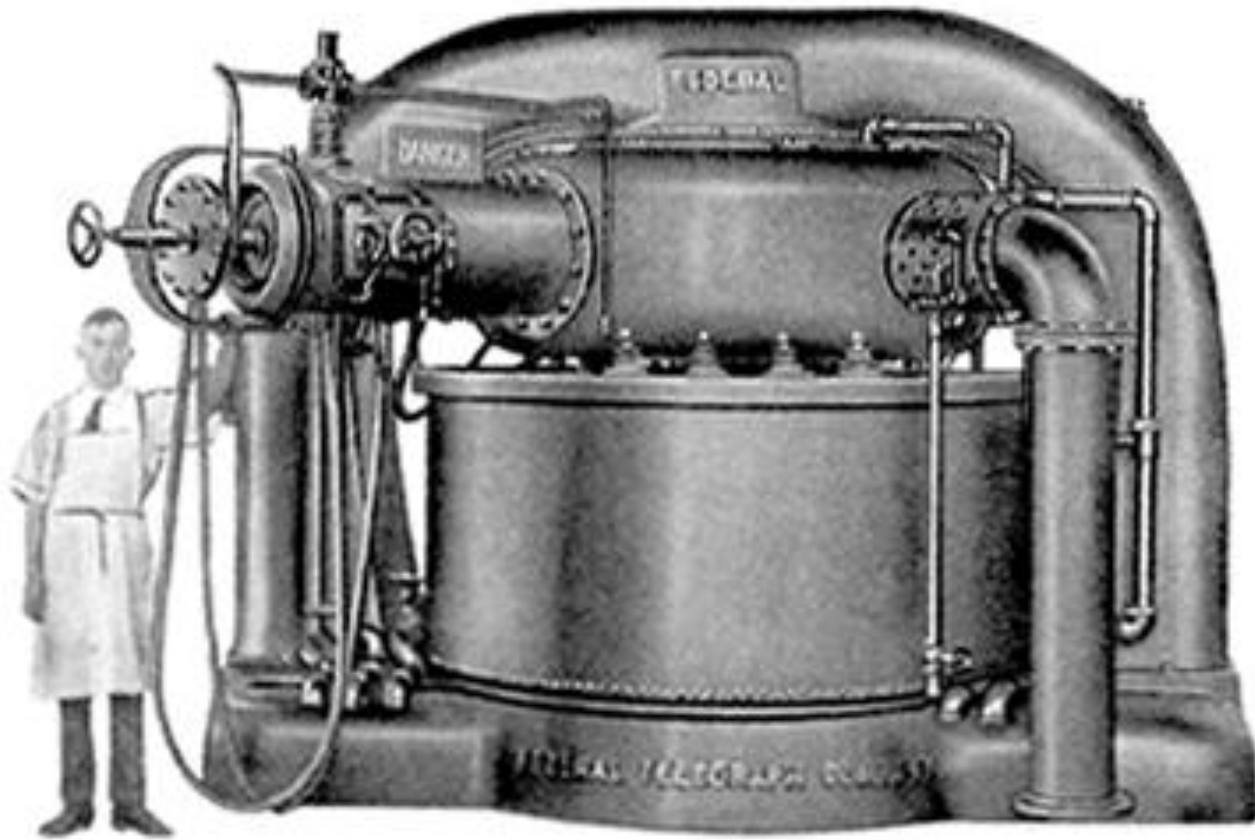
Arc Transmitter: Continuous Oscillation

Replace Sparks with an Arc
Negative Resistance Injects Energy
As Opposed to Dissipates Energy

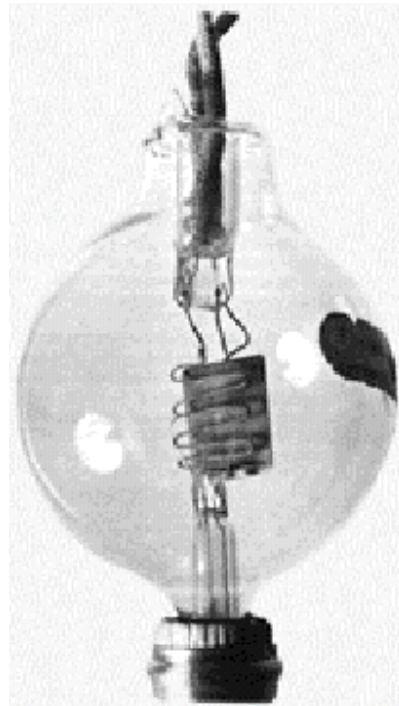
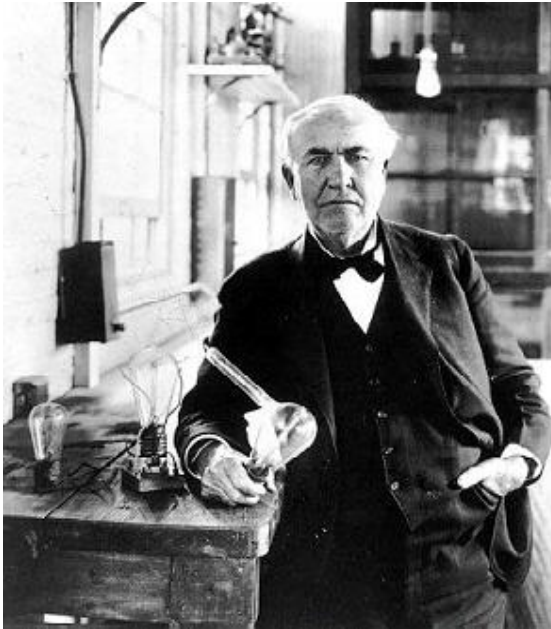


Valdemar Poulsen, 1869-1942

Poulsen 100 KW Arc Transmitter



The path to the Triode Thermionic Valve, Thomas Edison, John Fleming, Lee de Forest



Lee De Forest, 1877-1961



Patent No. 879532

Put those sparks to rest!

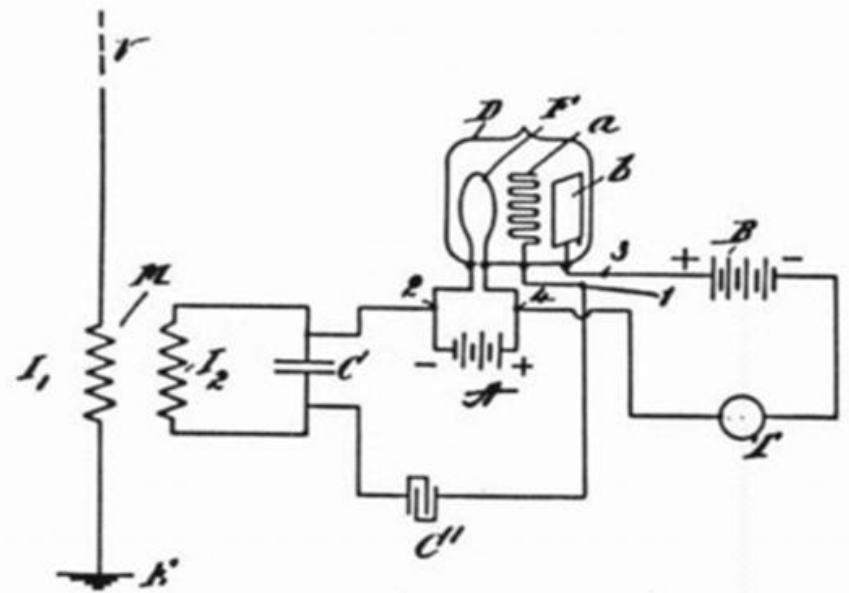
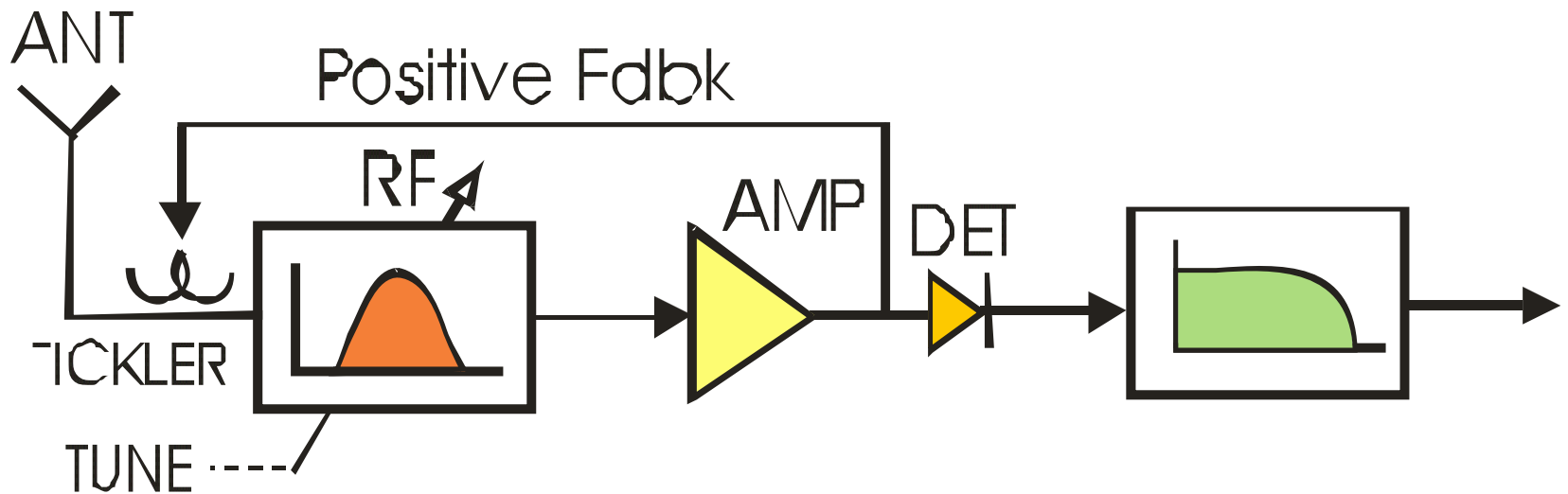
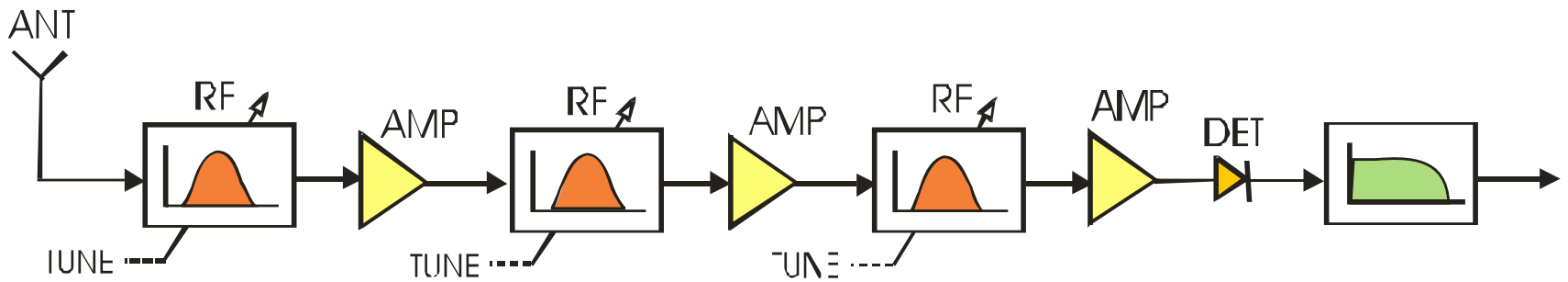
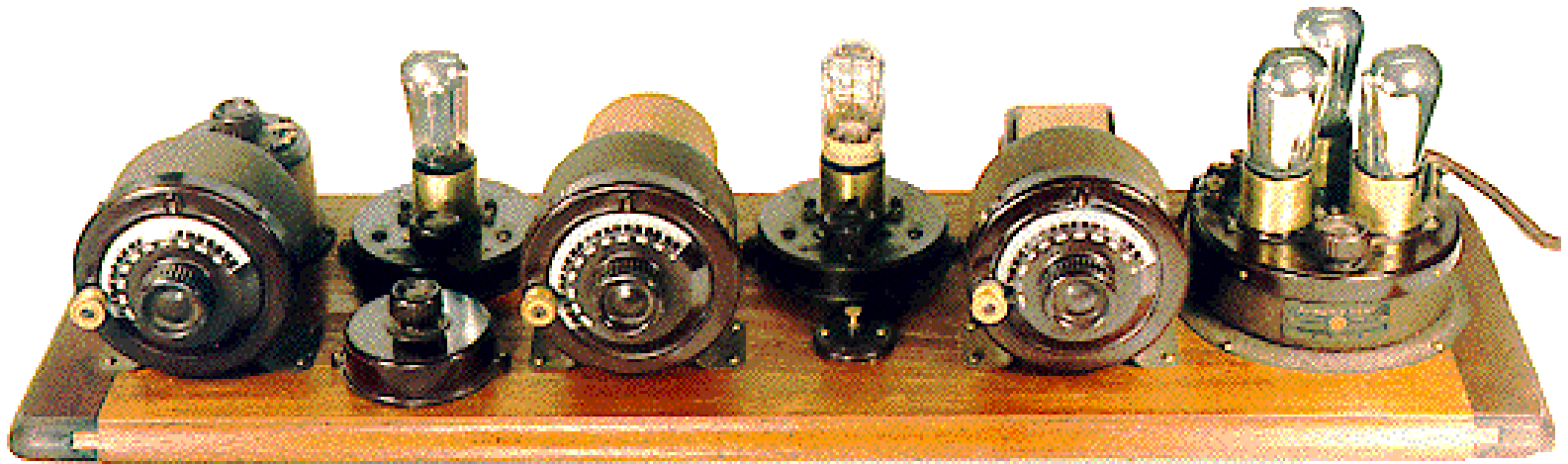


Fig. 1.

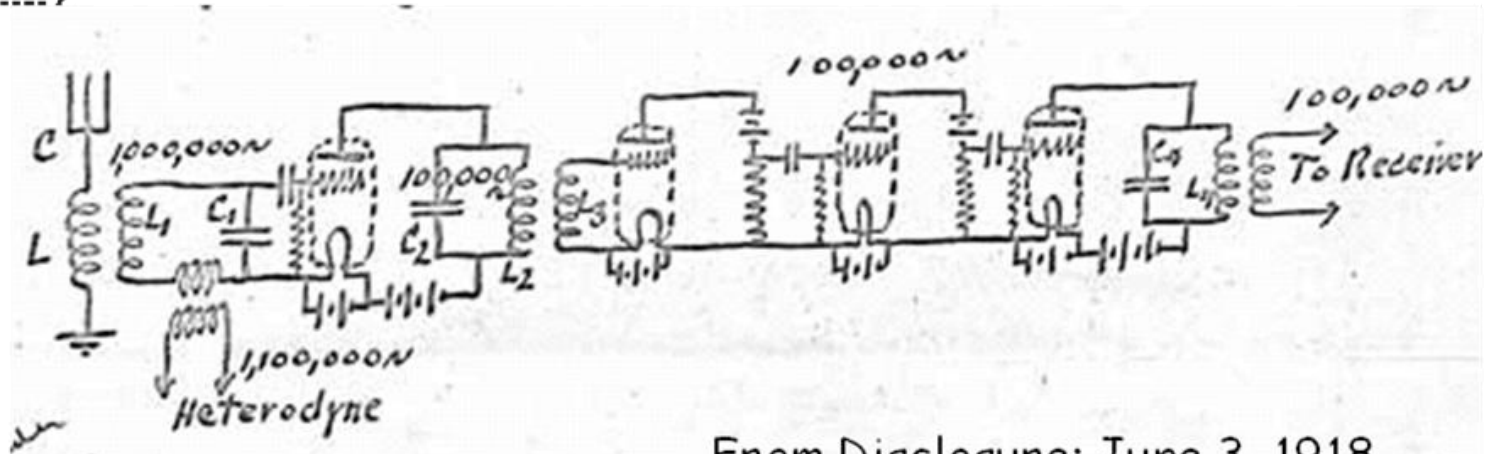
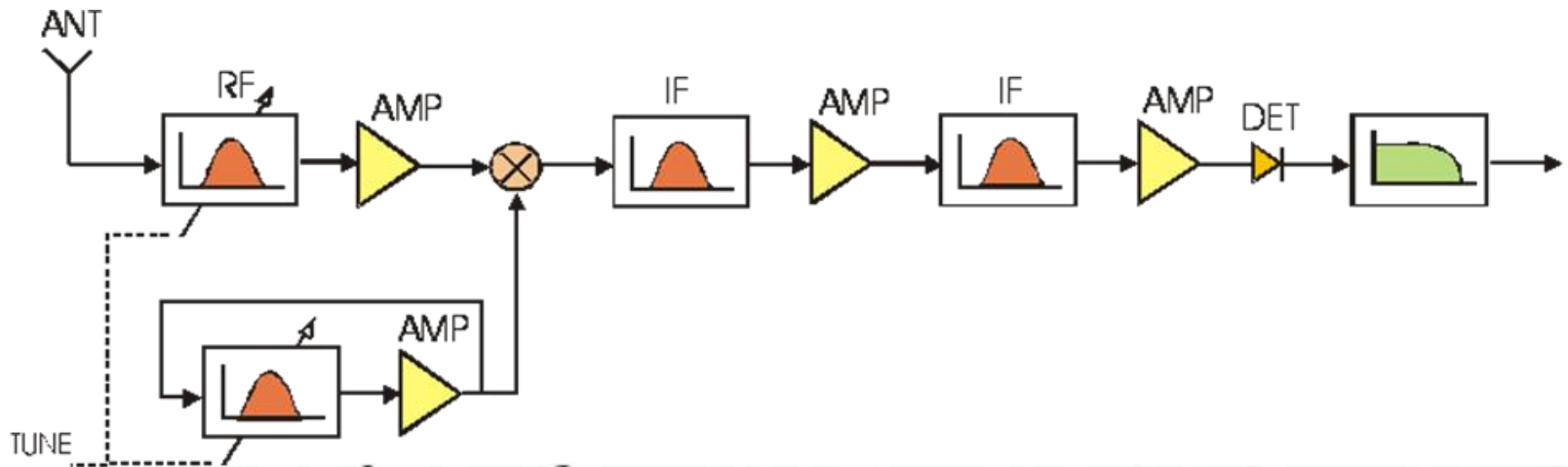
Regenerative Receiver: A Little Feedback Goes a Long Way



Tuned RF (TRF) Radio



Edwin Armstrong's Super Heterodyne Receiver



From Disclosure: June 3, 1918

Vacuum Tube Replacement



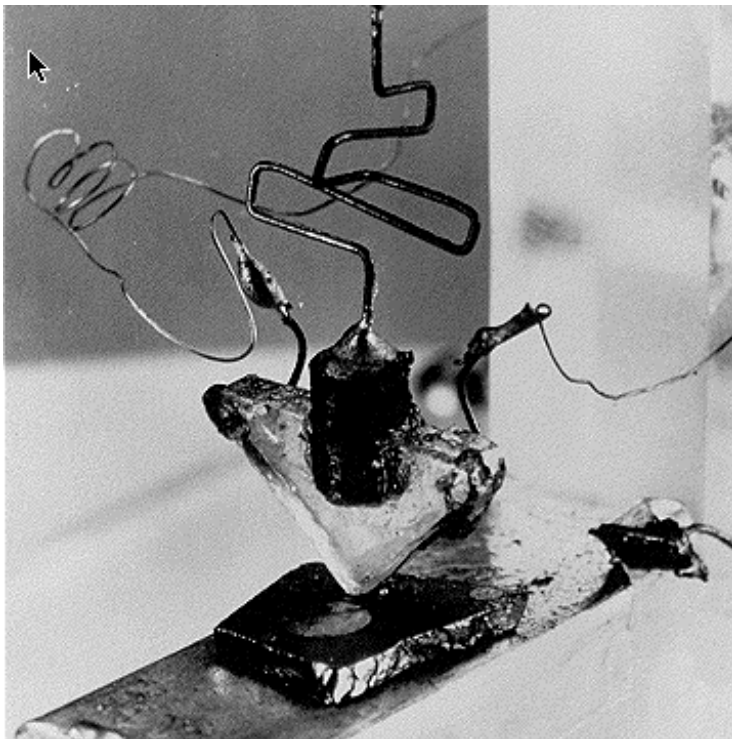
1947

Solid State Amplifier

John
Bardeen
1908-1991

Walter
Brattain
1902-1987

William
Shockley
1910-1989



Noble Prize 1956

Integrated Circuits

1958

Jack Kilby
TI



1923-2005

Noble Prize 2000



Robert Noyce,
Intel

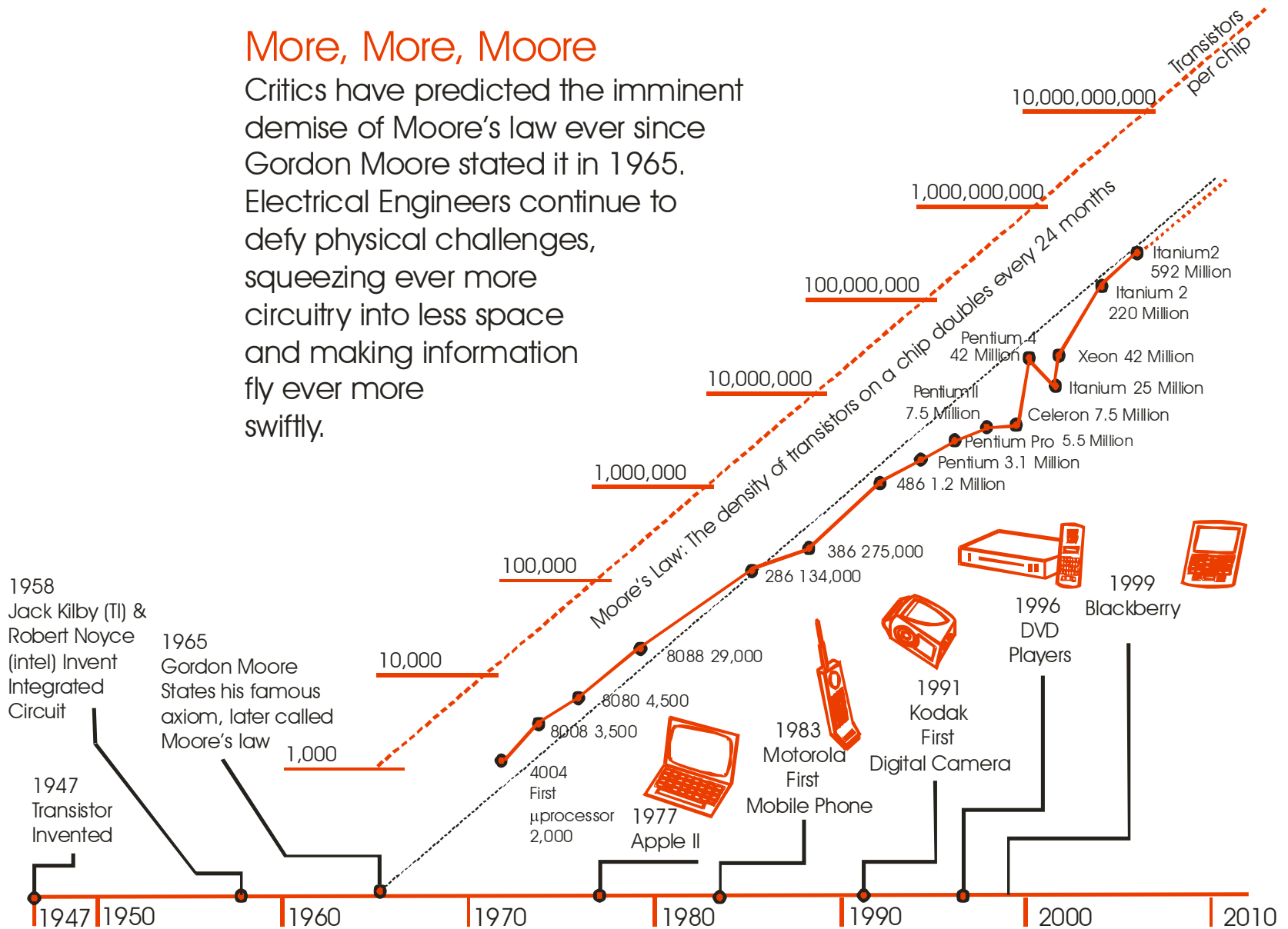


1928-1990

Noyce Founded Intel
Ted Hoff worked for Noyce

More, More, Moore

Critics have predicted the imminent demise of Moore's law ever since Gordon Moore stated it in 1965. Electrical Engineers continue to defy physical challenges, squeezing ever more circuitry into less space and making information fly ever more swiftly.



We all own a billion Transistors

We have an amazing wealth of
resources at our disposal!

Just how big is a Billion?

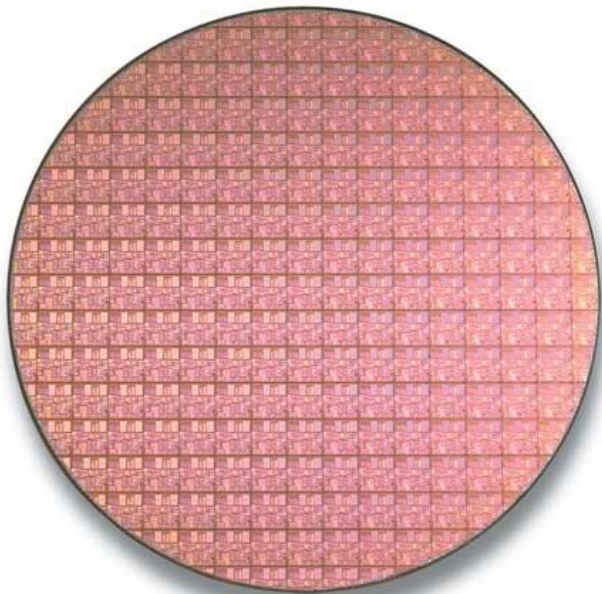
A stack of a billion bank notes would be
76.2 kilometers High.

A billion seconds is 32.5 years!

For Comparison, the Eiffel Tower
Contains 18,084 Parts. It is
Fastened Together by 2.5 Million Rivets



The world manufactures more transistors than it grows grains of rice.



0.13-micron, Intel Pentium 4
300-mm silicon wafer.

Wow!

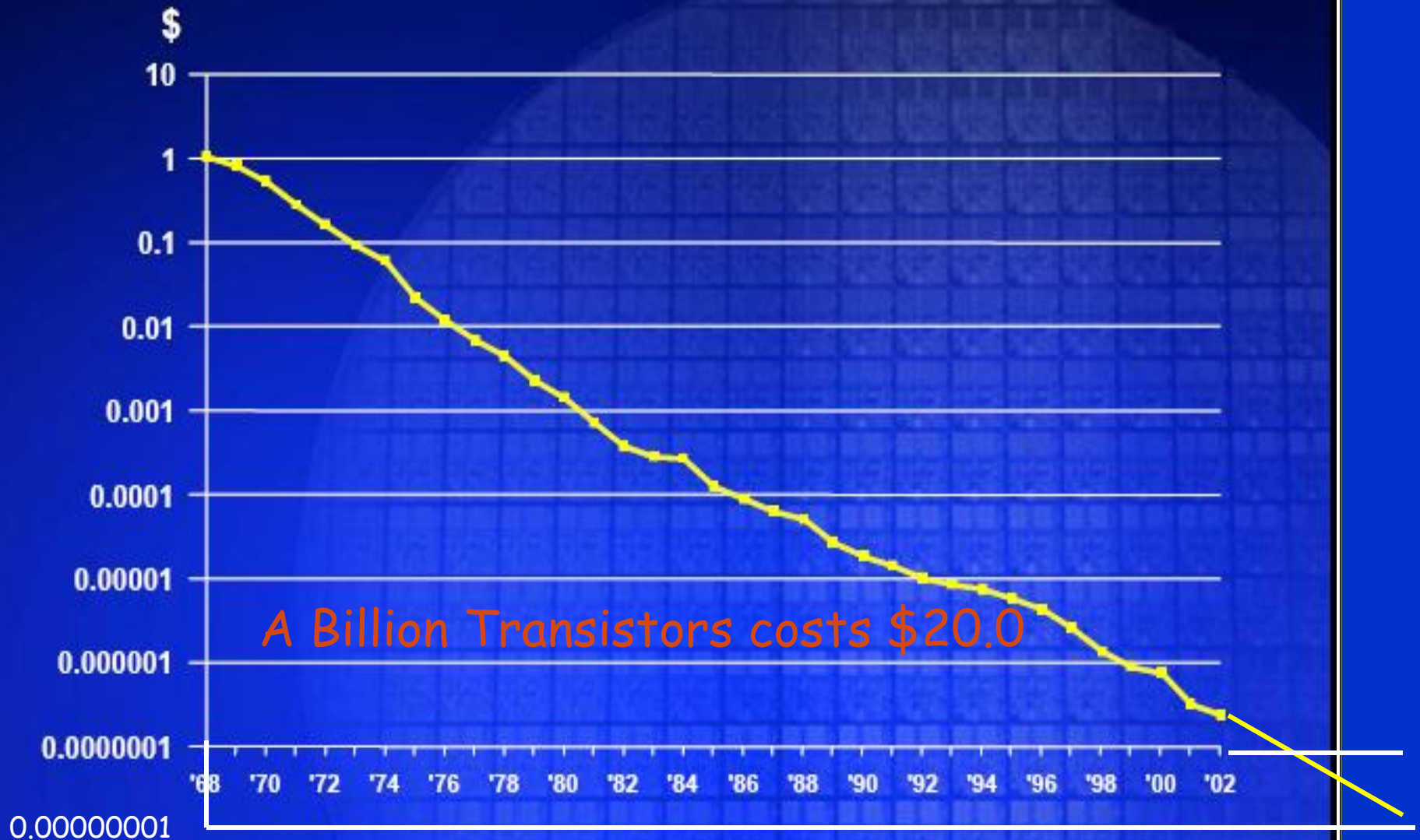


Long Grain Jasmine Rice

How big is a billion grains of rice?

- 8mm x 2mm x 2mm (Long Grain)
- 1-billion grains of rice
- 8 Meters x 2 Meters x 2 Meters
- Or 32 Cubic Meters
- Or a cube 3.2 Meters on a side
- It weighs 24,000 kg (26.6 tons)
- It costs \$26,000 (3-rd week April 2008)
- CLS-350 Mercedes Benz weighs 2,200 kg

Average Transistor Price By Year





TO LAPTOP OR NOTEBOOK
COMPUTER...



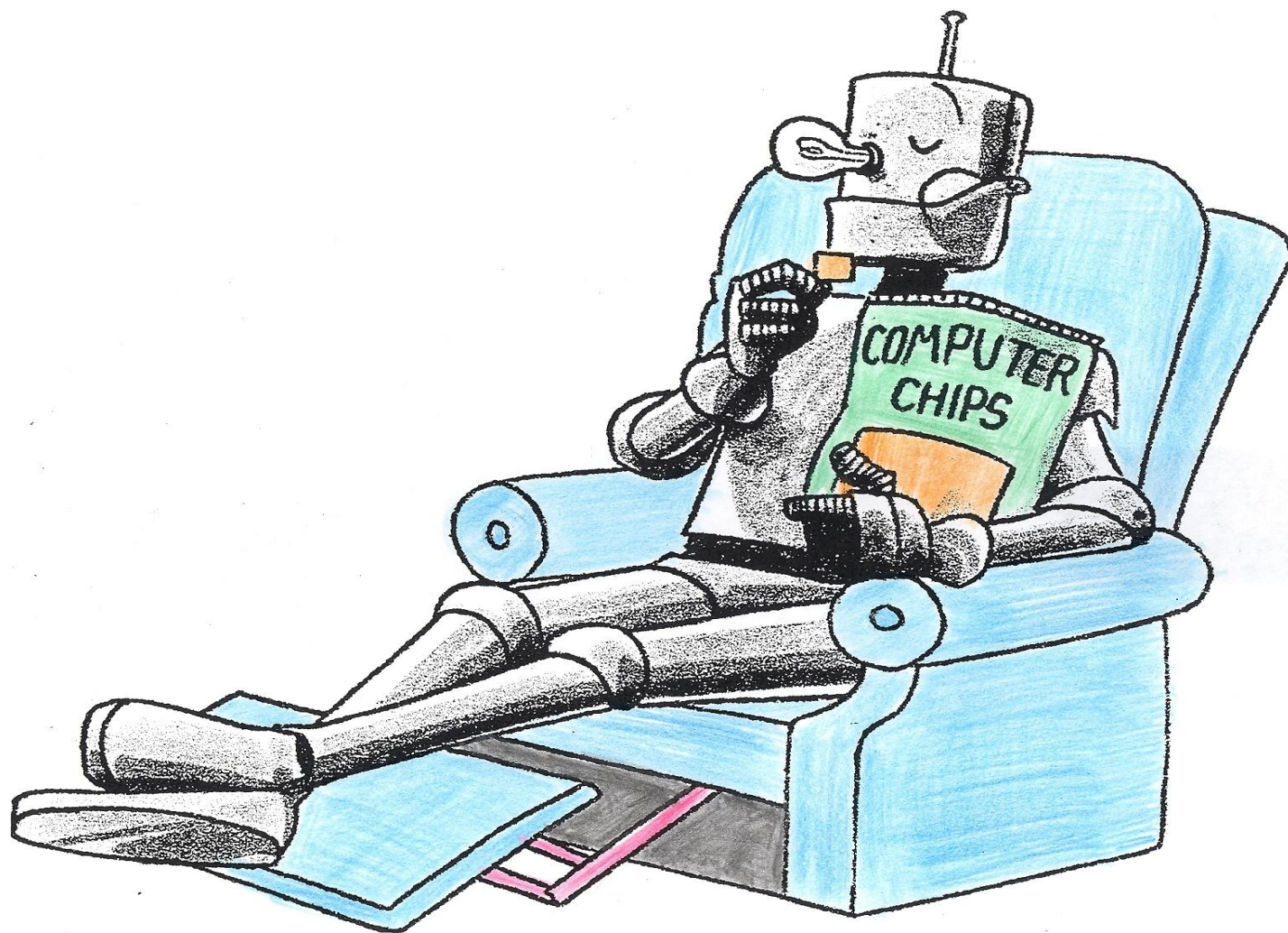


AND IN THE
NOT-TOO-DISTANT
FUTURE...



Adam @ Home
Brian Basset

It's all done with Computer Chips

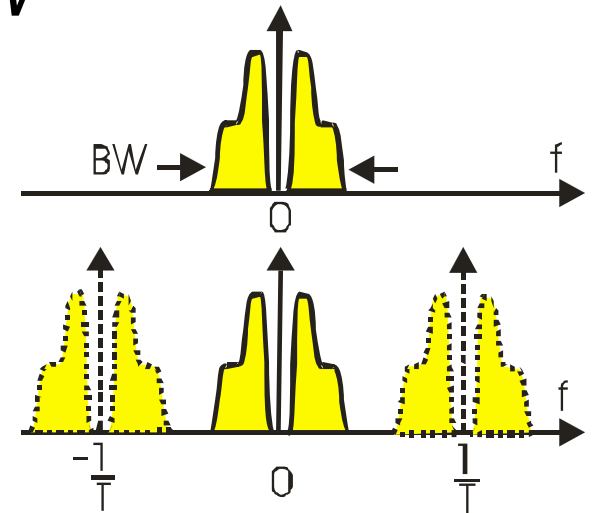
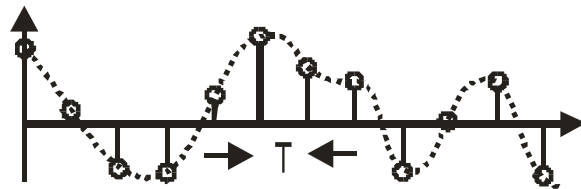
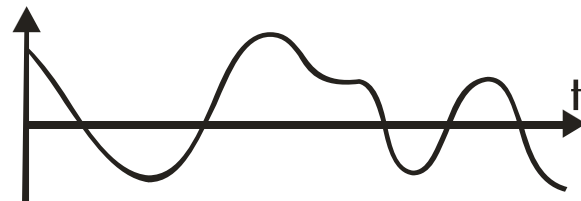


Harry Nyquist, (1889-1960)



The Sampling Theorem

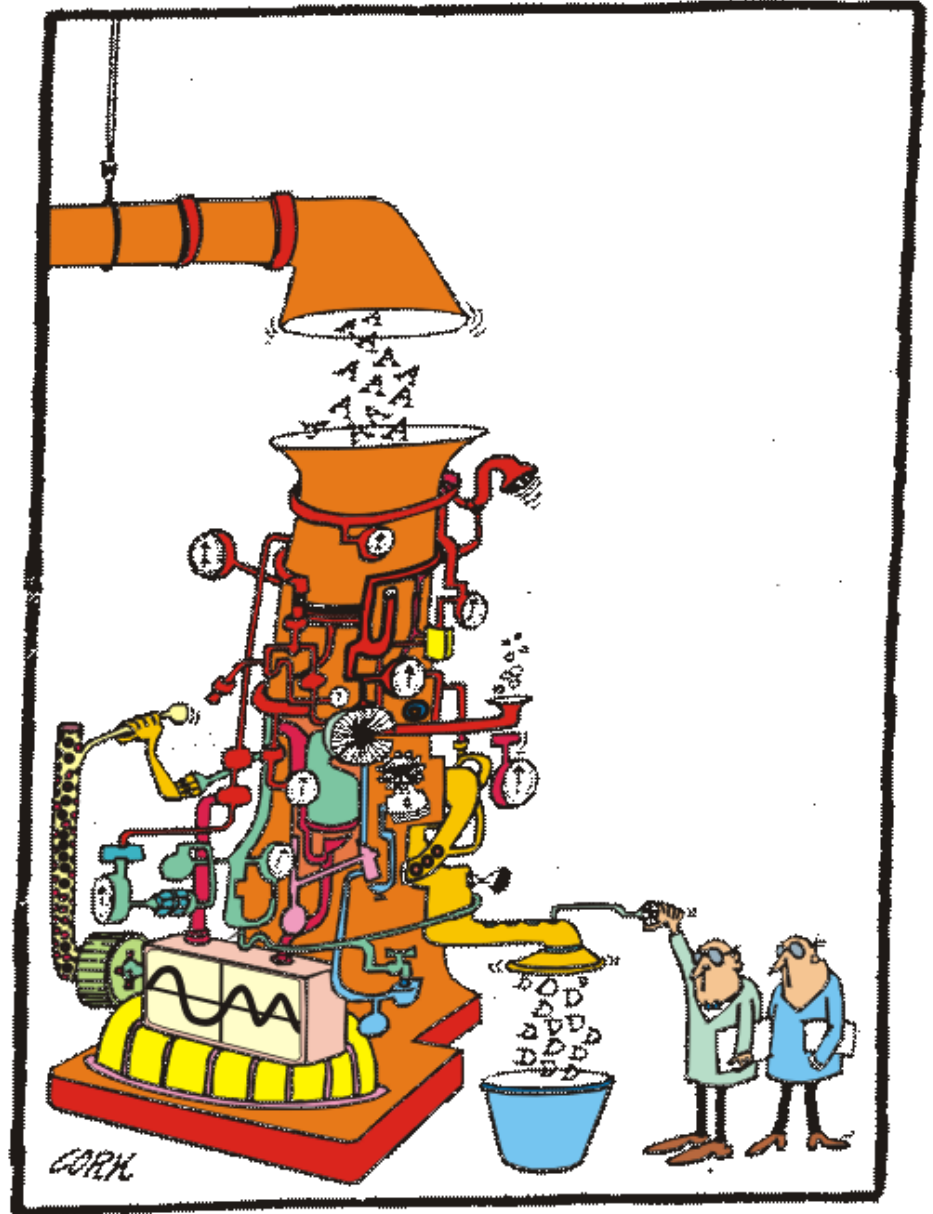
$$f_s > BW$$



Analog-to-Digital Converter

ADC

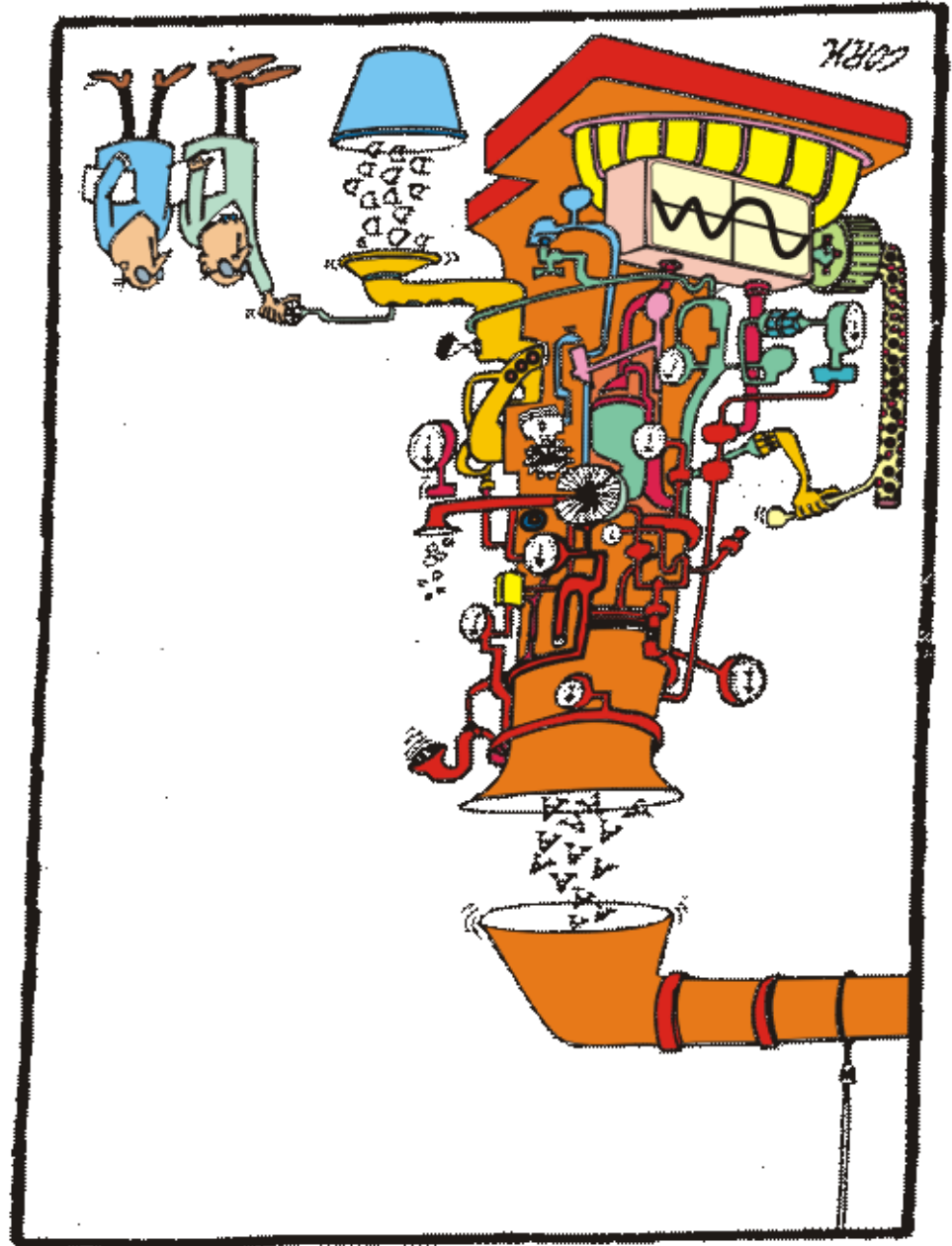
A-to-D



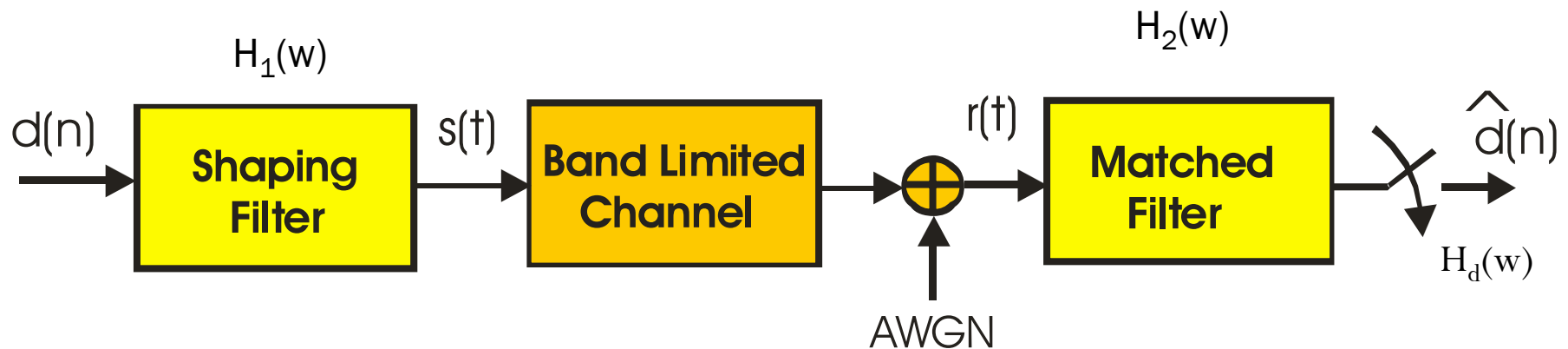
Digital-to-Analog Converter

DAC

D-to-A



Communication over Band Limited, AWGN Channel



$$H_2(\omega) = H_1^*(\omega) e^{j\omega\tau} \quad (\text{Maximize SNR})$$

$$H_d(\omega) = H_1(\omega) H_1^*(\omega) e^{j\omega\tau} = |H_1(\omega)|^2 e^{j\omega\tau}$$

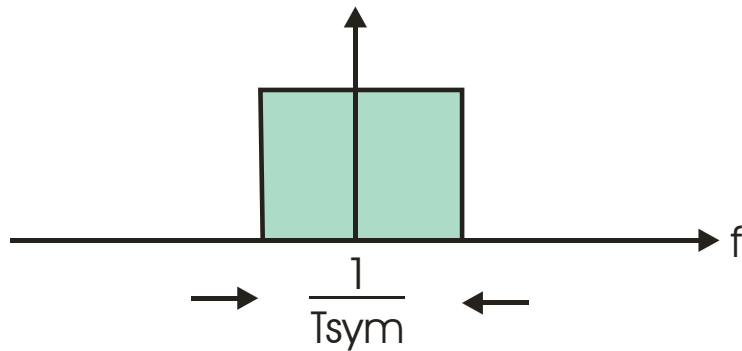
$$|H_1(\omega)|^2 e^{j\omega\tau} = H_{\text{NYQ}}(\omega) e^{j\omega\tau} \quad (\text{Zero ISI})$$

$$H_1(\omega) = \text{SQRT} \{H_{\text{NYQ}}(\omega)\}$$

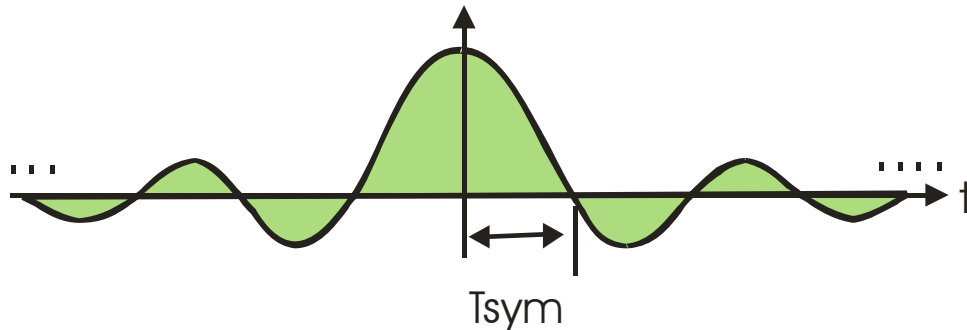
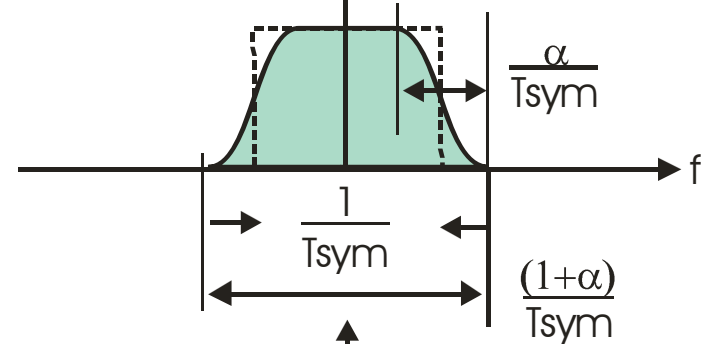
Band Limited Channel

Zero ISI and Causal Response

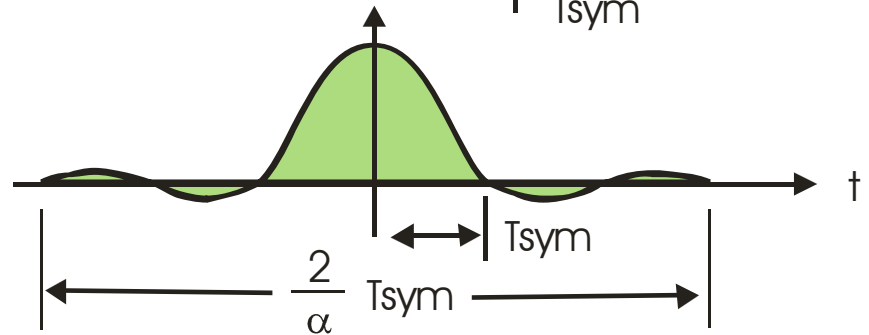
Nyquist Spectrum



Nyquist Spectrum With Cosine Taper



Infinite Duration
Nyquist Pulse



Finite Duration
Nyquist Pulse

It's not what you don't know
that gets you in trouble!

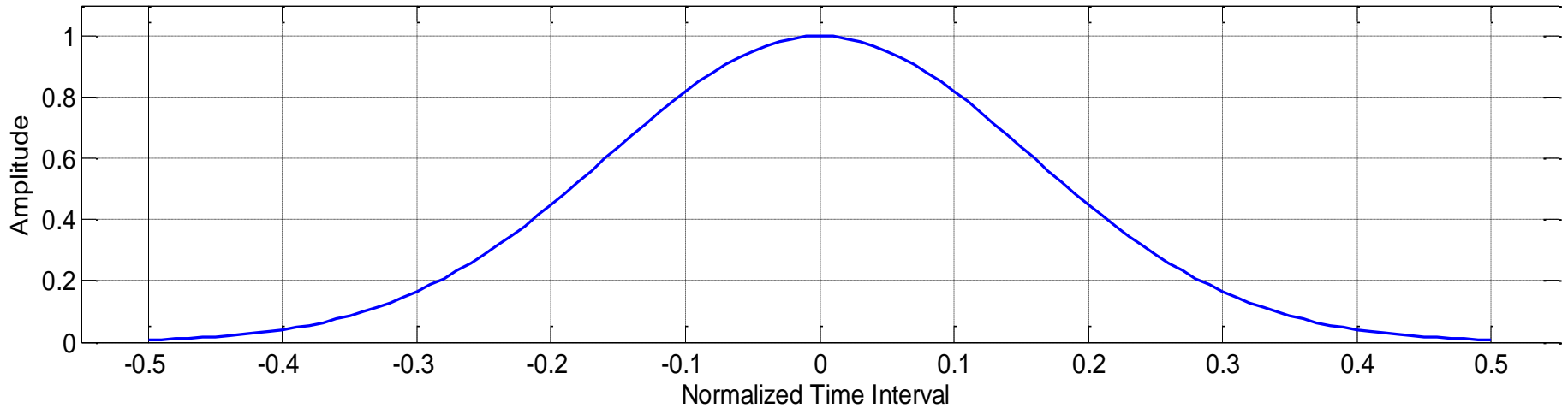
It's what you know for sure
to be true that just ain't so!

Samuel Clemens

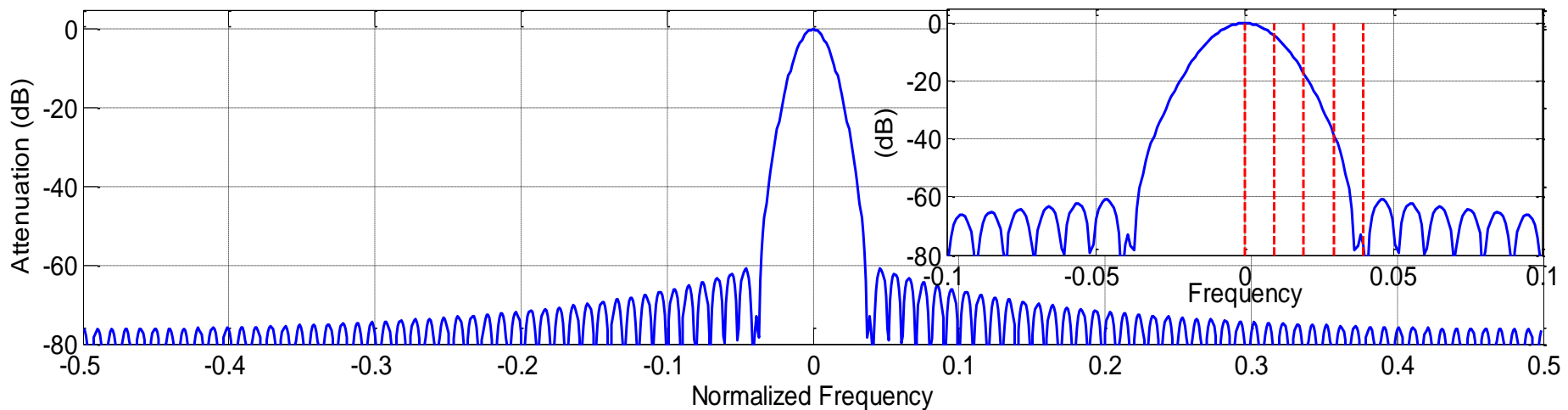
Spectral Resolution

Gaussian Window

Gaussian Window and Spectrum, Maximum Level Sidelobe -60 dB



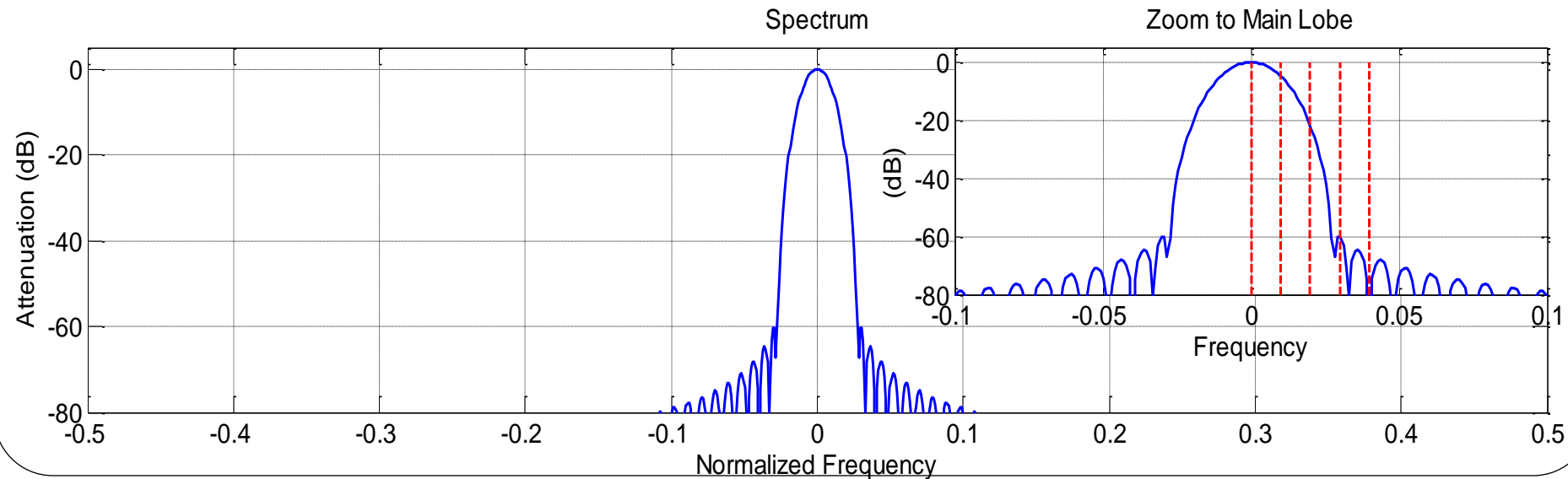
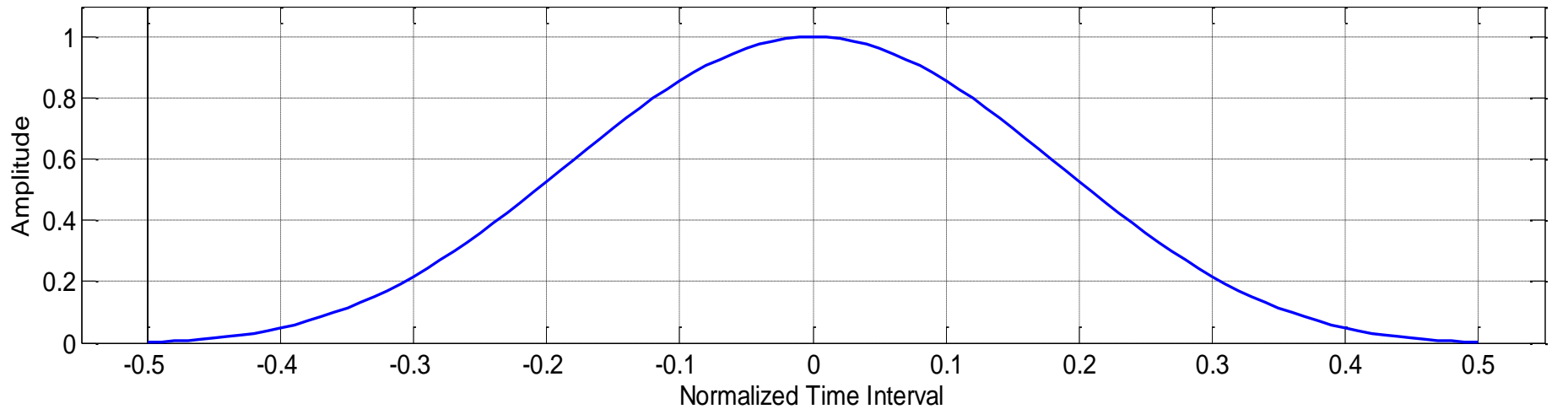
Zoom to Main Lobe



Spectral Resolution

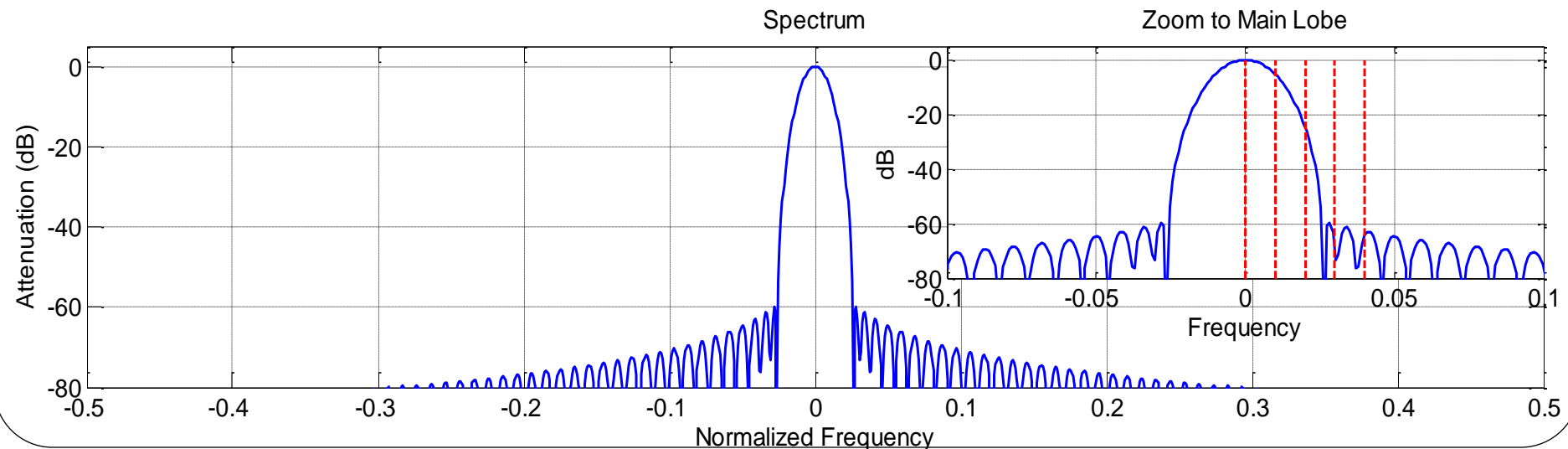
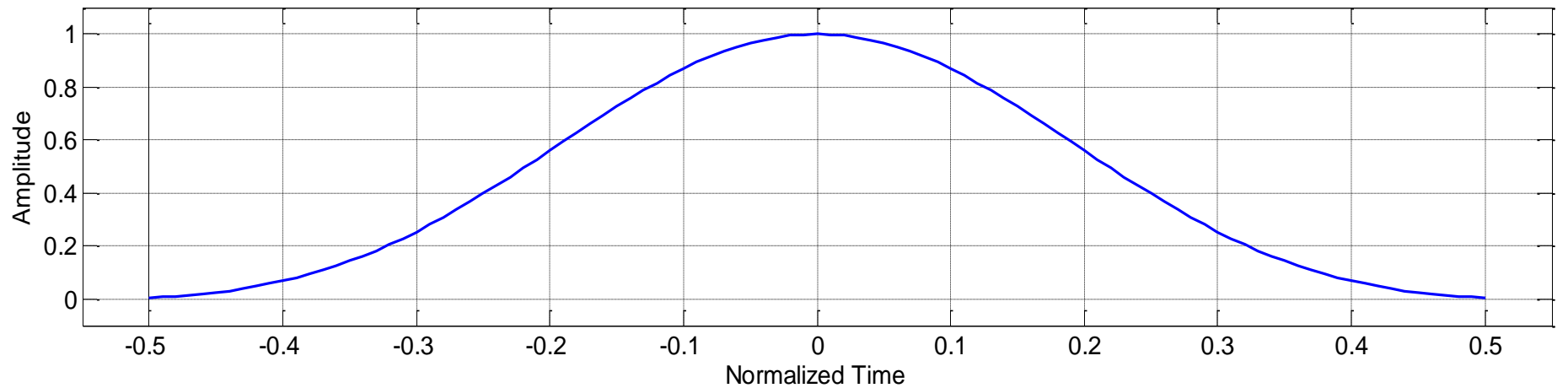
Kaiser-Bessel Window

Kaiser Window and Spectrum, Maximum Level Sidelobe -60 dB



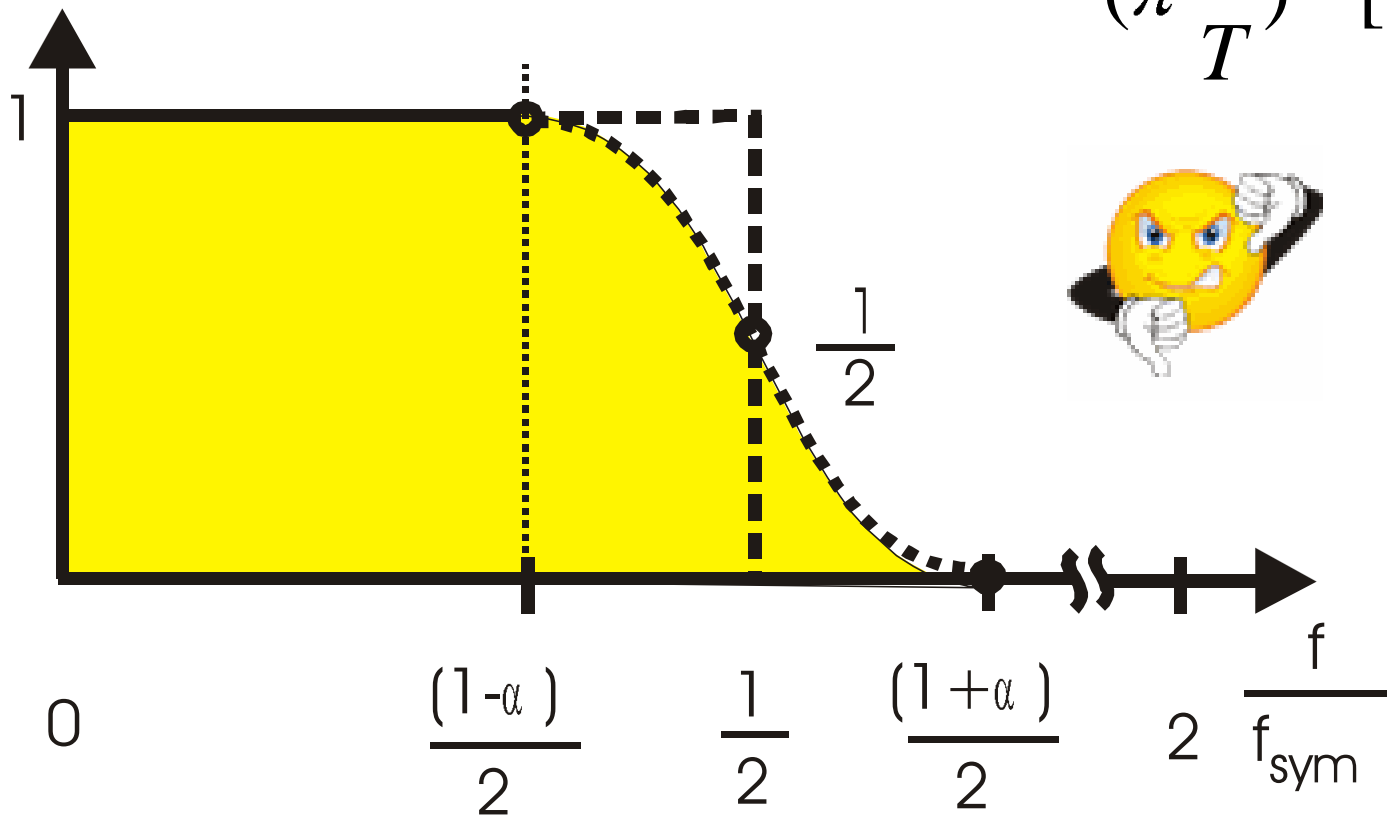
Spectral Resolution, Remez Minimum BW Window with -6-dB/Oct. Side Lobes

Remez Window and Spectrum, -6 dB/Octave, Maximum Level Sidelobe -60 dB

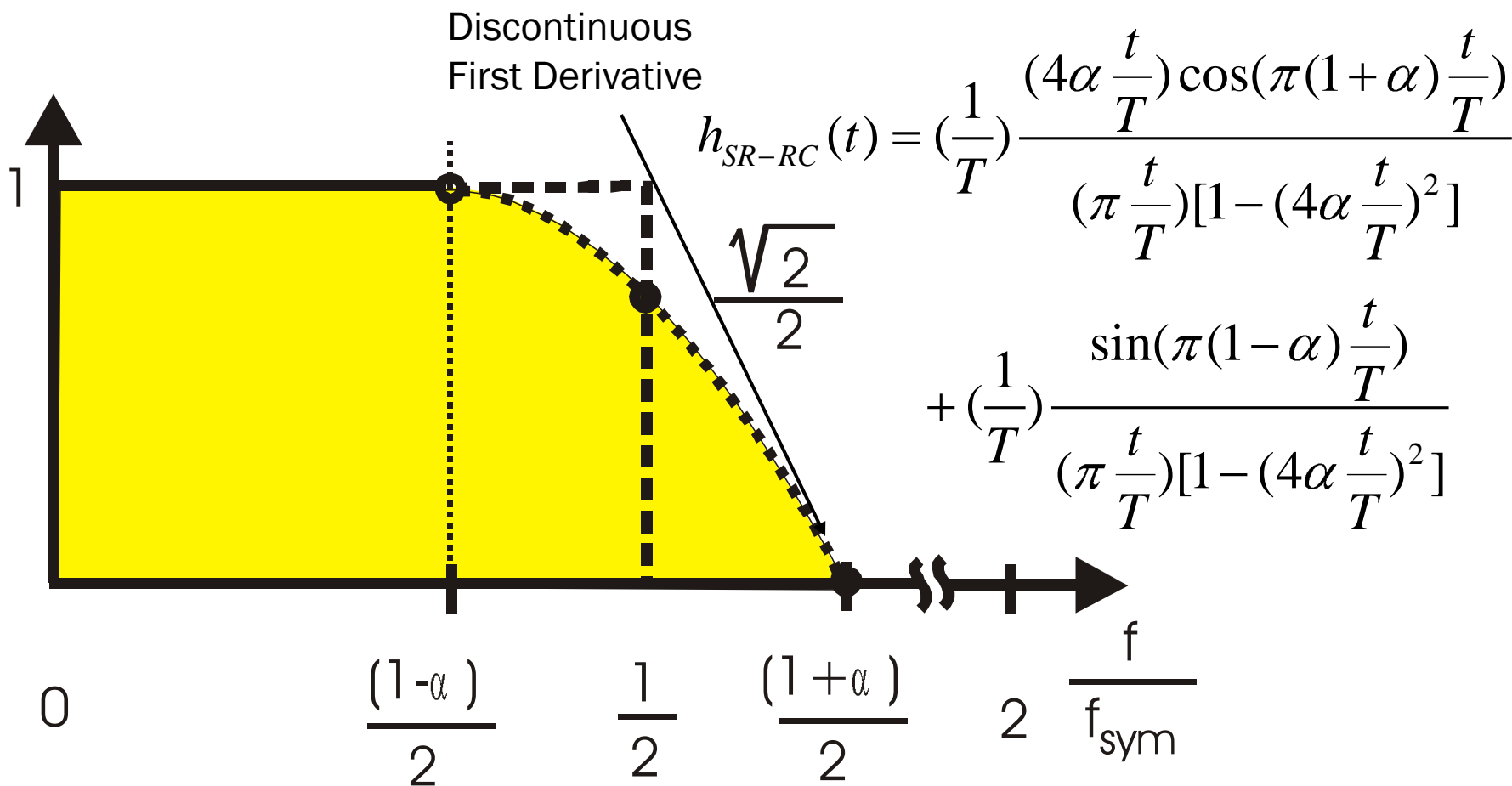


Cosine Tapered Nyquist Spectrum

$$h_{RC}(t) = \left(\frac{1}{T}\right) \frac{\sin\left(\pi \frac{t}{T}\right)}{\left(\pi \frac{t}{T}\right)} \frac{\cos\left(\pi \frac{\alpha}{T} t\right)}{\left[1 - \left(\frac{2\alpha}{T} t\right)^2\right]}$$



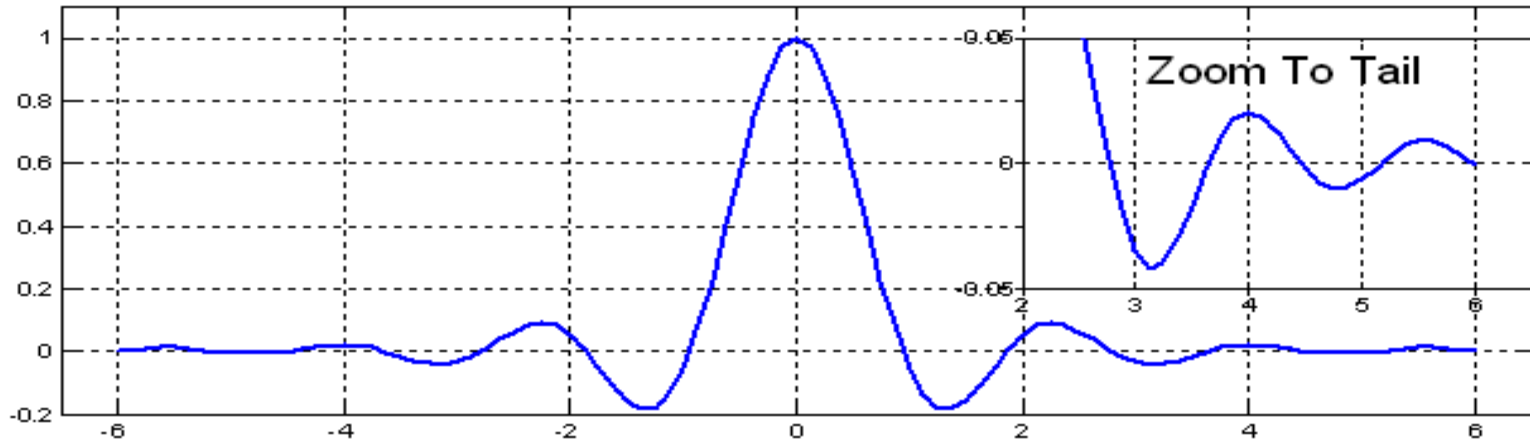
Square-Root Cosine Tapered Nyquist Filter



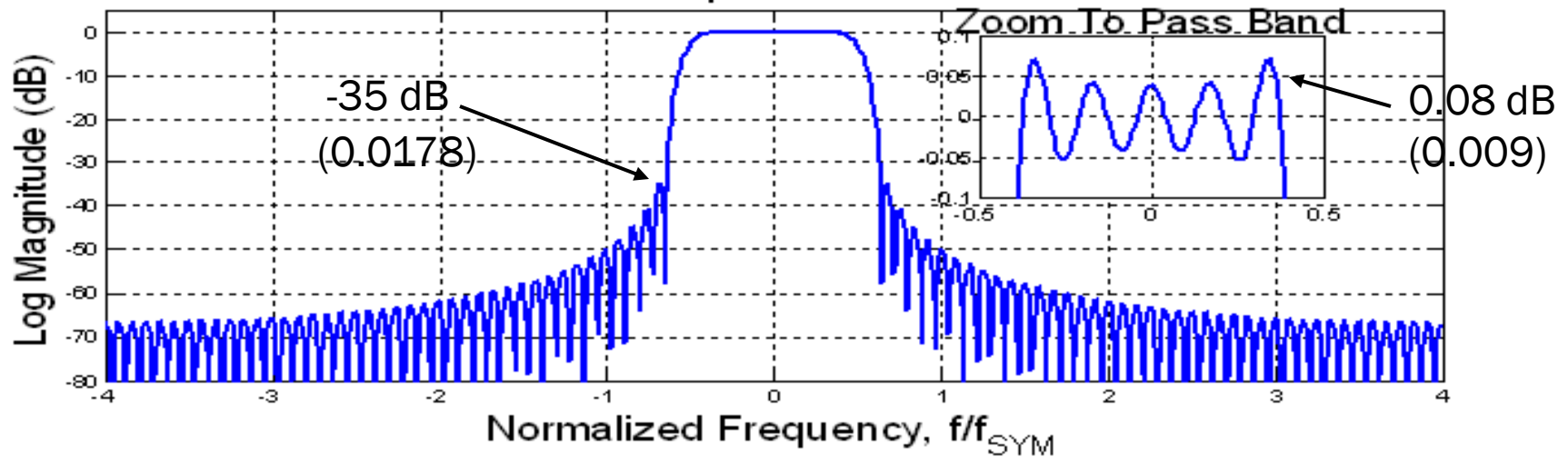
SQRT-RC Impulse Response

Finite Duration, Rectangle Window

Impulse Response SQRT-RC Filter

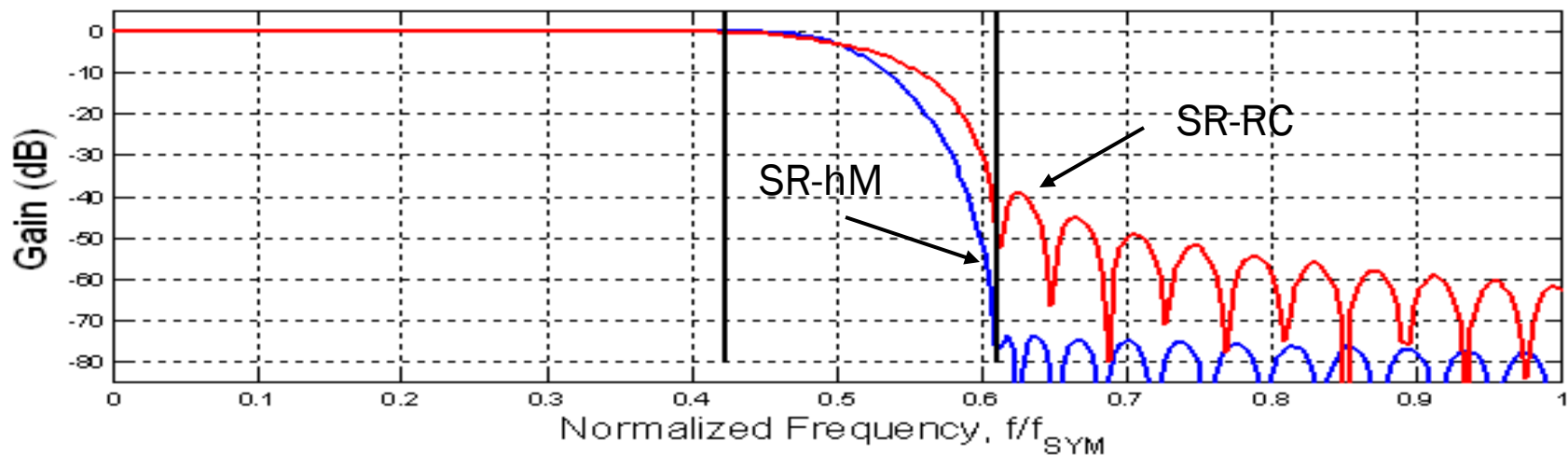


Spectrum

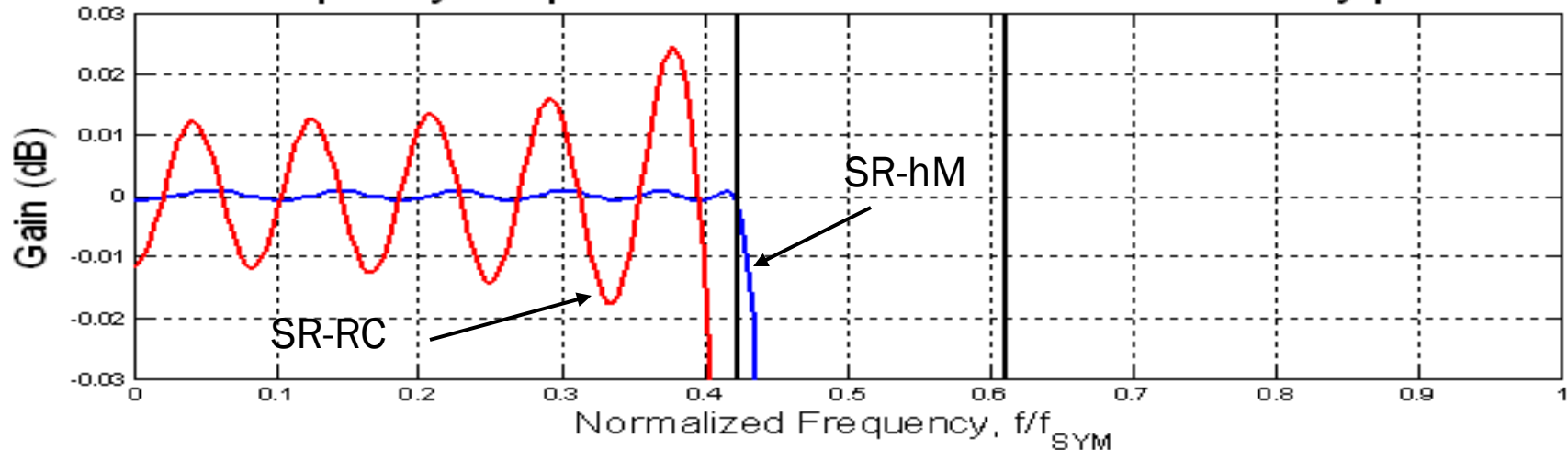


Spectra of SR-hM and SR-RC Nyquist Filter

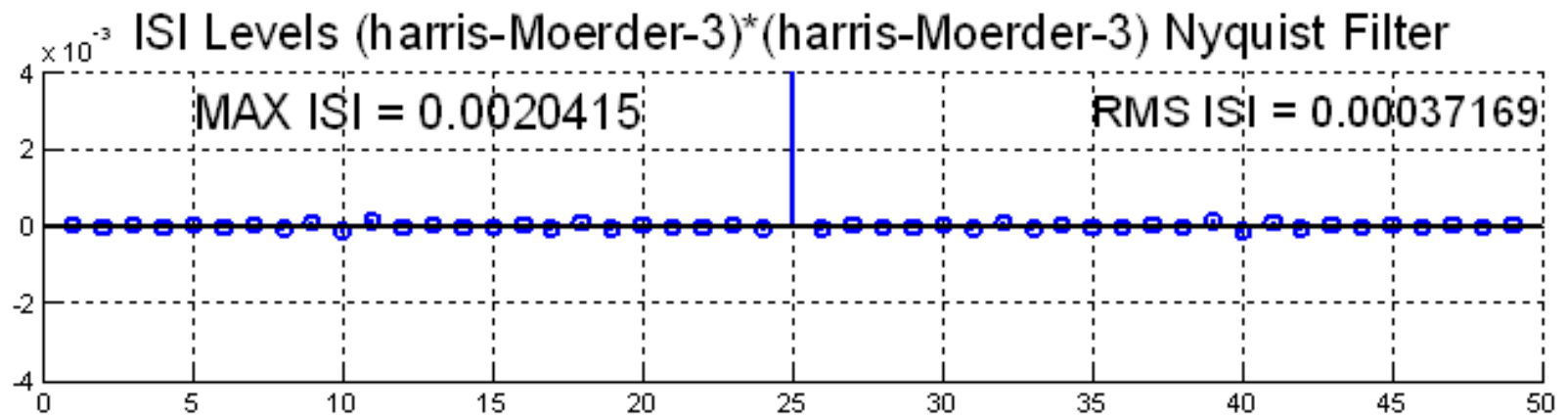
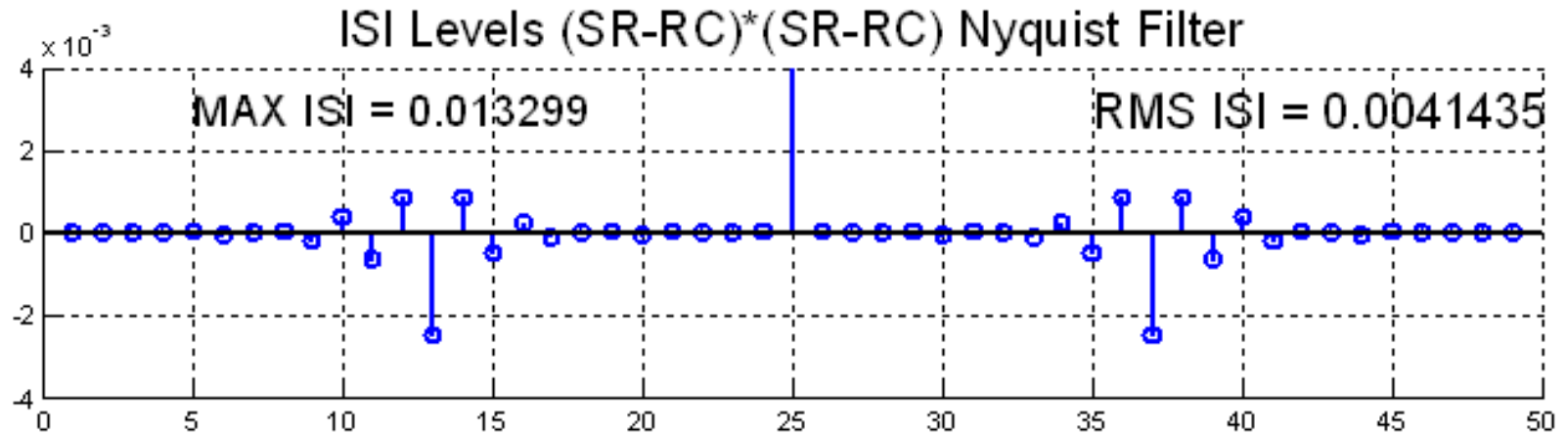
Frequency Response: harris-Moerder-3 and SR-RC Nyquist



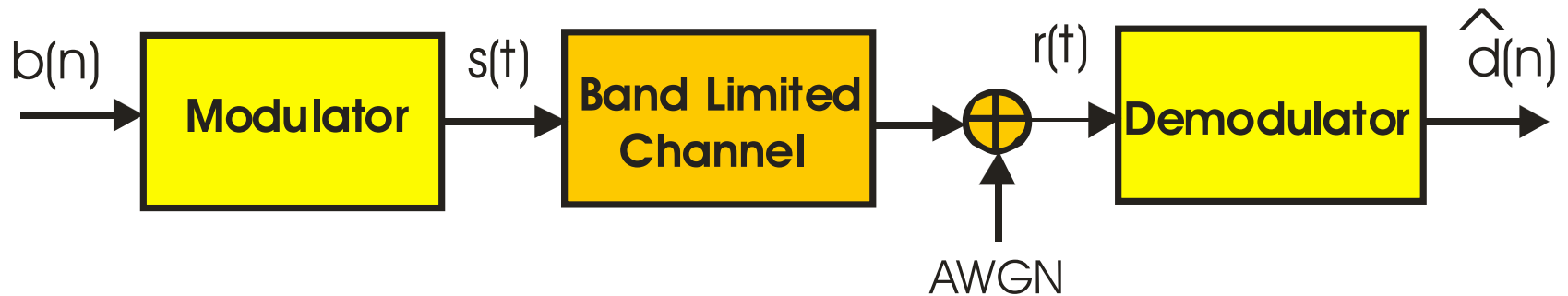
Frequency Response: harris-Moerder-3 and SR-RC Nyquist



ISI Levels: RC-RC and hM-hM



Transmitter and Receiver Modulator and Demodulator



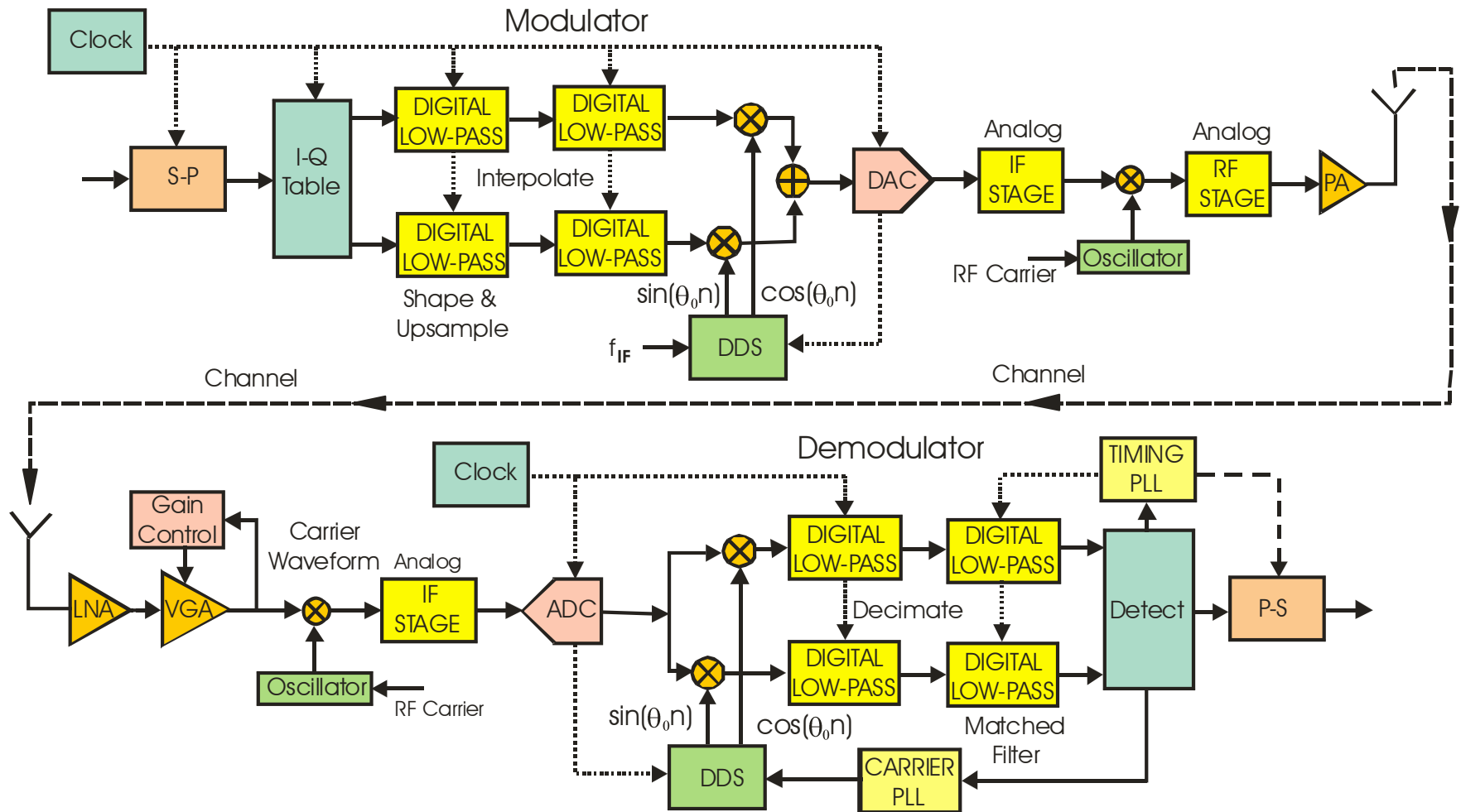
$$s(t) = \text{Re}\left\{ \left[\sum_k I_k g(t - kT) \right] e^{j\omega_c t} \right\}$$

$$= \text{Re}\left\{ R(t) e^{j\theta(t)} e^{j\omega_c t} \right\}$$

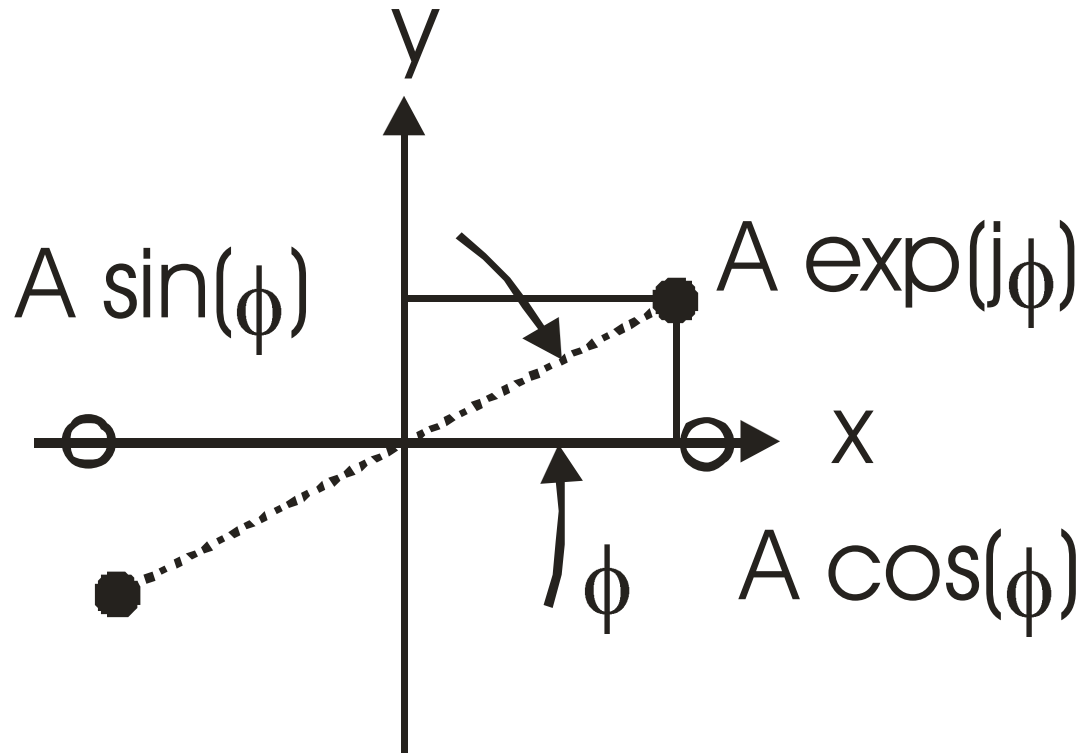
$$r(t) = \text{Re}\left\{ \left[A(t) * R(t - \tau) e^{j\theta(t - \tau)} \right] e^{j(\omega_c + \Delta\omega)(t - \tau)} \right\}$$

$$+ n(t) e^{j(\omega_c + \Delta\omega)t}$$

First Tier, Primary Signal Processing Tasks in a Typical Transmitter and Receiver



BPSK Phase Error

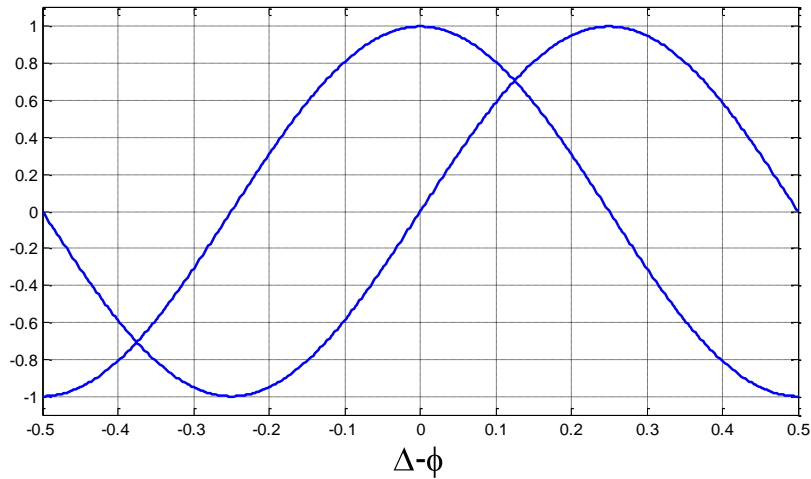


Consider $x(n) y(n)$

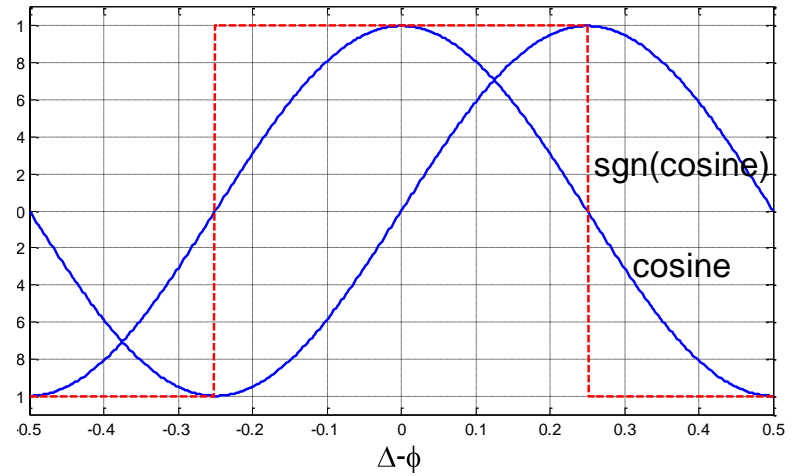
$$\begin{aligned} x(n) * y(n) &= A^2 \cos(\phi) * \sin(\phi) \\ &= \frac{A^2}{2} \sin(2\phi) \end{aligned}$$

Phase Detectors for Modulated BPSK

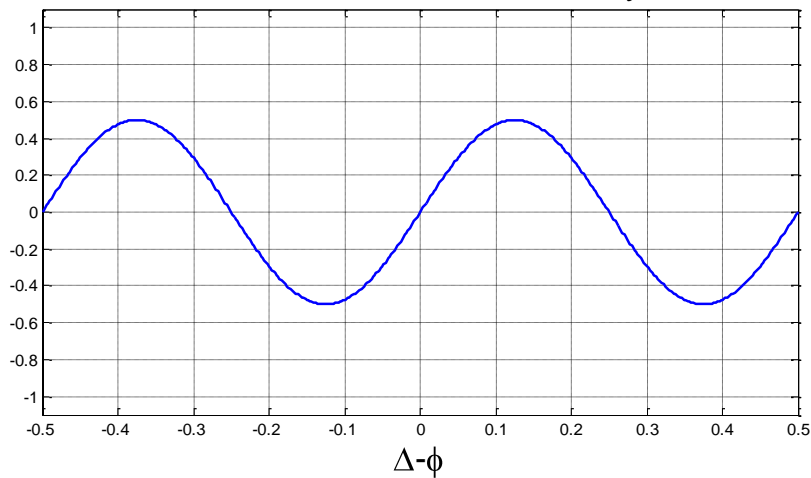
Inputs to Product Detector



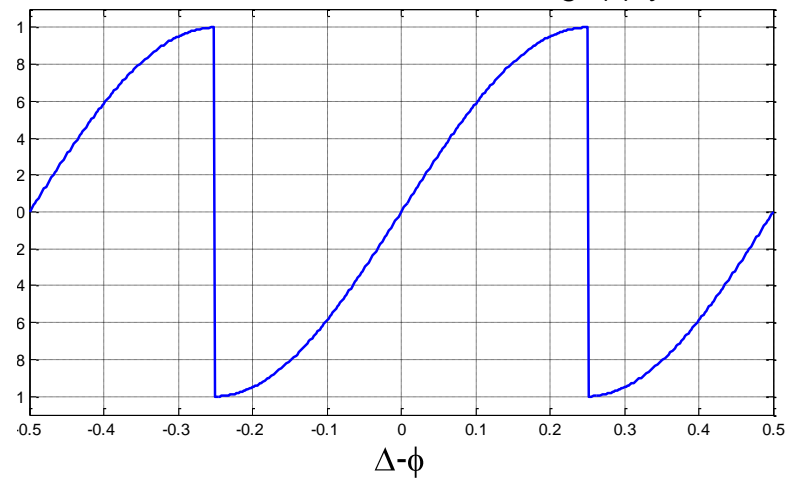
Inputs to Product Detector



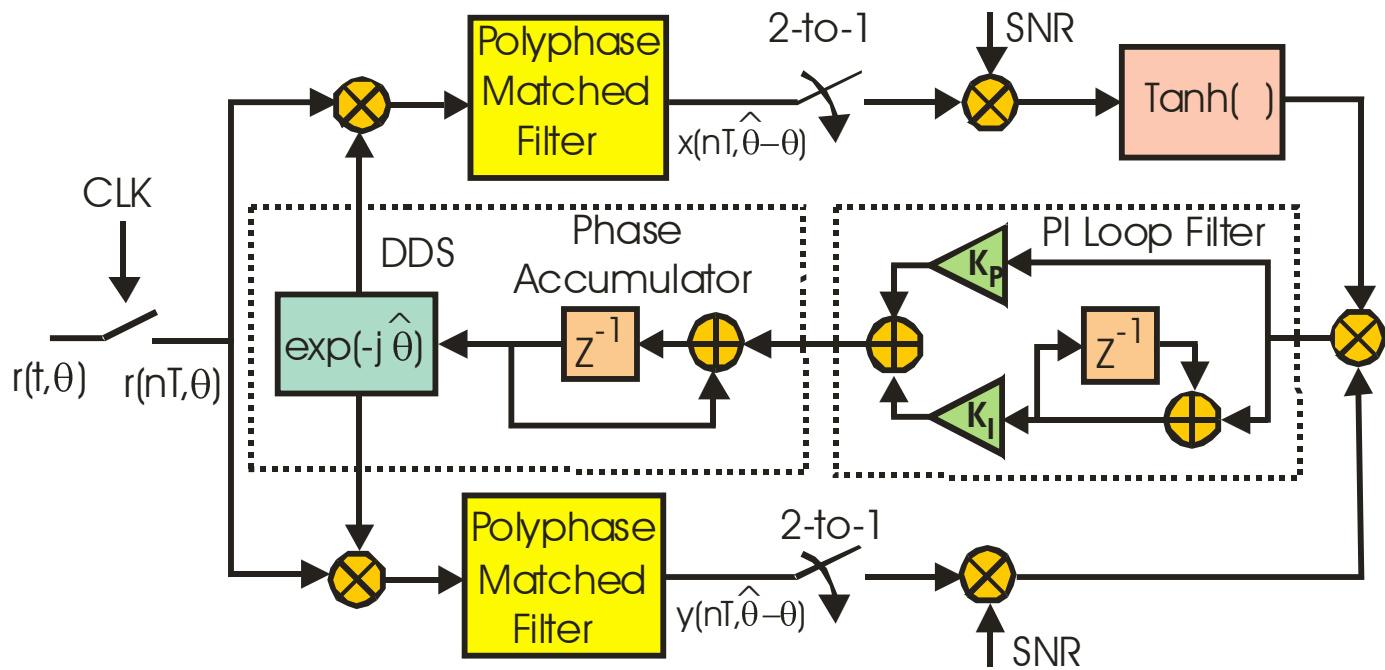
S-Curve Product detector $x*y$



S-Curve Product Detector $\text{sign}(x)*y$

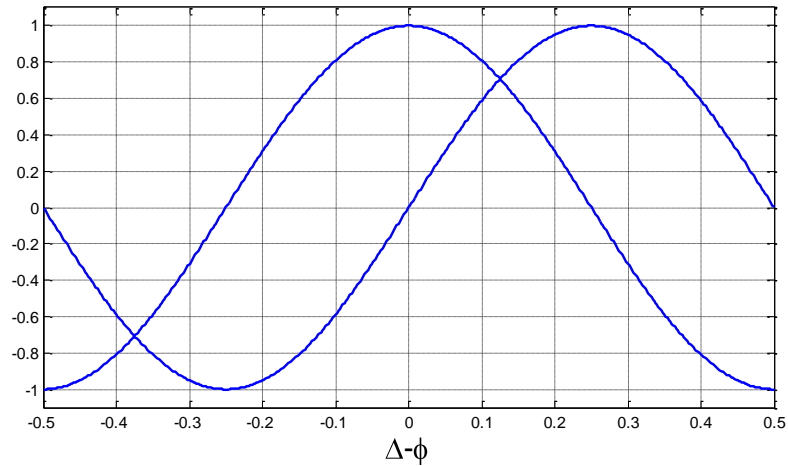


Second Tier Signal Processing Task, Carrier Recovery Phase Locked Loop

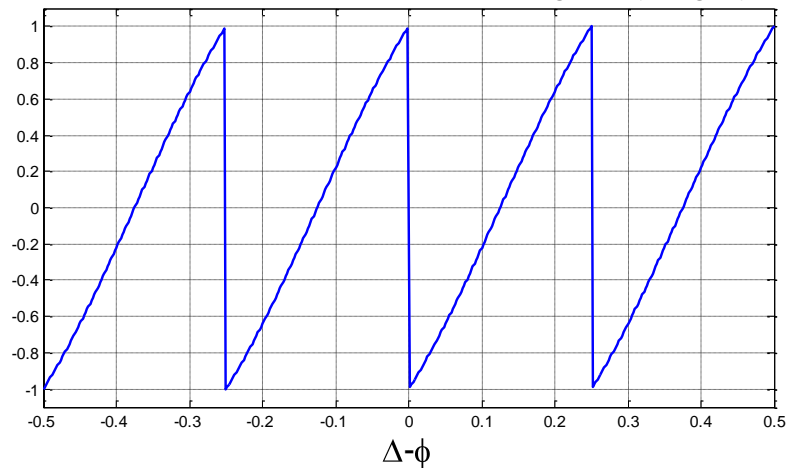


Phase Detectors for Modulated QPSK

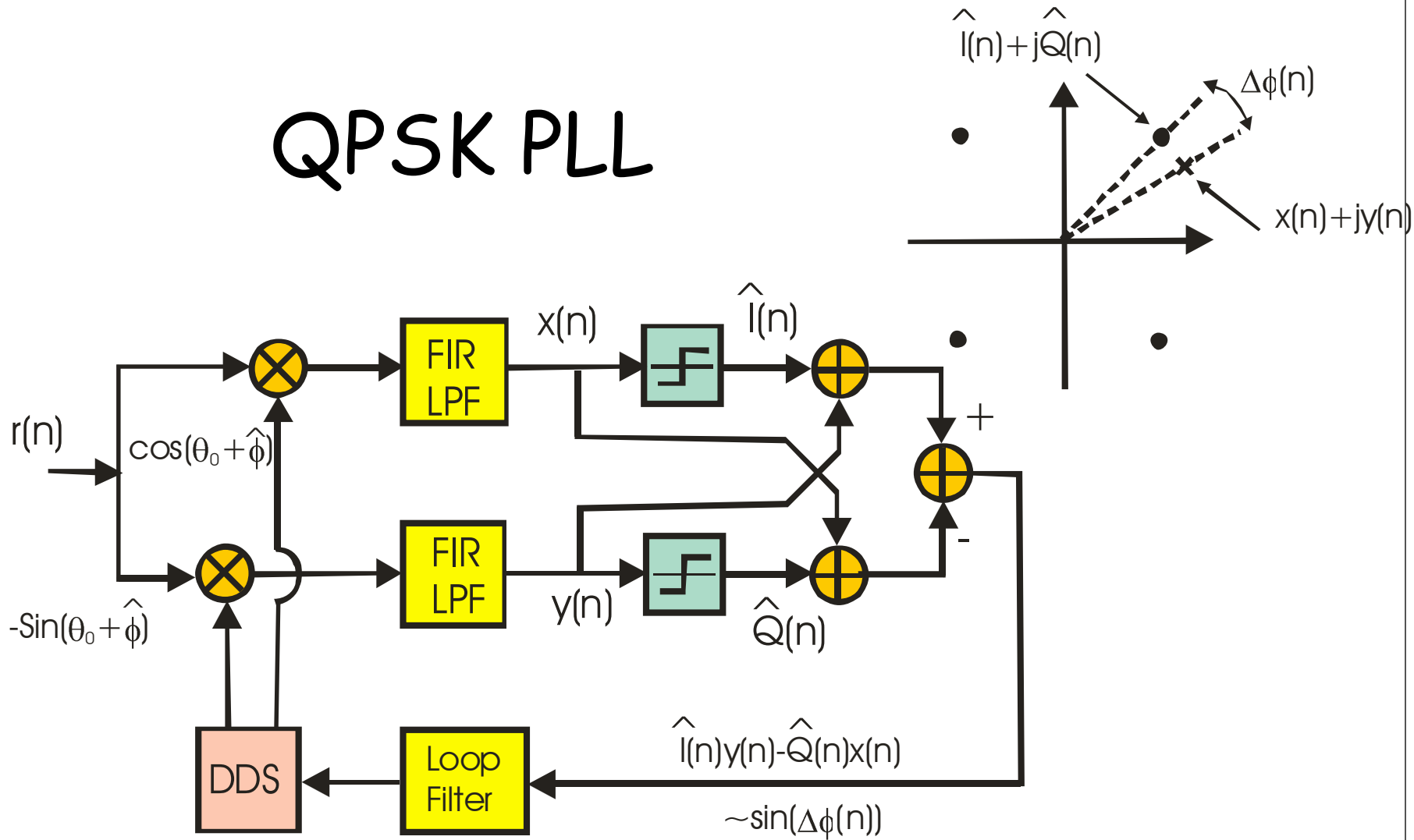
Inputs to Phase Detector



S-Curve Product Phase Detector: $\text{sign}(x)*y-\text{sign}(y)*x$

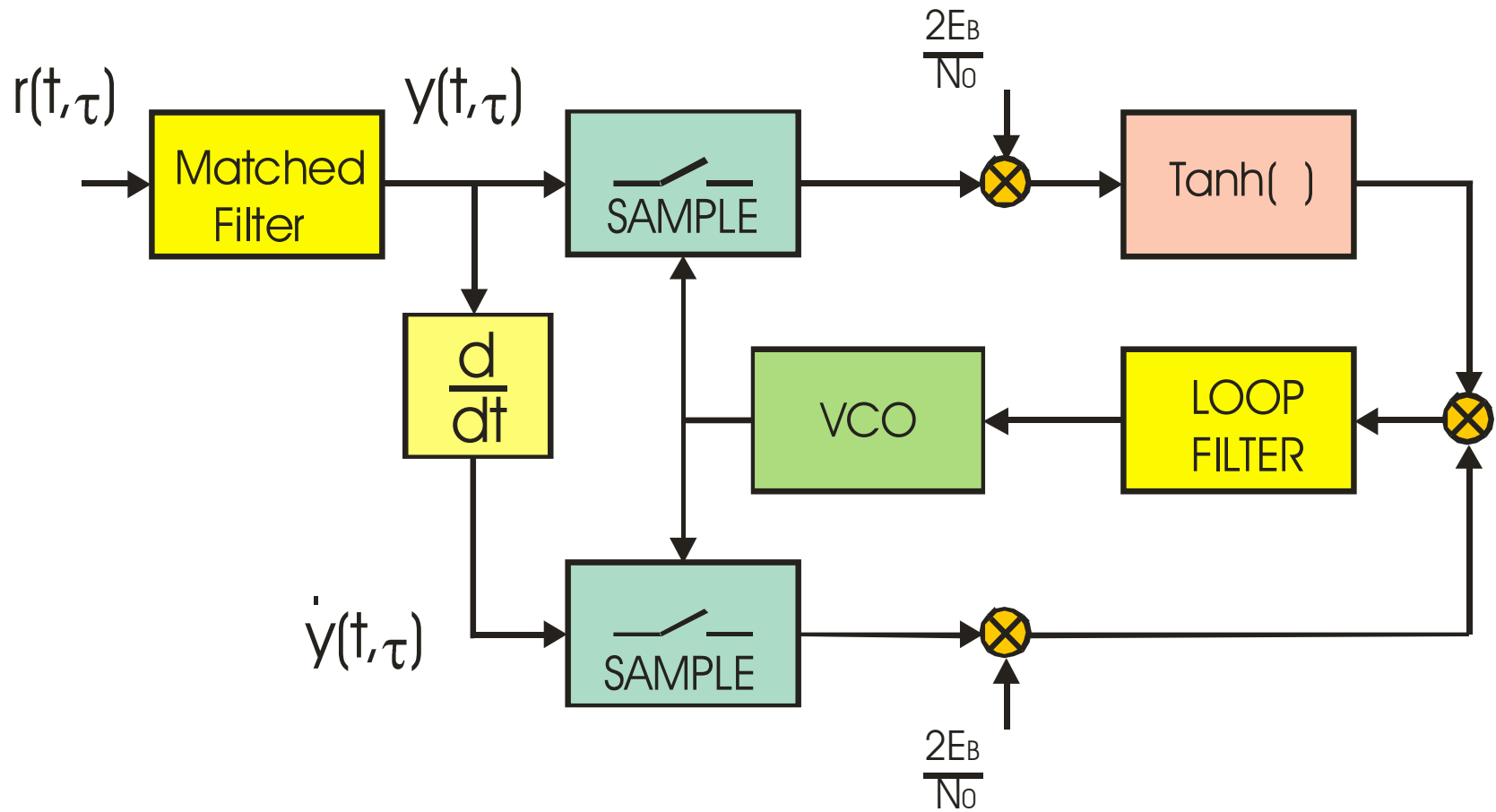


QPSK PLL

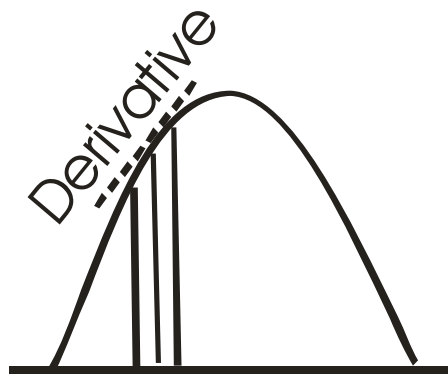


Direct Digital Synthesizer

Maximum Likelihood Timing Recovery



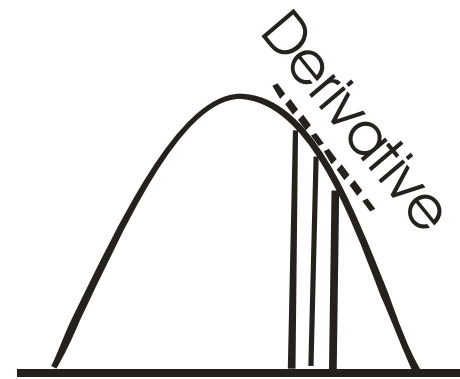
Derivative with Help of Nearby Neighbors (Early and Late)



Advance
Pointer

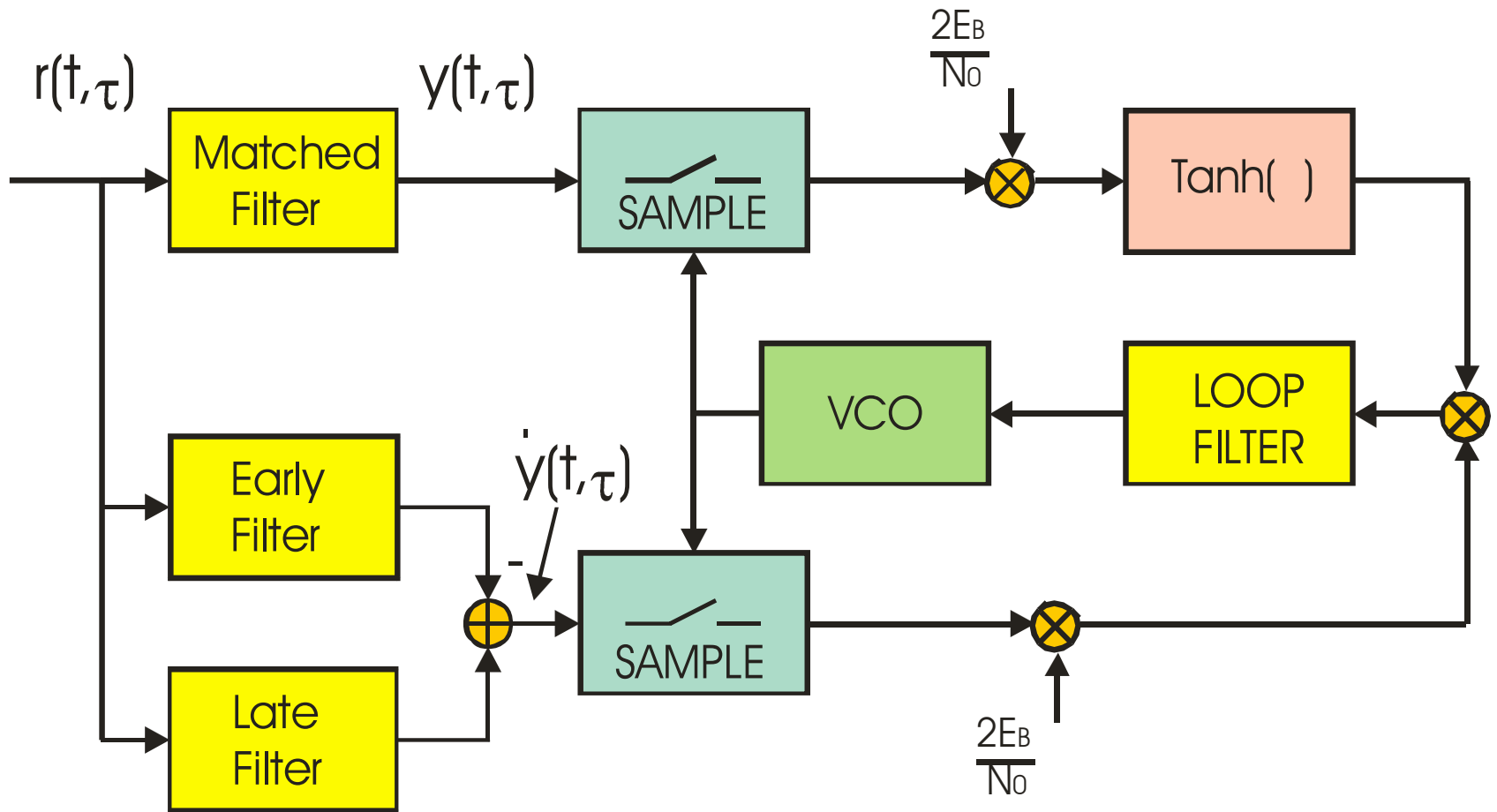


Hold
Pointer

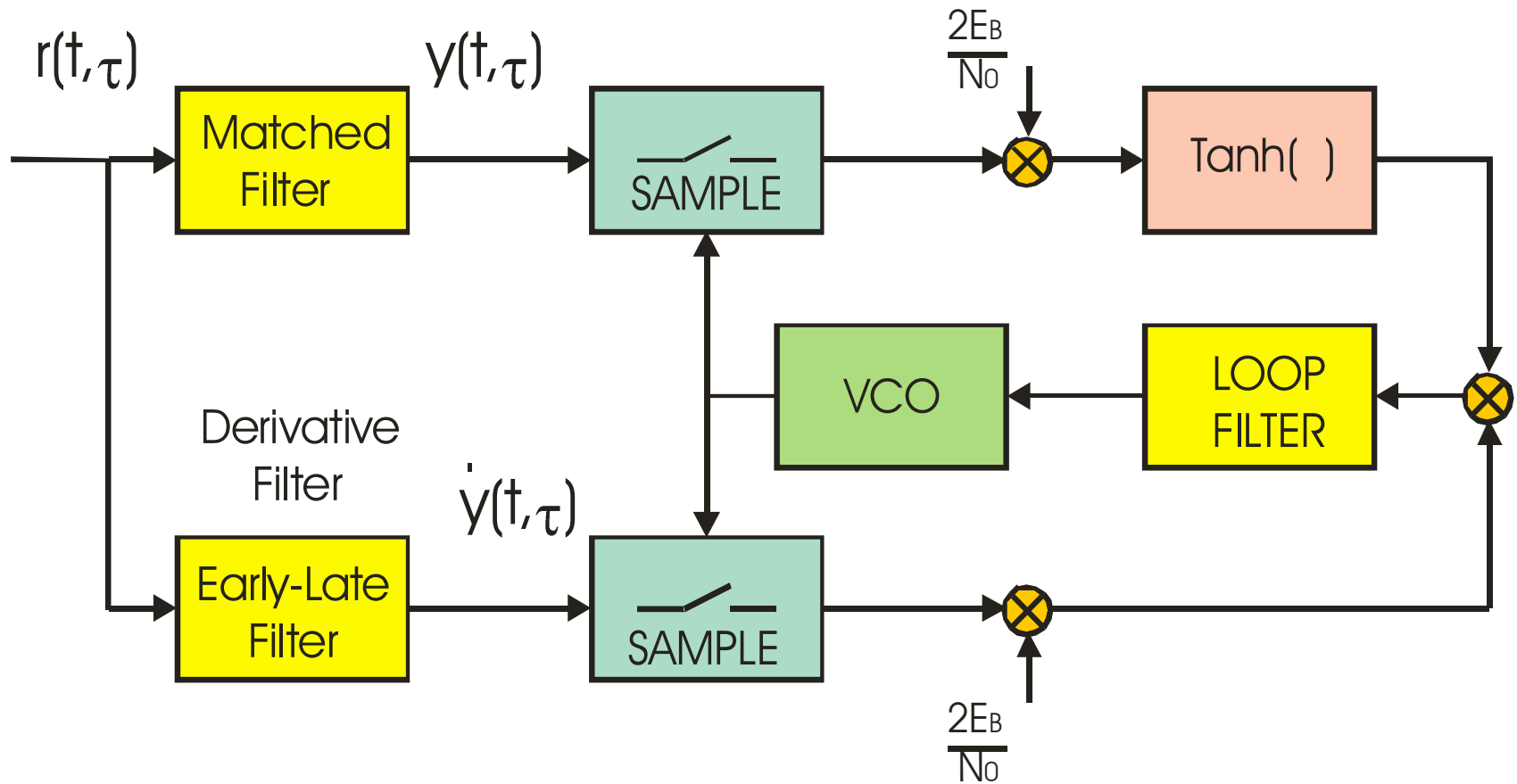


Retard
Pointer

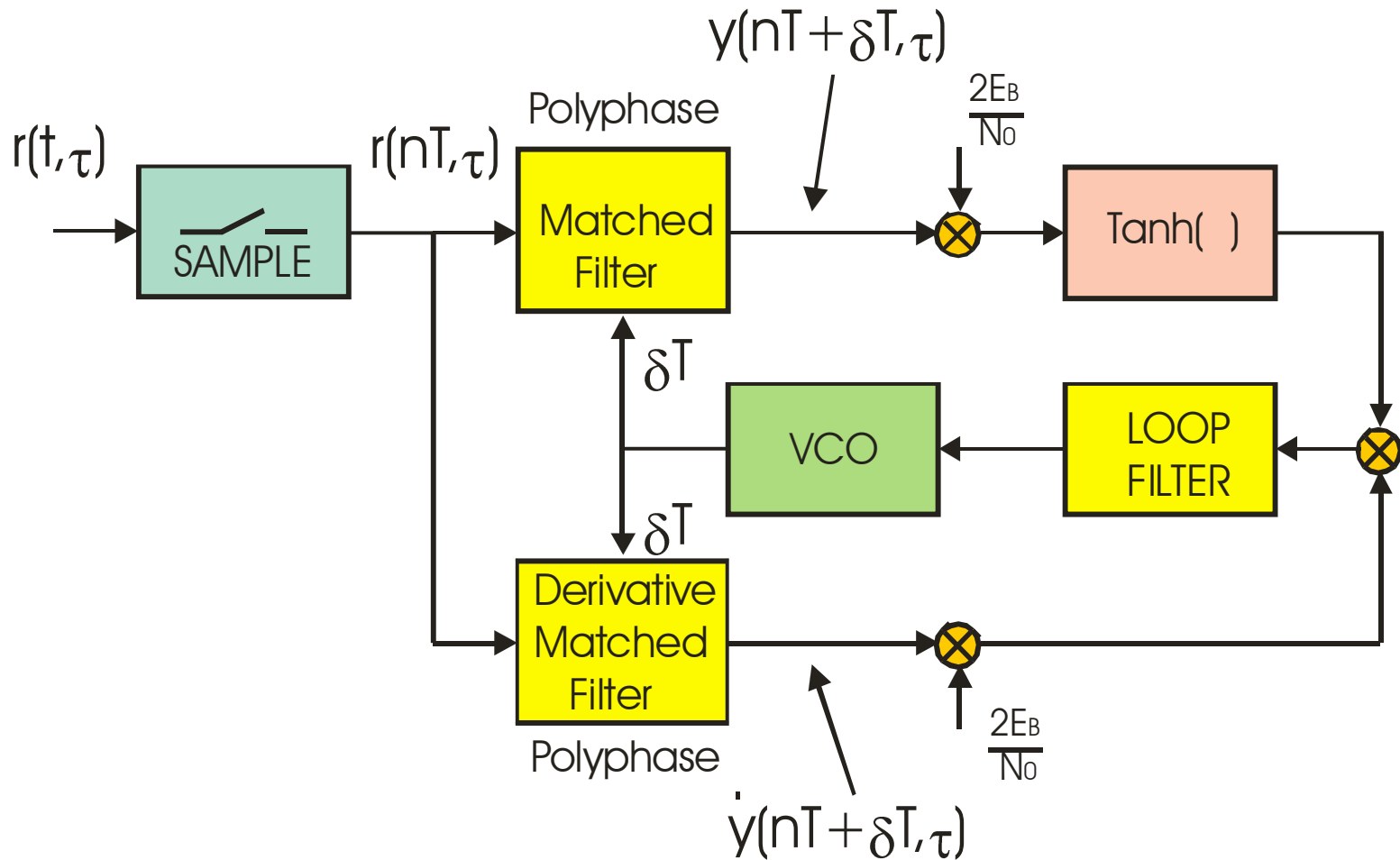
Early-Late Gate Derivative



Combining Early and Late Gates in a One Derivative Filter

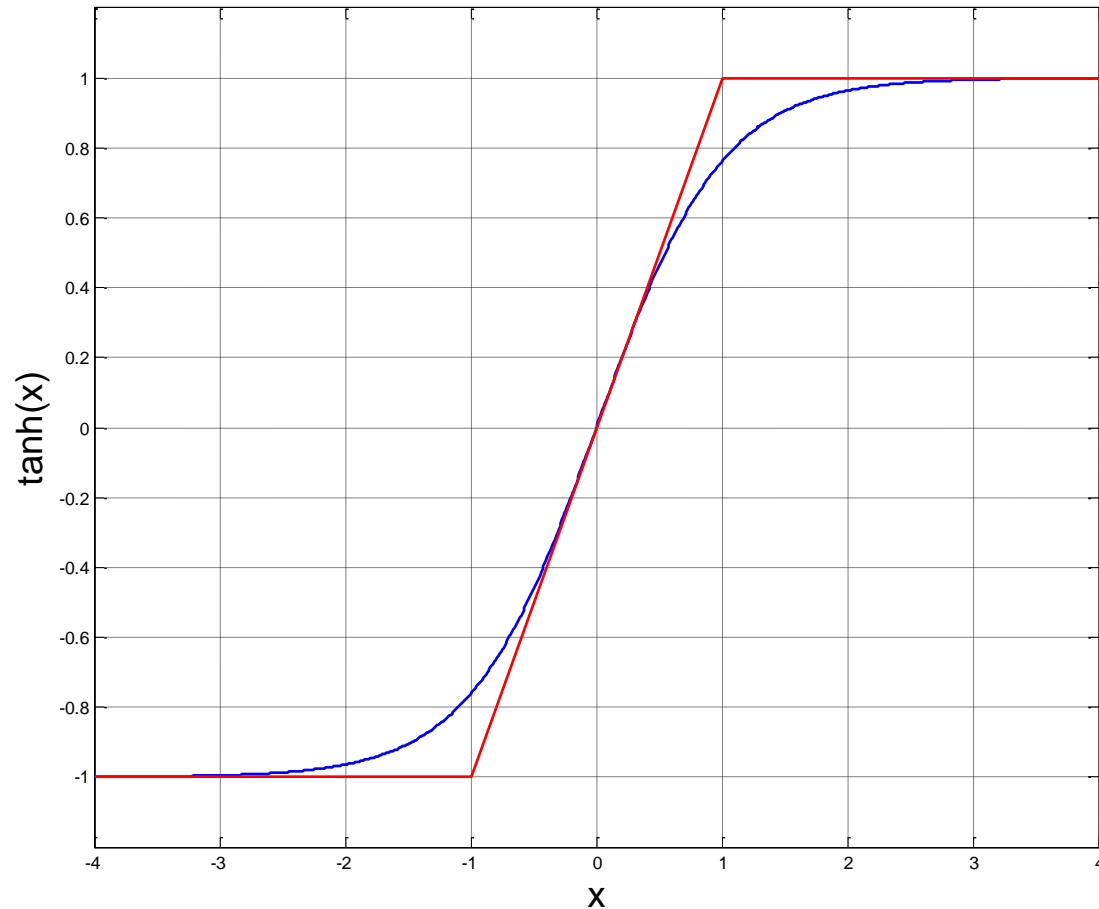


Slide Sampler to Input and Perform Timing Offset with Polyphase Digital Filter



Approximating Tanh(x)

Tanh(x) and Piecewise Linear Approximation



Sub Optimal Approximations

- Replace $2E_b/N_0$, SNR Gain with a Constant.
- Replace $\tanh(x)$ with Large SNR Approximation:

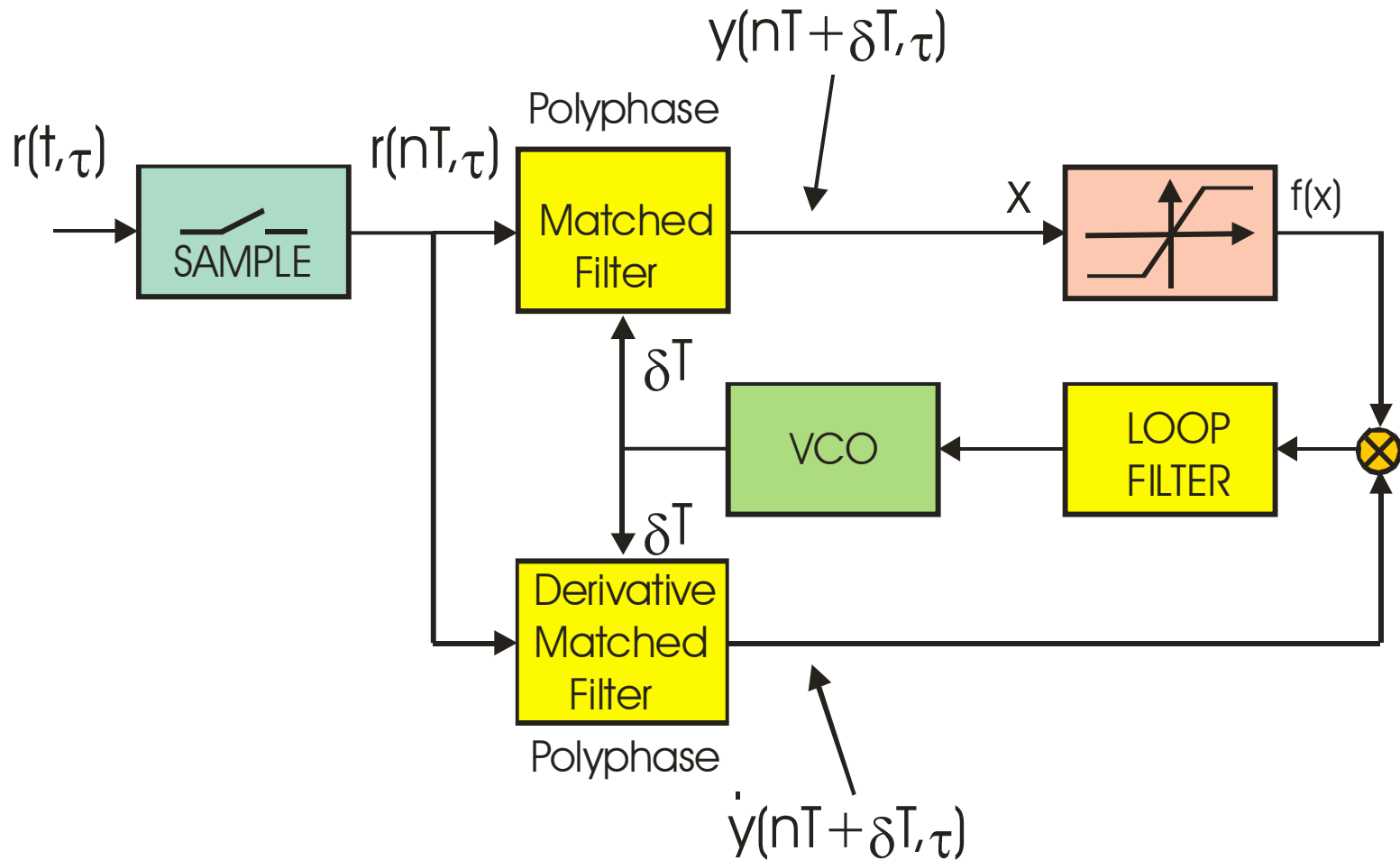
$$\tanh(x) \sim \text{sign}(x)$$

- Replace $\tanh(x)$ with Piecewise Approximation:

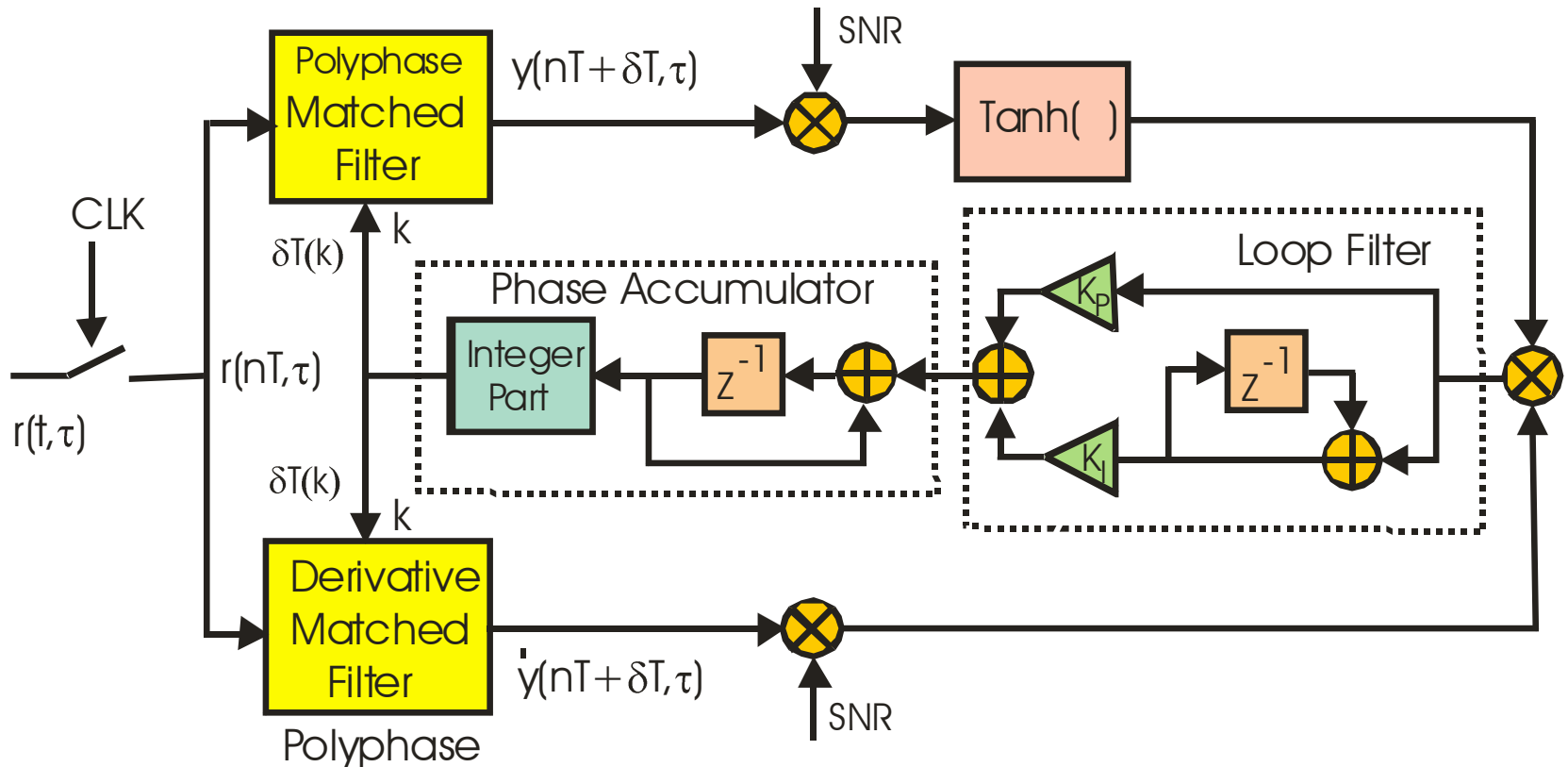
$$\tanh(x) \sim x \quad \text{for } |x| < 1$$

$$\tanh(x) \sim \text{sign}(x) \quad \text{for } |x| > 1$$

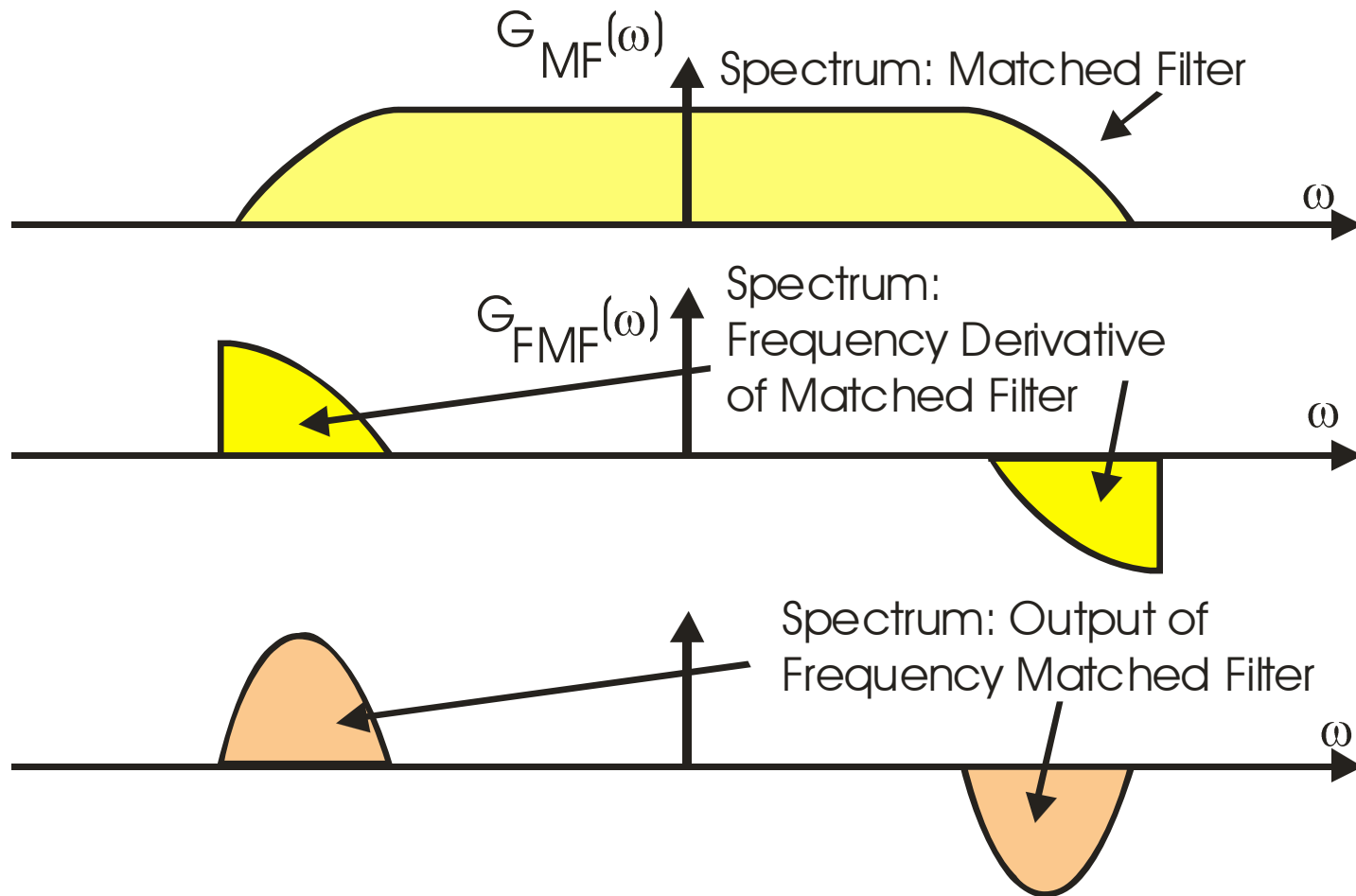
Sub Optimal Approximation



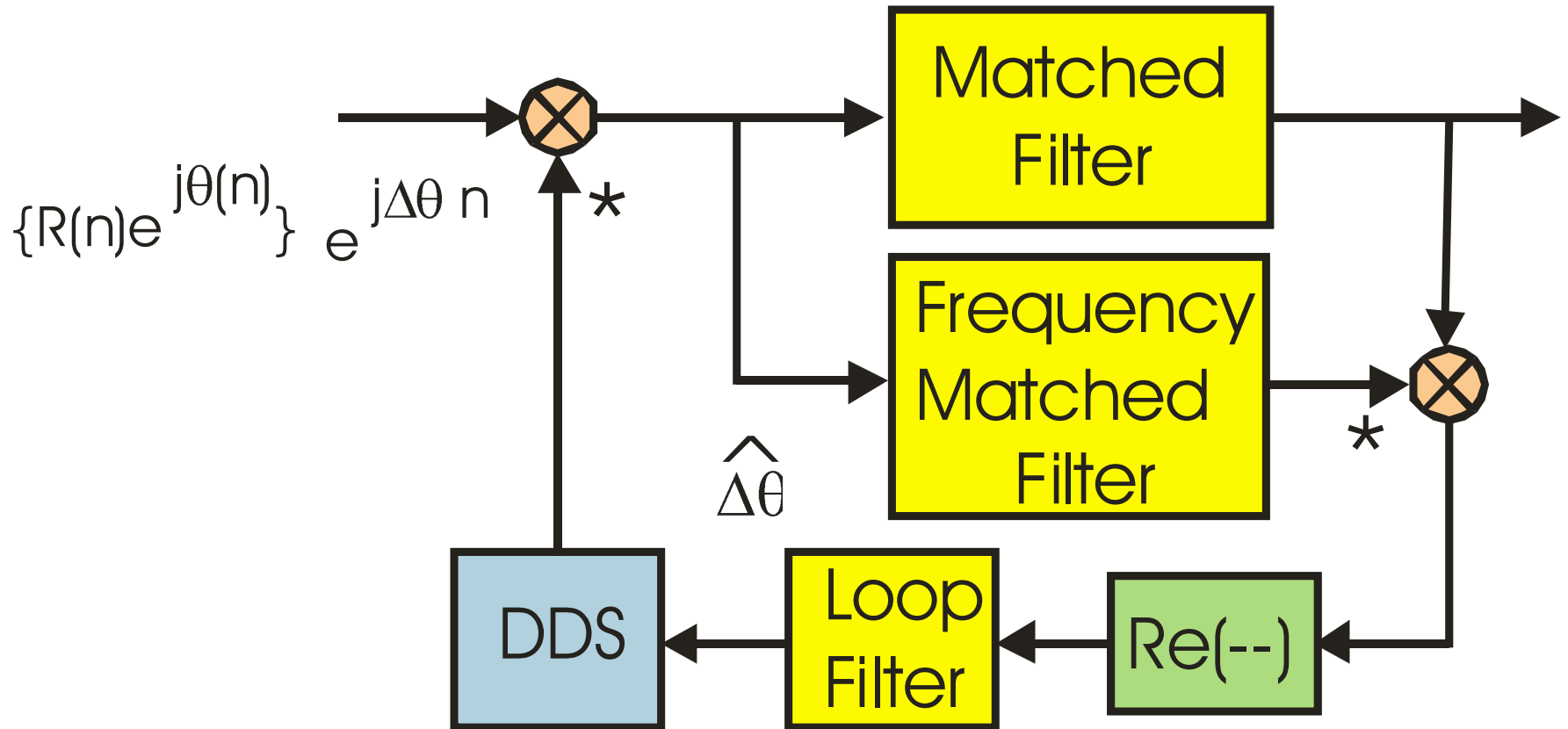
Second Tier Signal Processing Task, Timing Recovery Phase Locked Loop



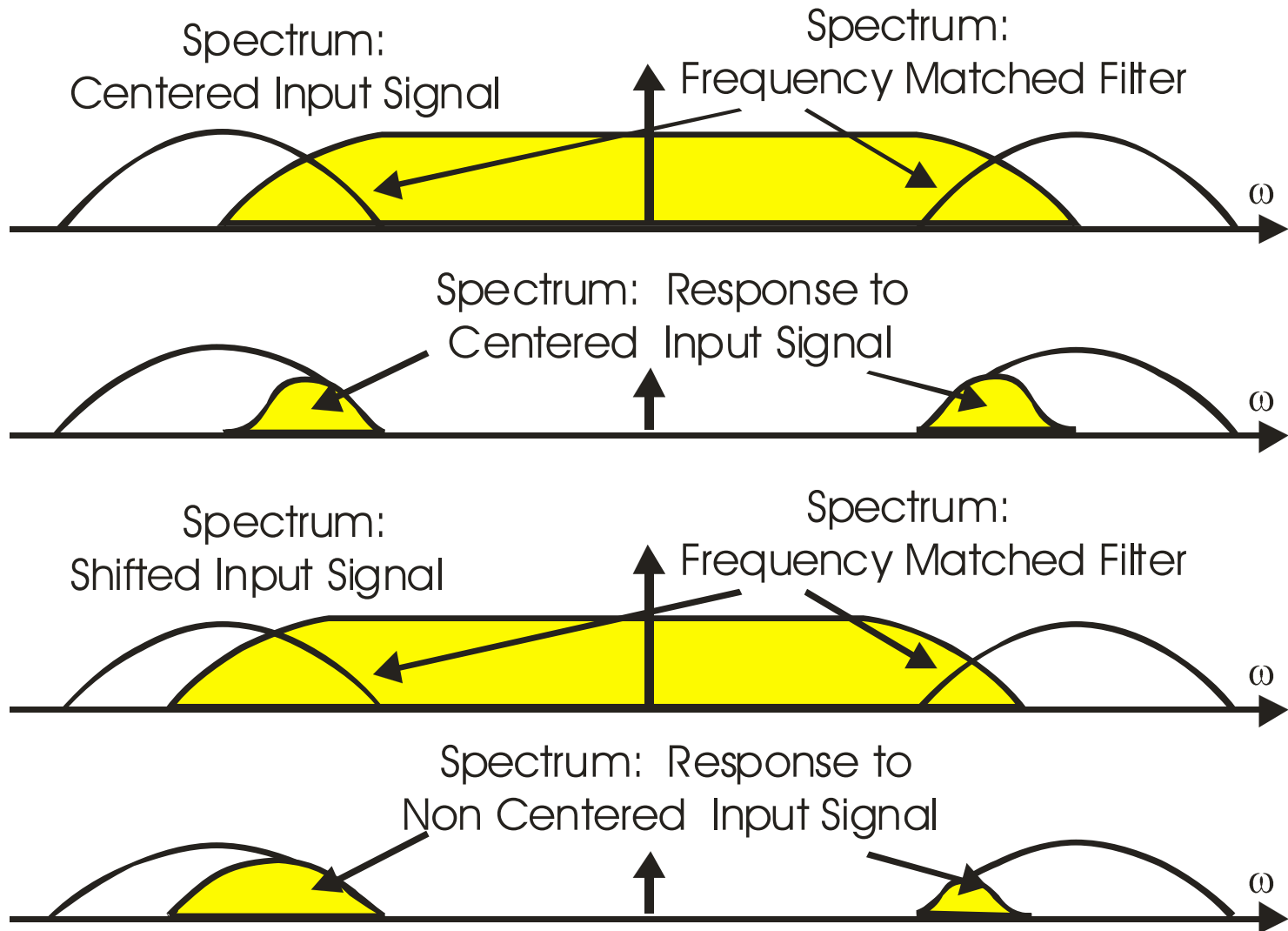
Band Edge Filter: $BE(\omega) = dH(\omega)/d\omega$



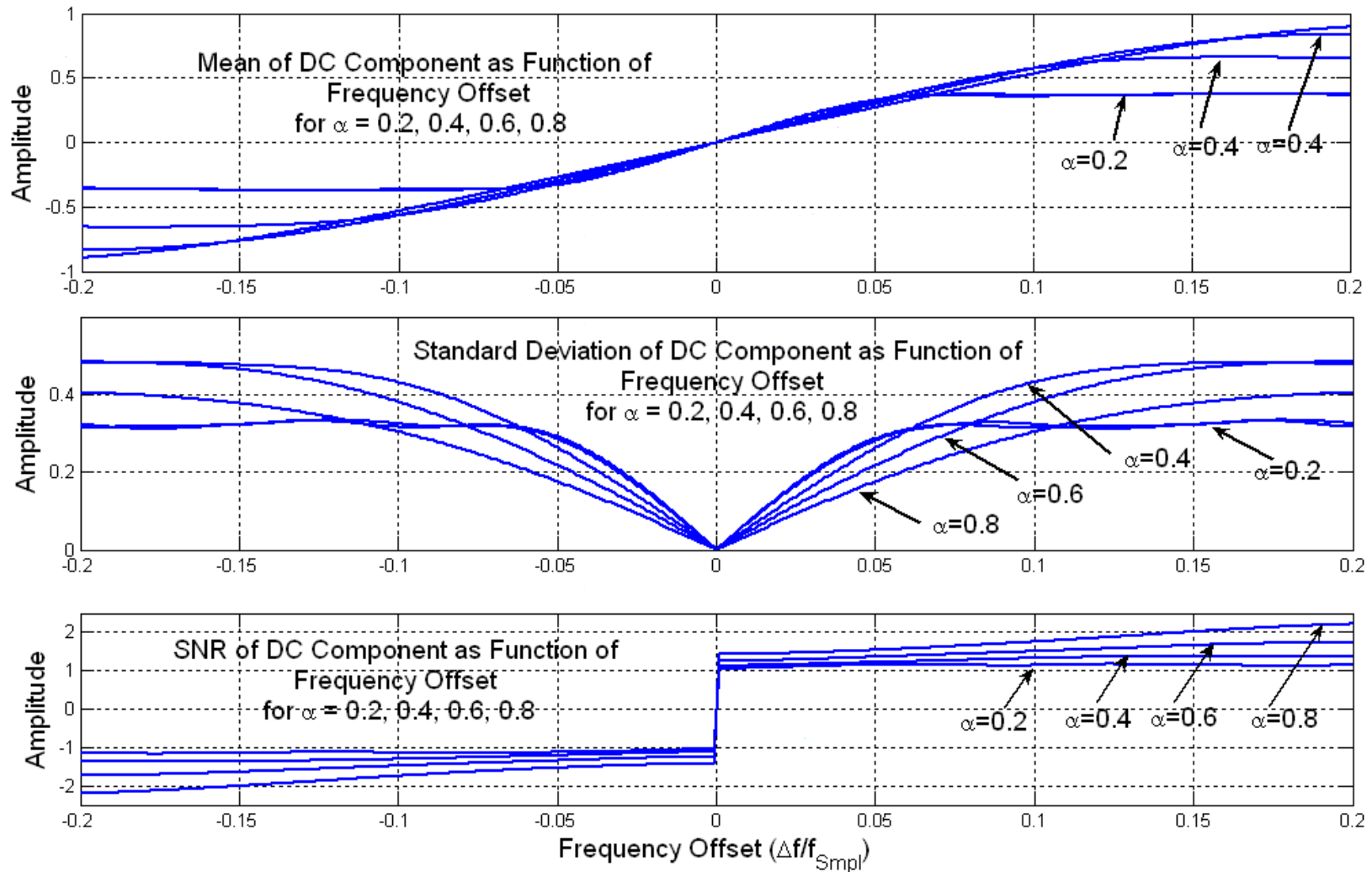
Band Edge Filter Based Frequency Locked Loop



Energy Difference in Band Edges Sufficient Statistic to Frequency Lock

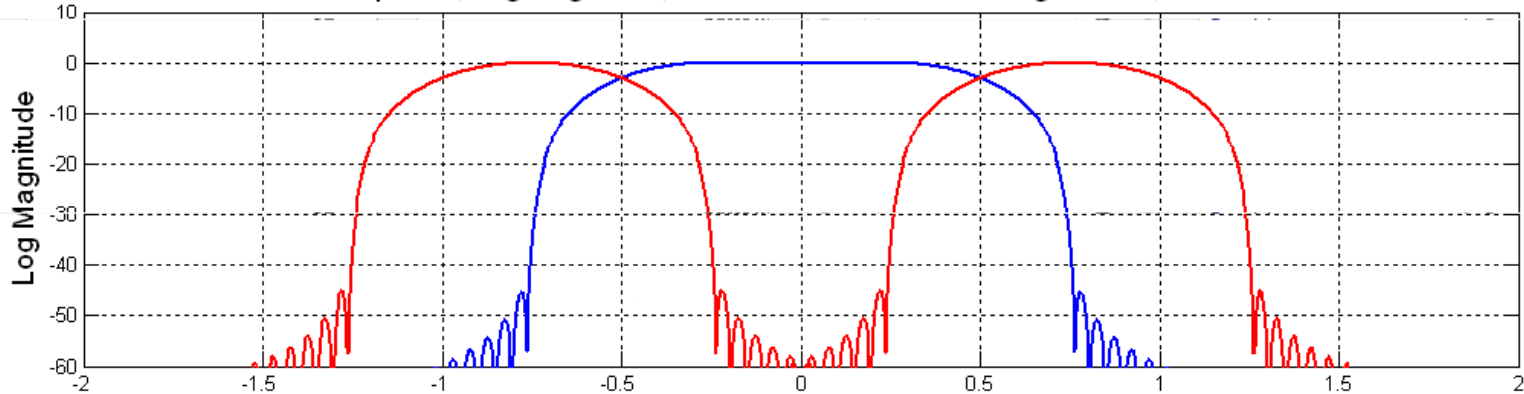


Mean and Variance of DC Term of Function of Frequency Offset

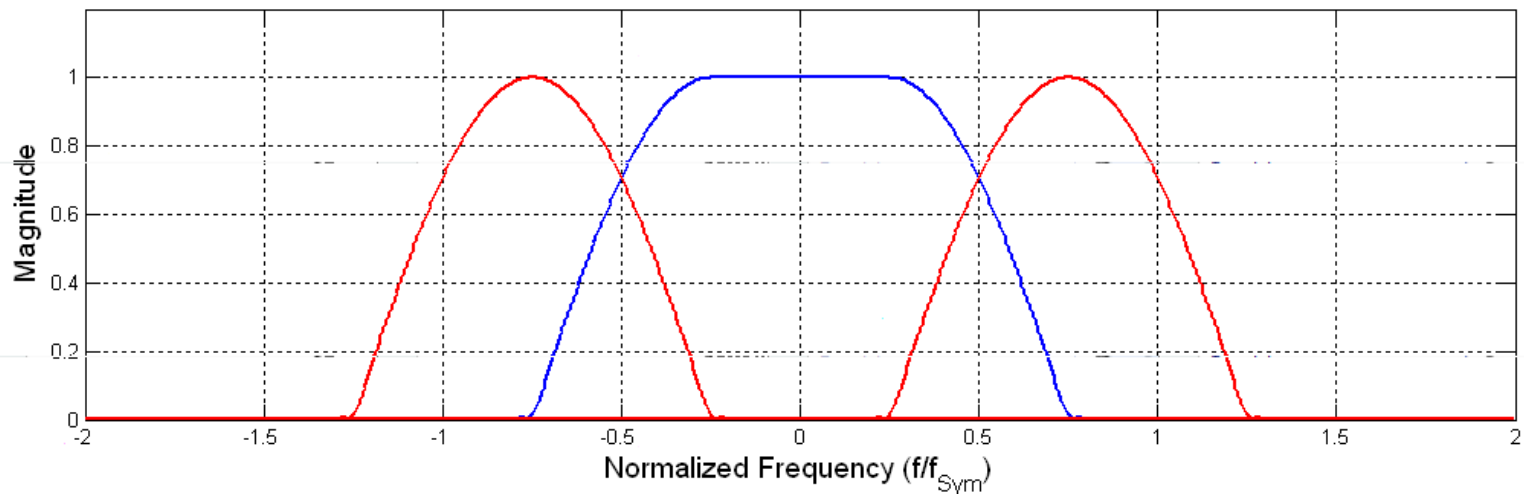


Spectra of Shaping and Band Edge Filters

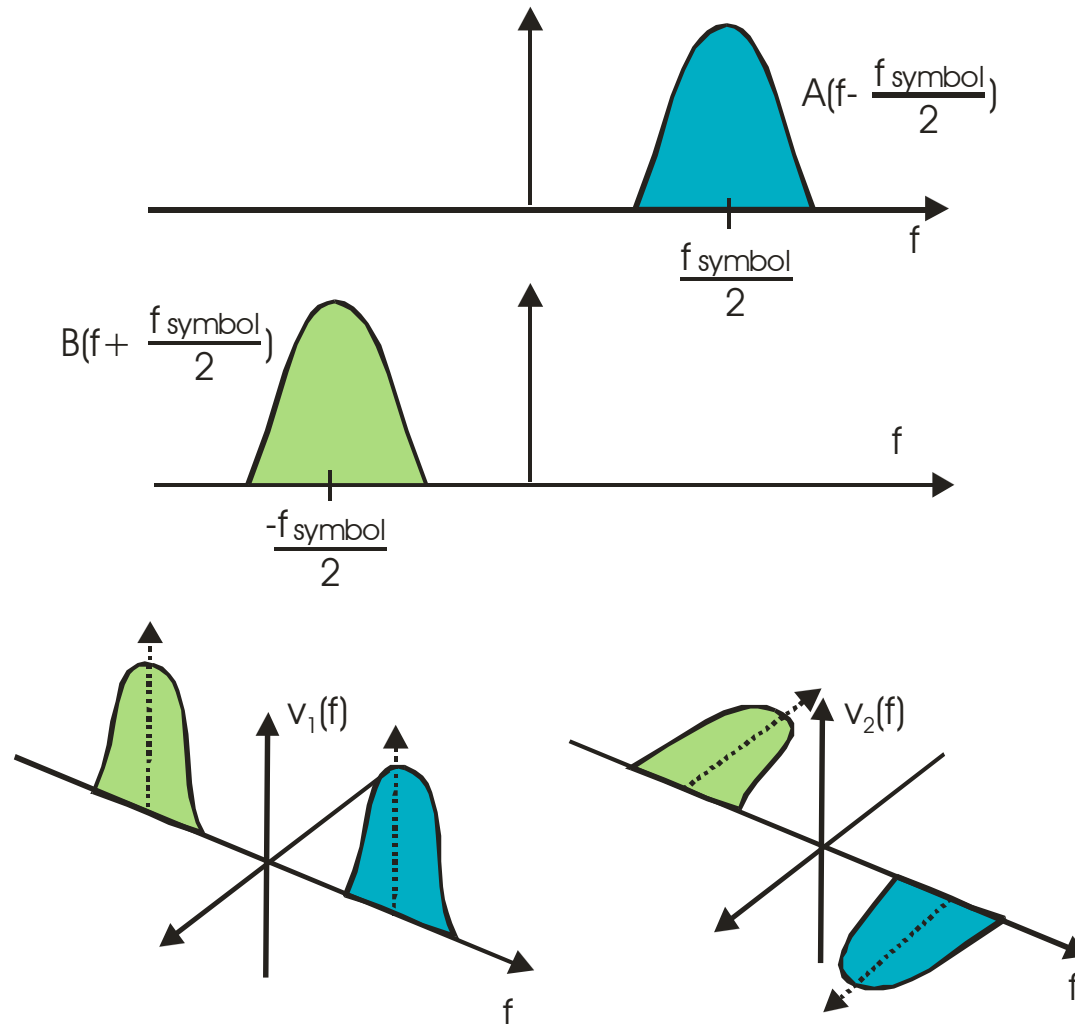
Spectra; Log Magnitude, Matched Filter and Band Edge Filters, $\alpha=0.5$



Spectra; Linear Magnitude, Matched Filter and Band Edge Filters, $\alpha=0.5$

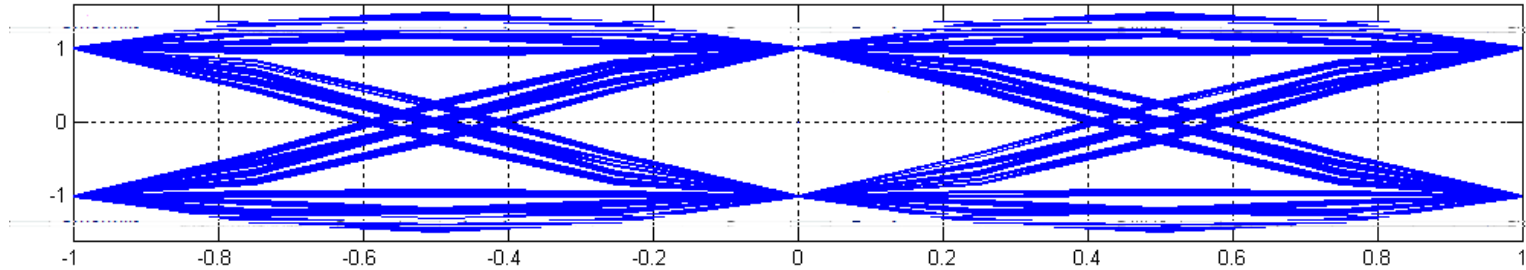


Spectra of Signals From Band Edges Combined to form Two New Signals

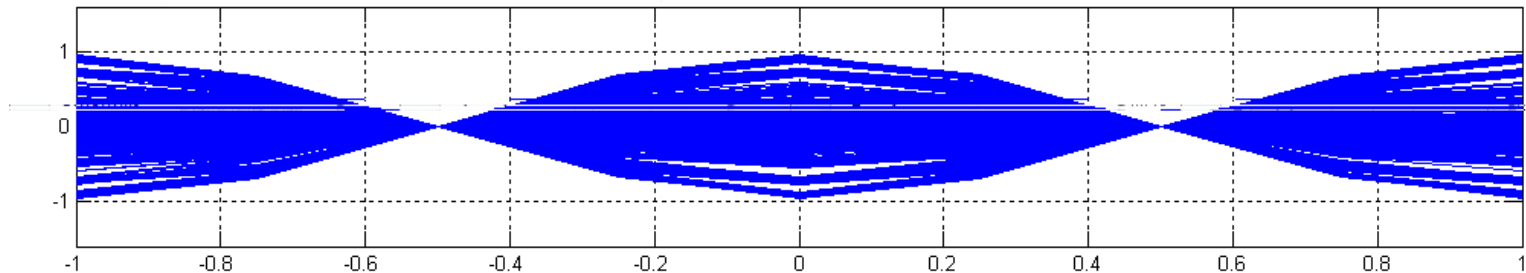


Eye Diagrams of Matched Filter and Sum and Difference Band-Edge Filters

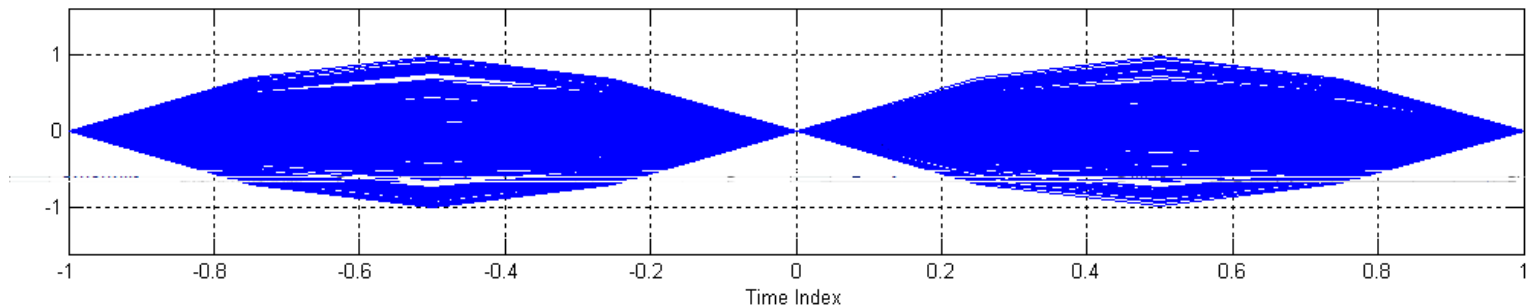
Eye Diagram: Matched Filter Output



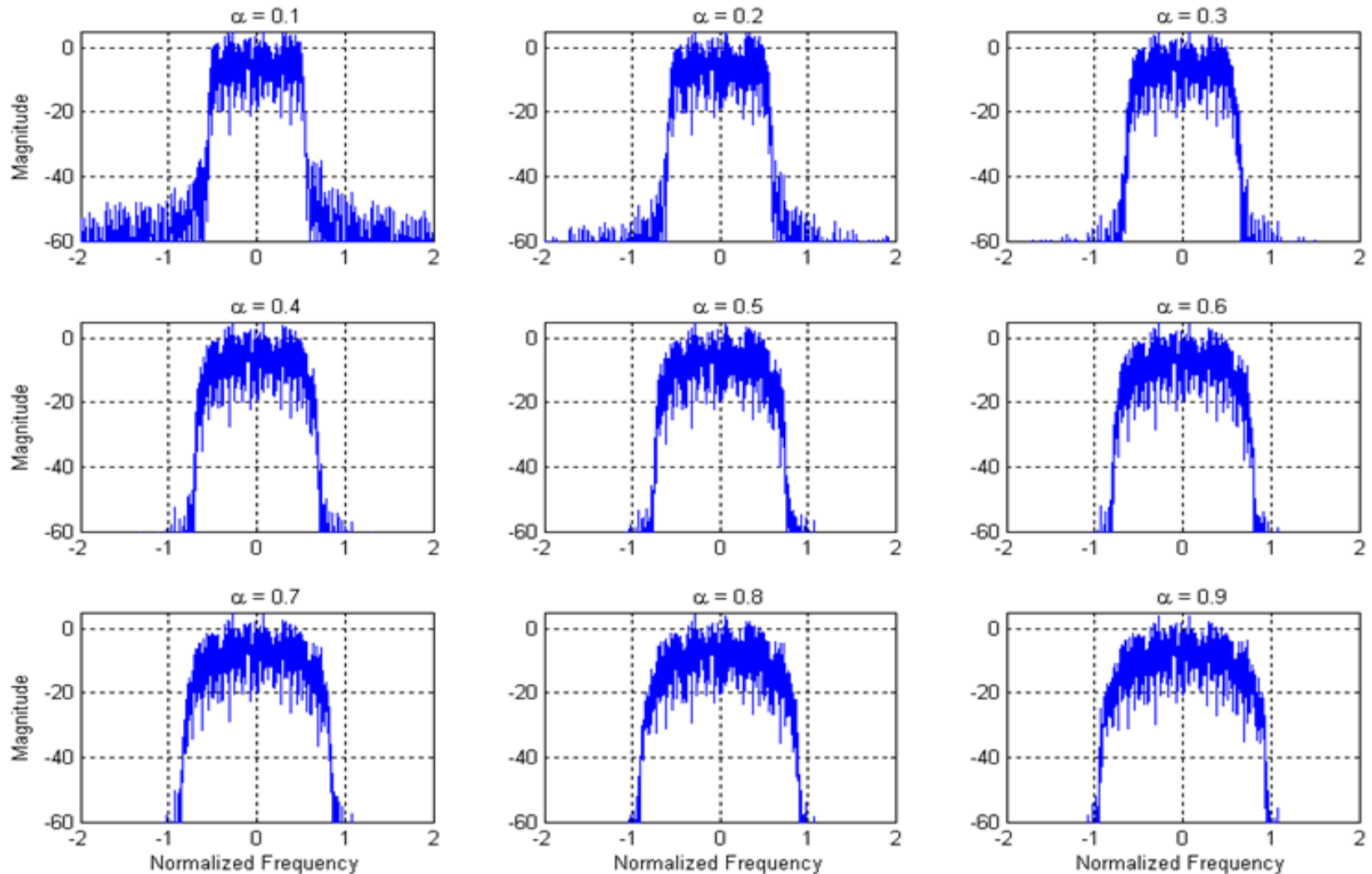
Eye Diagram: Sum of Band Edge Filter Outputs



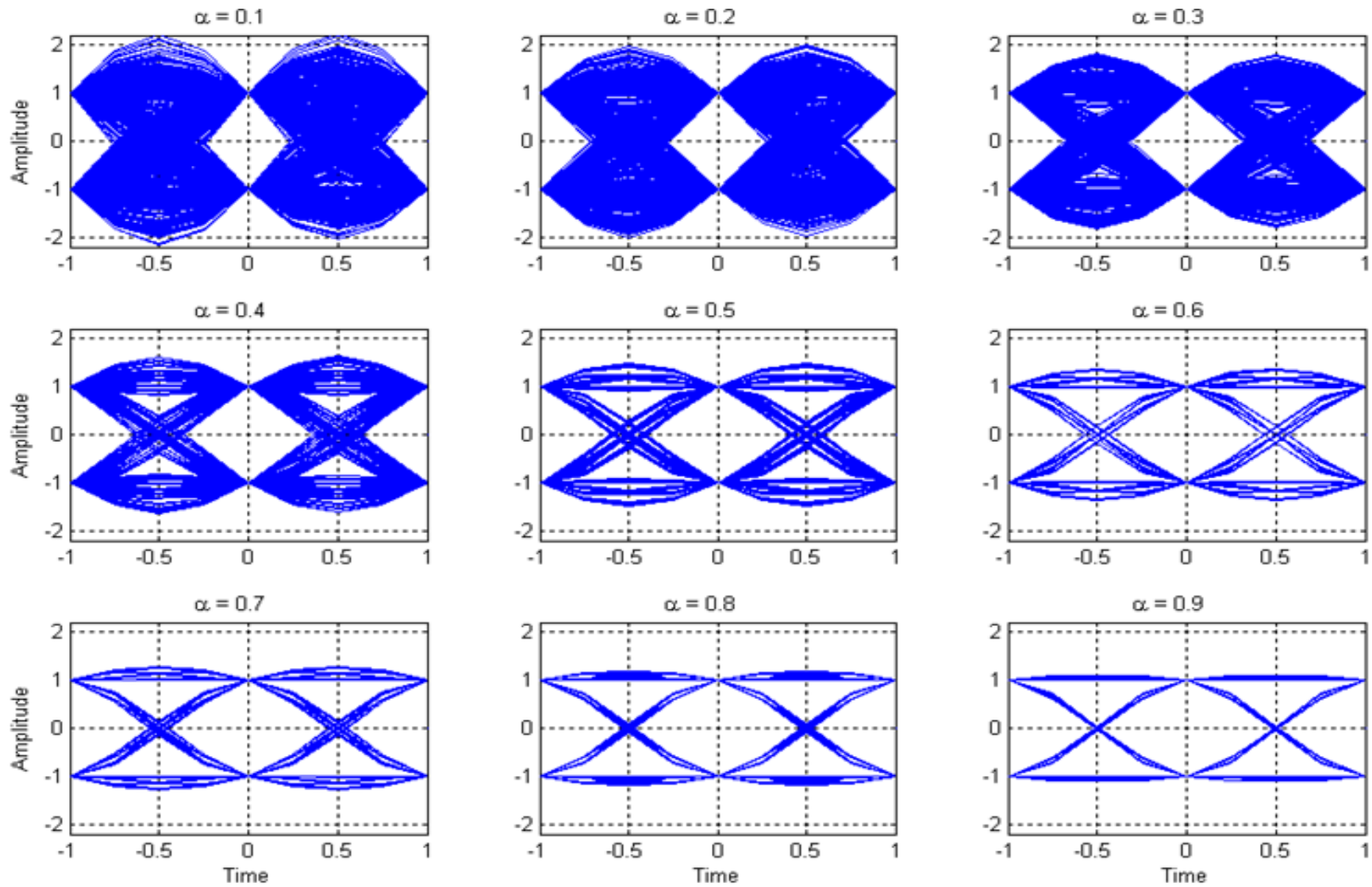
Eye Diagram: Difference of Band Edge Filter Outputs



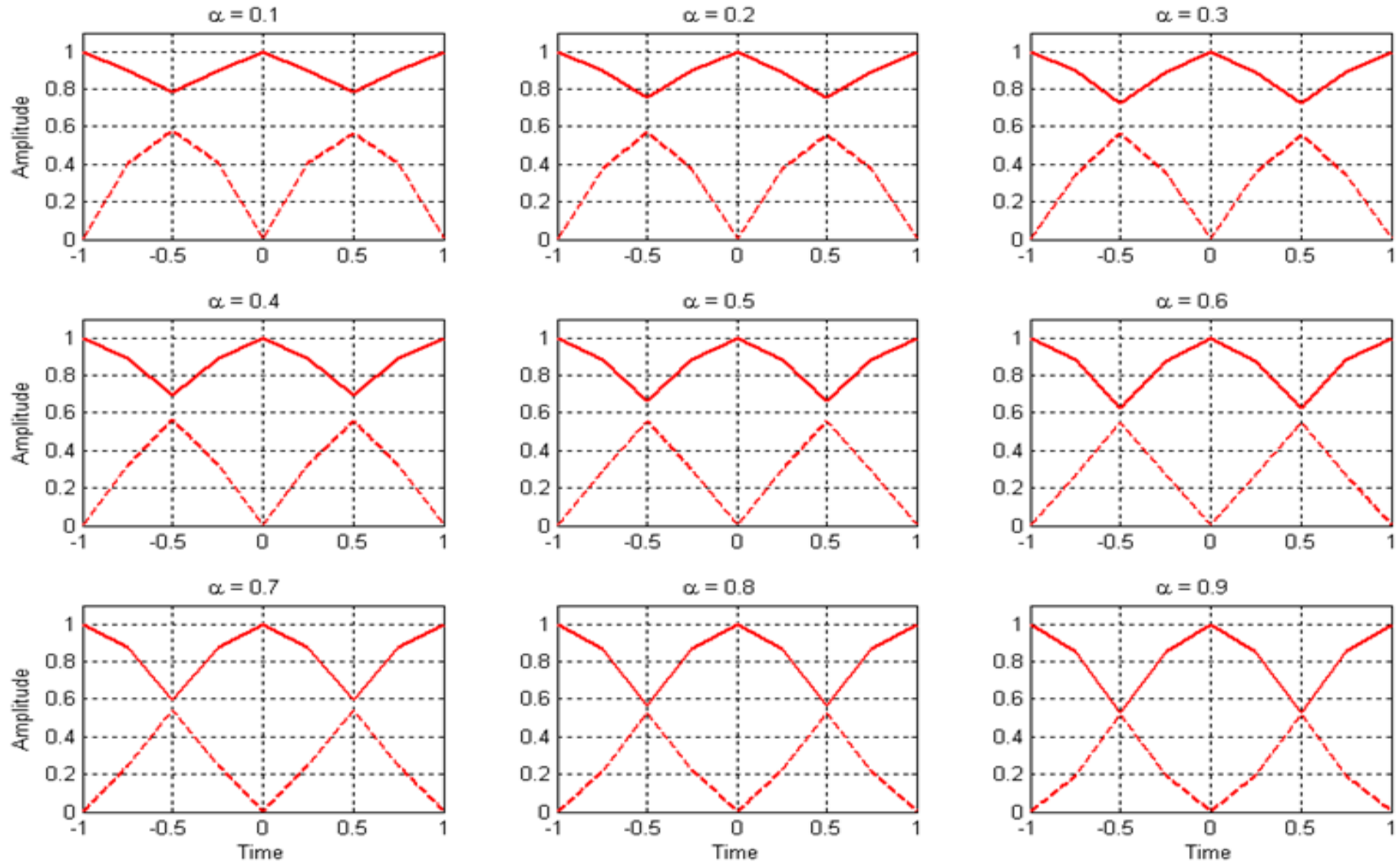
Spectra of SQRT Nyquist Shaped Modulation Signals over Range of Excess BW



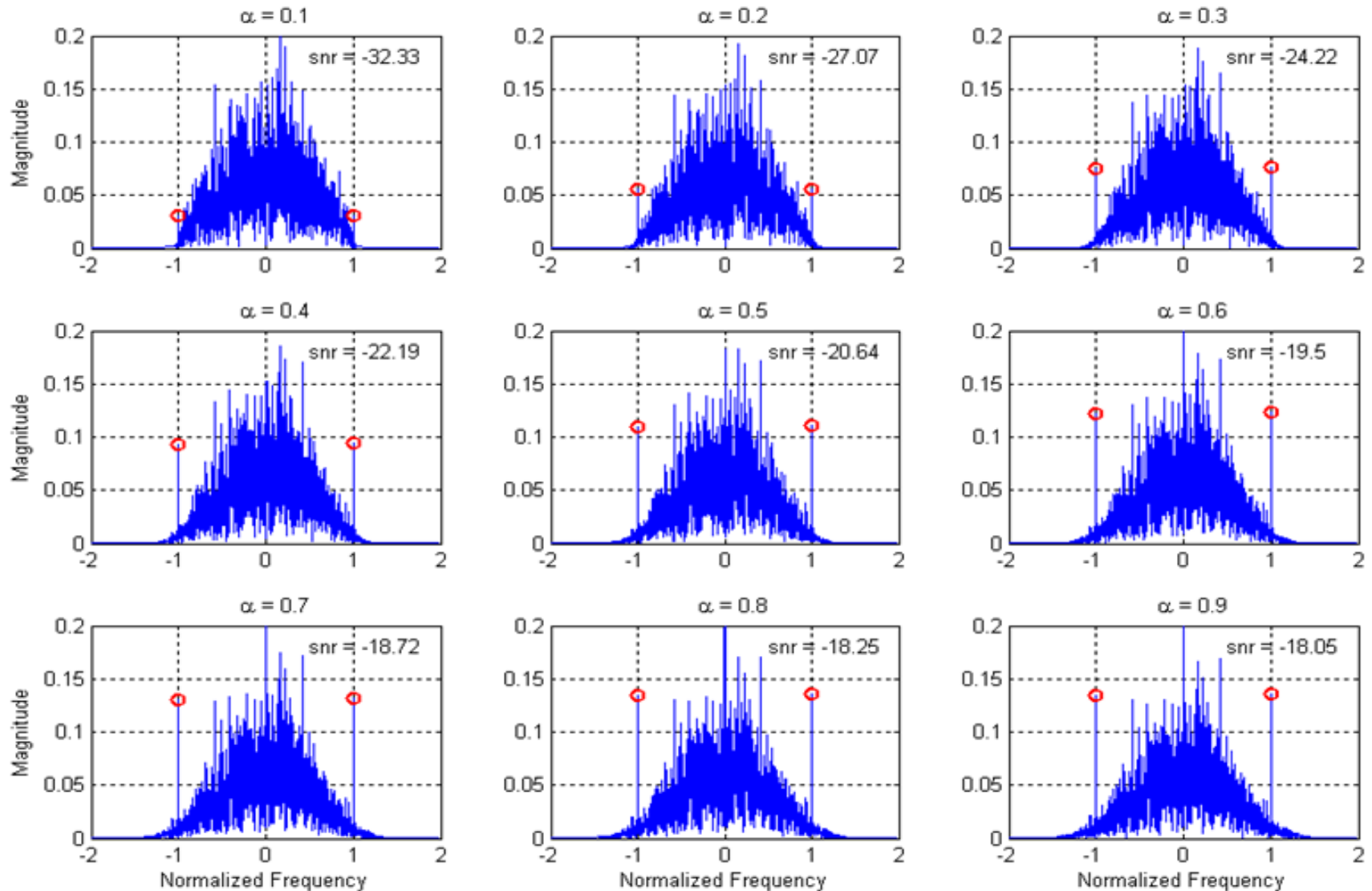
Eye Diagrams Matched Filter Output



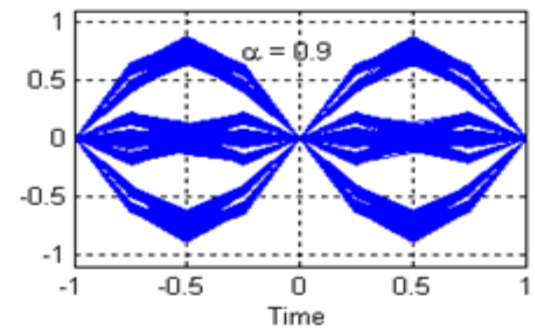
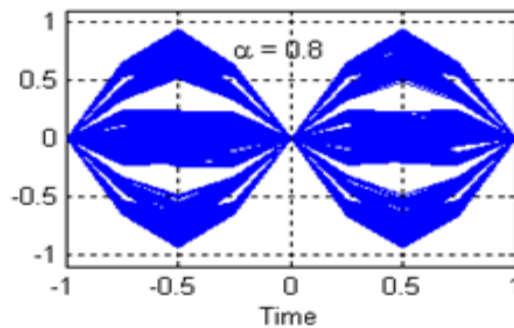
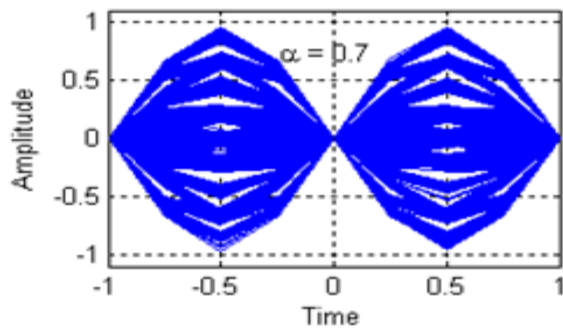
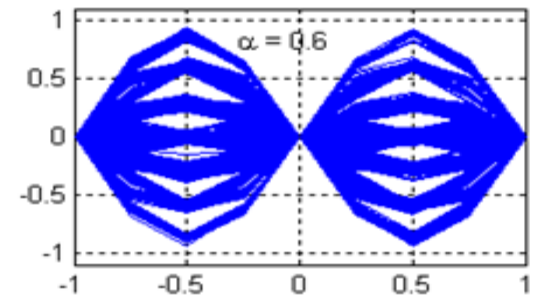
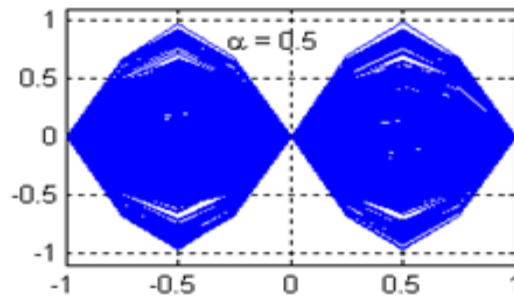
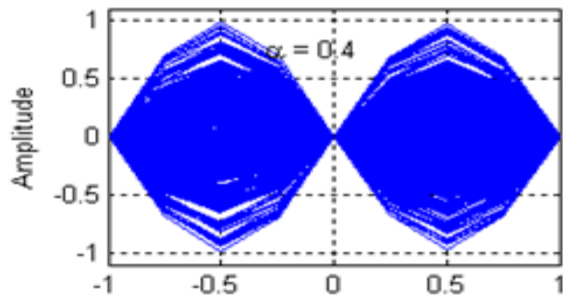
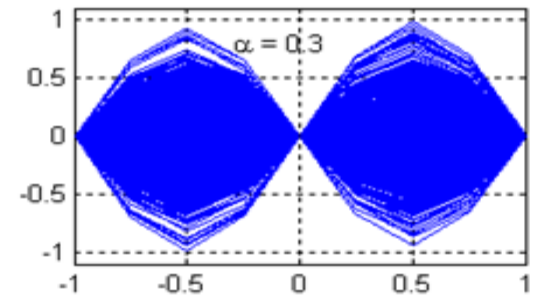
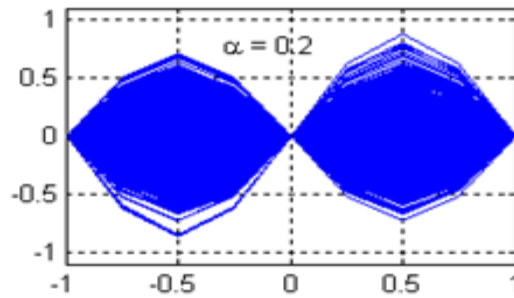
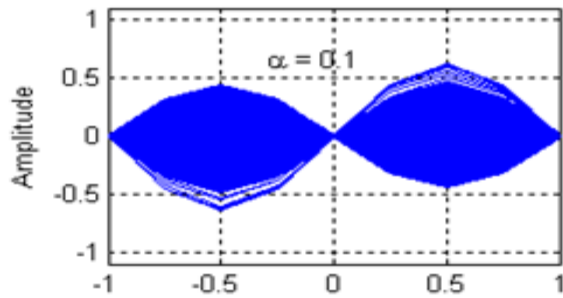
Cyclostationary Mean and Variance Eye Diagrams Magnitude Matched Filter



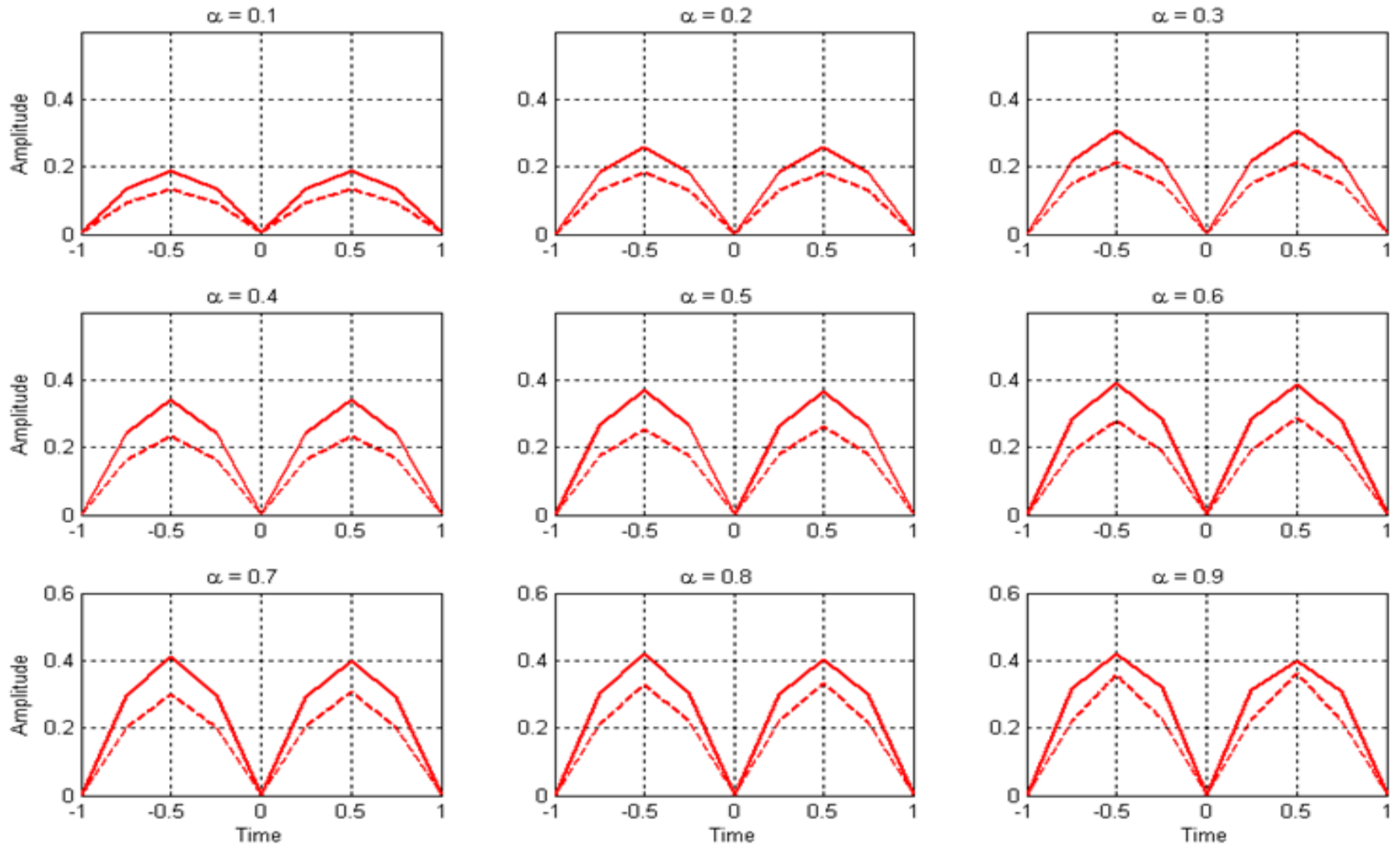
Spectral Lines from Excess BW: $MF(\omega) \times MF(\omega)^*$



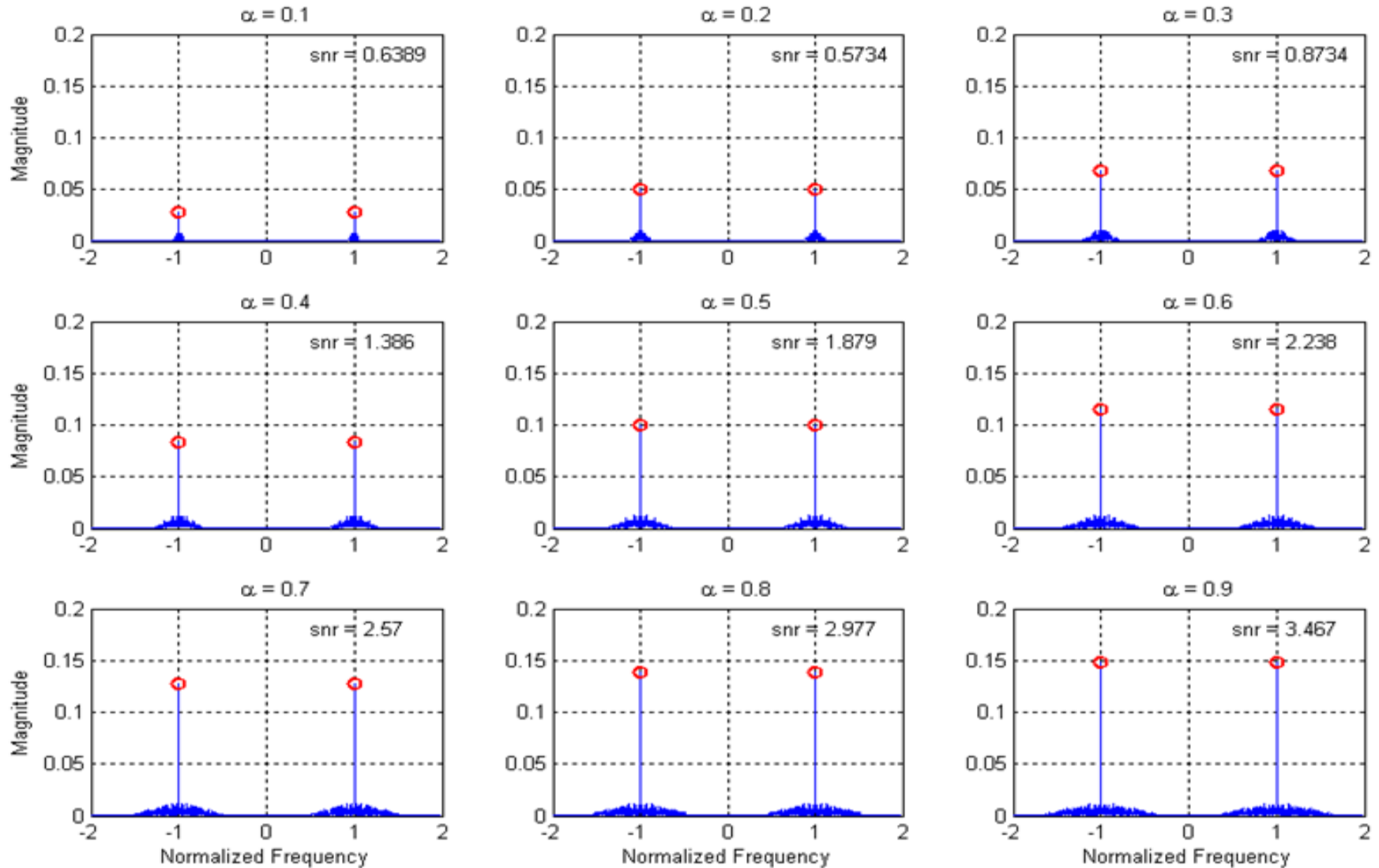
Eye Diagrams Band Edge Filter Output



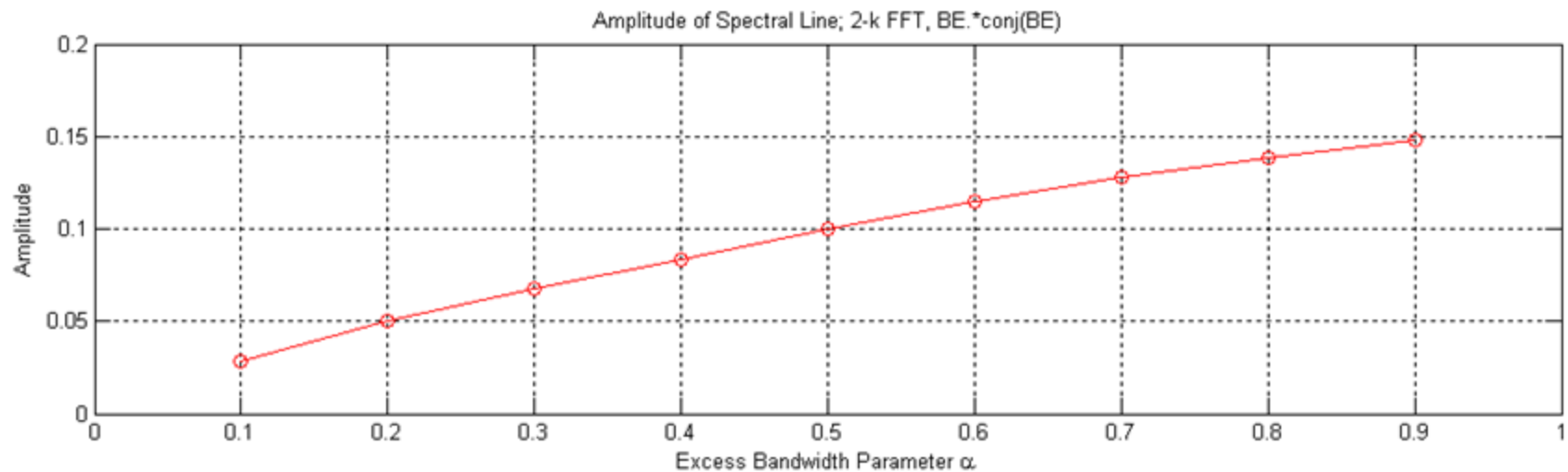
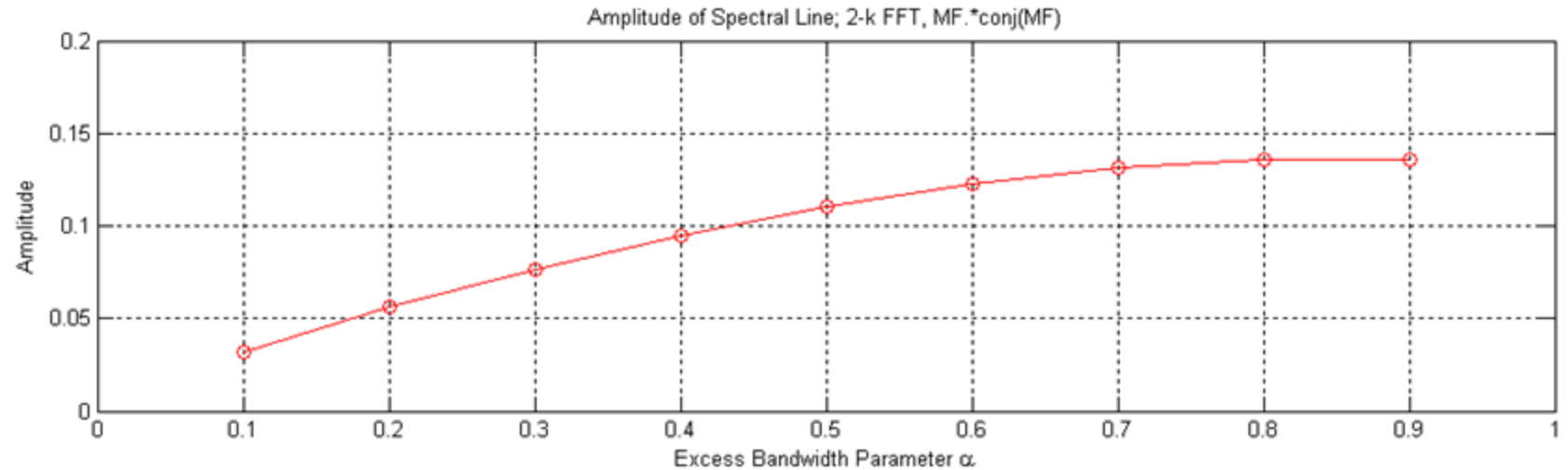
Cyclostationary Mean and Variance Eye Diagrams Magnitude Band Edge Filter



Spectra of $BE(\omega) \times BE(\omega)^*$



Amplitude of Spectral Timing Line from Excess Bandwidth



What Happens if there is no excess BW?

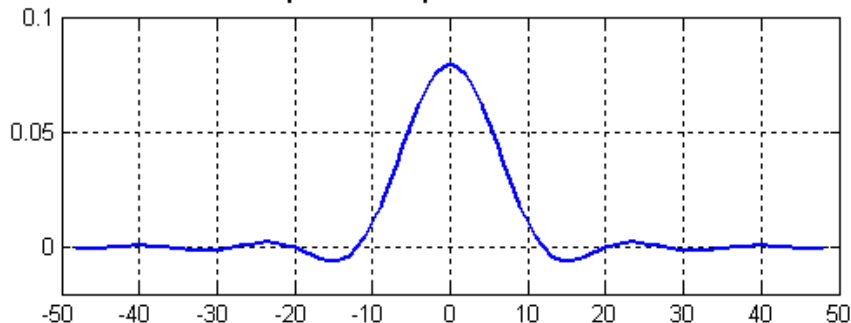
- As we reduce excess BW to obtain more efficient use of spectrum, we reduce the ability of the receiver to synchronize.
- When there is no excess BW we need to allocate a fraction of transmitted energy to pilot signals.
- Example: OFDM Has No excess Energy in Modulation Waveform: Excess Energy Resides in added secondary signals: Preamble, Cyclic Prefix, Unmodulated Stationary and Moving Pilots.
- Interesting Question: Is this energy accounted for when people discuss error correcting codes operating near Shannon Limit? (I'm sure it is not!)

The Synchronizers' Needle Point

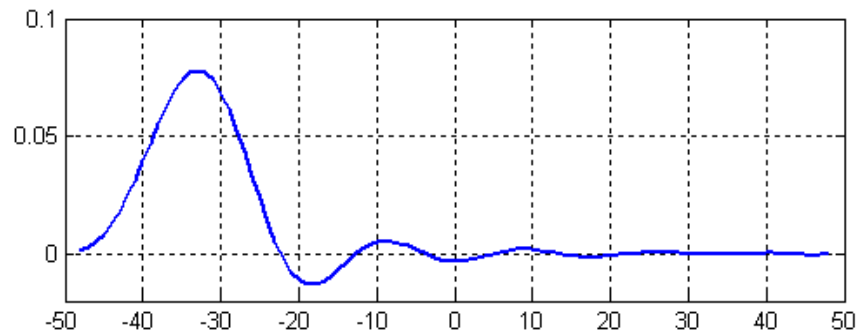
IF MOMMY
IS NOT HAPPY,
NOBODY IS
HAPPY!

Band Edge Filters and Approximations

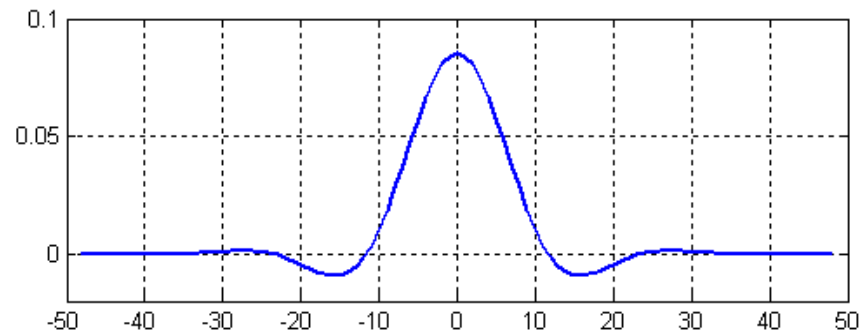
Impulse response BE Filter



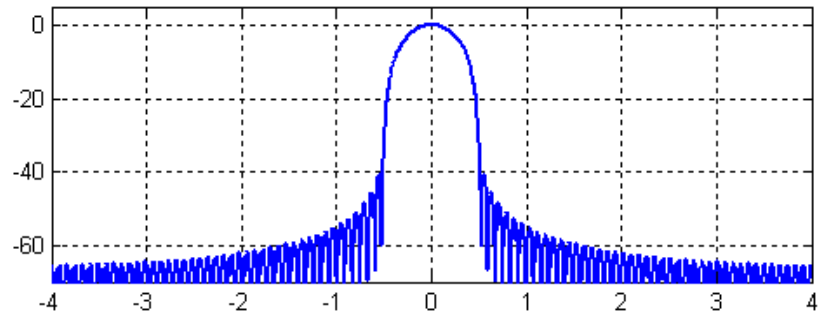
Minimum Phase Version



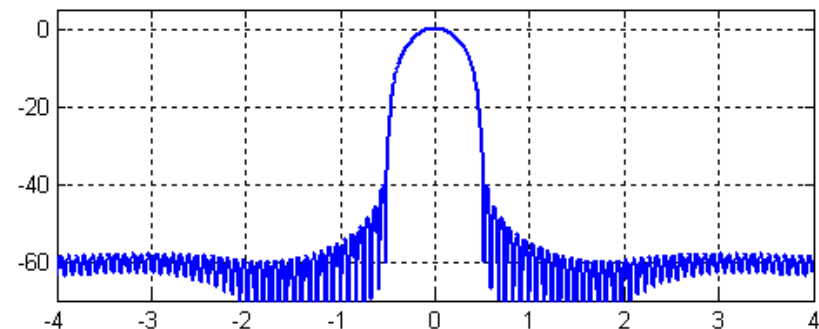
Linear Phase Filter



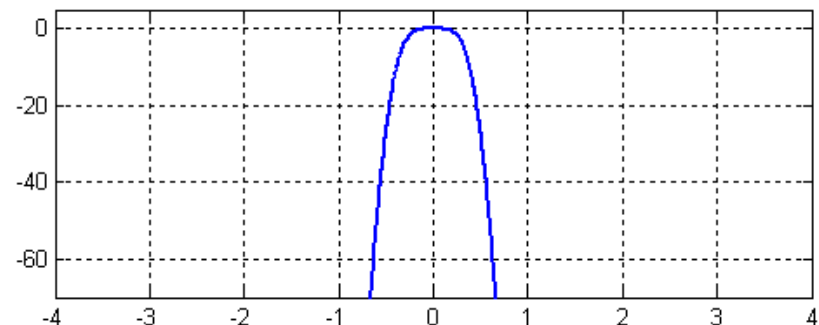
Spectral Response



Spectral Response

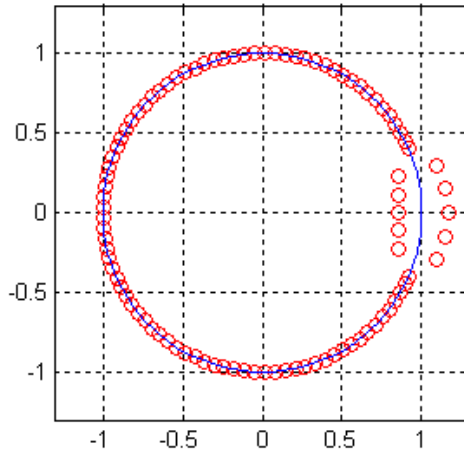


Spectral Response

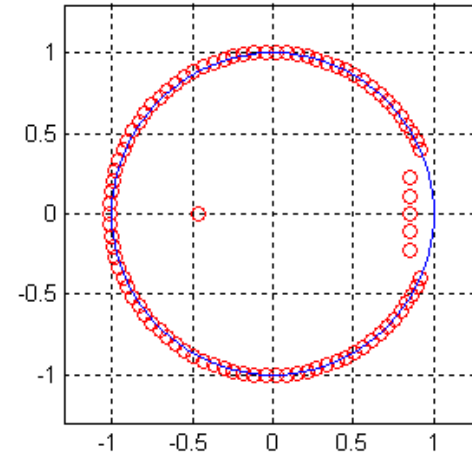


Linear and Minimum Phase BE Filters

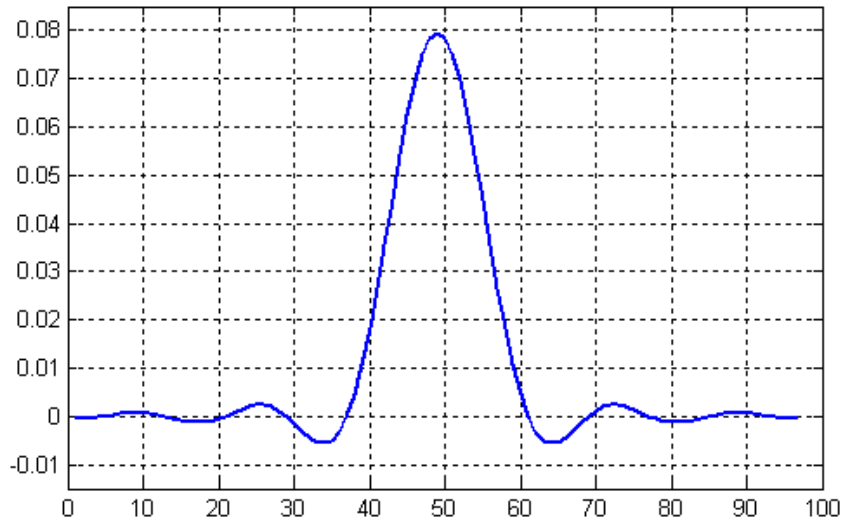
Zeros: Linear Phase BE



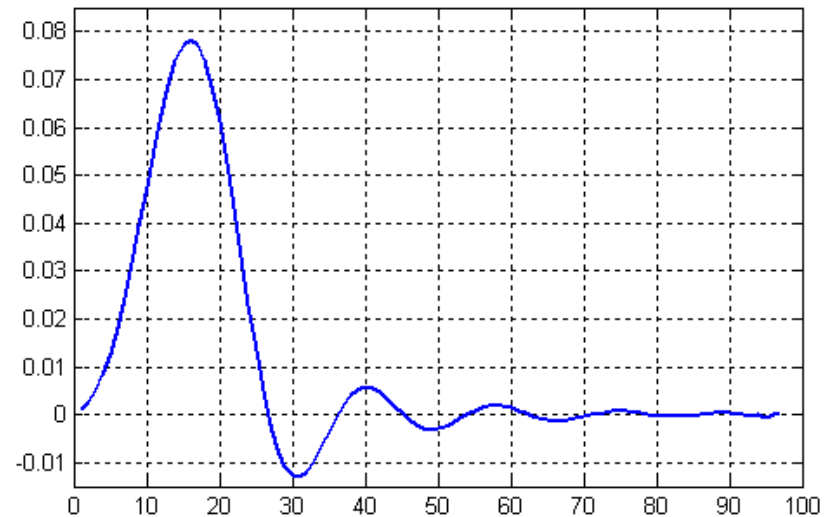
Zeros: Minimum Phase BE



Impulse Response

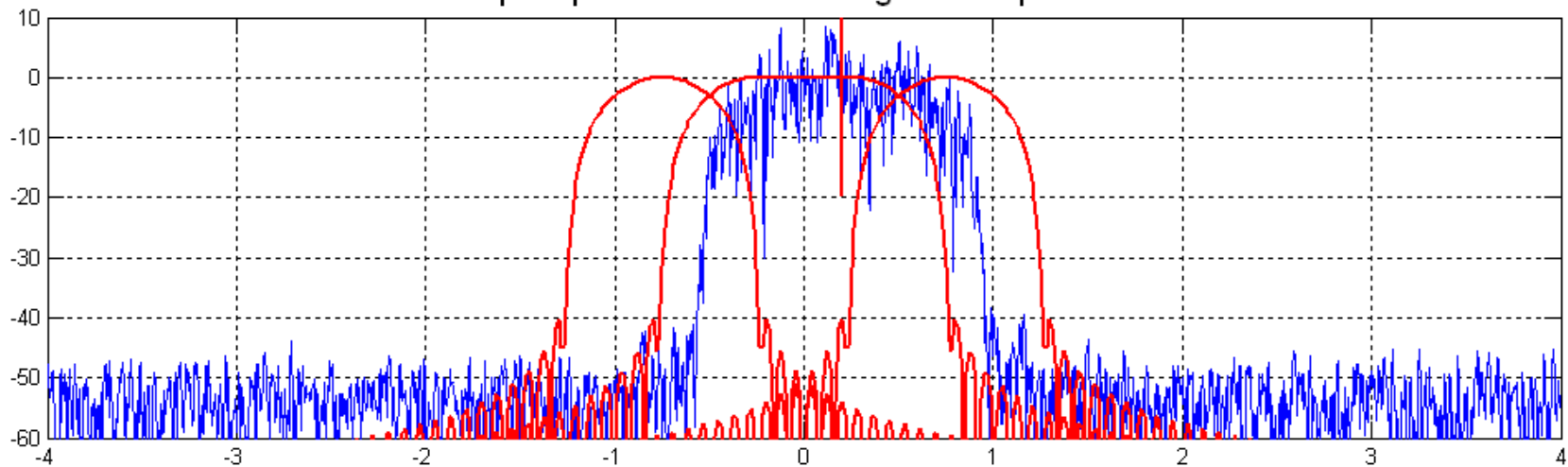


Impulse Response

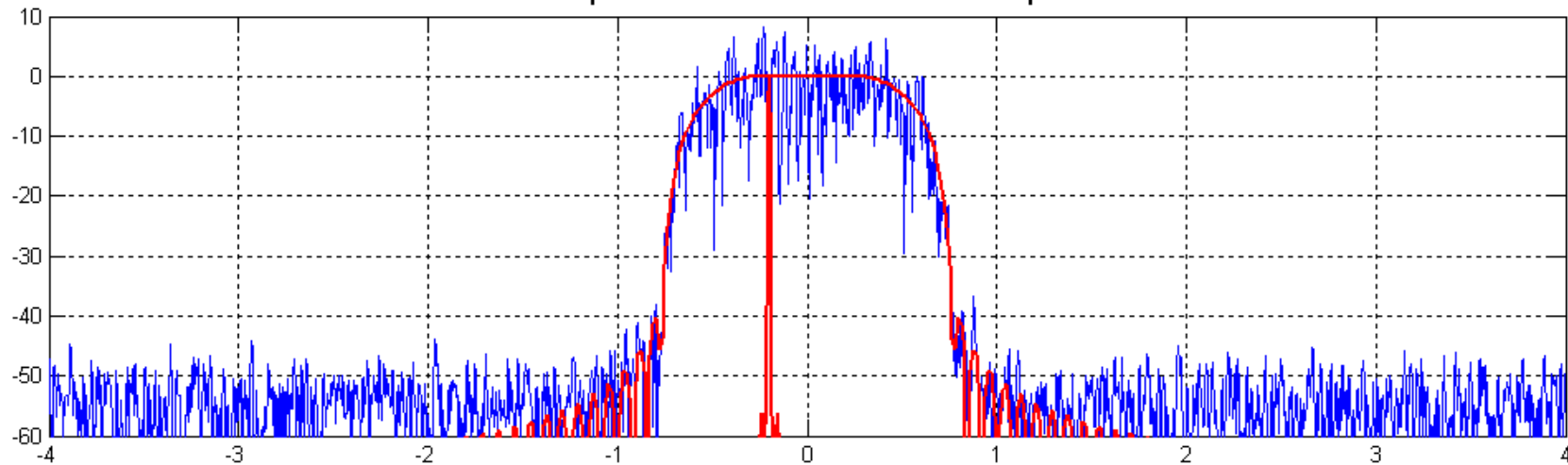


Frequency Offset Spectra and BE Filters in Frequency Lock Loop

Input Spectrum and Band Edge Filter Spectrum

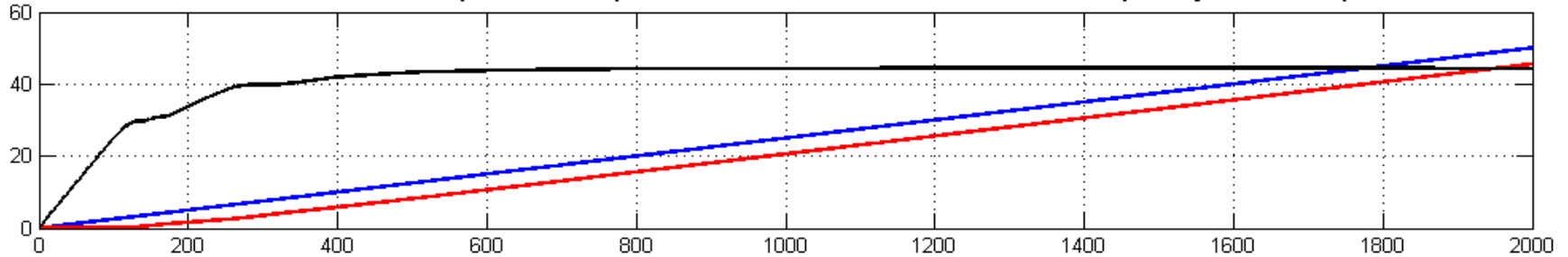


Shifted Spectrum and Down-Converter Spectrum

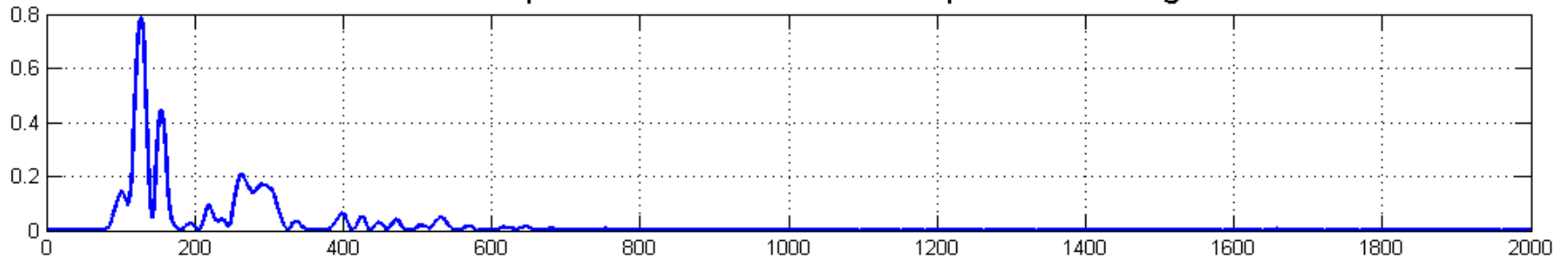


Phase Profiles of Freq Lock Loop

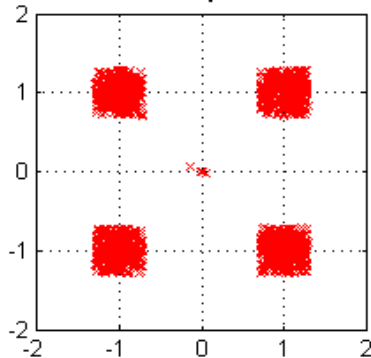
Phase Profile of Input and Output and 10 x Phase Difference of Frequency Lock Loop



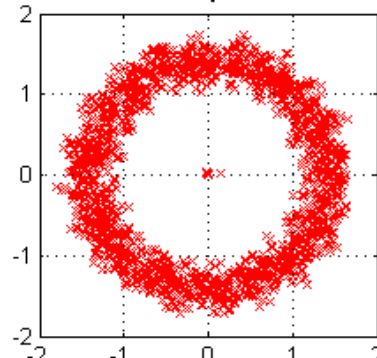
Instantaneous Amplitude Difference Between Outputs of Band Edge Filters



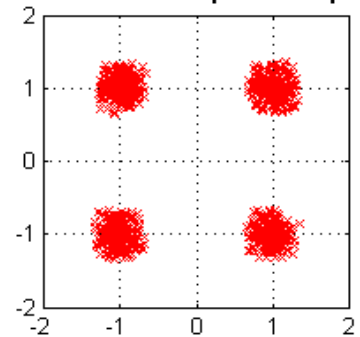
Constellation Input to Channel



Constellation Input to Receiver

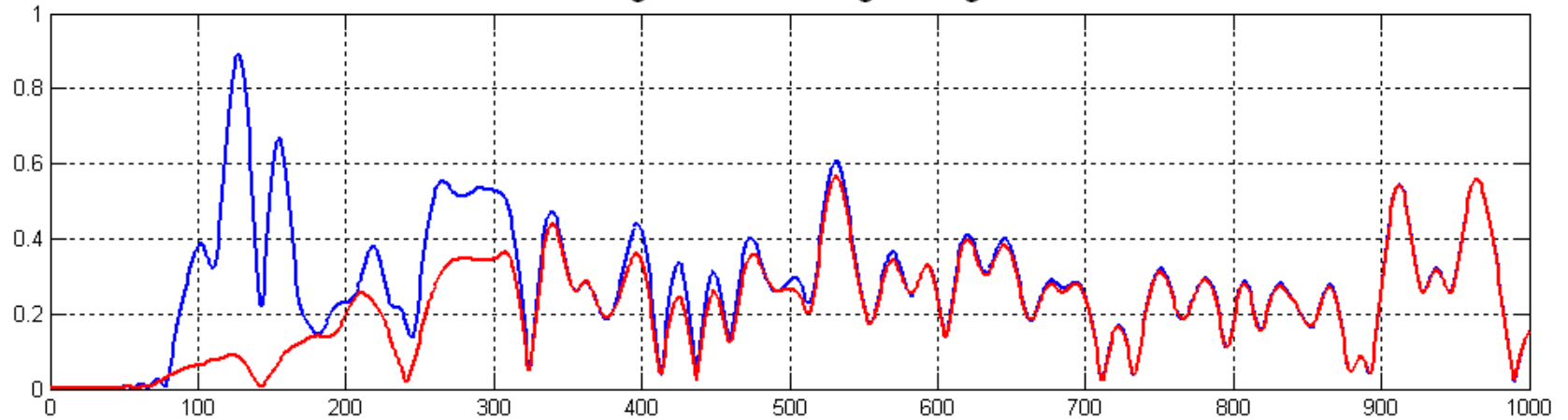


Constellation Output Freq. Loop

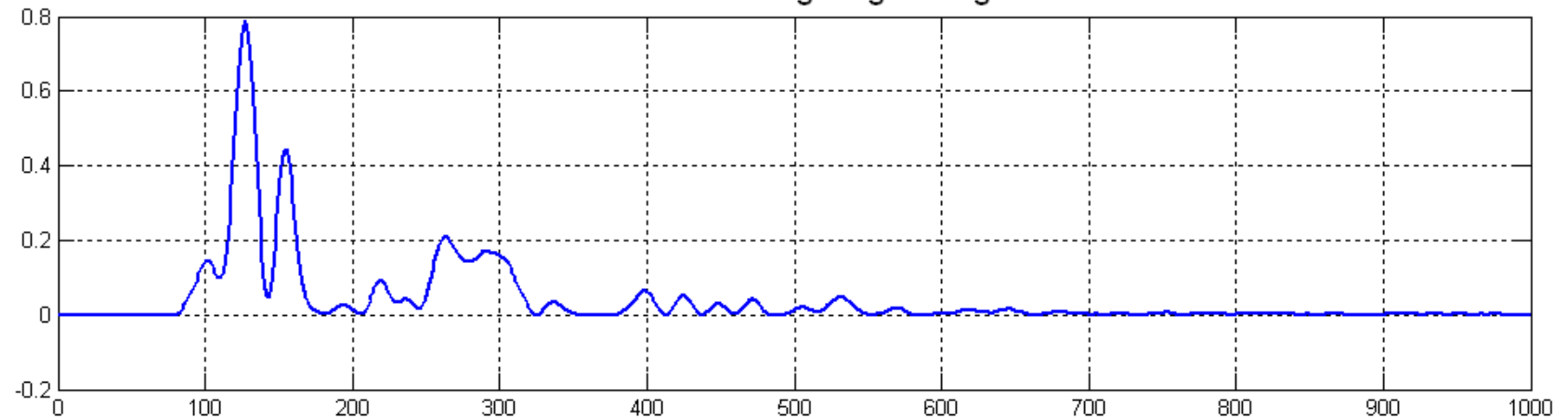


Time Series from BE Filters During Frequency Acquisition

Band Edge Filter Time Signal Magnitude

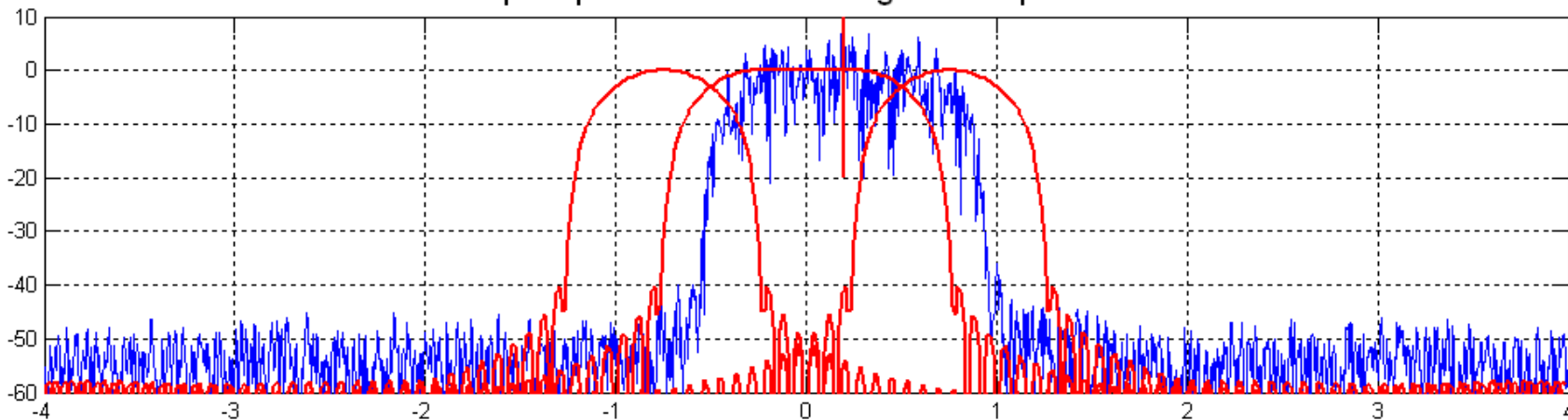


Difference in Band Edge Signal Magnitudes

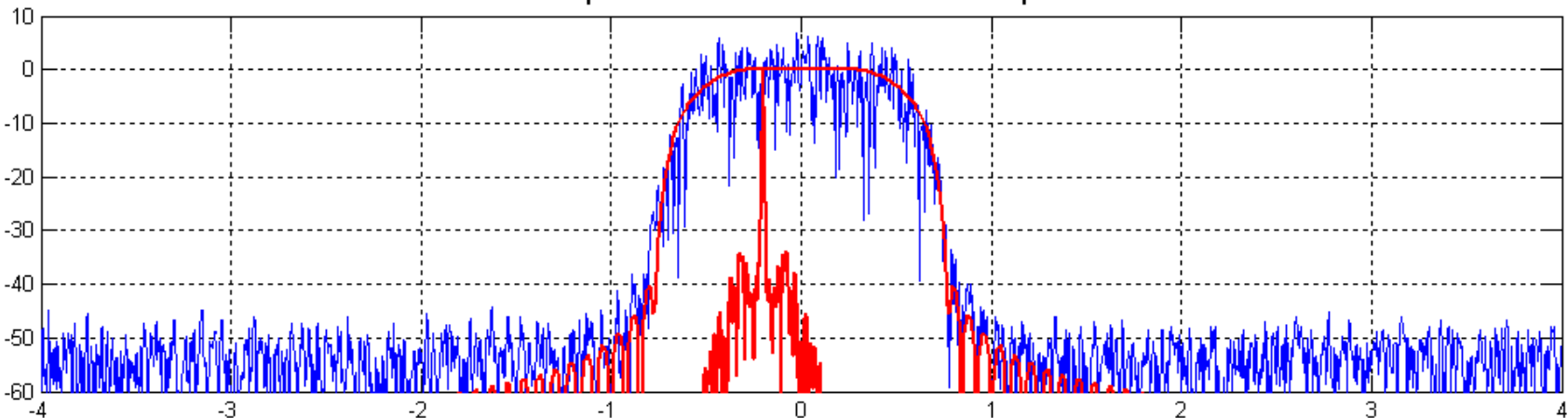


Frequency Offset Spectra and Minimum Phase BE Filters in Frequency Lock Loop

Input Spectrum and Band Edge Filter Spectrum

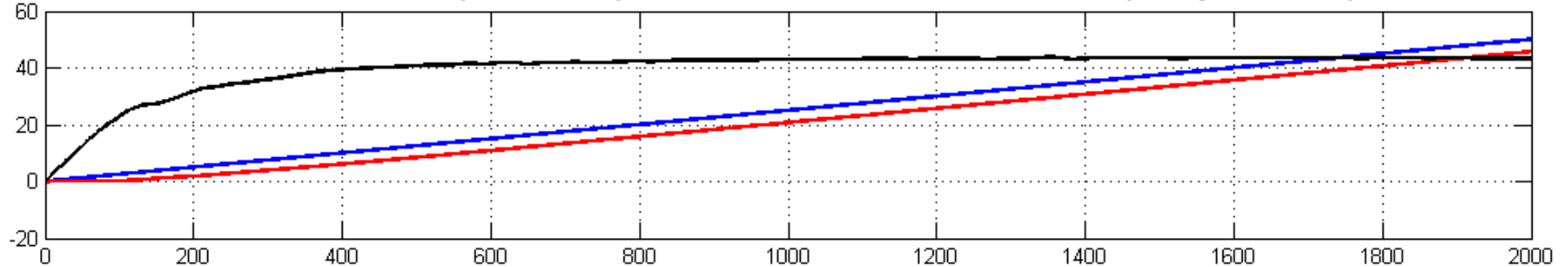


Shifted Spectrum and Down-Converter Spectrum

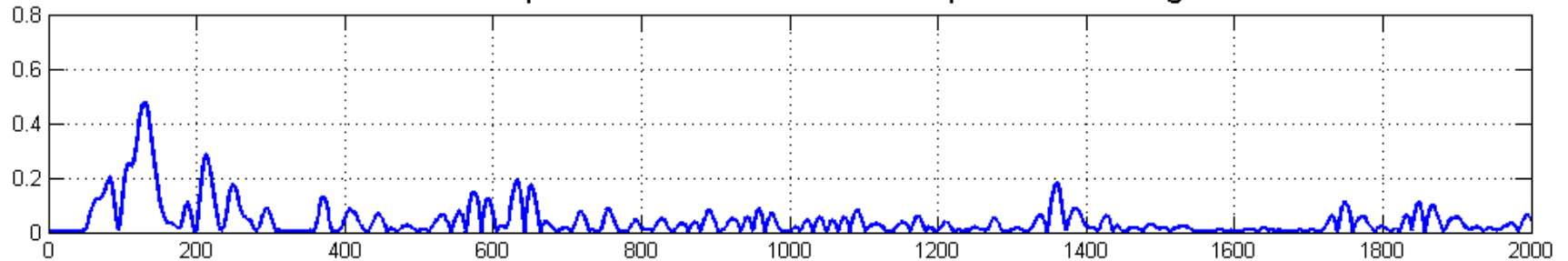


Phase Profiles of Freq Lock Loop

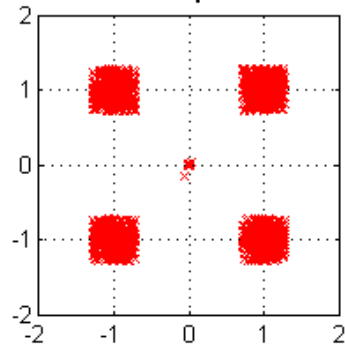
Phase Profile of Input and Output and 10 x Phase Difference of Frequency Lock Loop



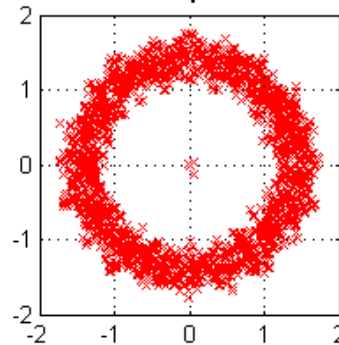
Instantaneous Amplitude Difference Between Outputs of Band Edge Filters



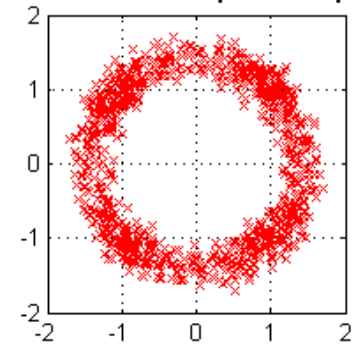
Constellation Input to Channel



Constellation Input to Receiver

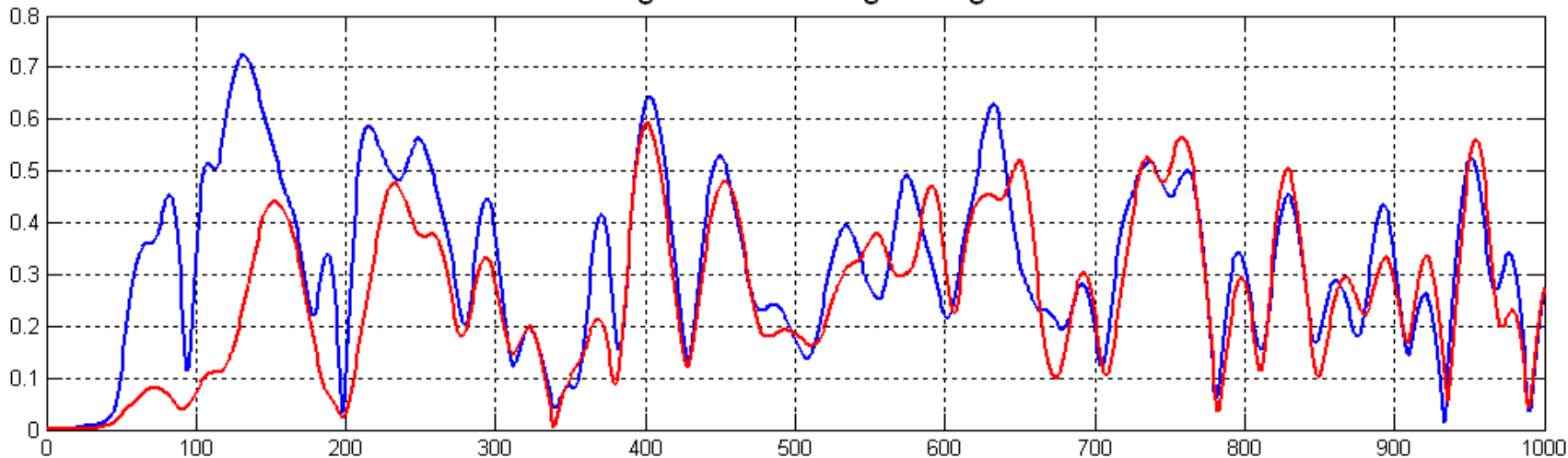


Constellation Output Freq Loop

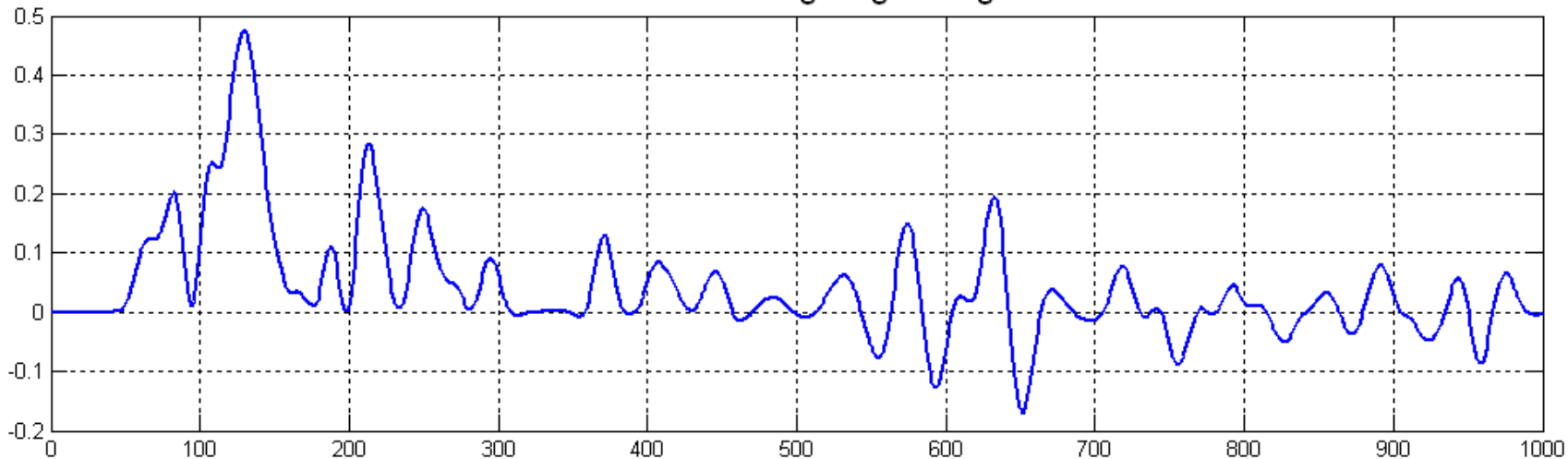


Time Series from BE Filters During Frequency Acquisition

Band Edge Filter Time Signal Magnitude

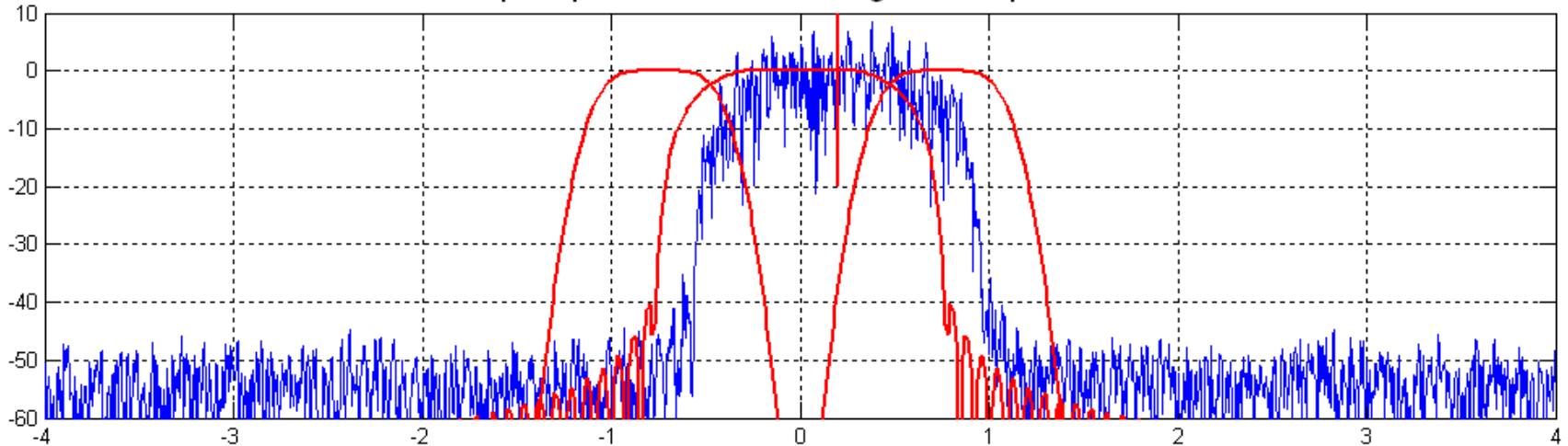


Difference in Band Edge Signal Magnitudes

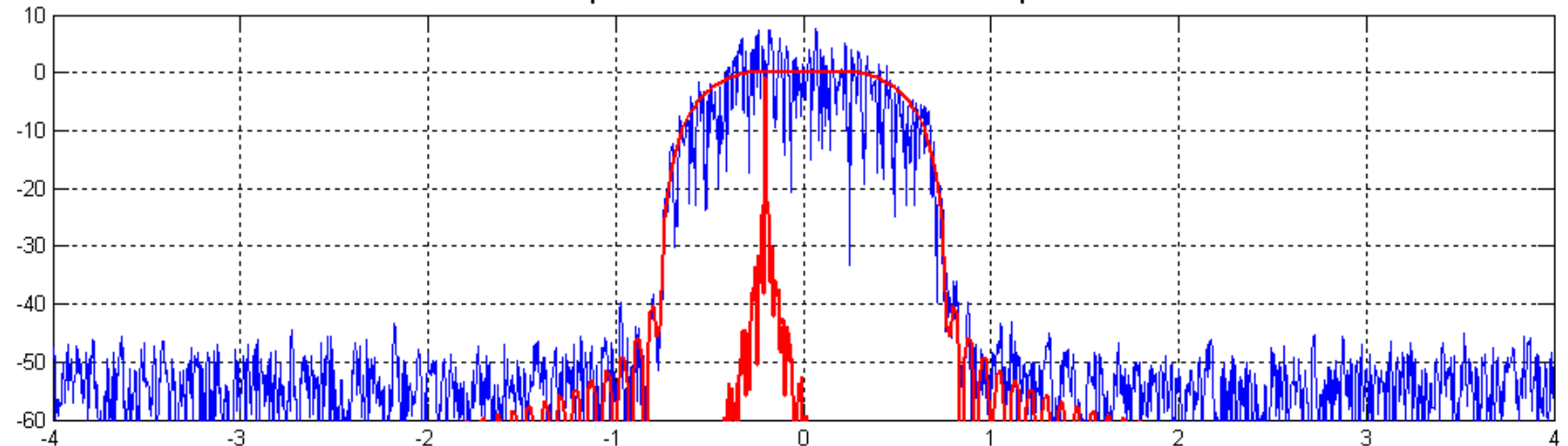


Frequency Offset Spectra and Linear Phase FIR Substitute for BE Filters in Frequency Lock Loop

Input Spectrum and Band Edge Filter Spectrum

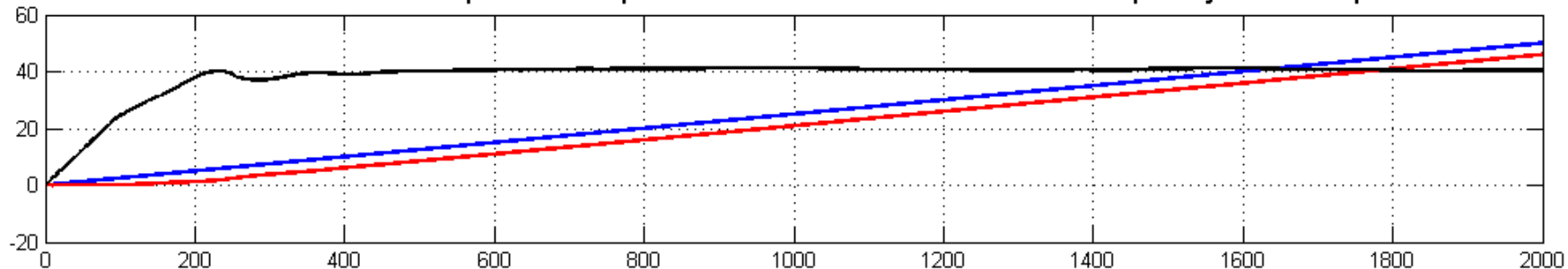


Shifted Spectrum and Down-Converter Spectrum

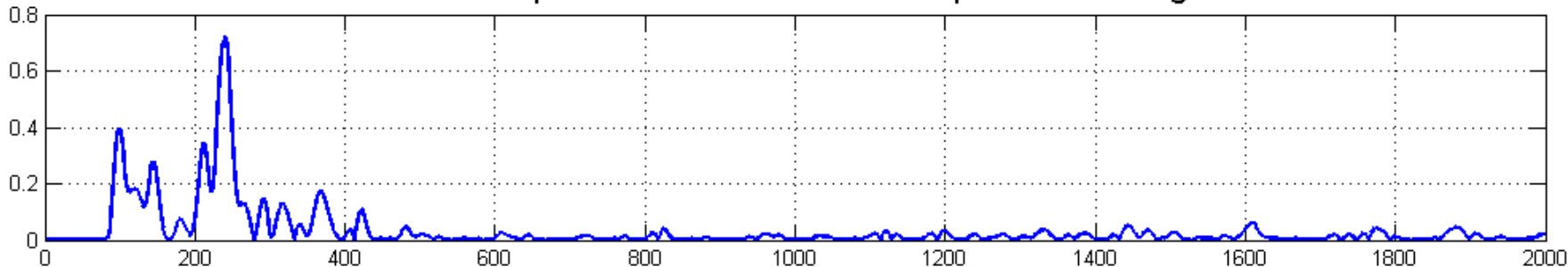


Phase Profiles of Freq Lock Loop

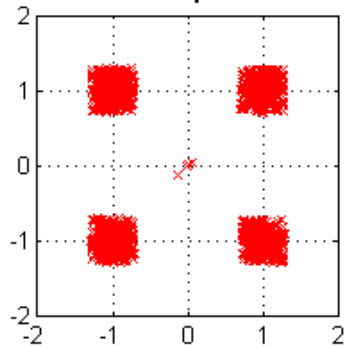
Phase Profile of Input and Output and $10 \times$ Phase Difference of Frequency Lock Loop



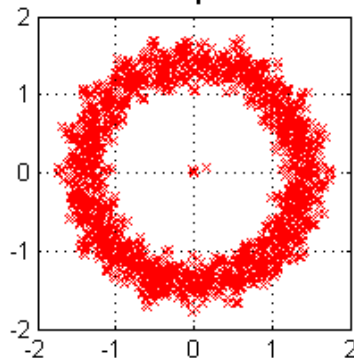
Instantaneous Amplitude Difference Between Outputs of Band Edge Filters



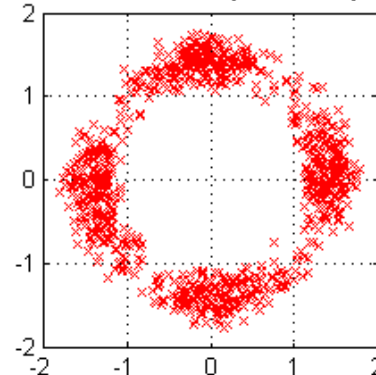
Constellation Input to Channel



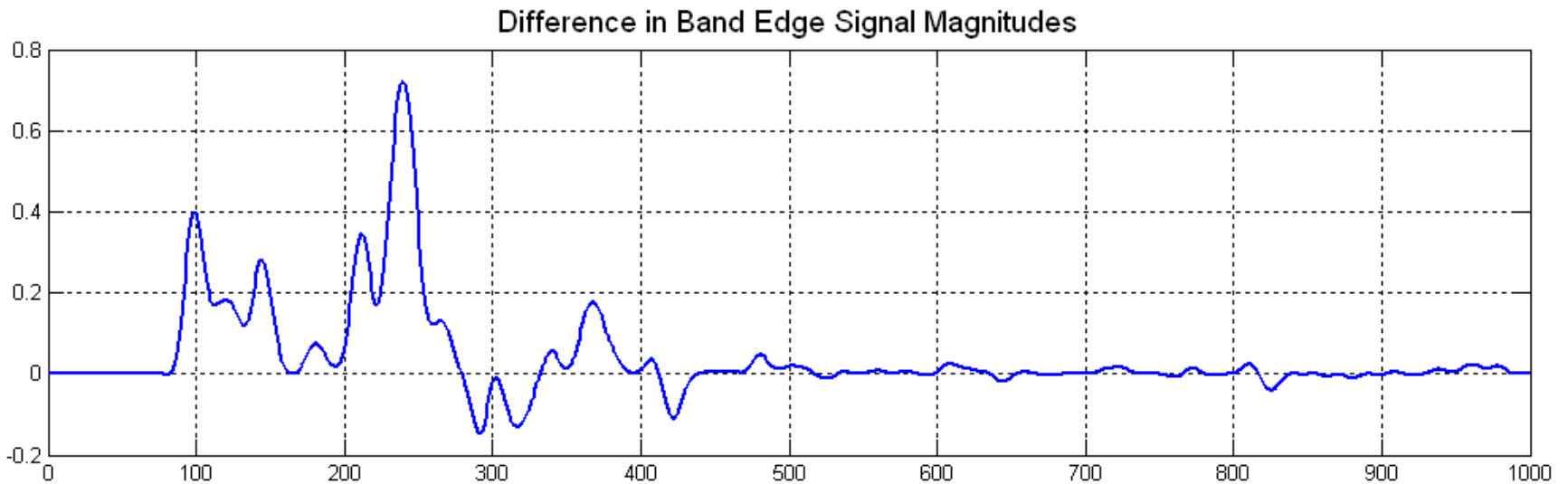
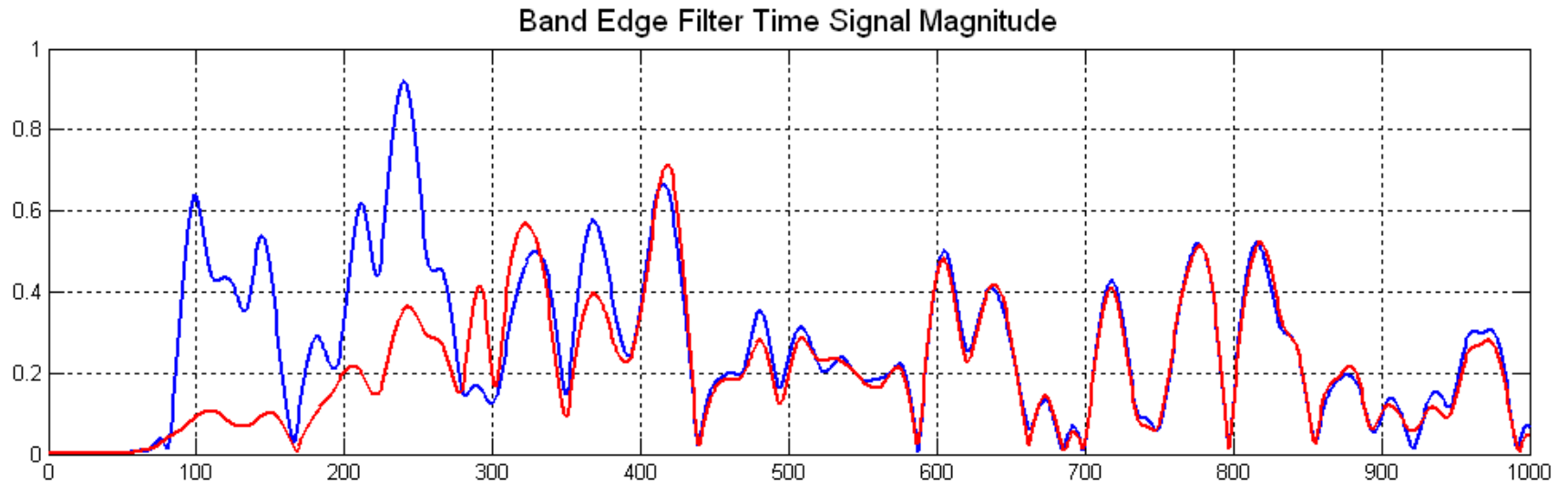
Constellation Input to Receiver



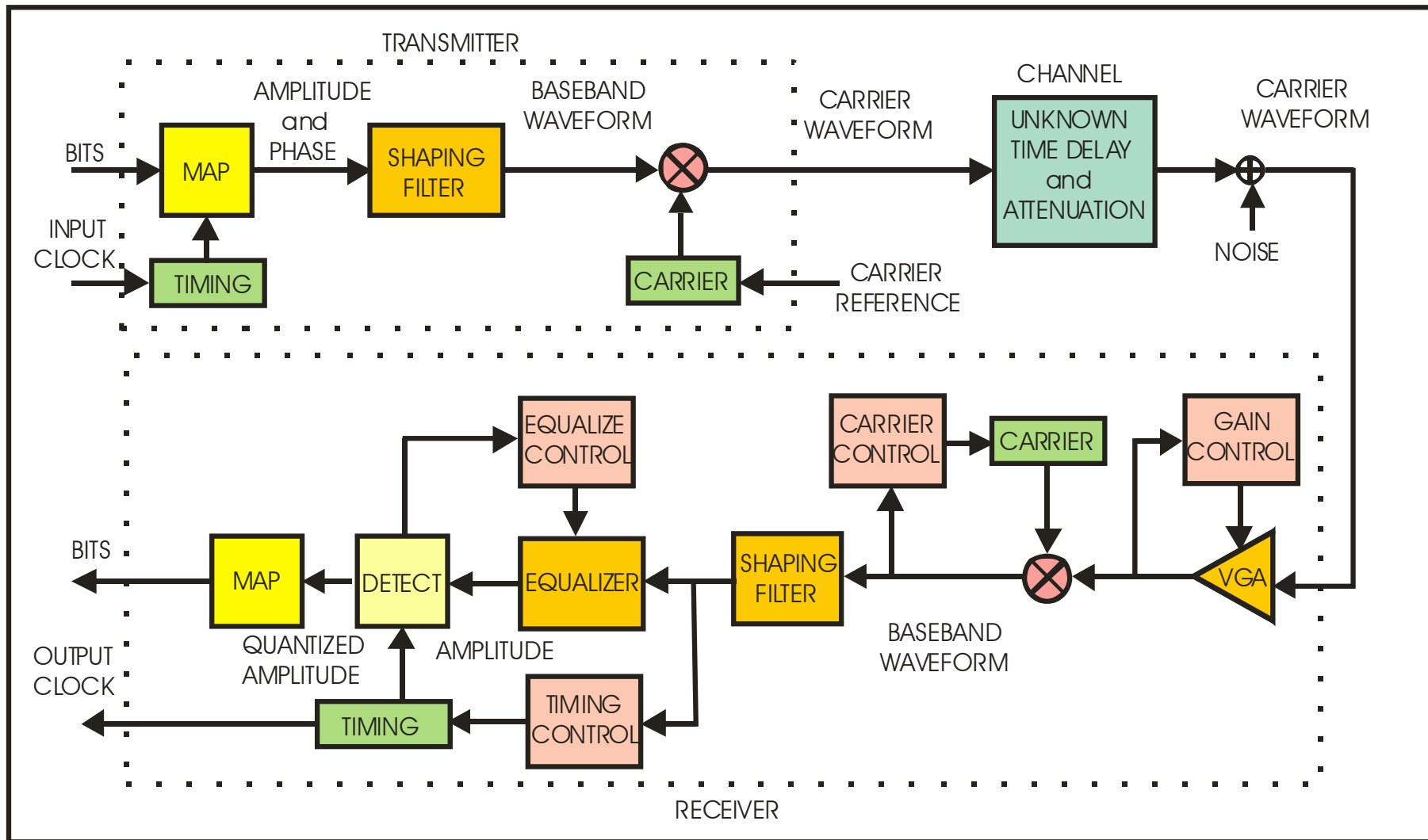
Constellation Output Freq Loop



Time Series from BE Filters During Frequency Acquisition

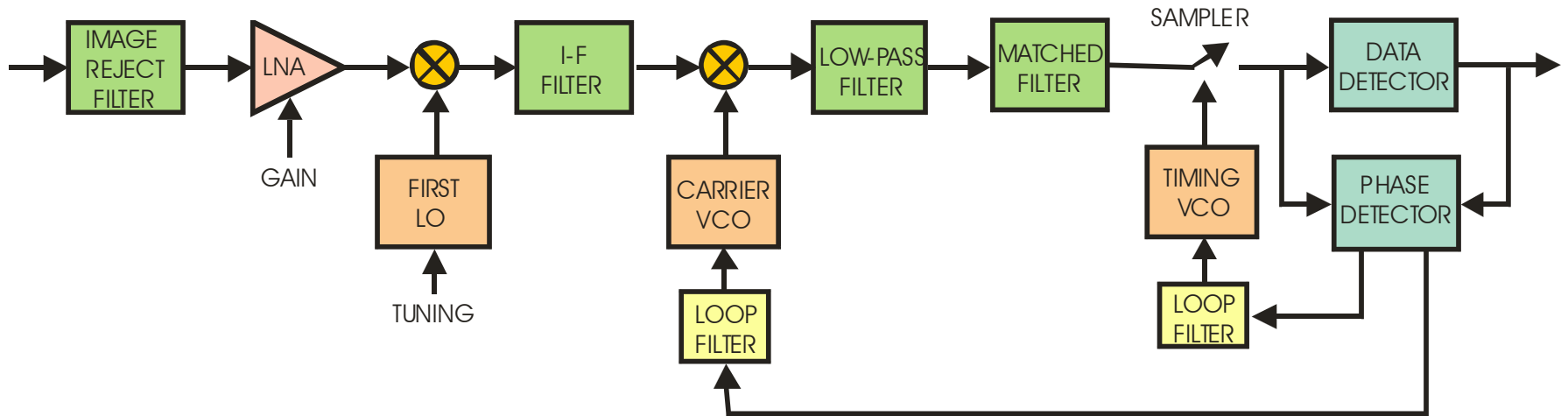


Asymmetric Processing

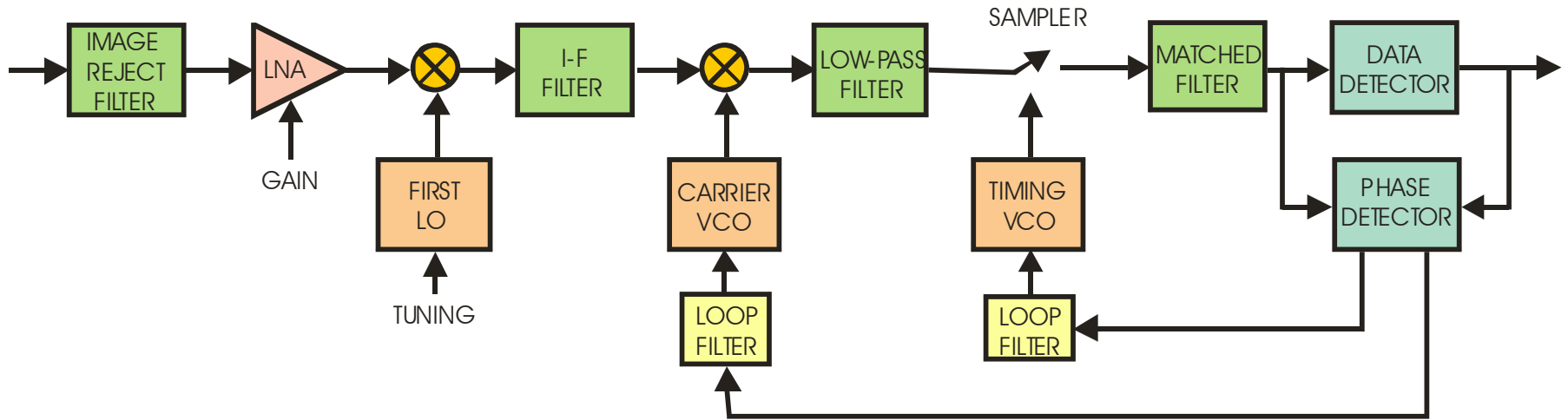


First Generation Receiver

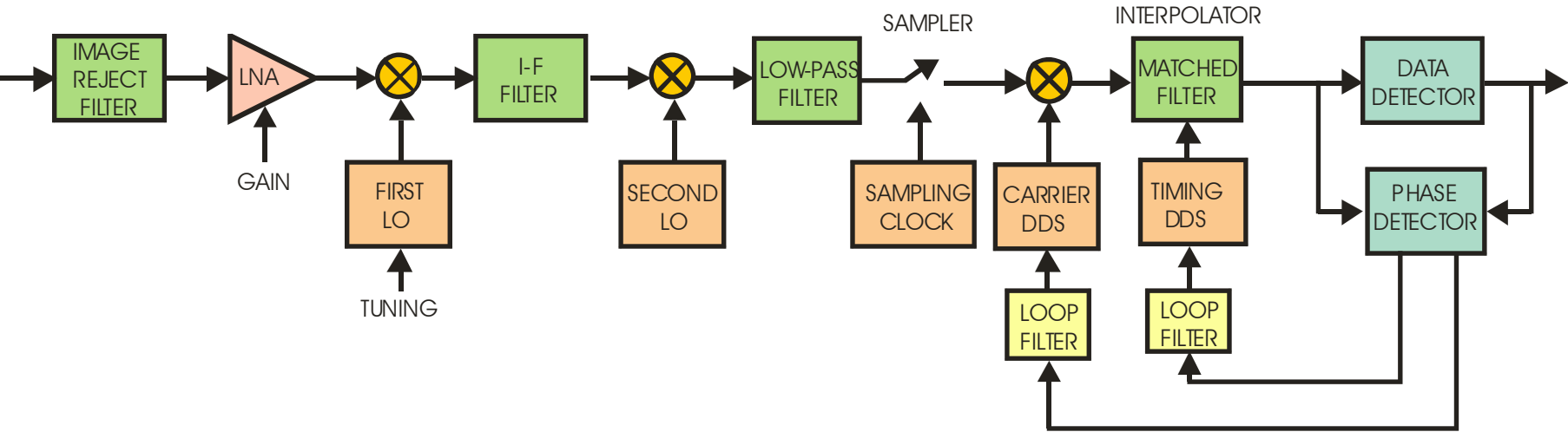
Analog Signal Conditioning



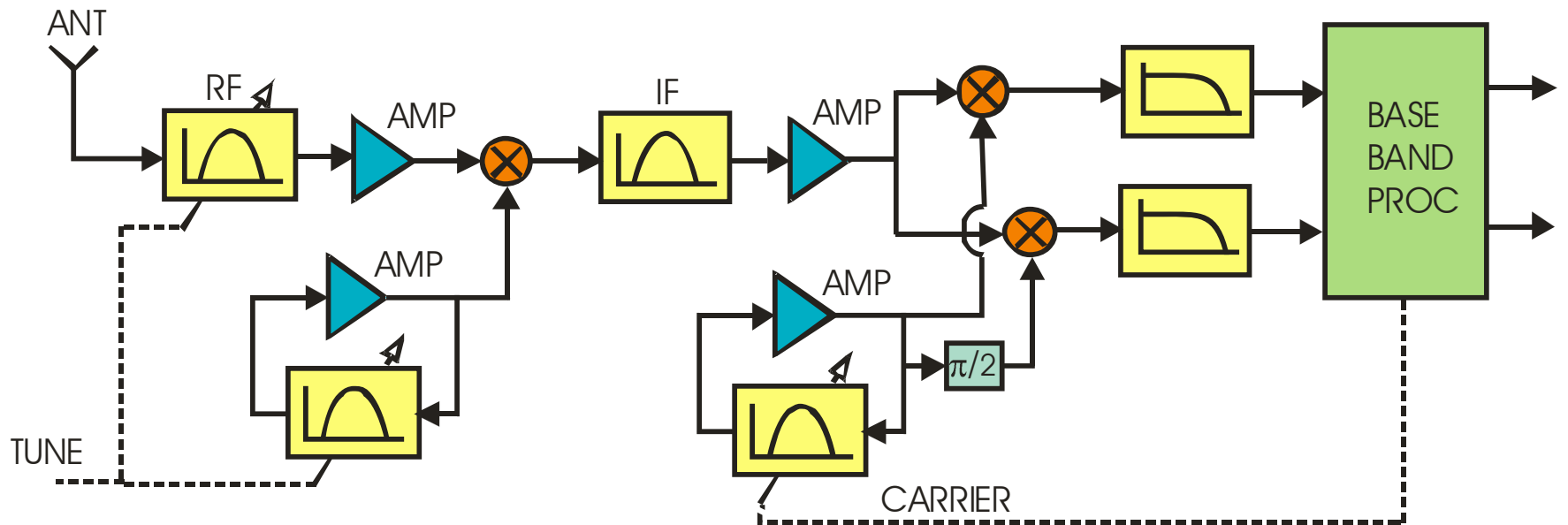
Second Generation Receiver DSP Based Signal Processing



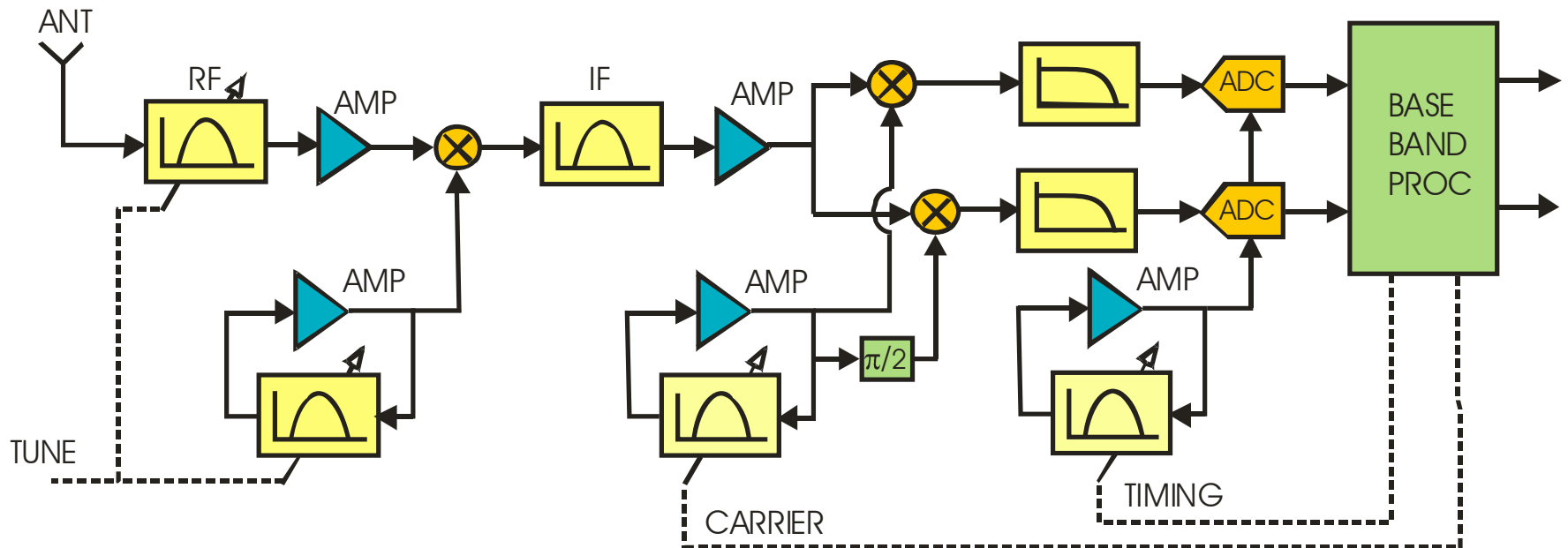
Third Generation Receiver DSP Based Signal Conditioning



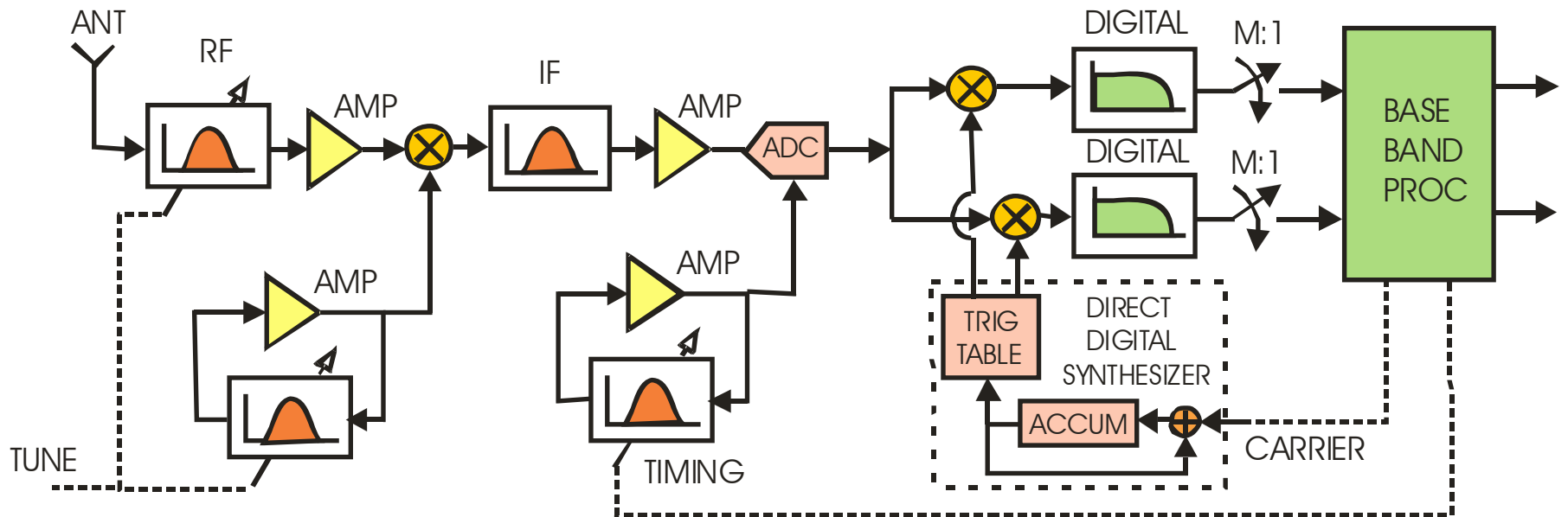
Build Your Own Carrier for Final Down Conversion



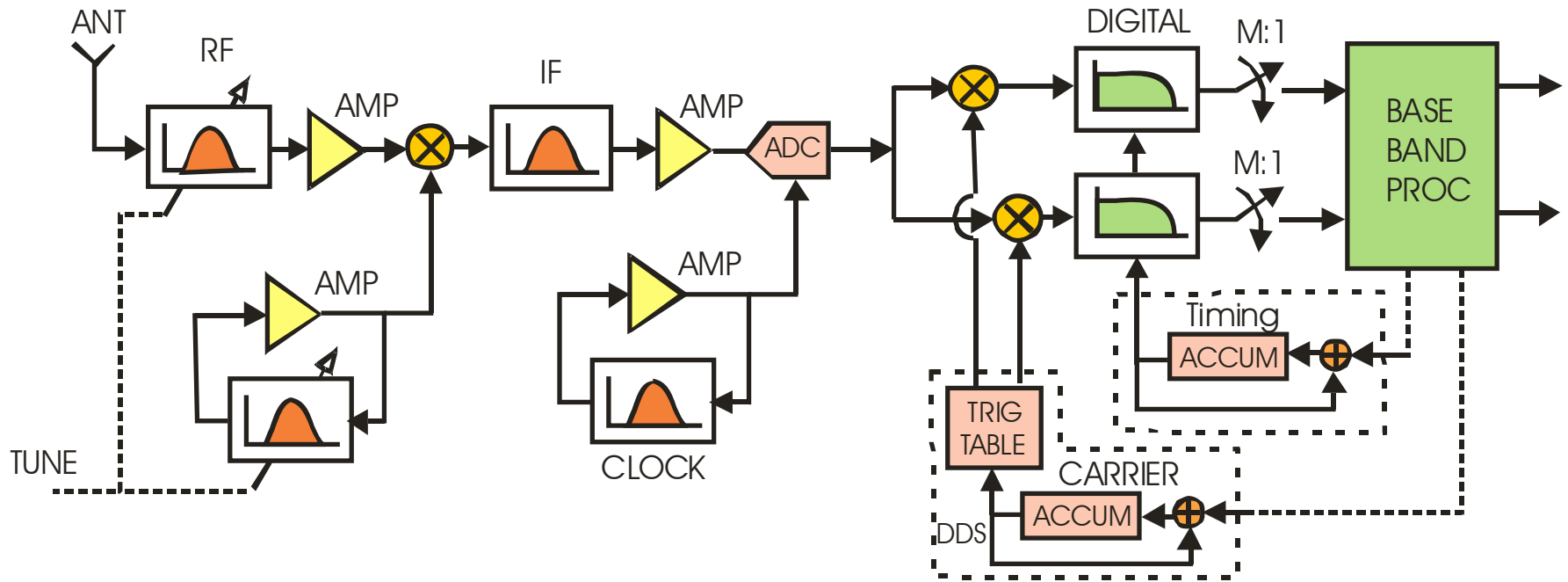
First Generation Digital Receiver



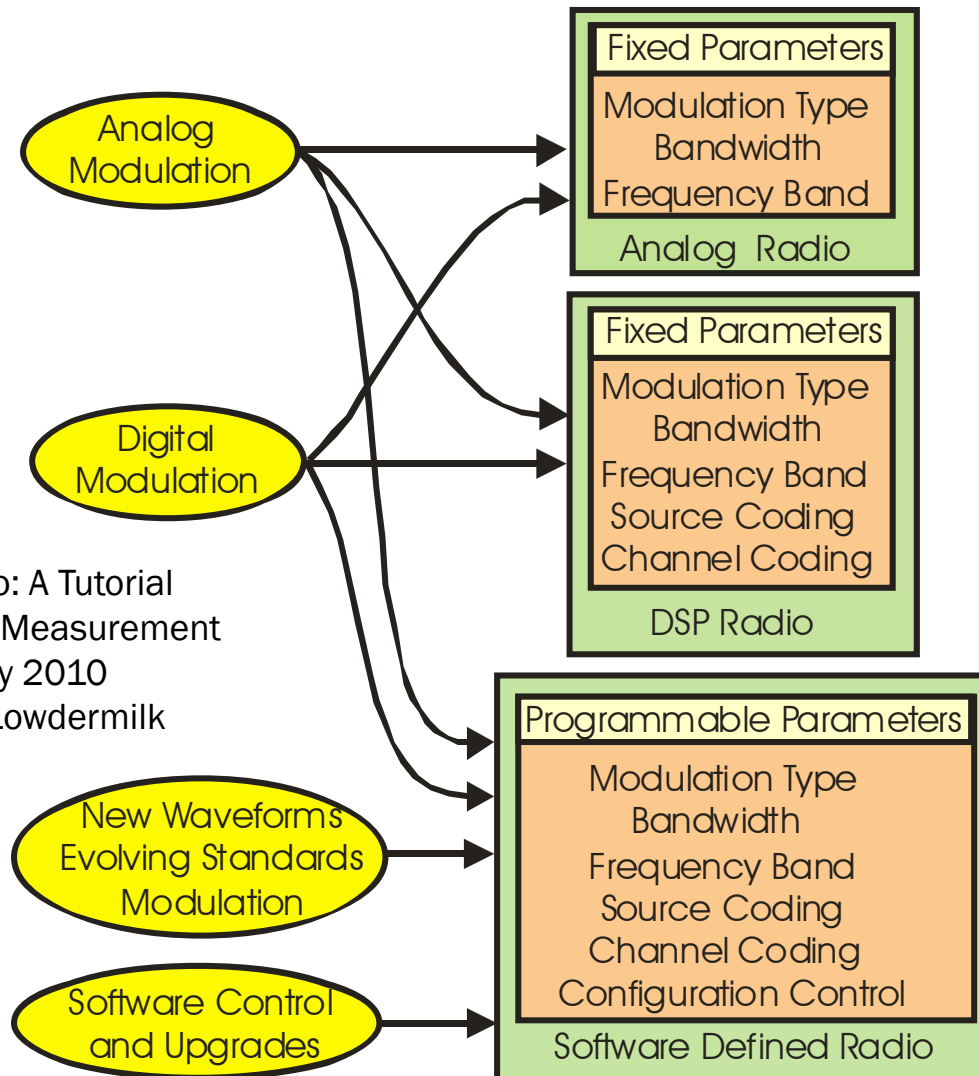
Second Generation Digital Receiver



Third Generation Digital Receiver

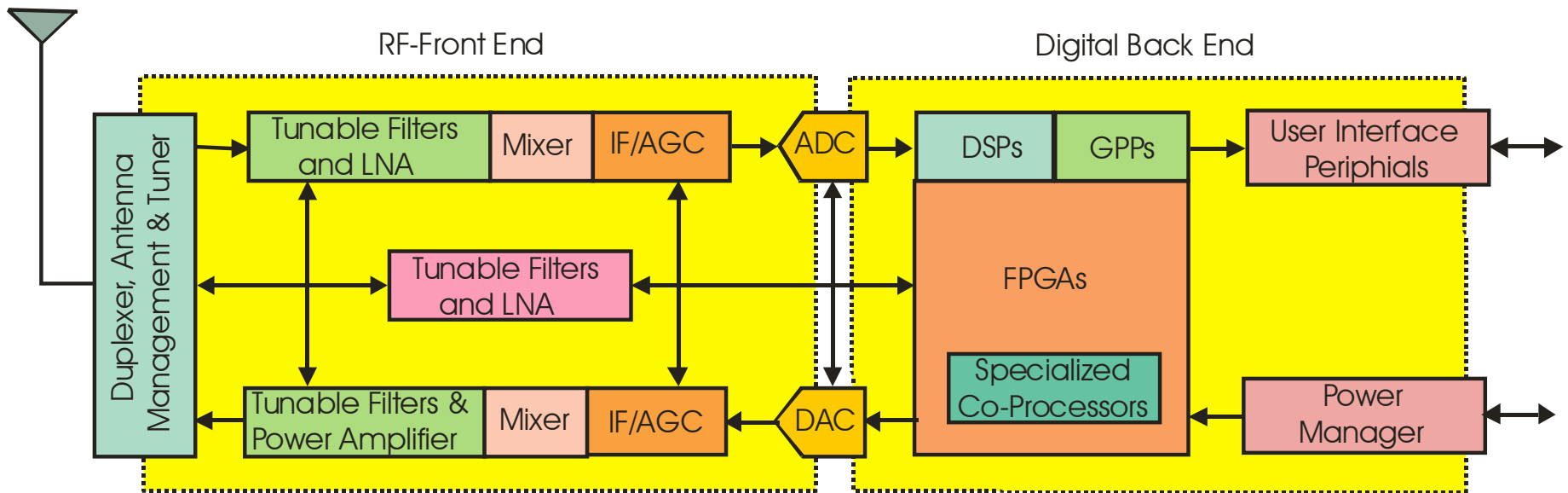


Signals and Underlying Structure of Analog Radio, DSP Radio, and Software Defined Radio

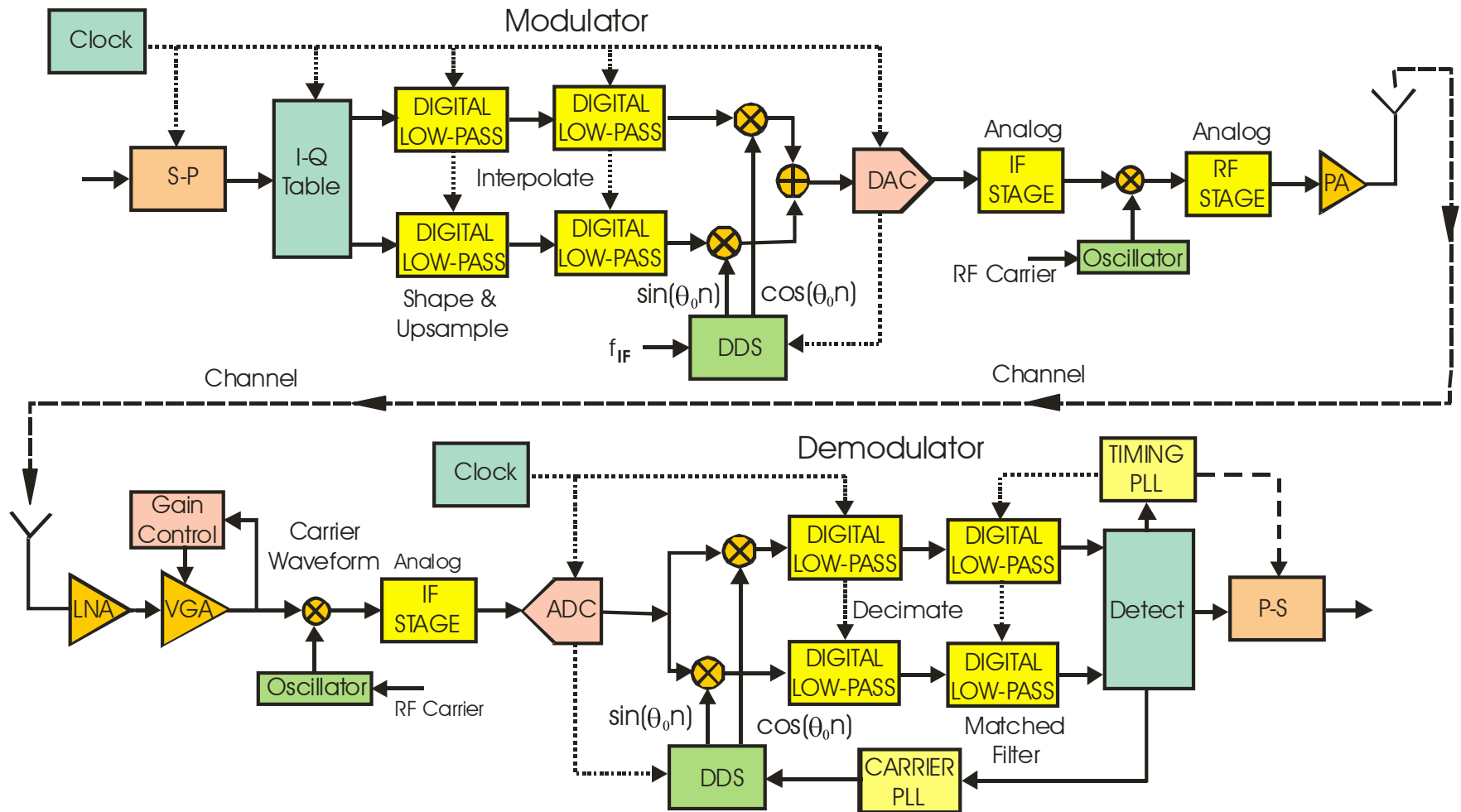


Software Defined Radio: A Tutorial
IEEE Instrumentation and Measurement
Magazine, February 2010
fred harris and Wade Lowdermilk

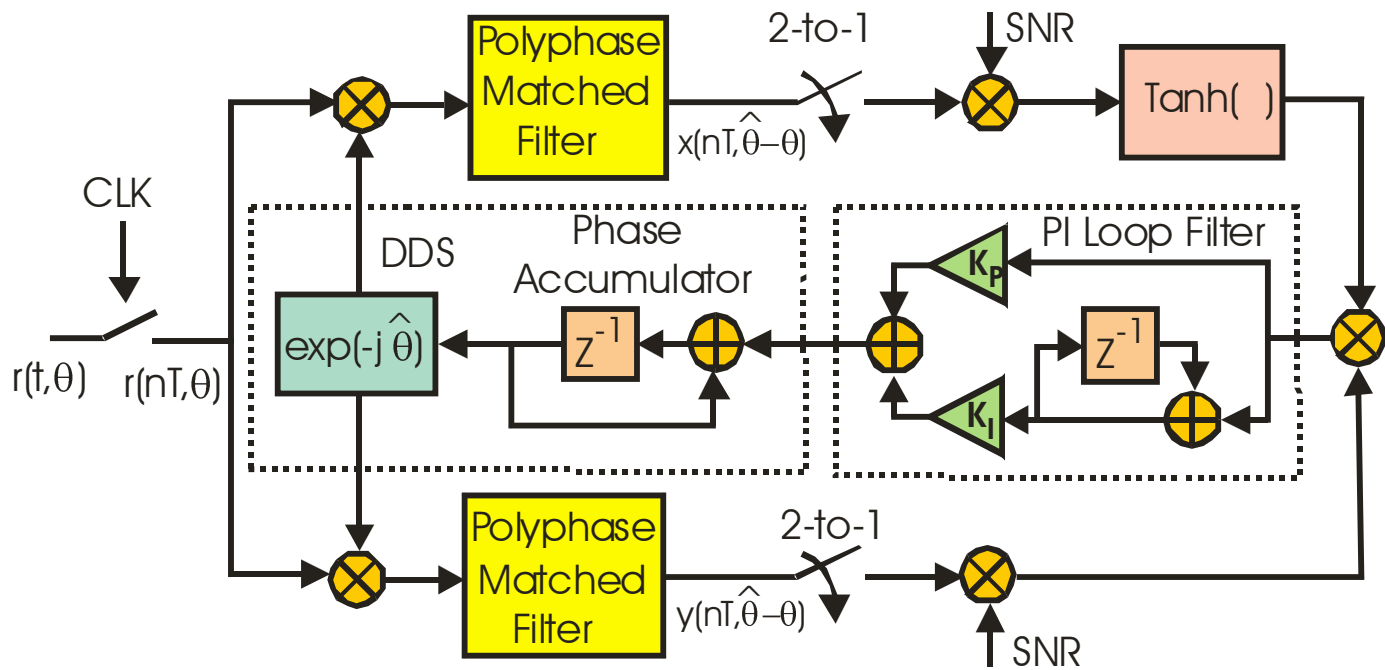
High Level Block Diagram of Software Defined Radio. Radio is segmented into RF Processing Front End Block, Baseband Waveform Digital Signal Processing Back End Block, and Interface to Data Processing Higher Level User Application and Interface Blocks.



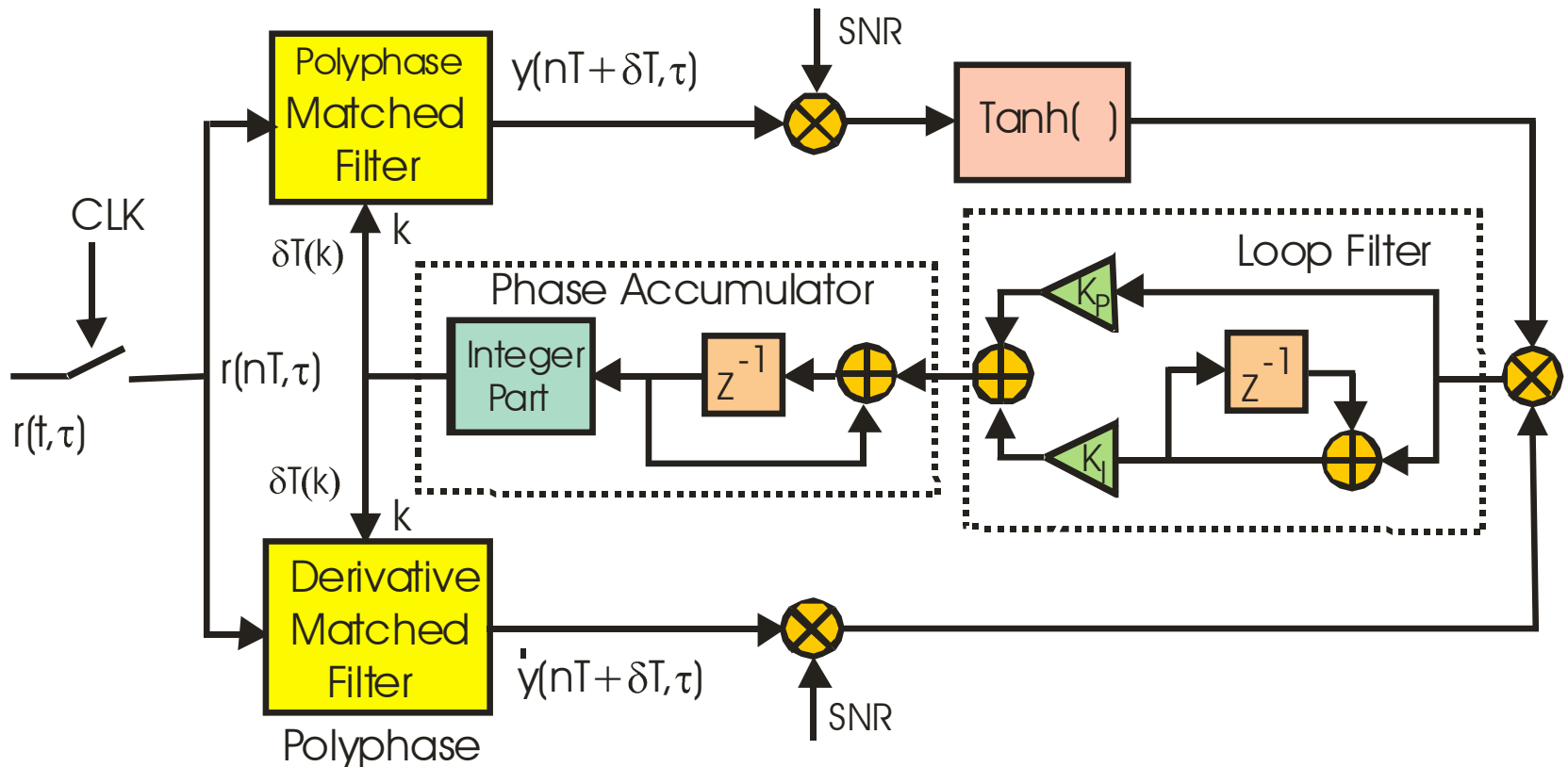
First Tier, Primary Signal Processing Tasks in a Typical Transmitter and Receiver



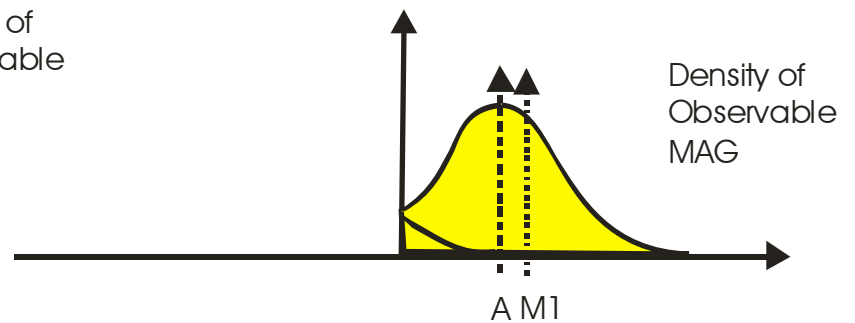
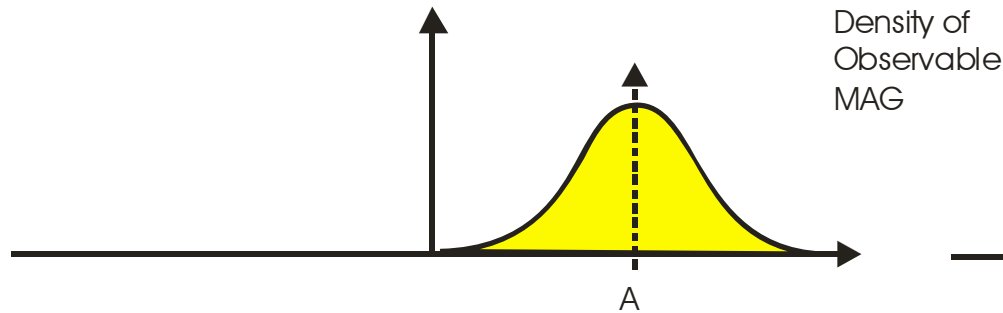
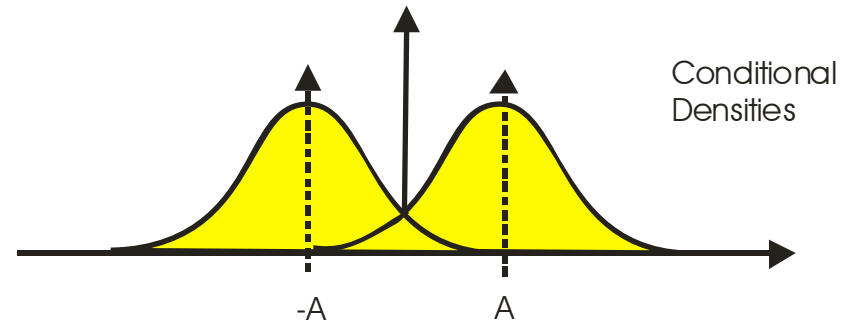
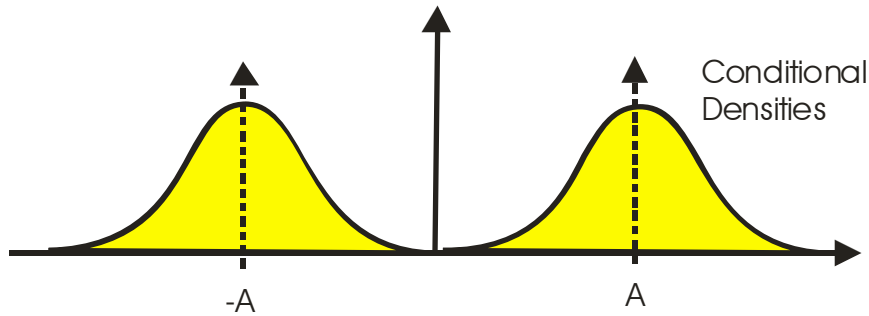
Second Tier Signal Processing Task, Carrier Recovery Phase Locked Loop



Second Tier Signal Processing Task, Timing Recovery Phase Locked Loop



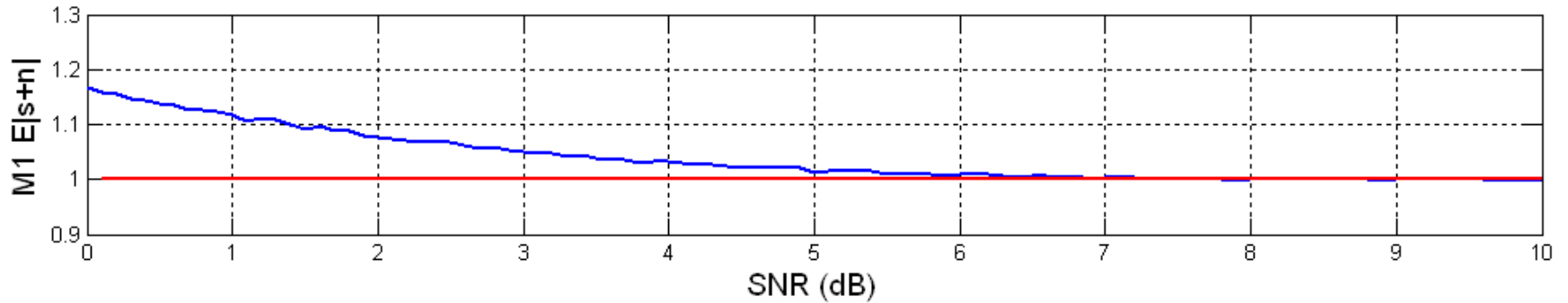
Estimate Signal Mean and Variance at High SNR and Low SNR



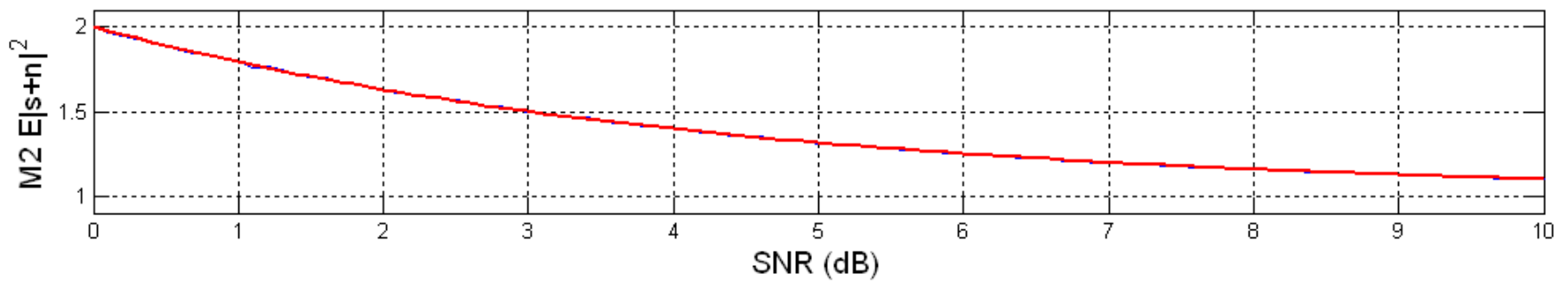
Estimate of Mean is too High
Estimate of variance is too Low

Estimates of Moments and SNR as Function of SNR

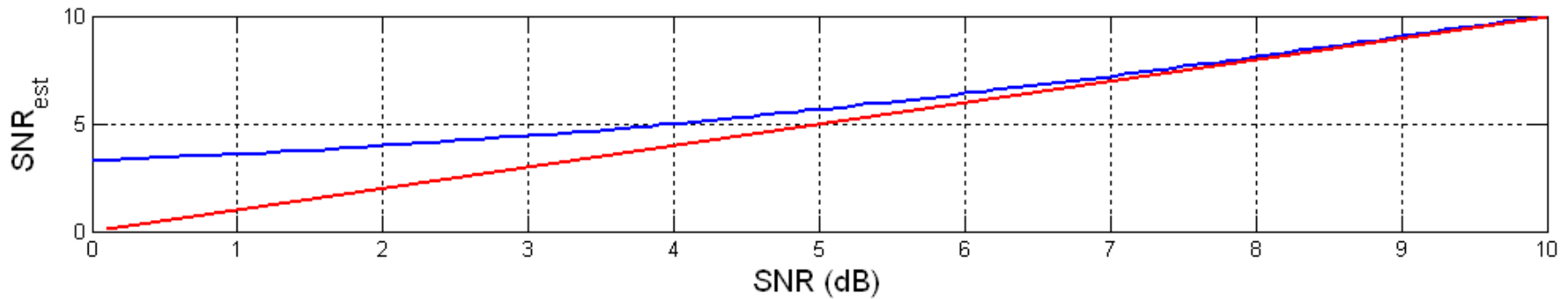
Estimate of M1



Estimate of M2

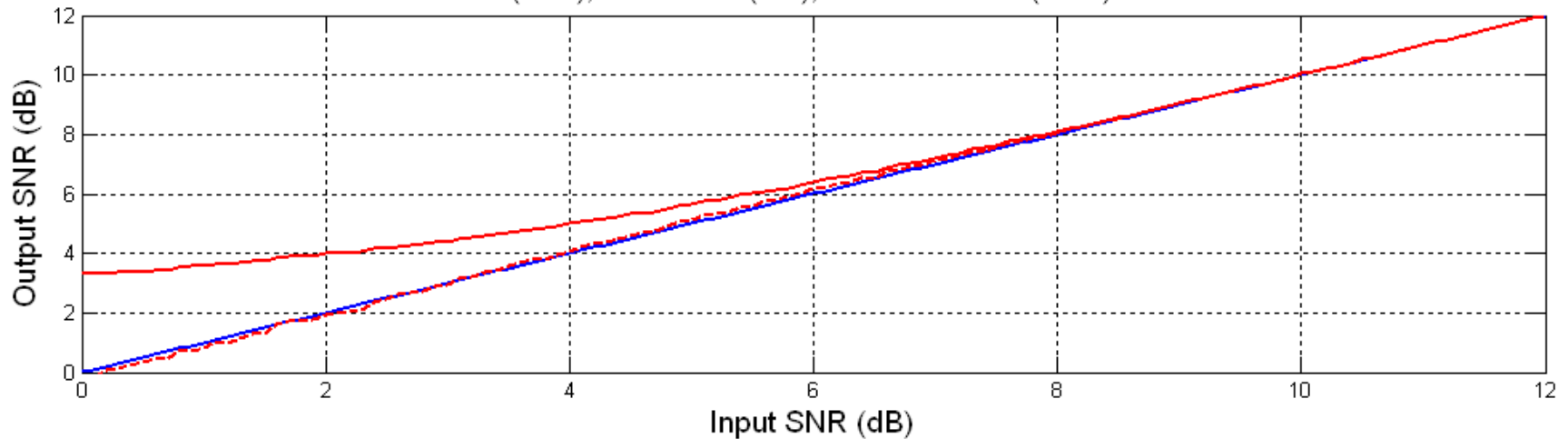


Estimate of SNR

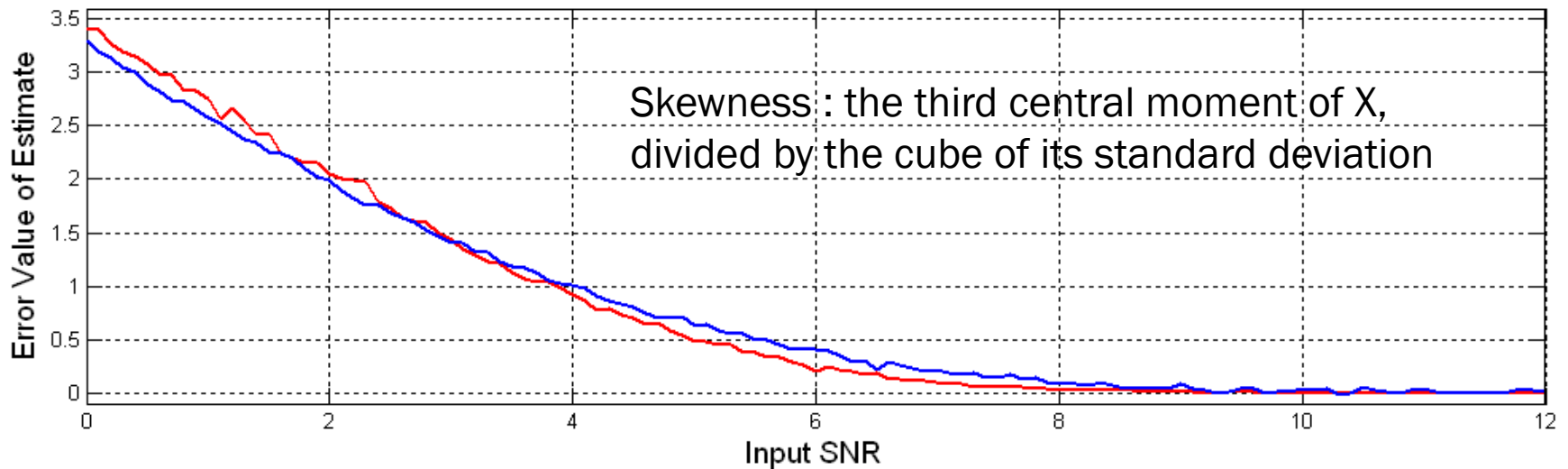


Skewness: A Measure of Estimated SNR Error

True (blue), Estimated (red), and Corrected (---red) SNR

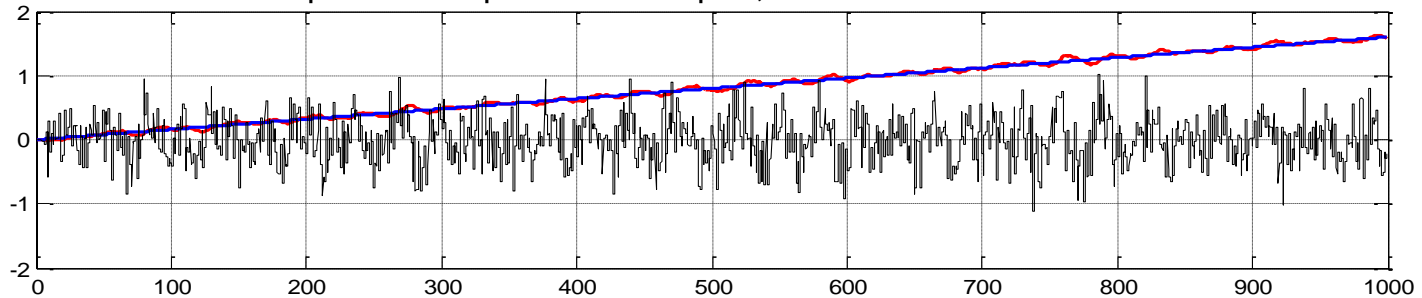


SNR Error (blue) and $7 \cdot \text{Skewness}^2$ (red)

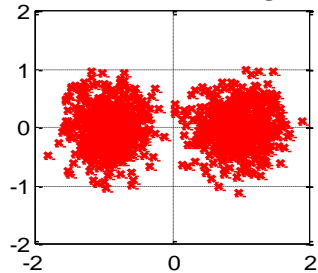


BPSK Large SNR Approximation to ML

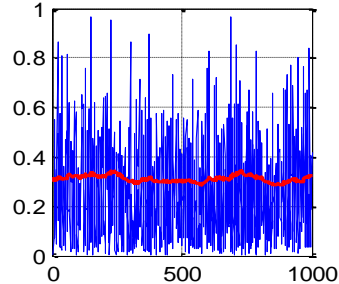
$\det(n) = \text{sign}(I(n)) * Q(n)$: Large SNR Approximation to ML Carrier Recovery
snr = 10.21dB Input and Output Phase Slopes, and Detected Phase Error



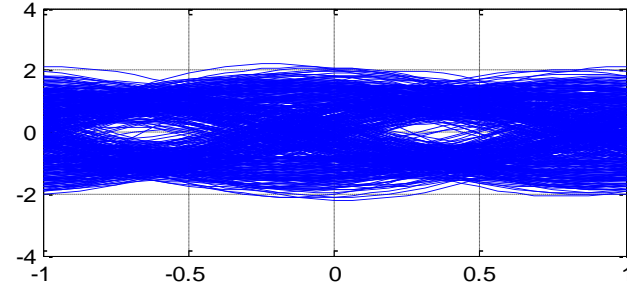
Constellation Diagram



Variance Estimate

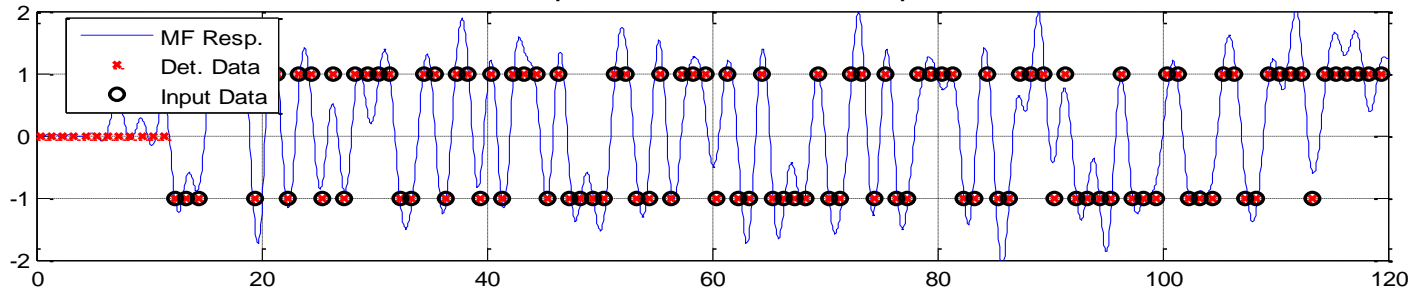


Eye Diagram



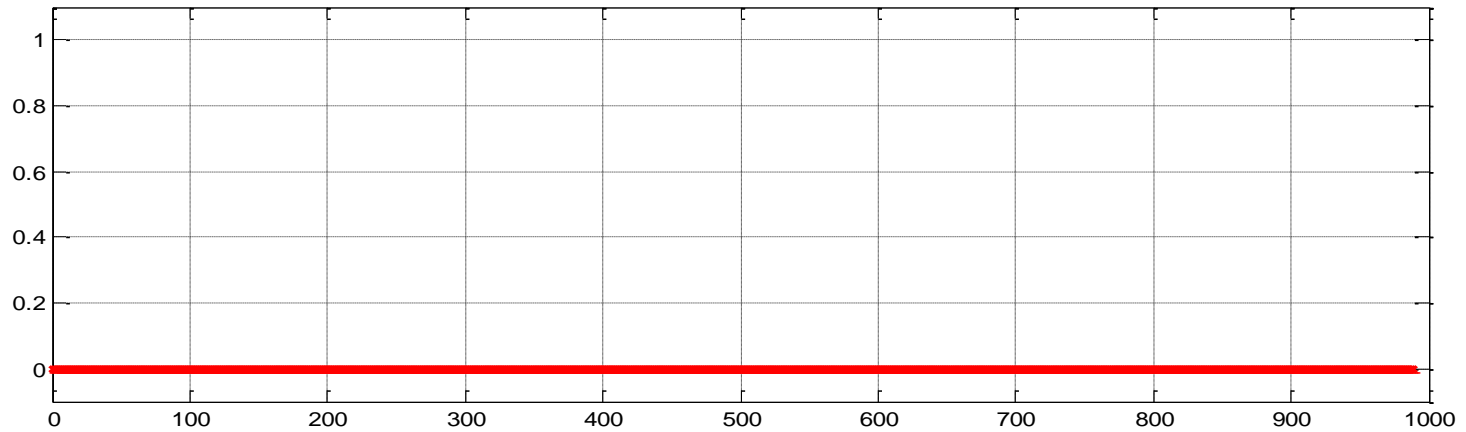
error rate = 0.00 %

De-Spun Matched Filter Output

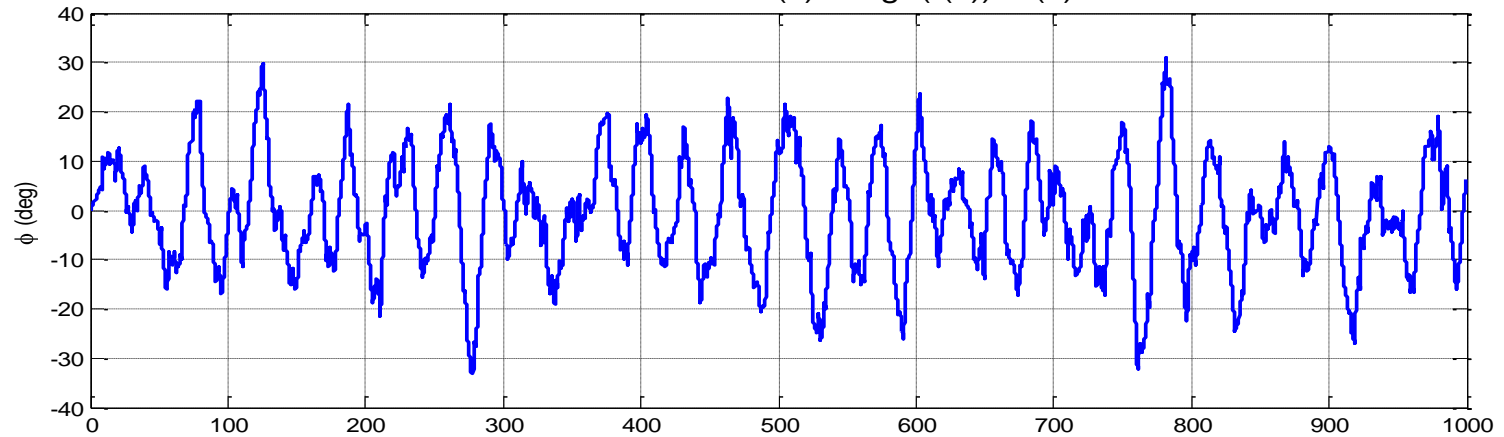


BPSK Large SNR Approximation to ML

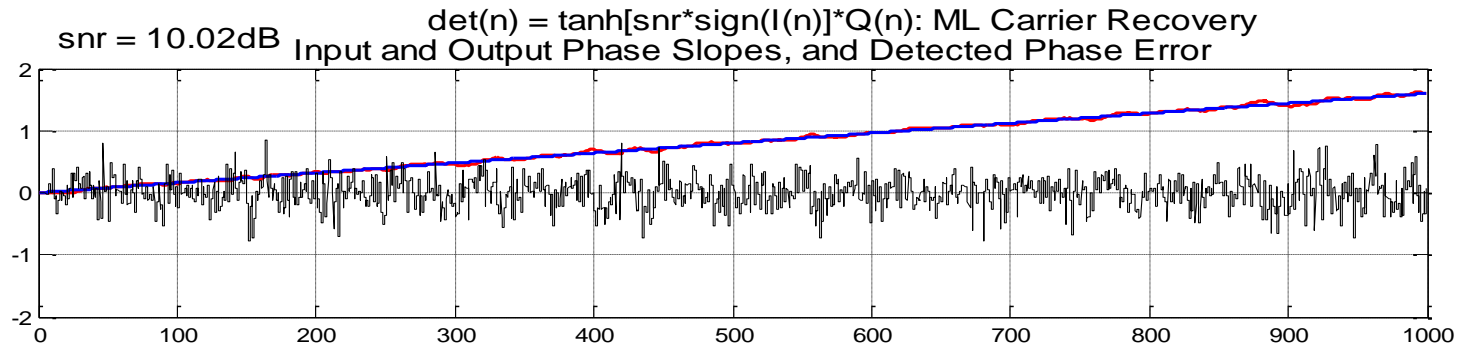
Error Locations



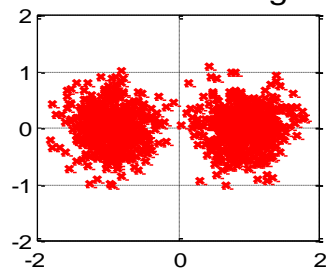
Phase Error for $\text{det}(n) = \text{sign}(I(n)) * Q(n)$



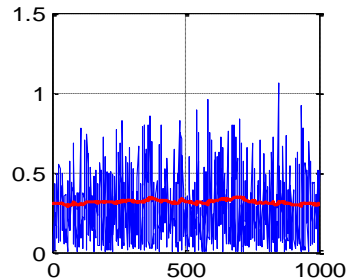
BPSK ML Carrier Recovery Loop



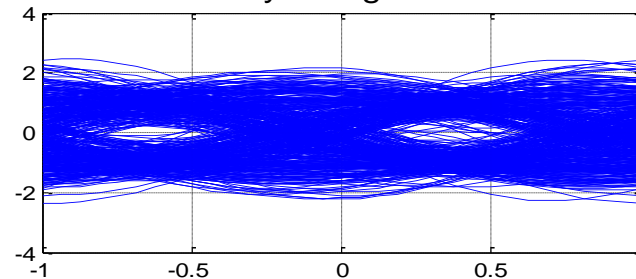
Constellation Diagram



Variance Estimate

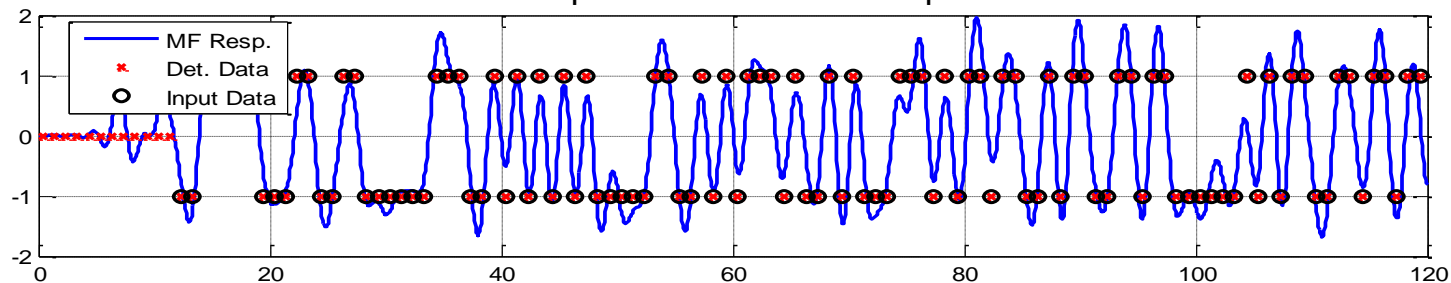


Eye Diagram



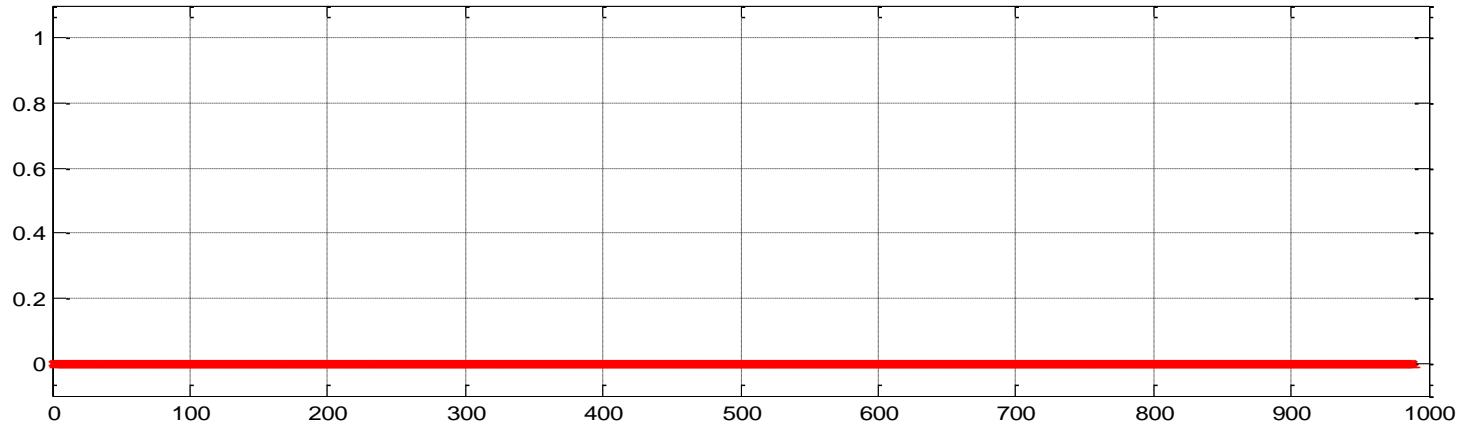
error rate = 0.00 %

De-Spun Matched Filter Output

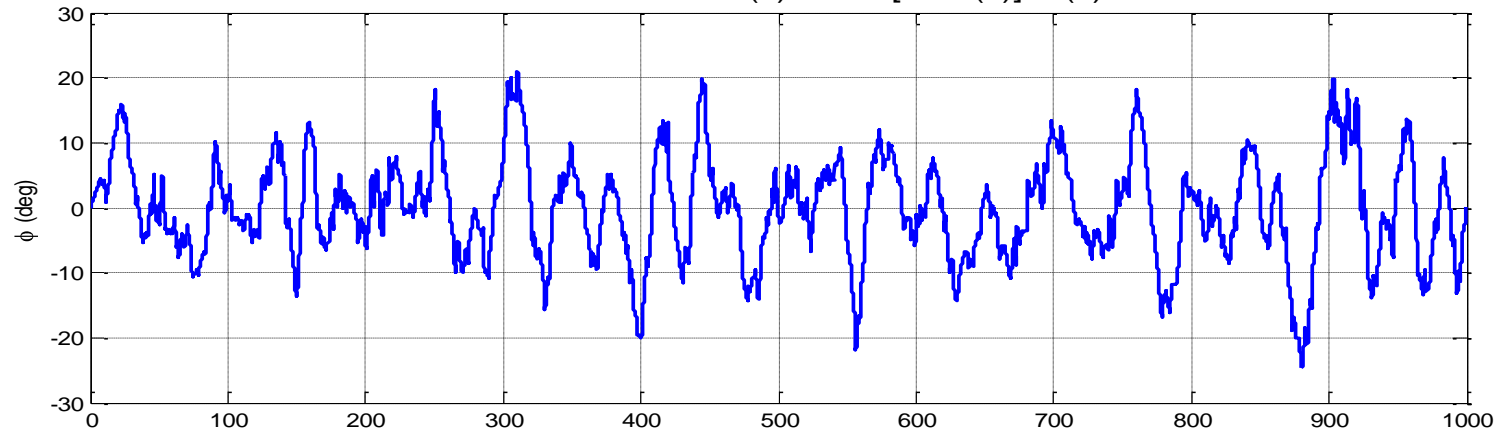


BPSK ML Carrier Recovery Loop

Error Locations

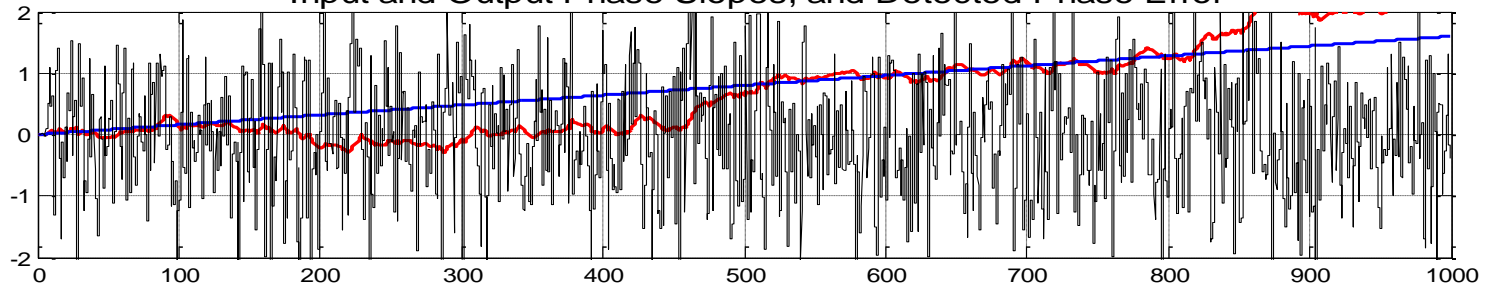


Phase Error for $\text{det}(n) = \tanh[\text{snr} \cdot I(n)] \cdot Q(n)$

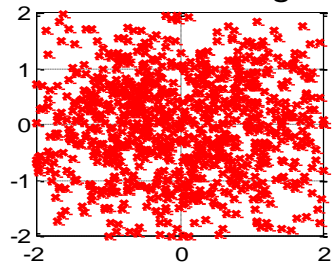


BPSK Large SNR Approximation to ML

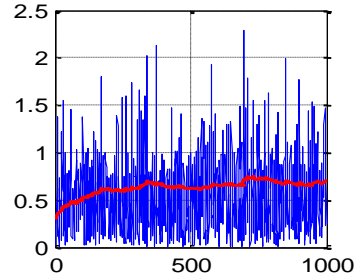
snr = 3.42dB $\det(n) = \text{sign}(I(n)) * Q(n)$: Large SNR Approximation to ML Carrier Recovery
Input and Output Phase Slopes, and Detected Phase Error



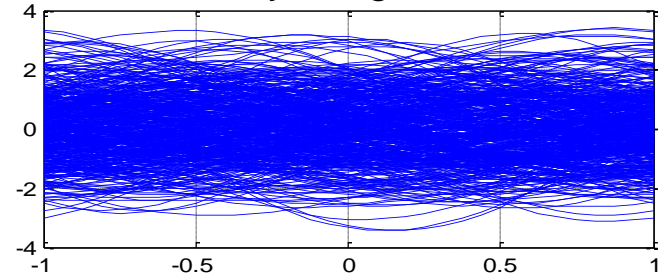
Constellation Diagram



Variance Estimate

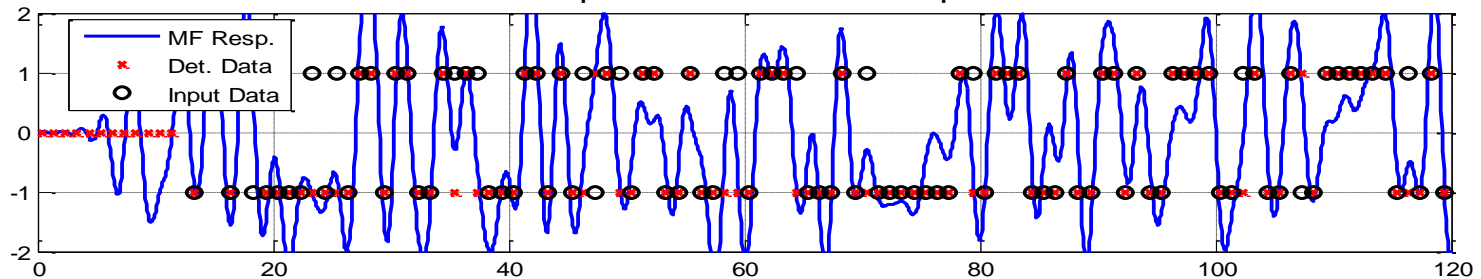


Eye Diagram



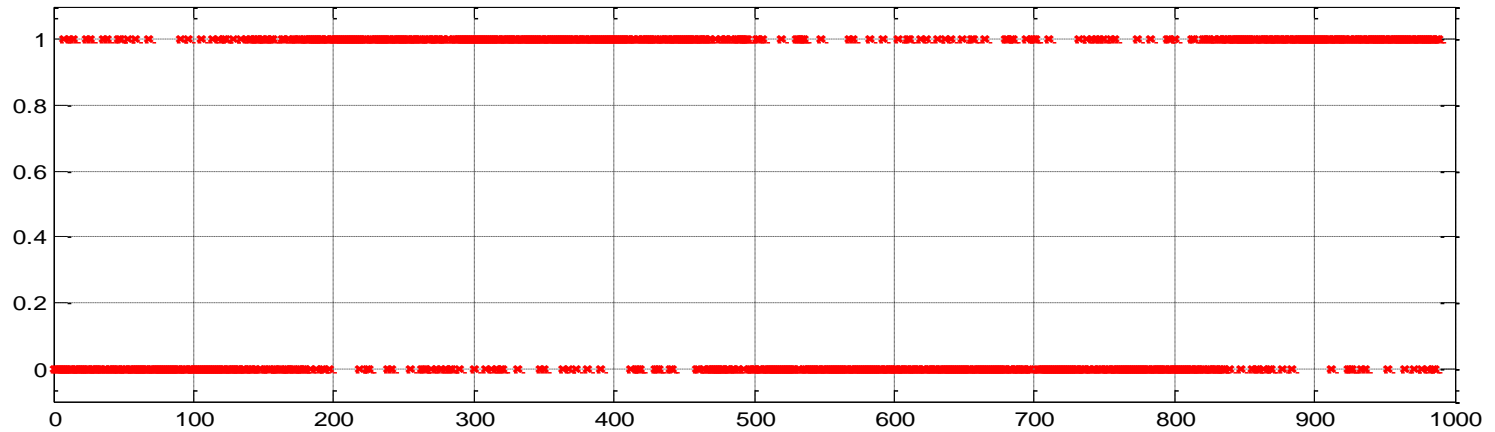
error rate = 48.53 %

De-Spun Matched Filter Output

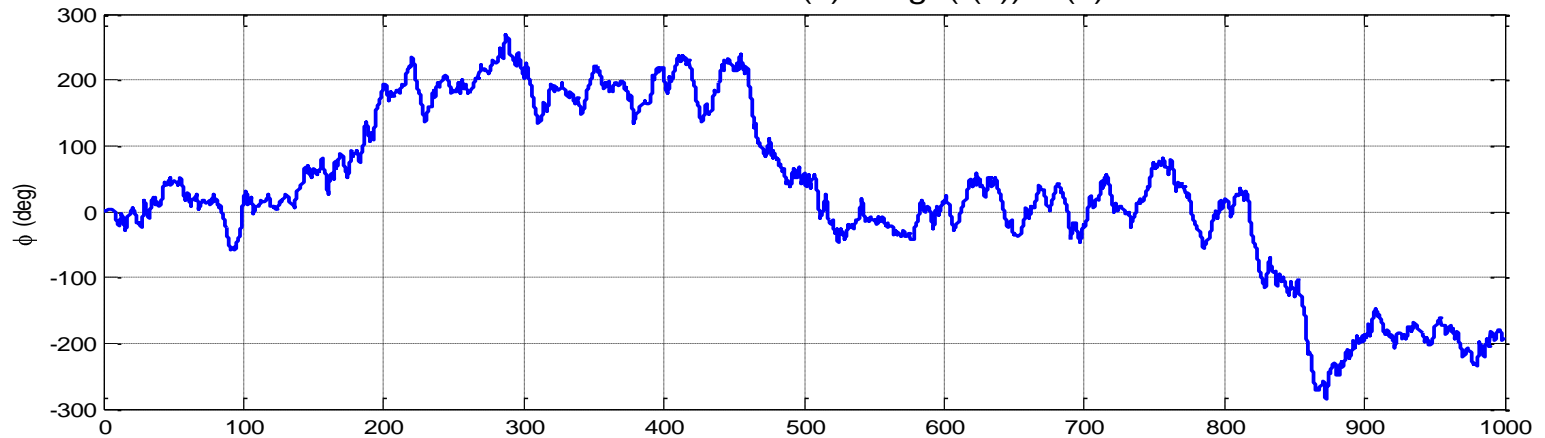


BPSK Large SNR Approximation to ML

Error Locations

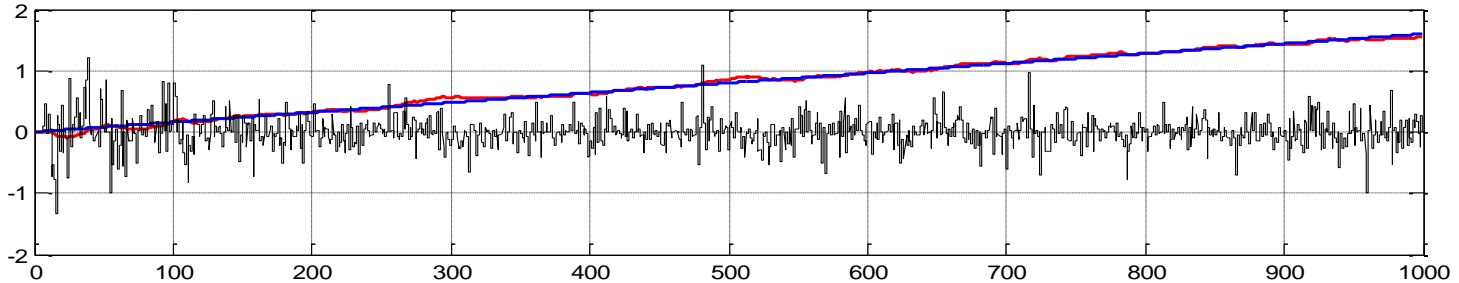


Phase Error for $\text{det}(n) = \text{sign}(I(n)) * Q(n)$

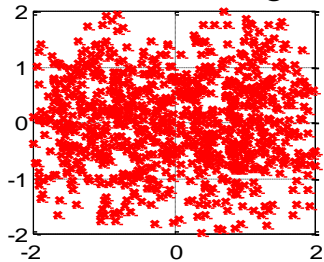


BPSK ML Carrier Recovery Loop

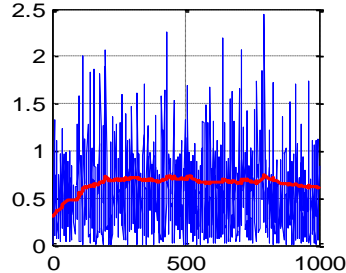
$\text{det}(n) = \tanh[\text{snr} \cdot \text{sign}(I(n)) \cdot Q(n)]$: ML Carrier Recovery
snr = 3.46dB Input and Output Phase Slopes, and Detected Phase Error



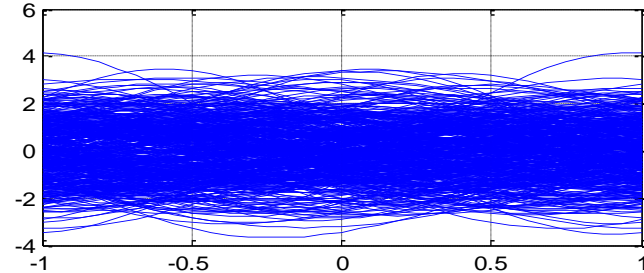
Constellation Diagram



Variance Estimate

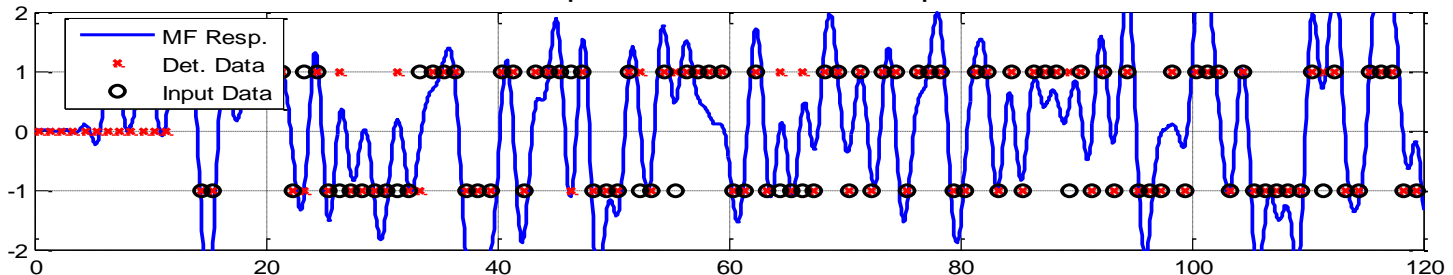


Eye Diagram

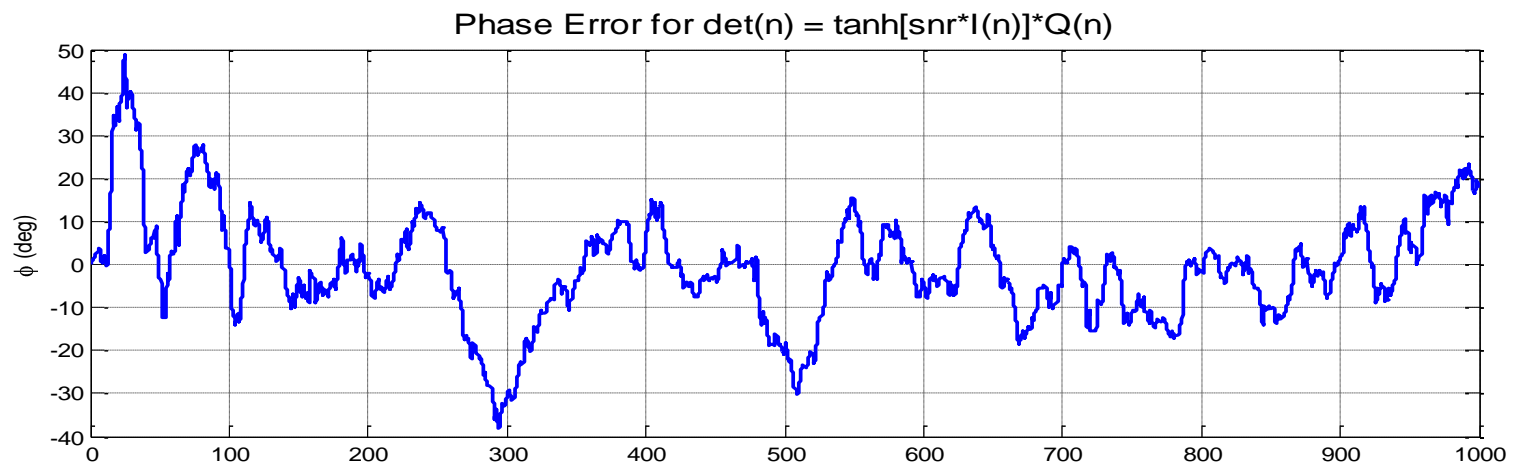


error rate = 12.44 %

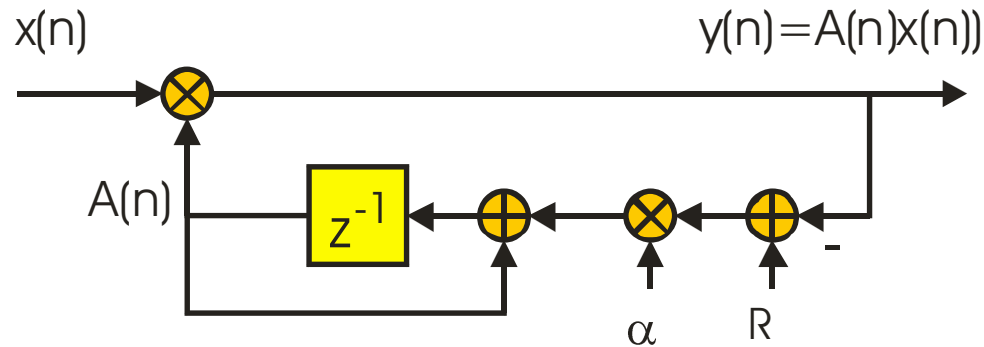
De-Spun Matched Filter Output



BPSK ML Carrier Recovery Loop



Automatic Gain Control (1)



$$y(n) = A(n) x(n)$$

$$A(n+1) = A(n) + \alpha [R - y(n)]$$

$$A(n+1) = A(n) + \alpha [R - A(n) x(n)]$$

$$A(n+1) = A(n)[1 - \alpha x(n)] + \alpha R$$

Suppose $x(n) = c u(n)$, $c = \text{constant}$
then

$$A(n+1) = A(n)[1 - \alpha c] + \alpha R$$

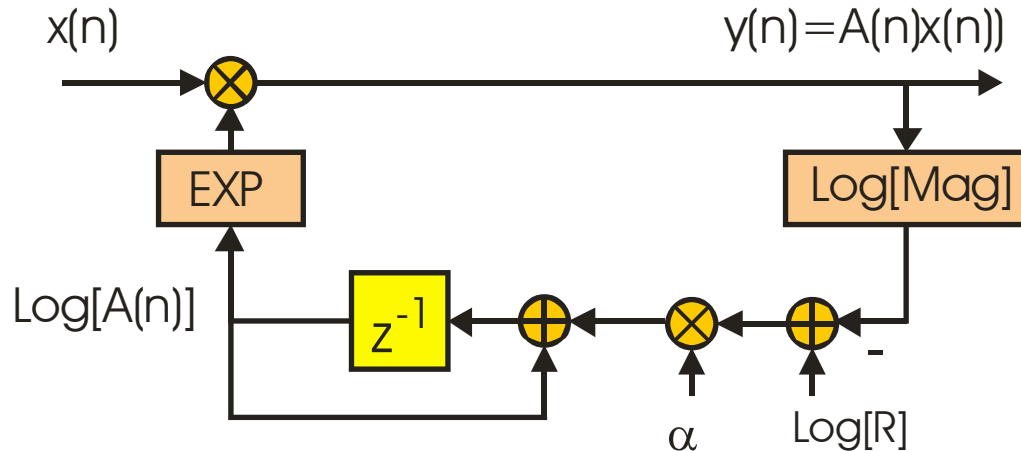
note that $\alpha c < 2.0$.

Steady state of this system is $1/c$ so that the steady state gain $A(\infty)$ is R/c and the steady state output $y(\infty)$ is $c R/c$ or R . The steady state output level equals the desired reference level R .

The time constant is $1/\alpha c$ samples.

If c is small, long transient. If c is large, short transient

Automatic Gain Control (2)



$$y(n) = A(n) x(n)$$

$$\text{Log}[A(n+1)] = \text{Log}[A(n)] + \alpha \{ [\text{Log}[R] - \text{Log}[y(n)]] \}$$

$$\text{Log}[A(n+1)] = \text{Log}[A(n)] + \alpha \{ \text{Log}[R] - \text{Log}[A(n) x(n)] \}$$

$$\text{Log}[A(n+1)] = \text{Log}[A(n)][1 - \alpha] - \alpha \text{Log}[x(n)/R]$$

Suppose $x(n) = c u(n)$, $c = \text{constant}$

then

$$\text{Log}[A(n+1)] = \text{Log}[A(n)][1 - \alpha] - \alpha \text{Log}[c/R]$$

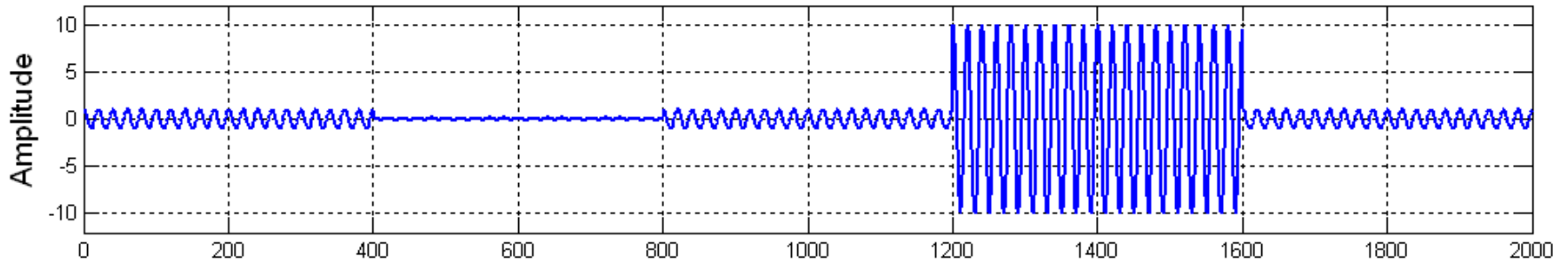
note that $\alpha < 2.0$.

Steady state of this system is $1/c$ so that the steady state gain $A(\infty)$ is R/c and the steady state output $y(\infty)$ is $c R/c$ or R .

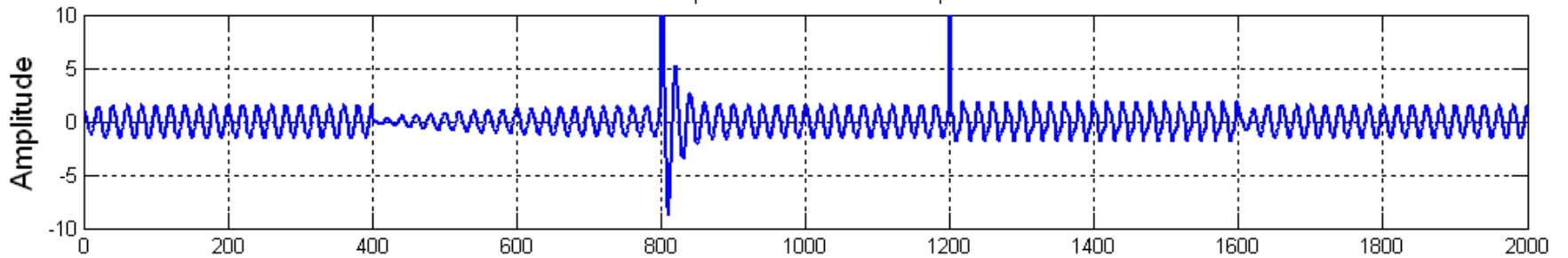
The steady state output level equals the desired reference level R . The time constant is $1/\alpha$ samples, and is independent of input amplitude.

Linear Loop AGC Responses

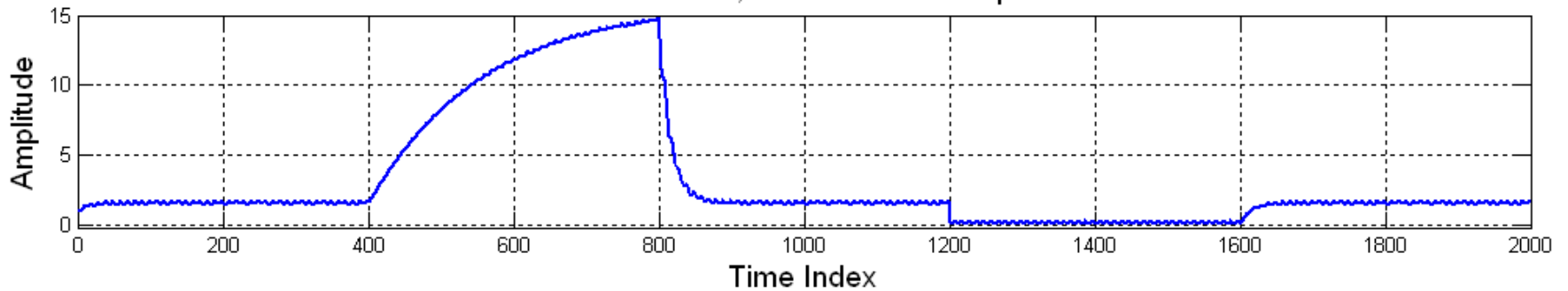
Input With Amplitude Jumps



Output of Linear AGC Loop

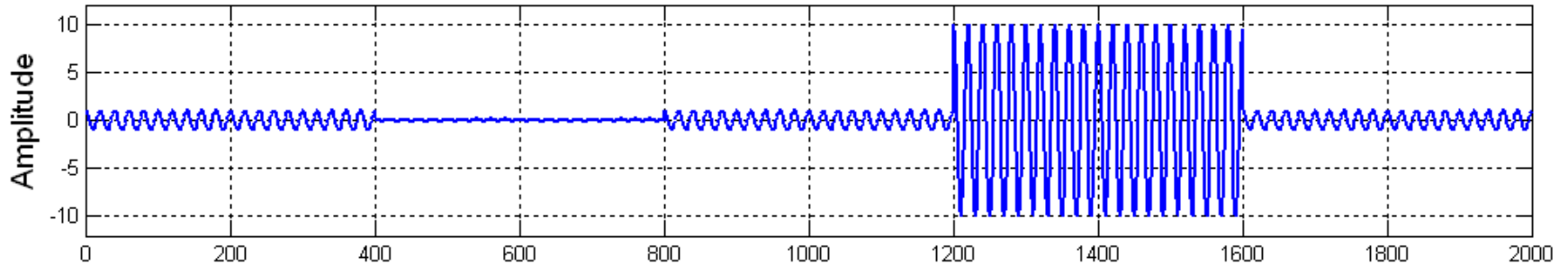


AGC Level, Linear Control Loop

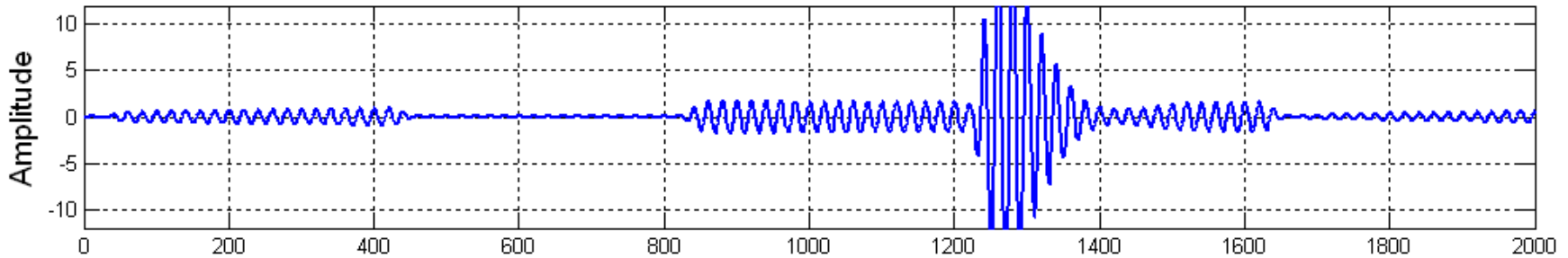


Linear Loop AGC Responses: with Filter Delays

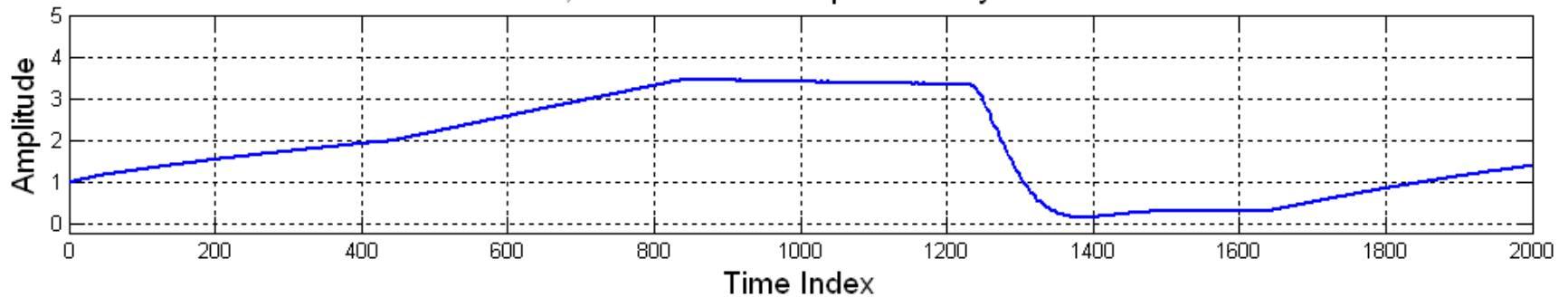
Input With Amplitude Jumps



Output of Linear AGC Loop with Delays Due to Filter

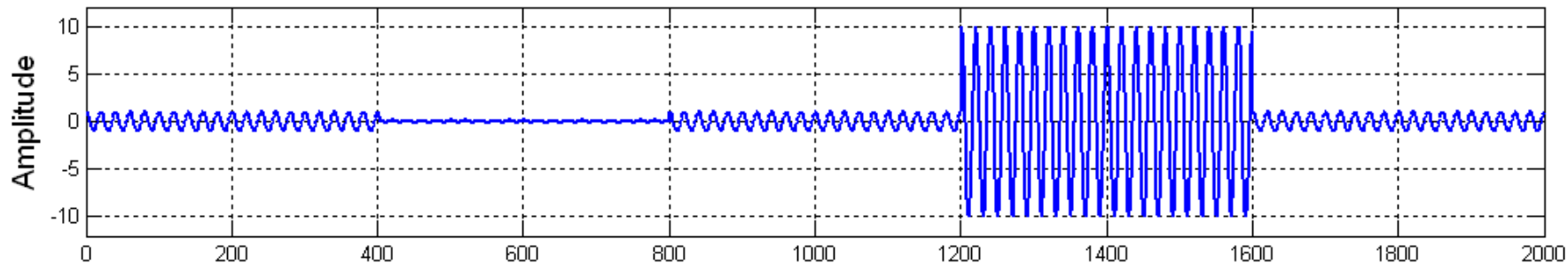


AGC Level, Linear Control Loop with Delays Due to Filter

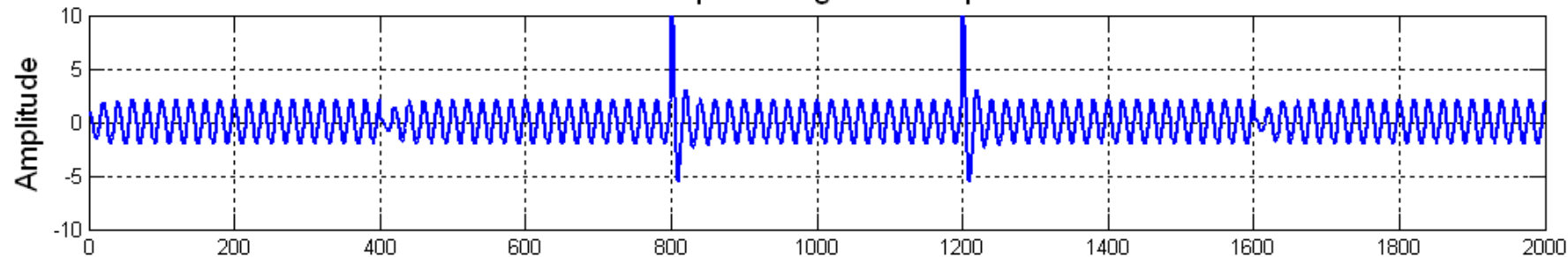


Log Loop AGC Responses

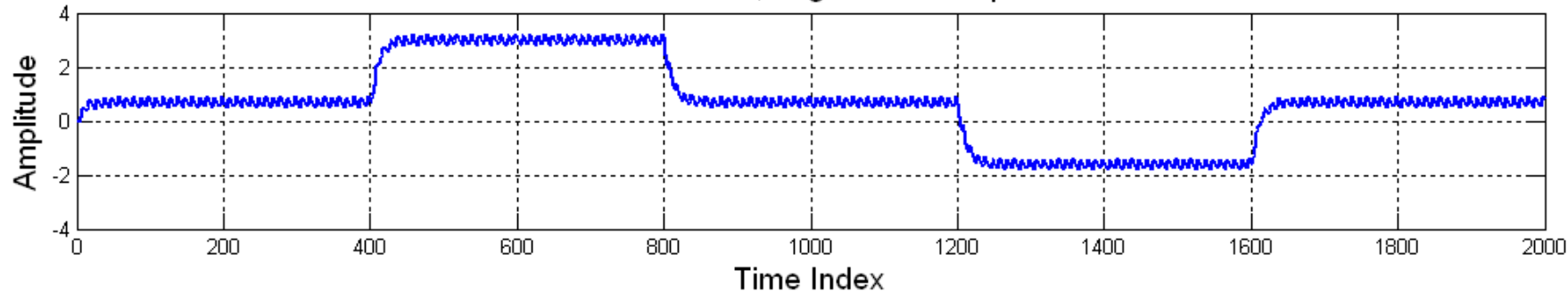
Input With Amplitude Jumps



Output of Log AGC Loop

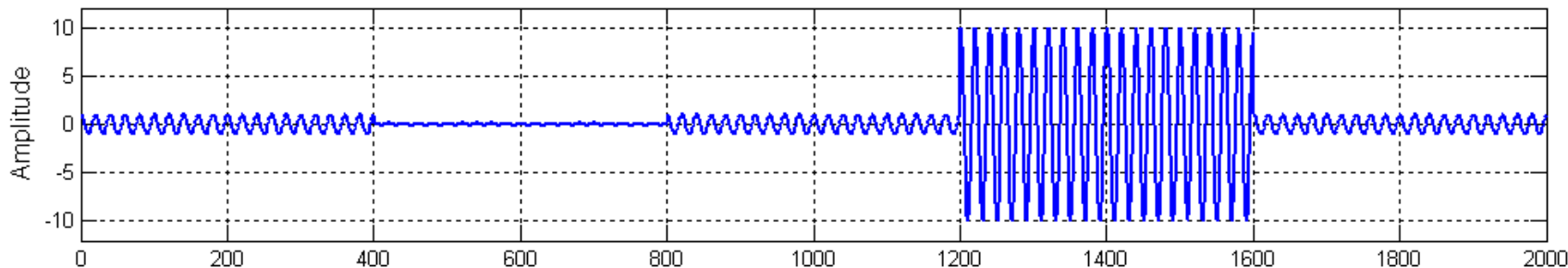


AGC Level, Log Control Loop

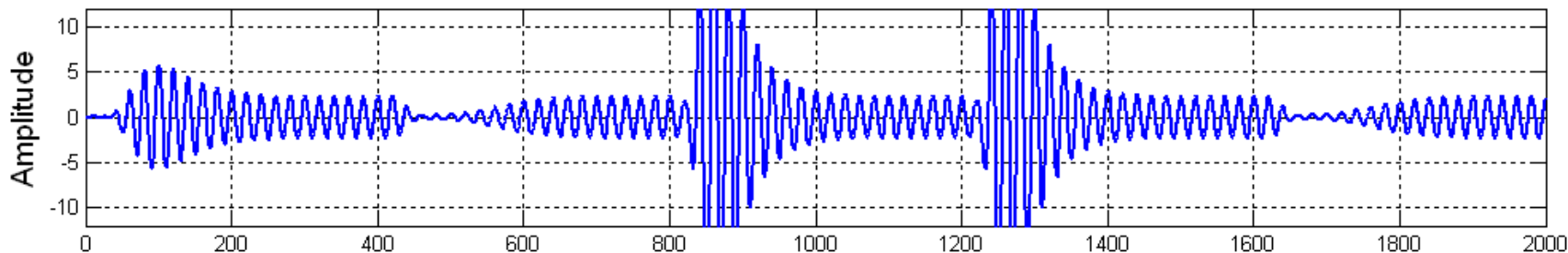


Log Loop AGC Responses: with Filter Delays

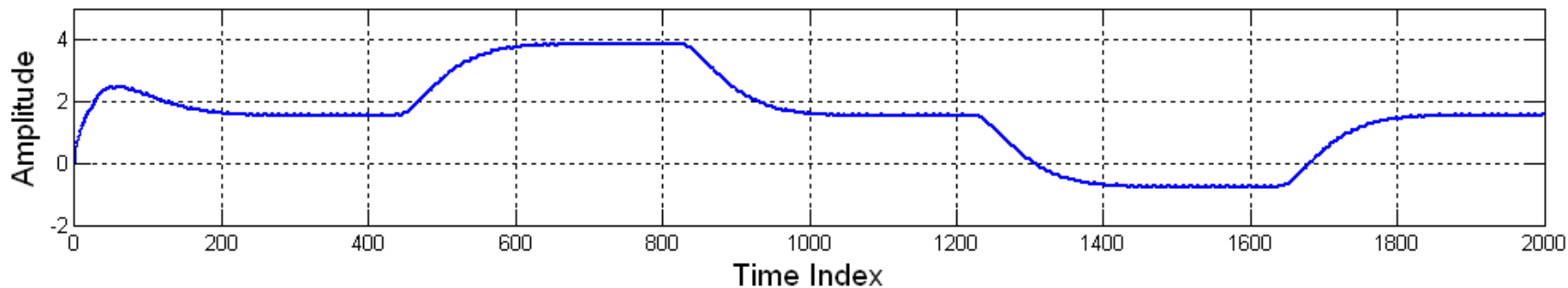
Input With Amplitude Jumps



Output of Log AGC Loop with Delays Due to Filter

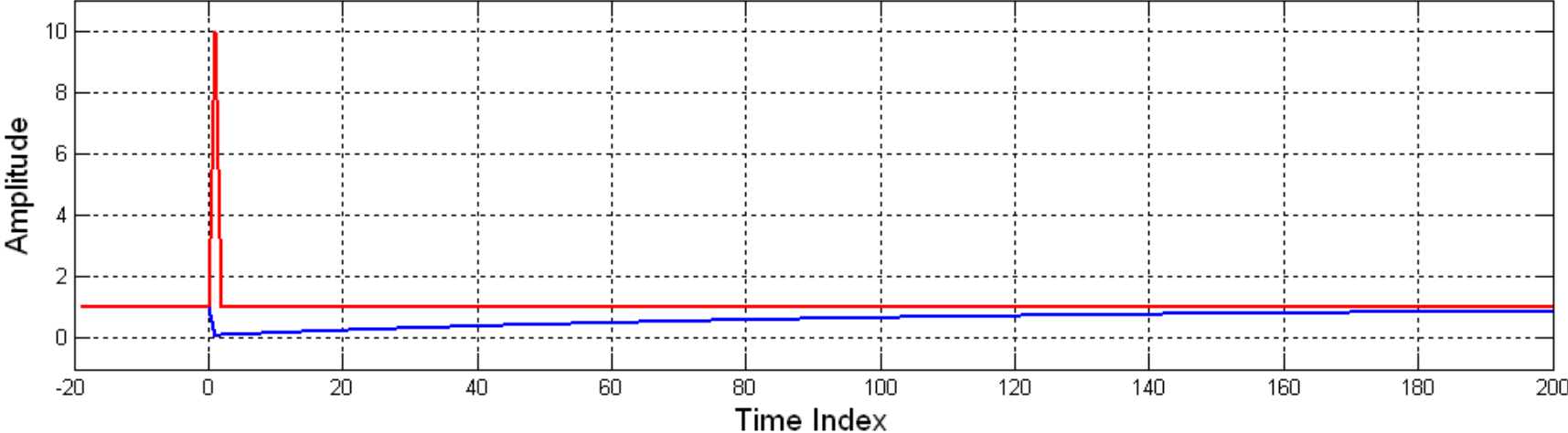


AGC Level, Log Control Loop with Delays Due to Filter

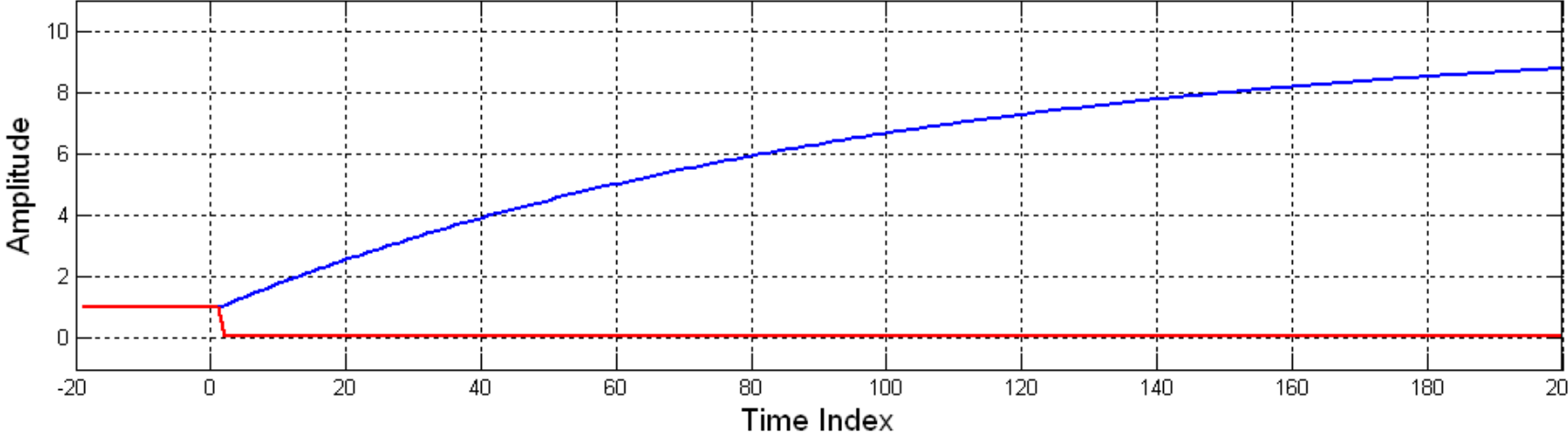


Linear Loop AGC Output and Control Levels

AGC Output Level, Linear Control Loop

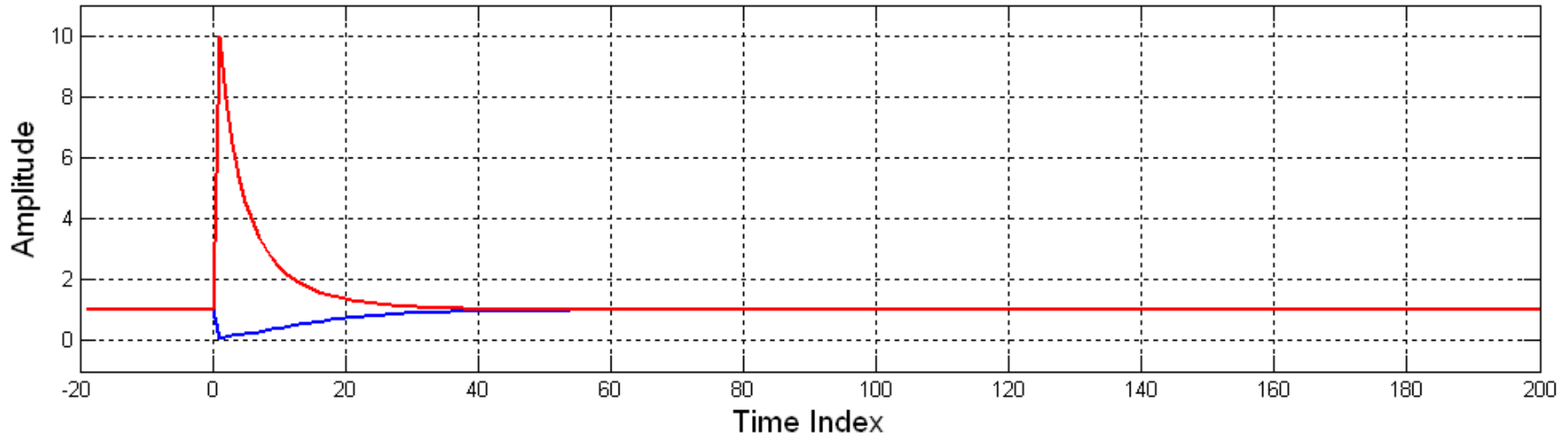


AGC Control Level, Linear Control Loop

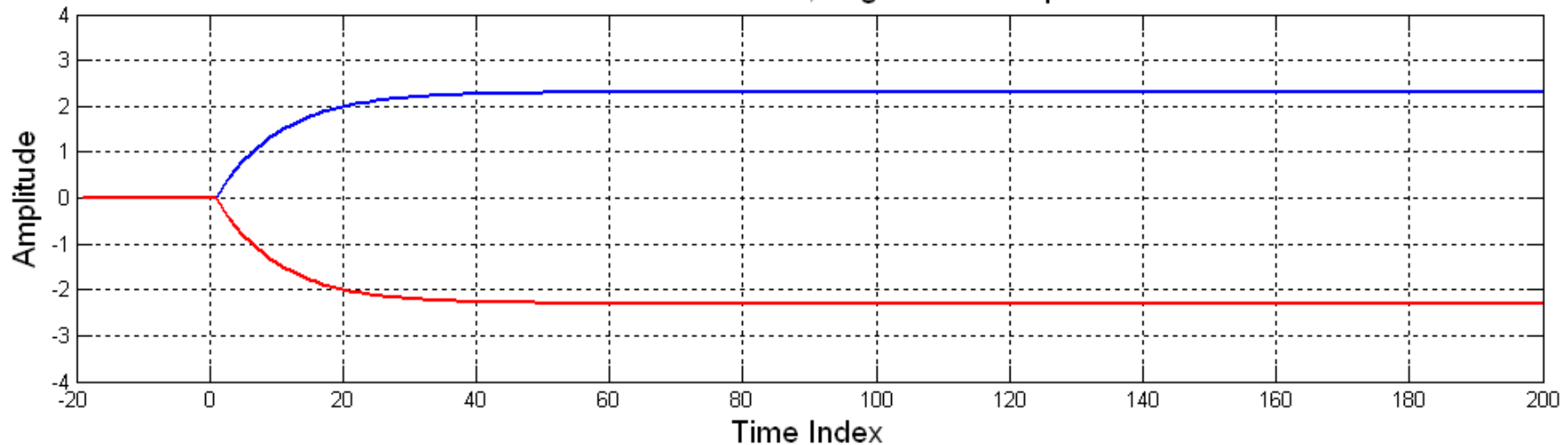


Log Loop AGC Output and Control Levels

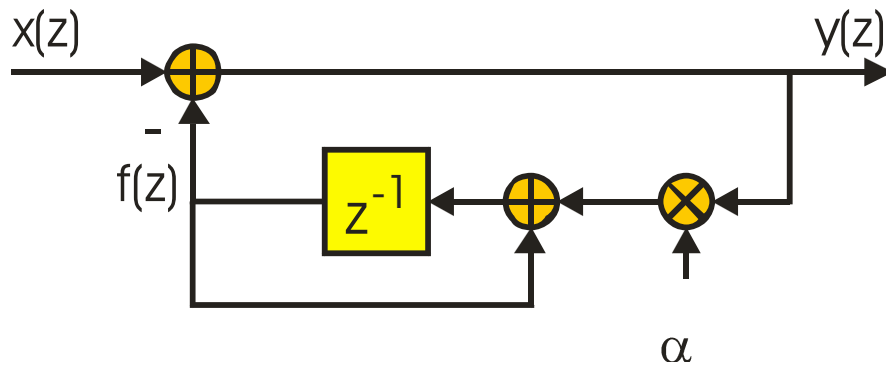
AGC Output Level, Log Control Loop



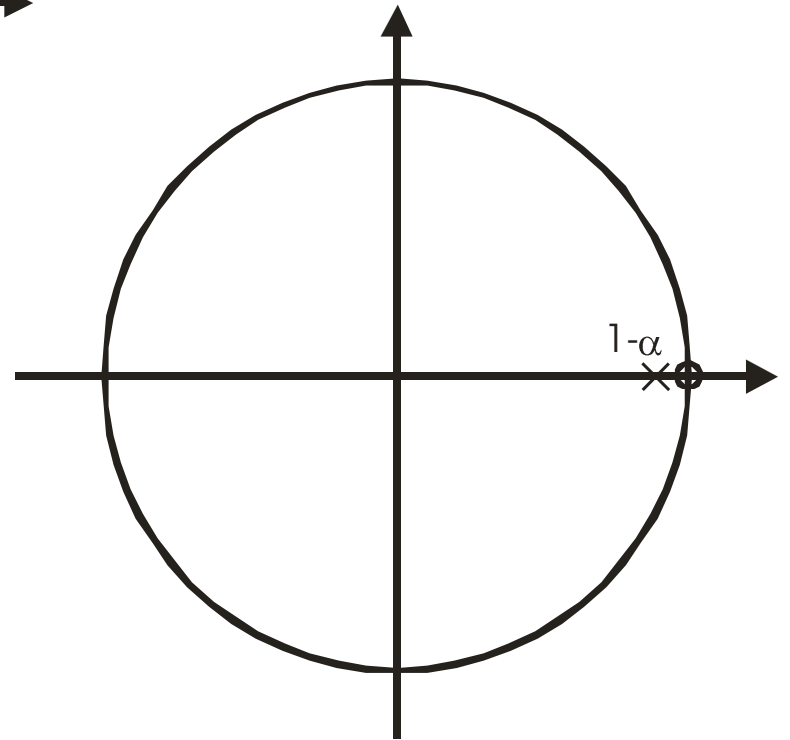
AGC Control Level, Log Control Loop



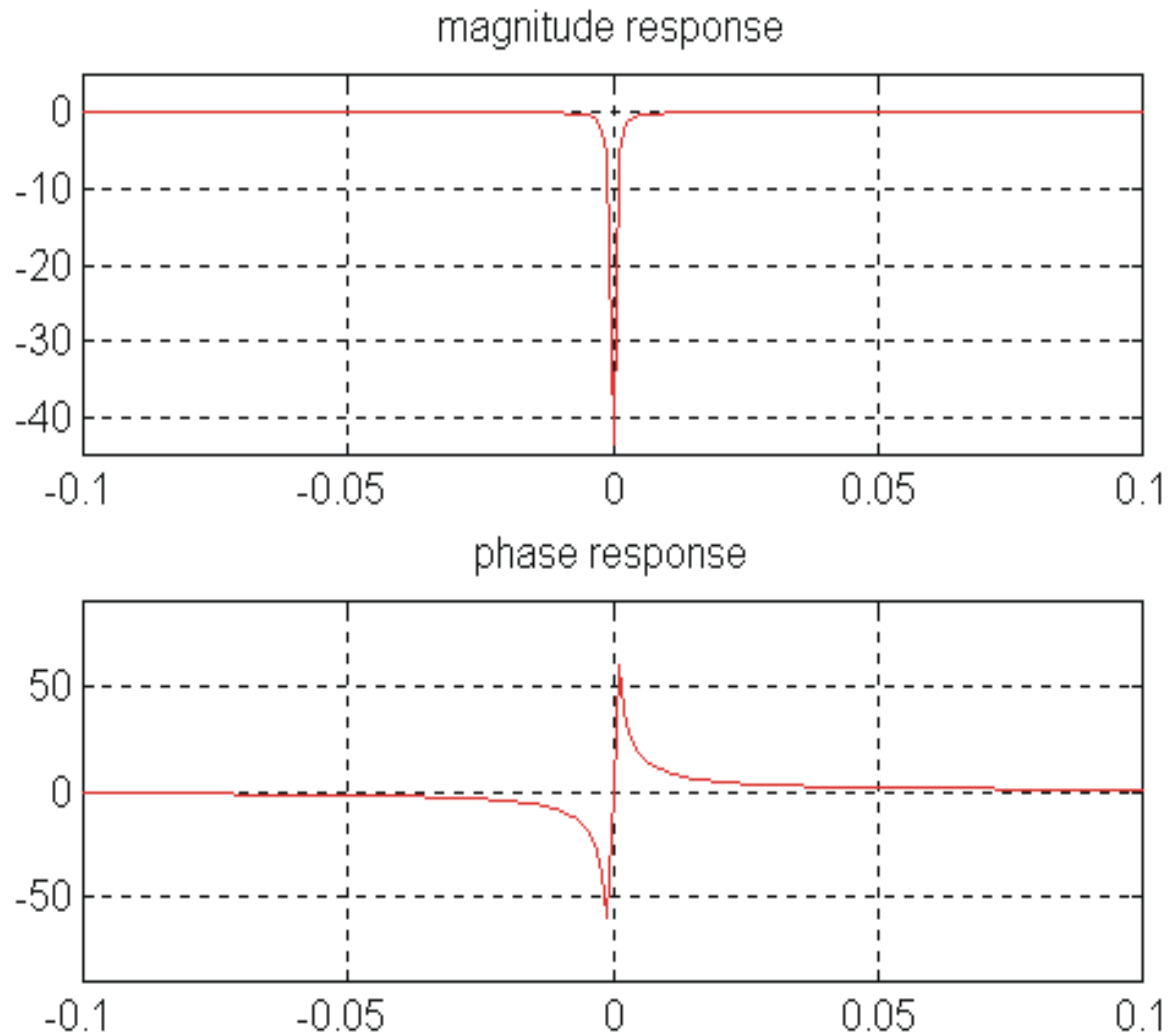
DC Canceller, DC Notch Filter



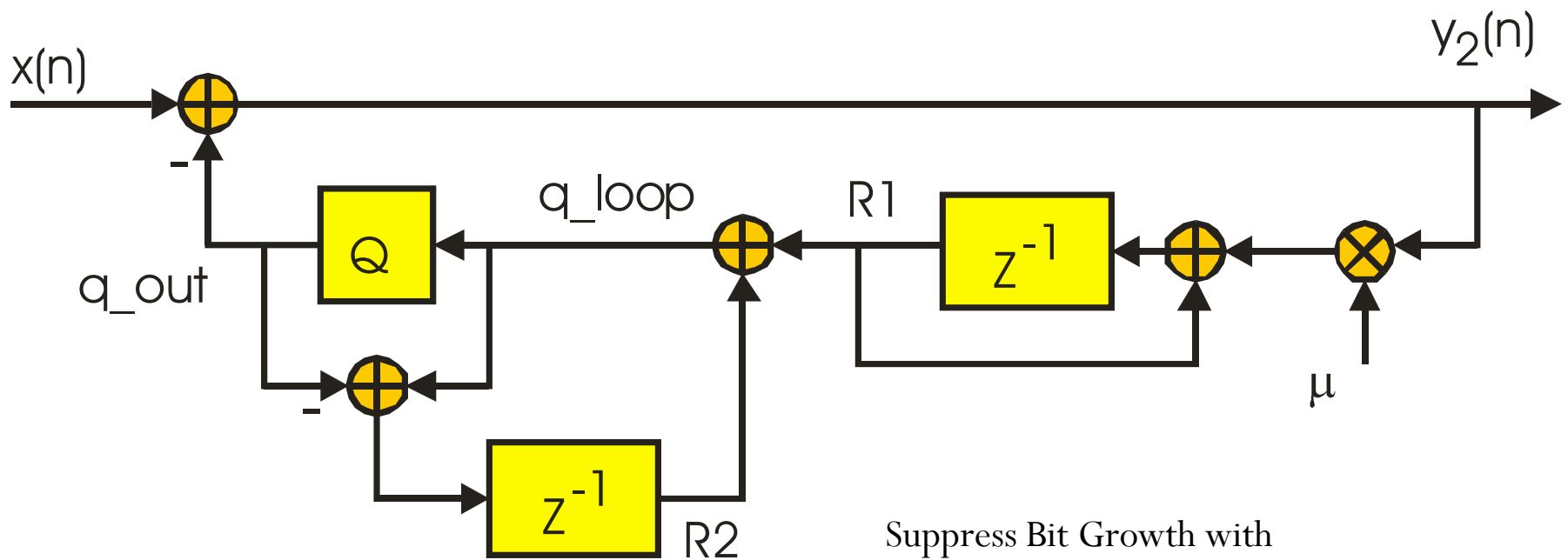
$$H(Z) = \frac{Z - 1}{Z - (1 - \alpha)}$$



Spectral Response

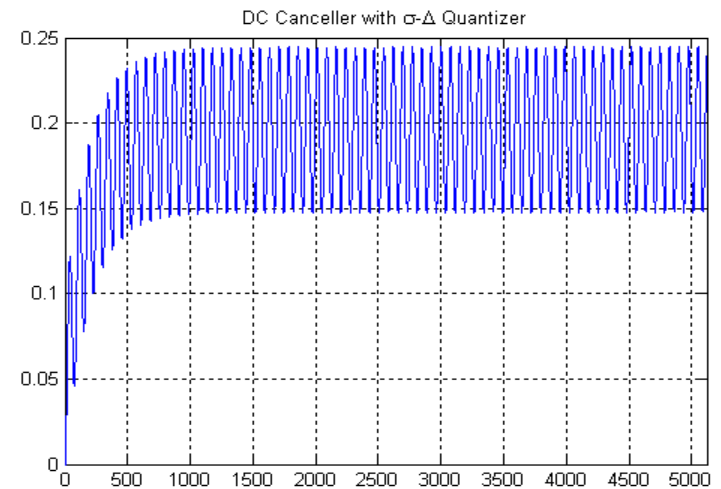
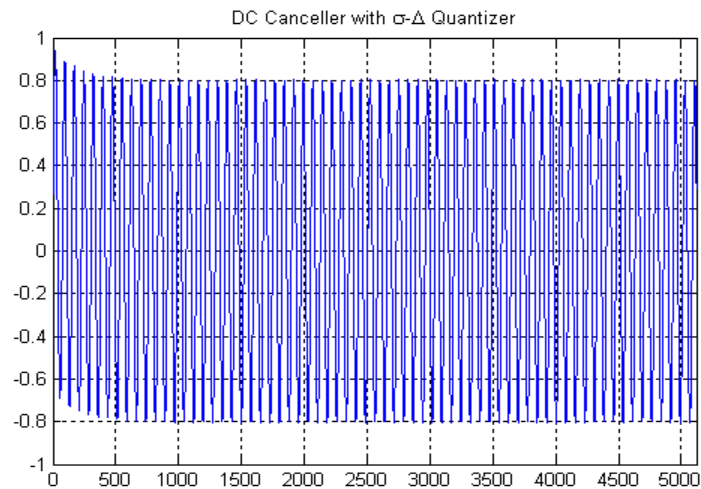
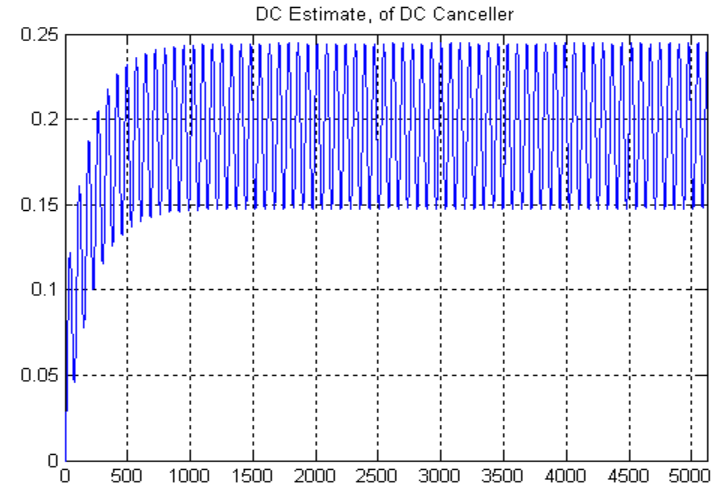
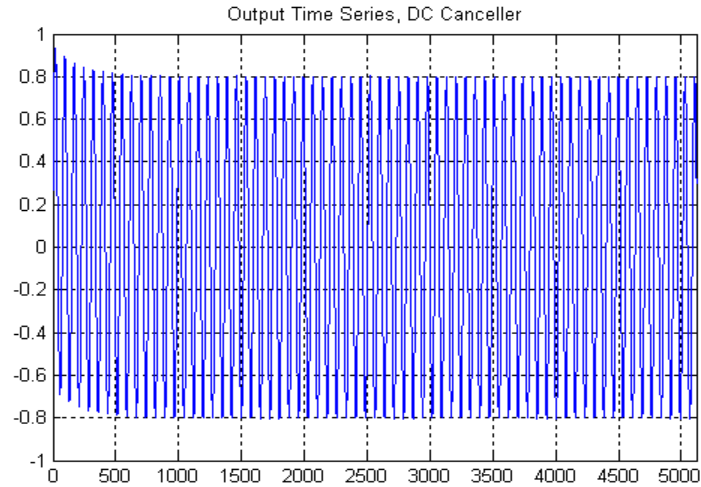


DC Cancellor with Embedded Sigma-Delta Converter



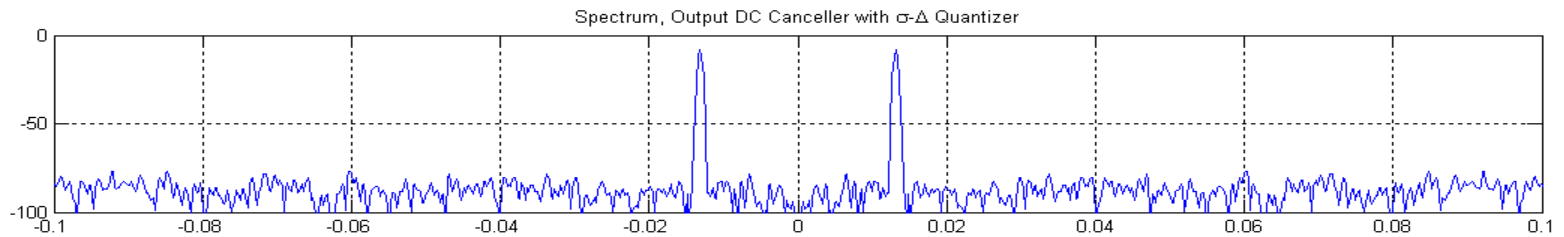
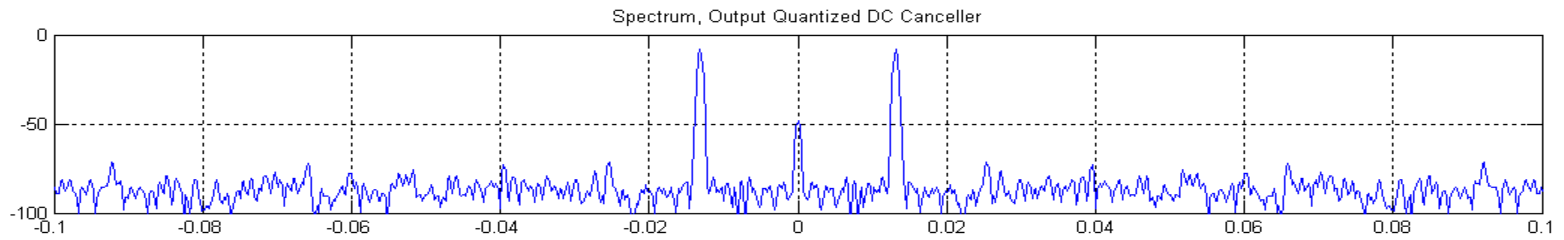
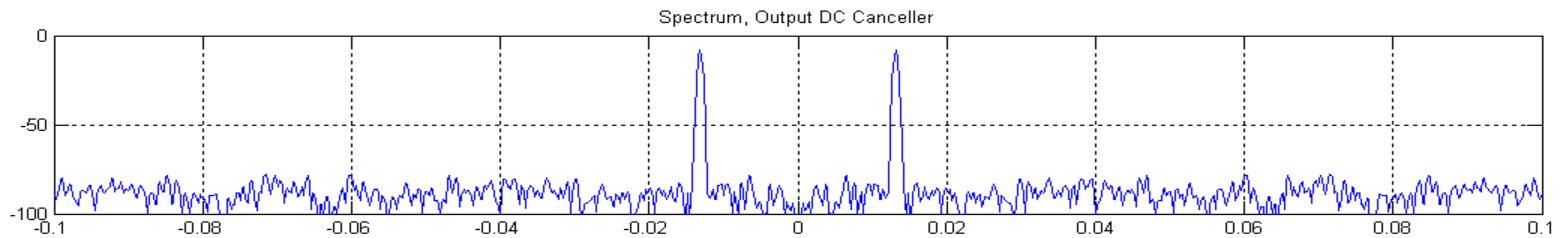
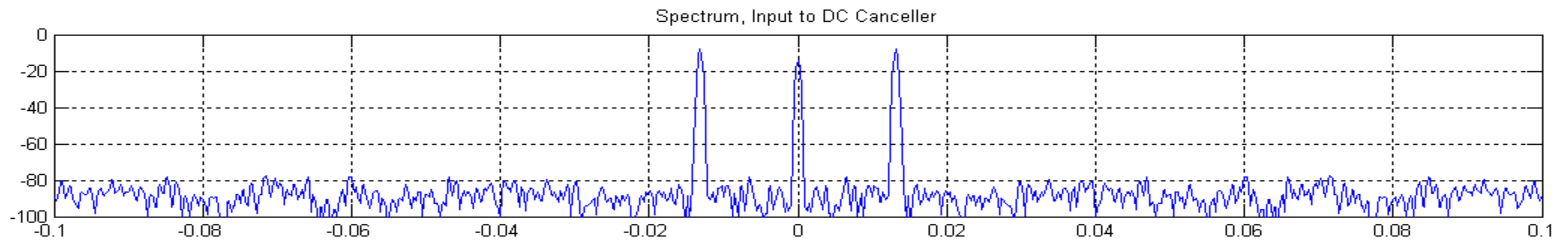
Suppress Bit Growth with
Sigma-Delta Converter in
Feedback Path

DC Cancellor Time Series

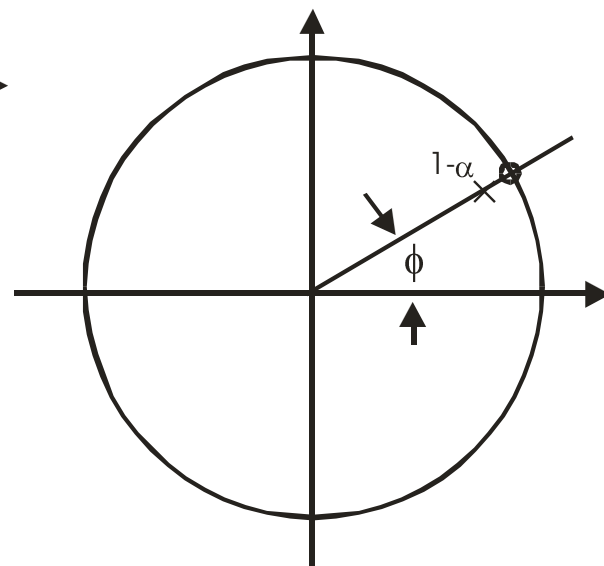
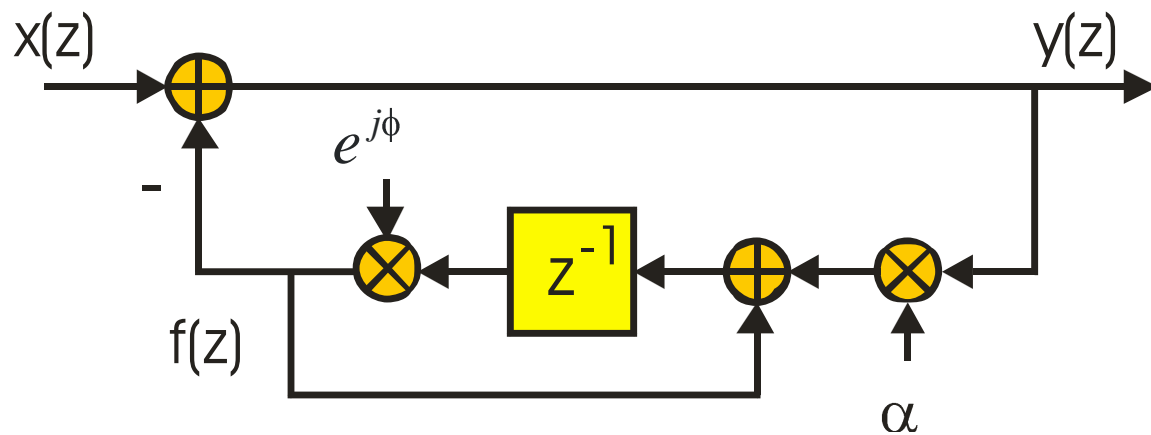


Spectra

Input and Output of Canceller



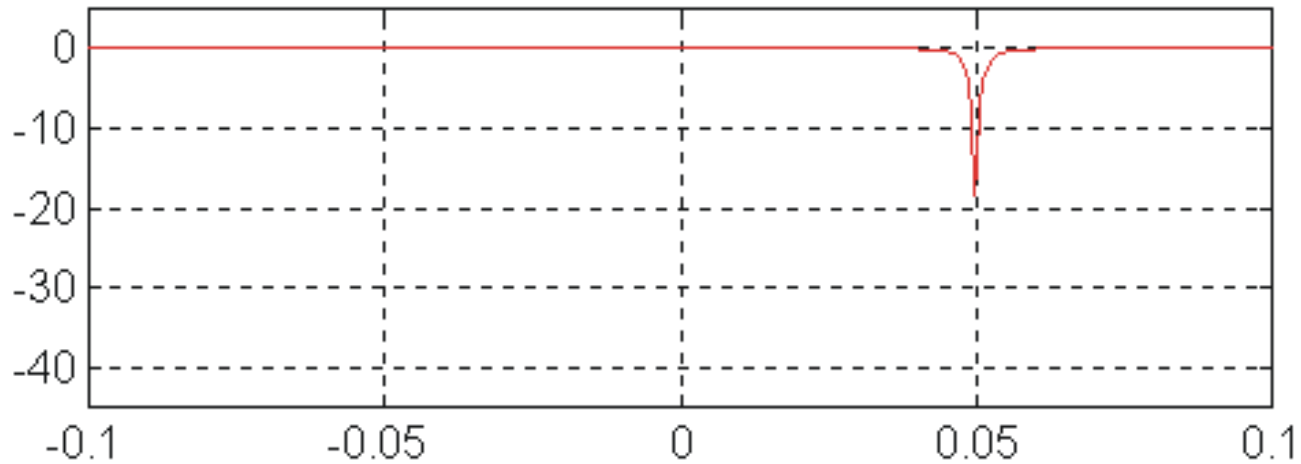
Tunable Notch, Spin the Delay Line



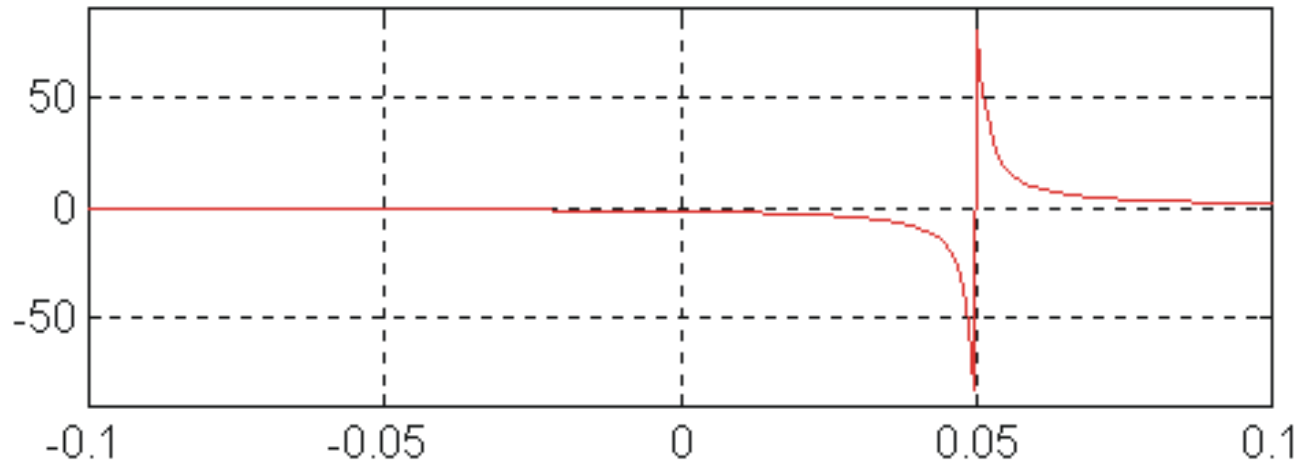
$$H(Z) = \frac{Z - e^{j\phi}}{Z - (1-\alpha)e^{j\phi}}$$

Spectral Response

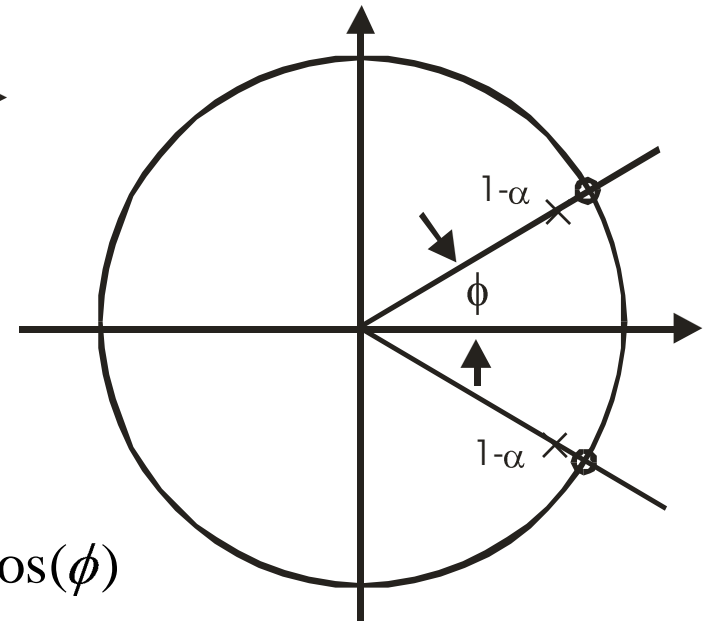
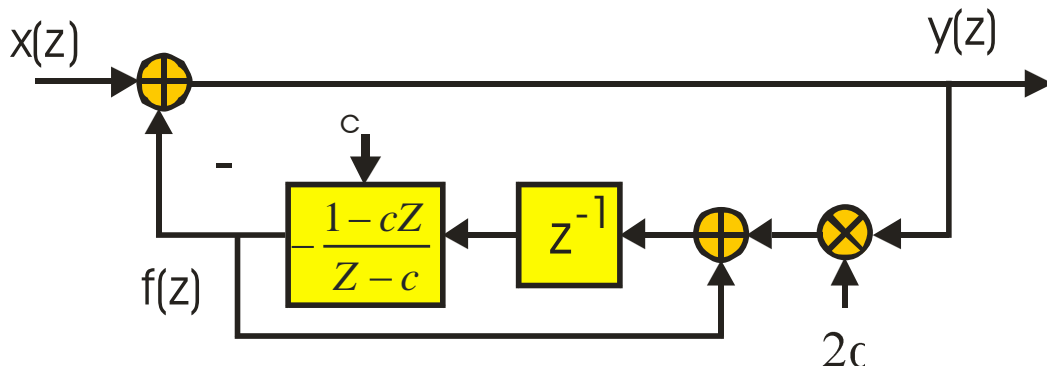
Magnitude Response



Phase Response

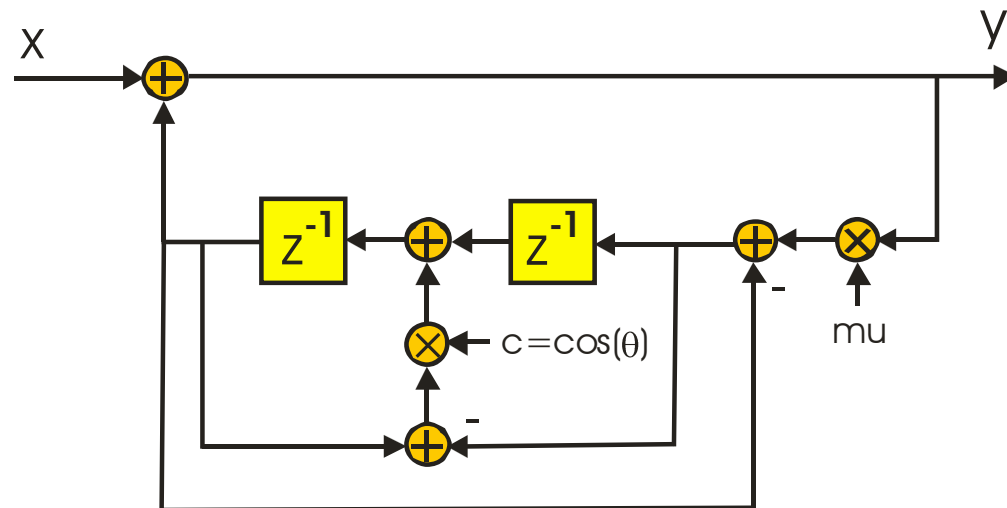
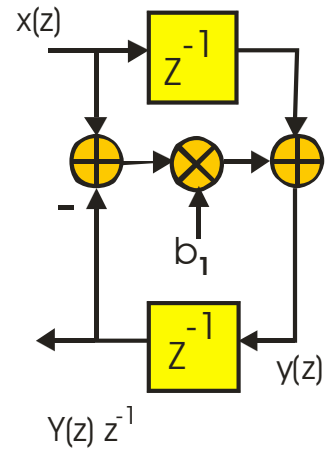
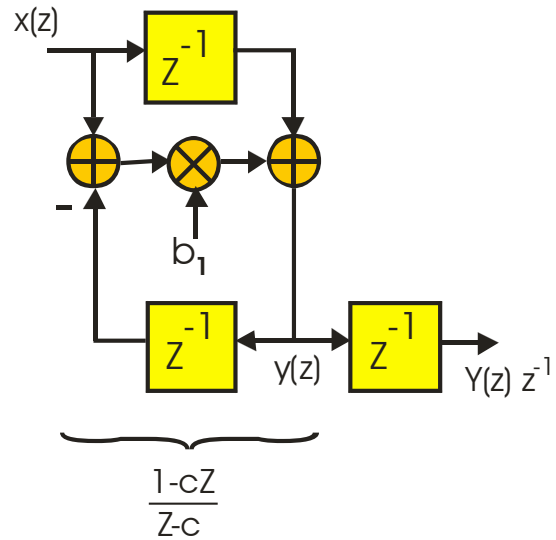


Tuning With LP-to-BP Transformation



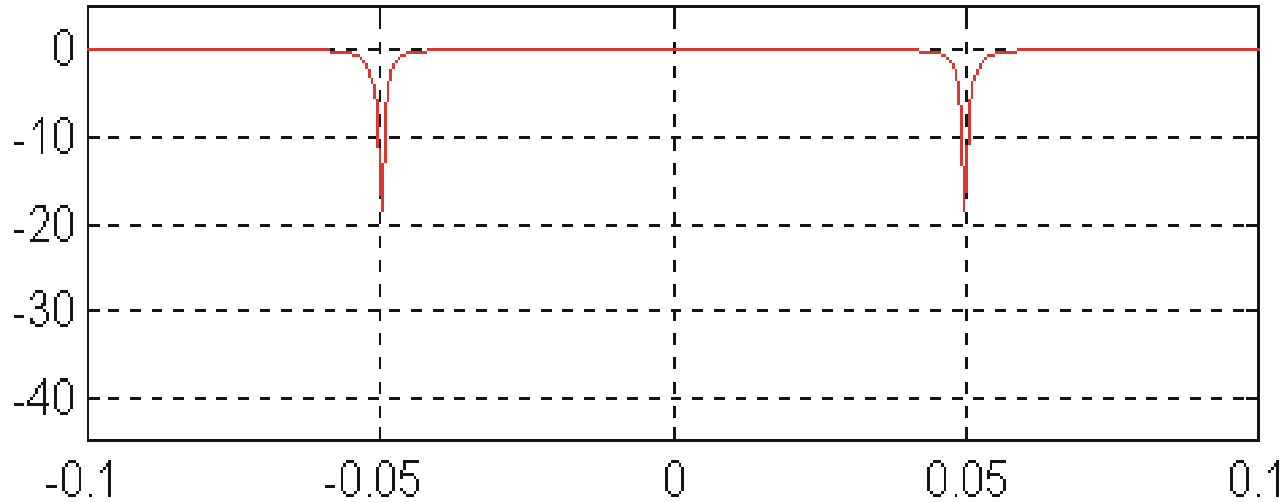
$$H(Z) = \frac{Z^2 - 2cZ + 1}{Z^2 - 2c(1-\alpha)Z + (1-2\alpha)} : c = \cos(\phi)$$

Implementing LP-to-BP Transformation

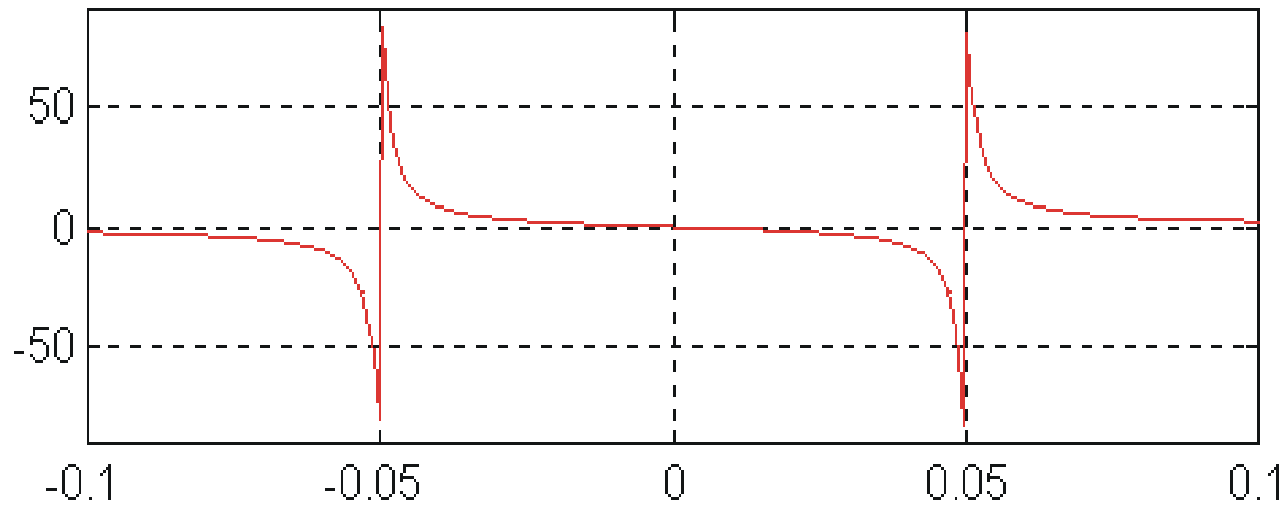


Spectral Response

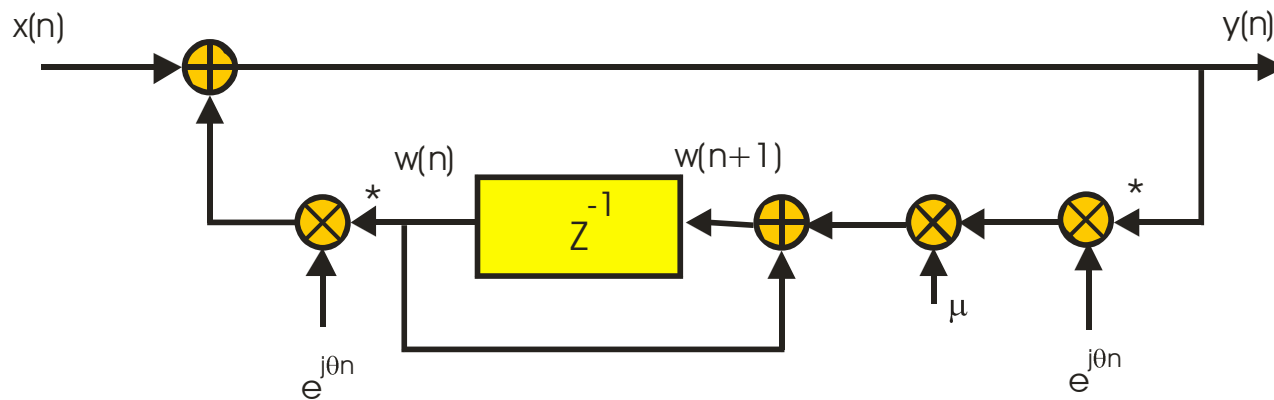
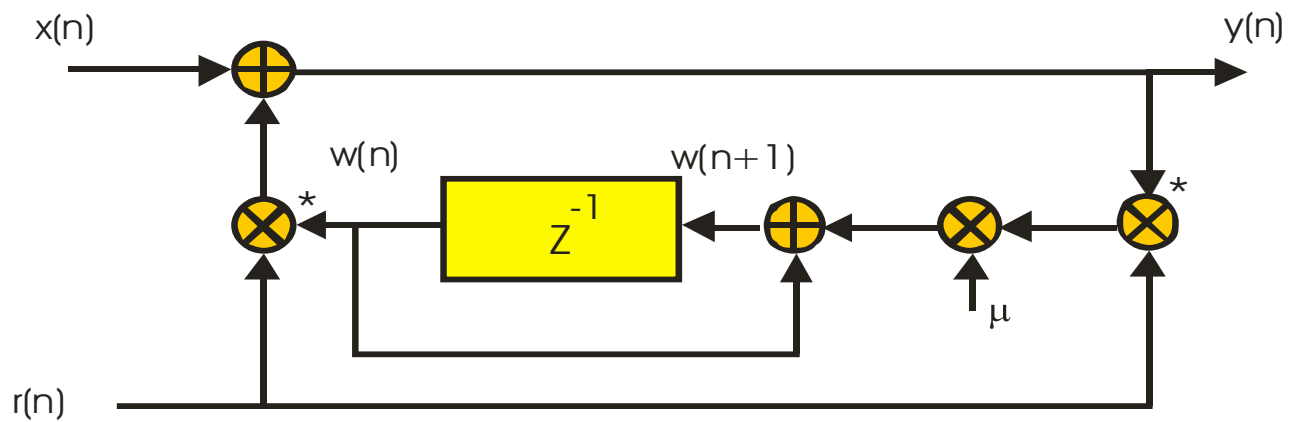
Magnitude Response



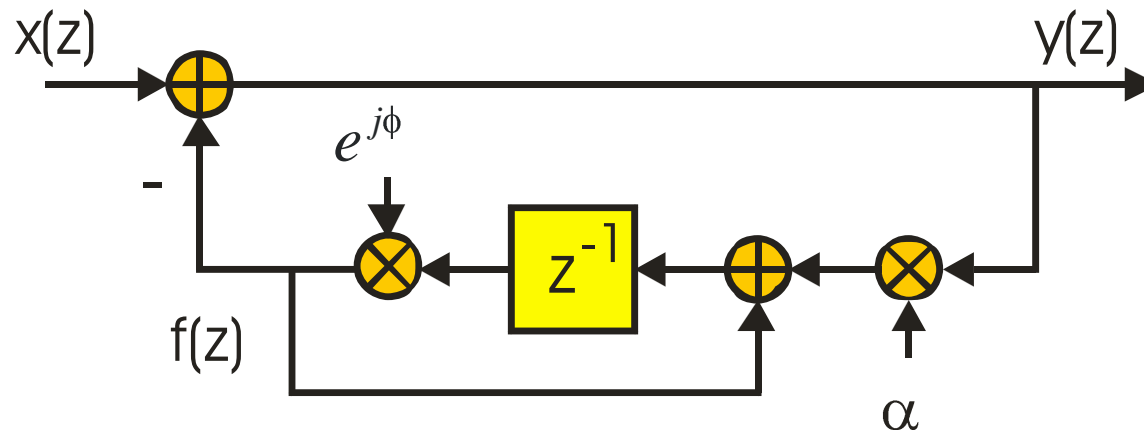
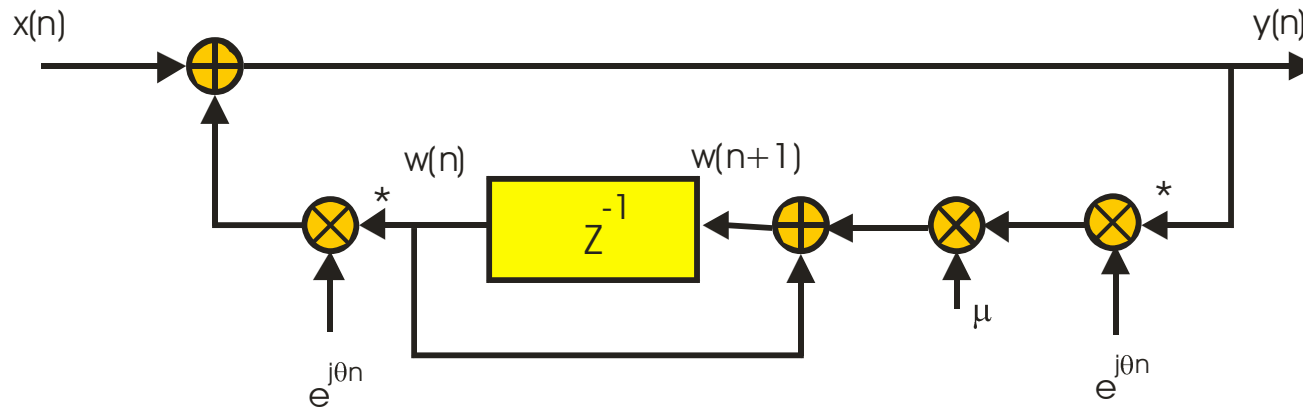
Phase Response



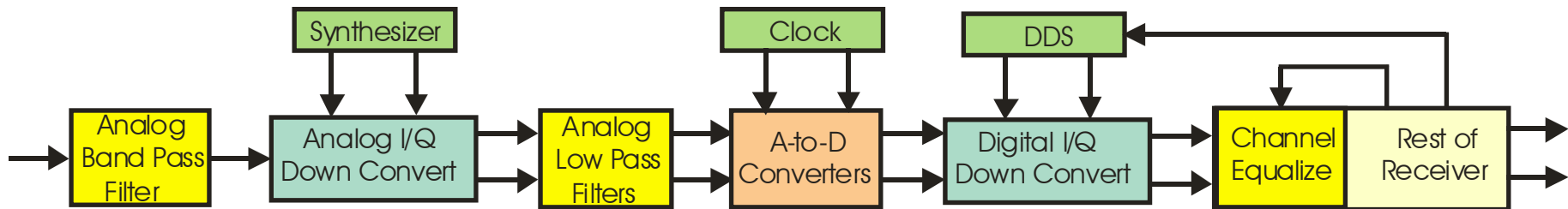
Self Tuning: Reference Canceling



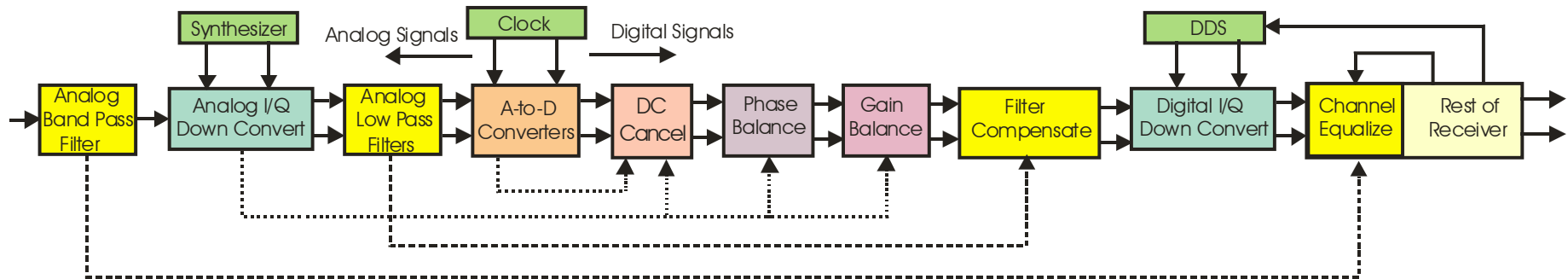
Filters have Same Transfer Function



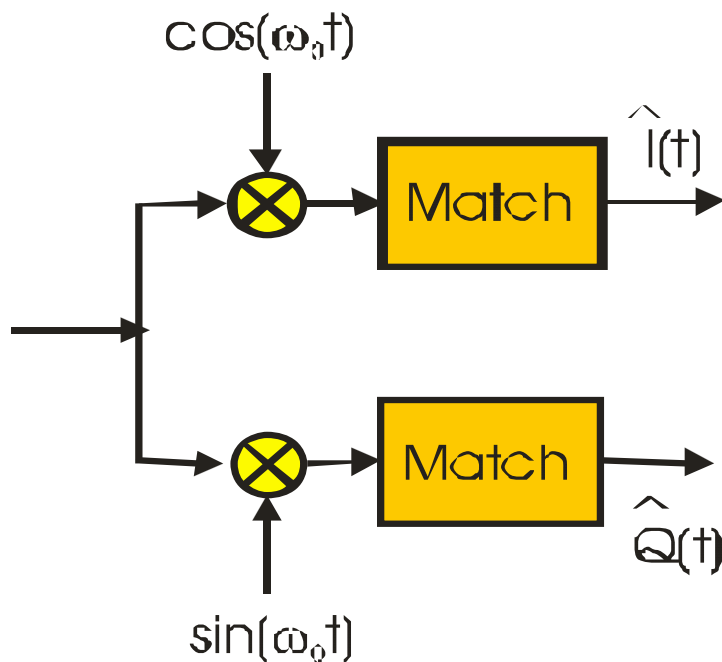
Block Diagram of Receiver with Ideal Signal Processing Blocks



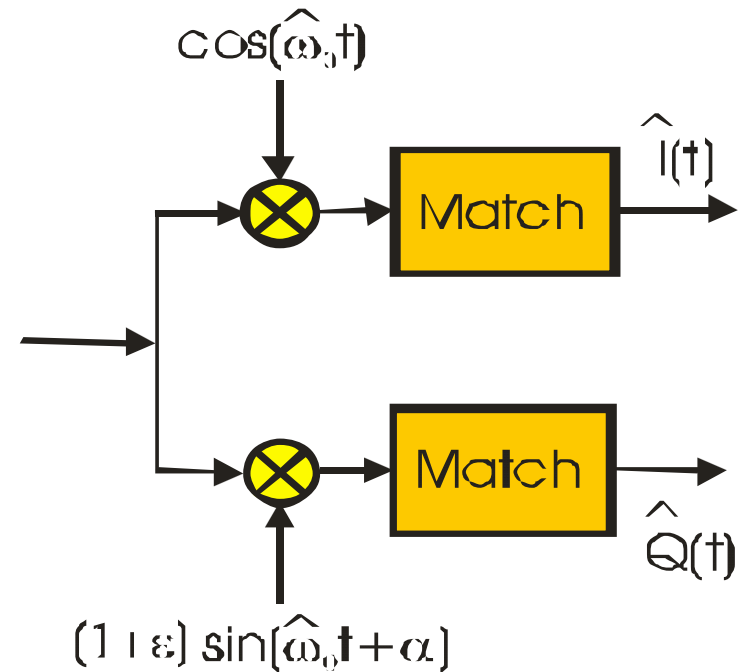
Block Diagram of Receiver with Non-Ideal Signal Processing Blocks and Associated Compensating Blocks



Gain and Phase Imbalance in Analog I-Q Mixers Used for Up or Down Conversion

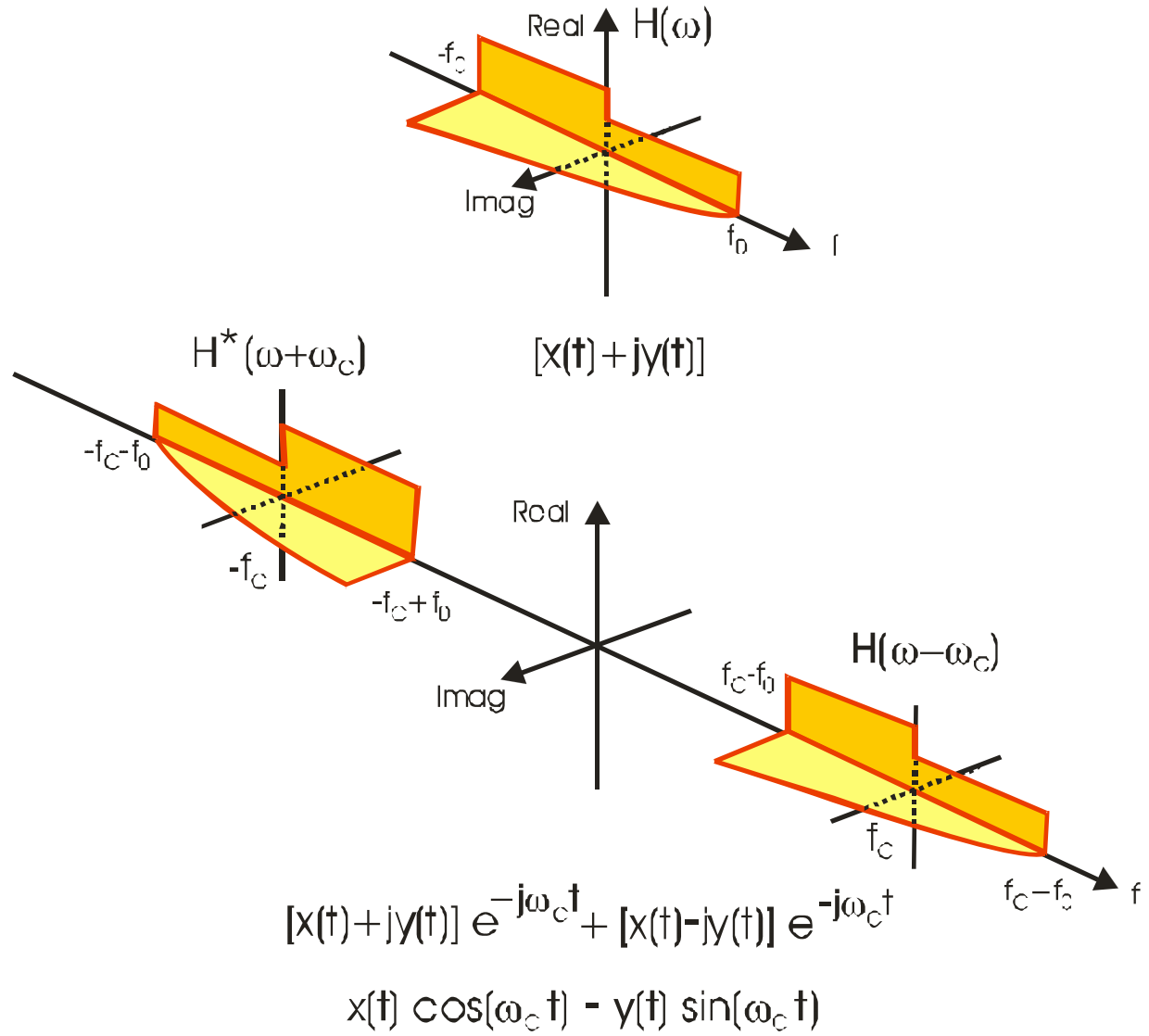


Balanced

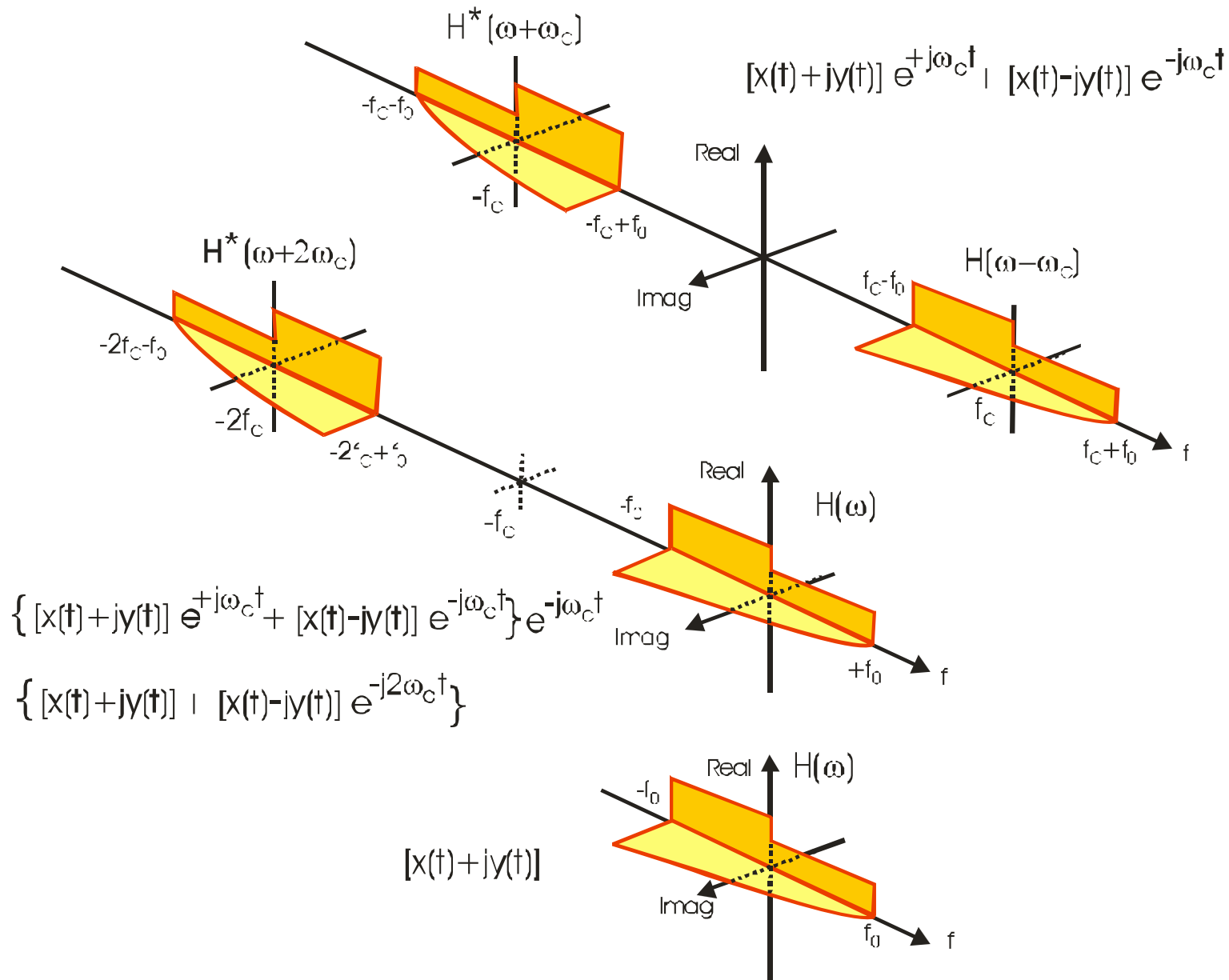


Imbalanced

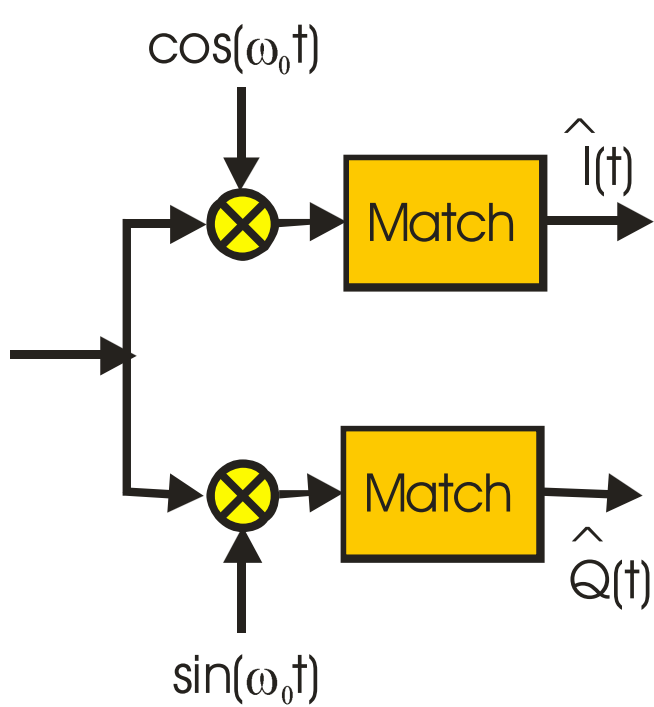
Complex Baseband & Real Band-Centered



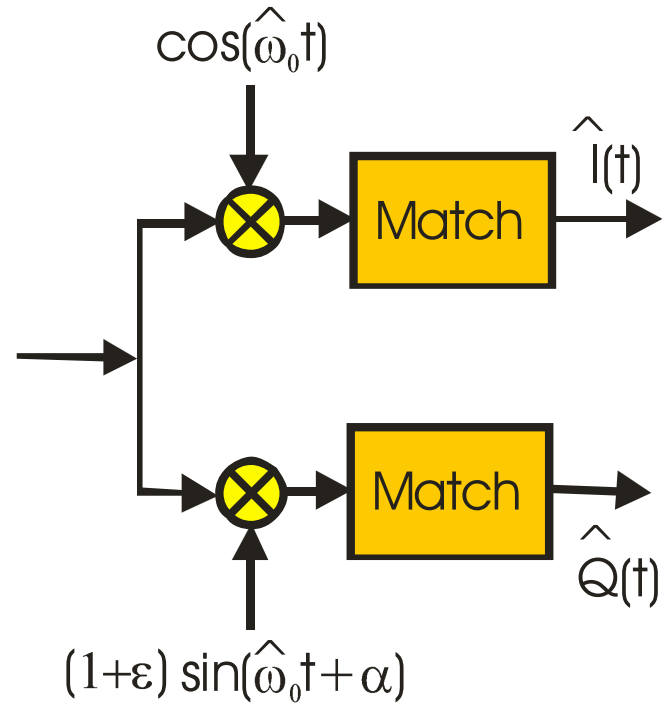
Complex Down Conversion



I-Q Gain and Phase Imbalance

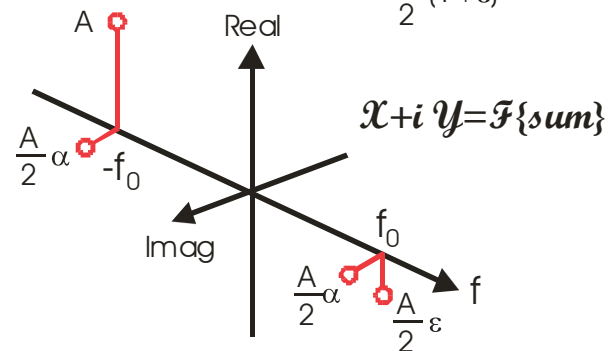
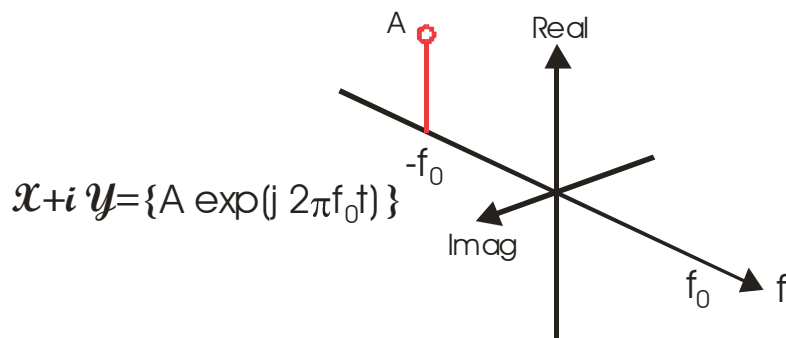
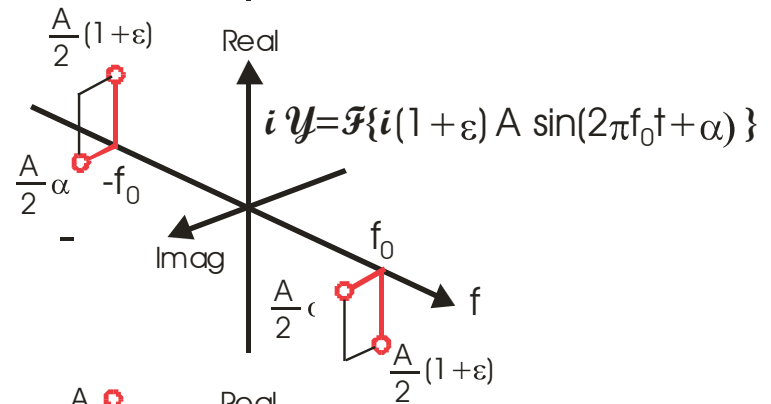
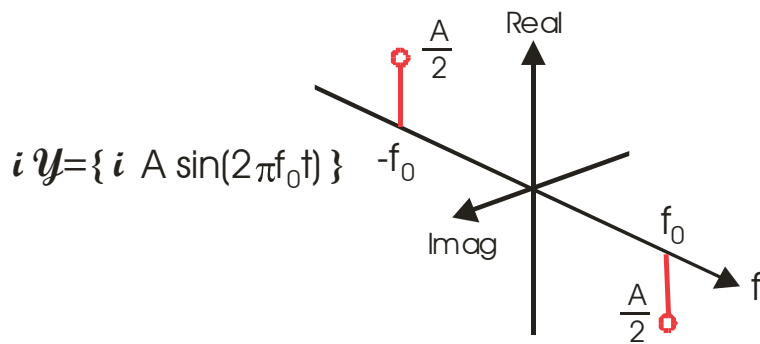
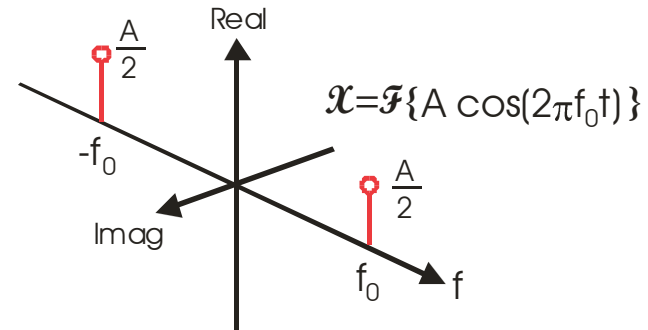
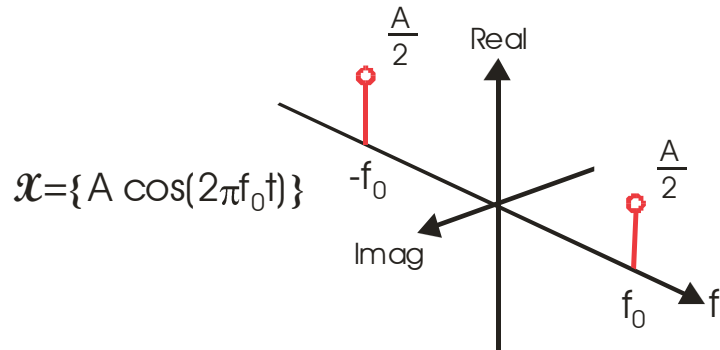


Balanced

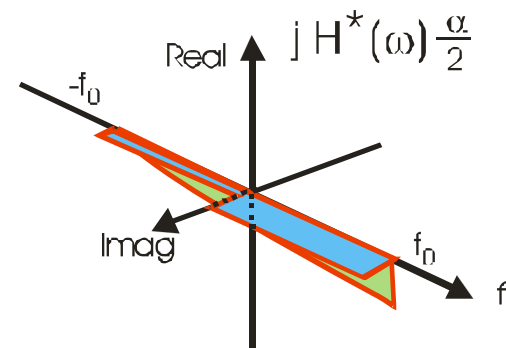
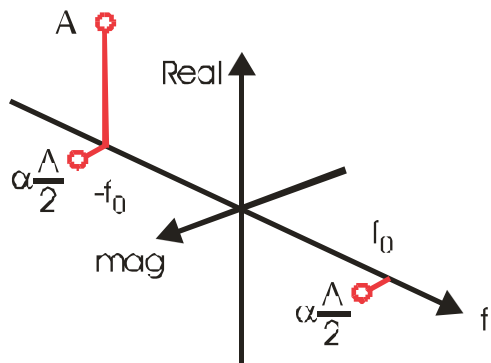
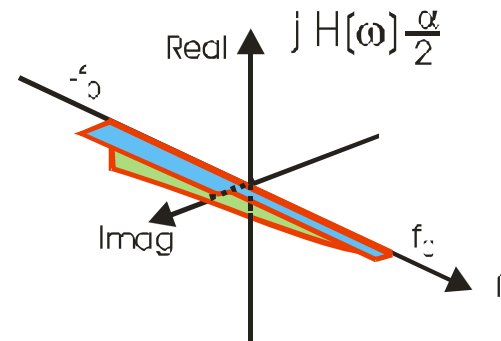
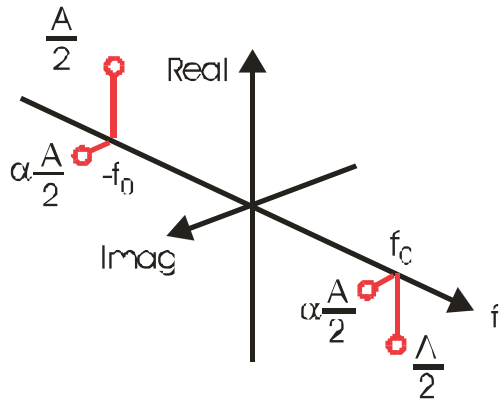
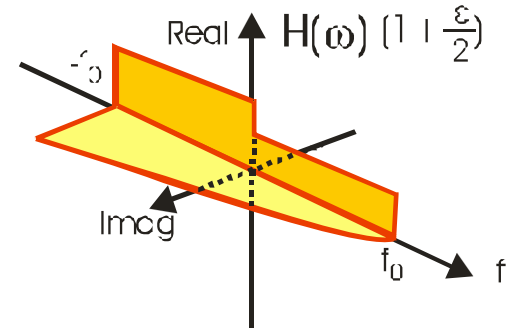
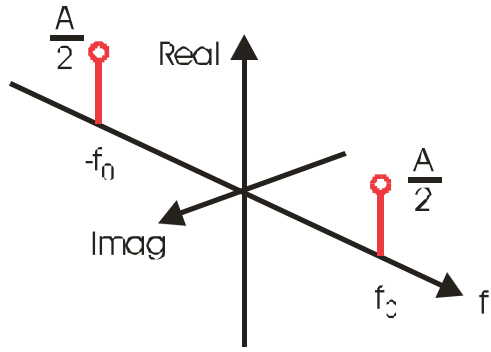


Imbalanced

I-Q Imbalance: Image Spectral Terms



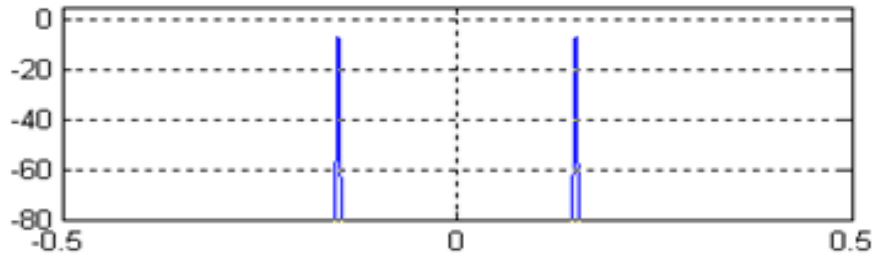
Effect of I-Q Imbalance



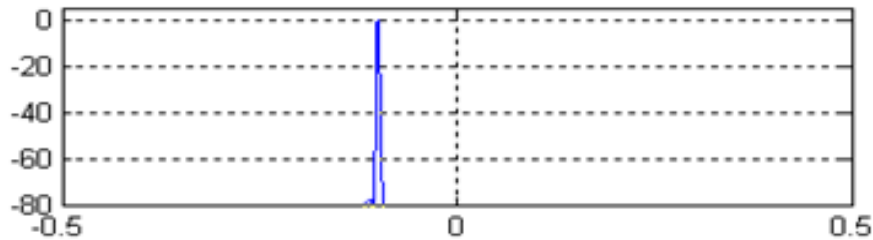
Due to Phase Imbalance

Balanced Mixers

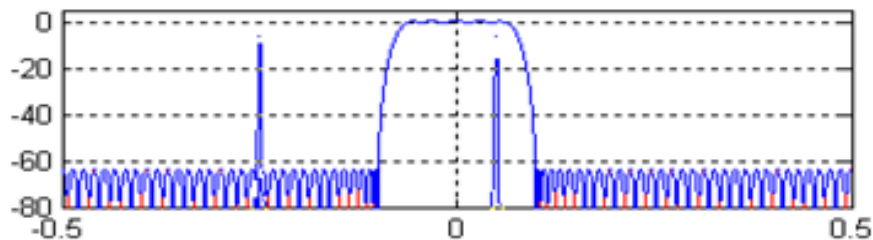
Input Spectrum: Signal at $f = +0.15$



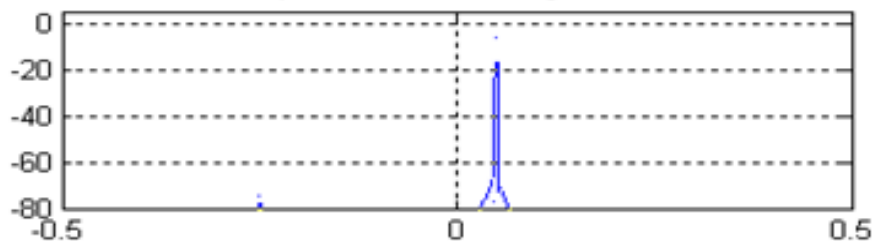
Quadrature Local Oscillator Spectrum: at $f = -0.1$



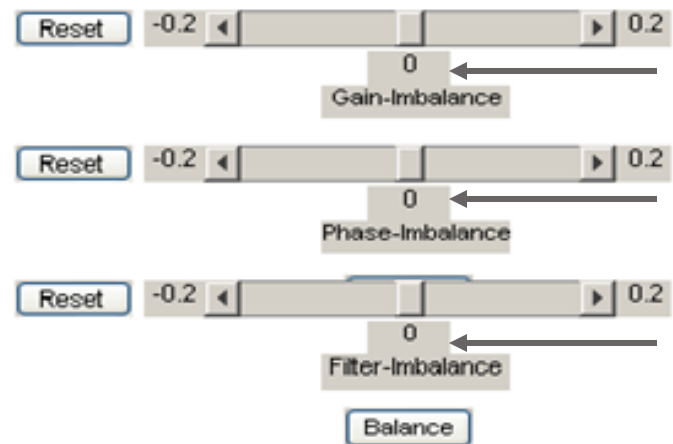
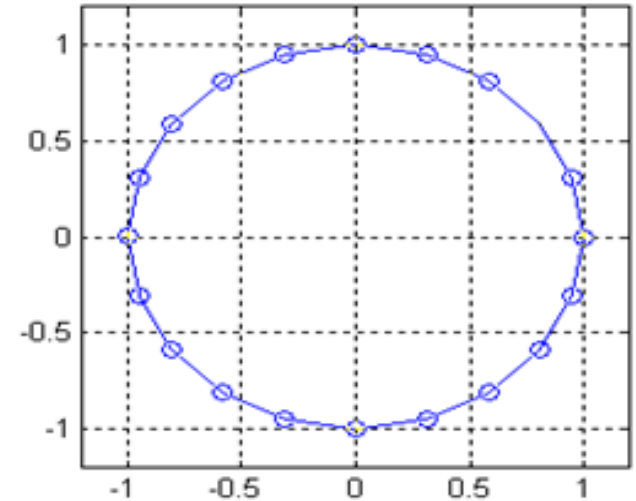
Down Converted Spectrum: Desired Signal at $f = +0.05$



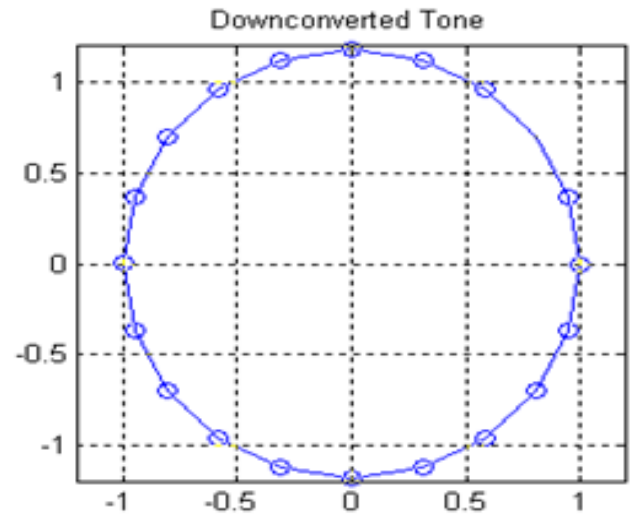
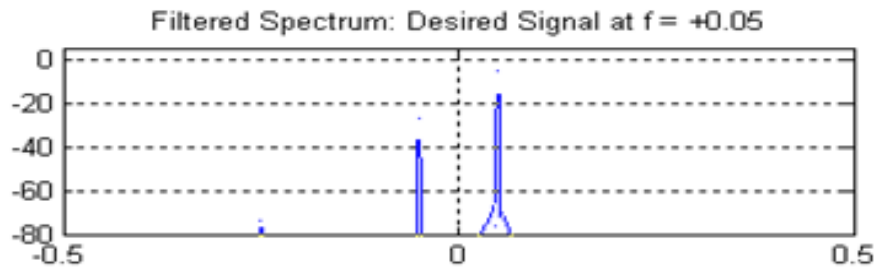
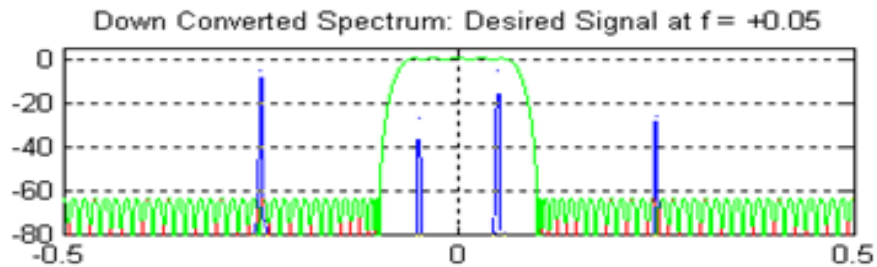
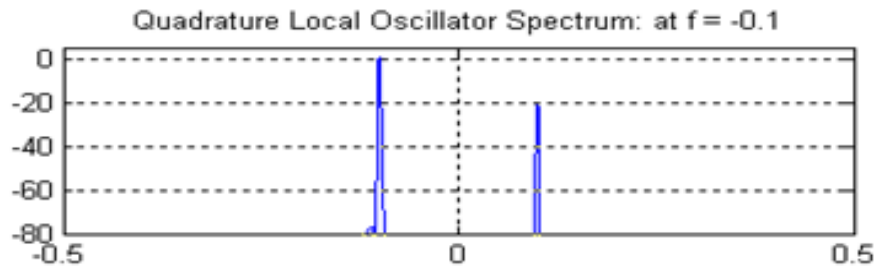
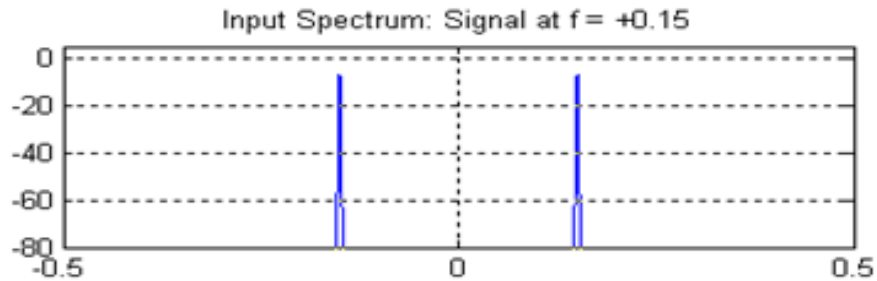
Filtered Spectrum: Desired Signal at $f = +0.05$



Downconverted Tone

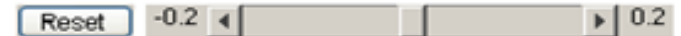


Gain Imbalance



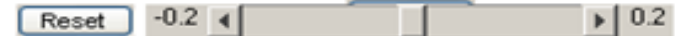
0.1867%

Gain-Imbalance



0

Phase-Imbalance



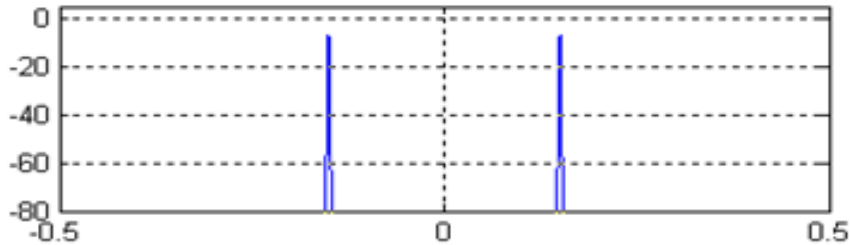
0

Filter-Imbalance

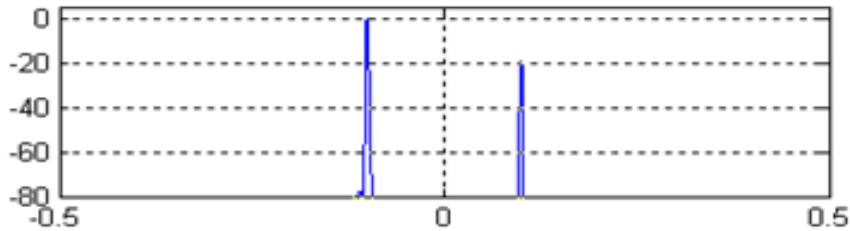
Balance

Phase Imbalance

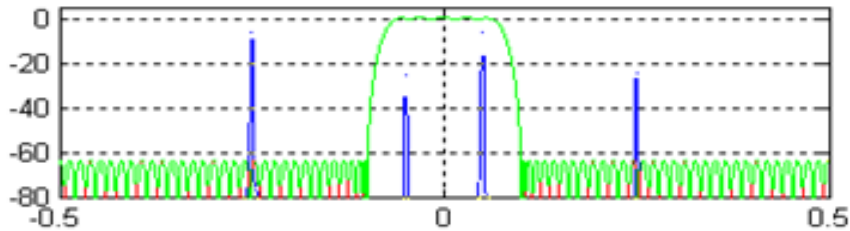
Input Spectrum: Signal at $f = +0.15$



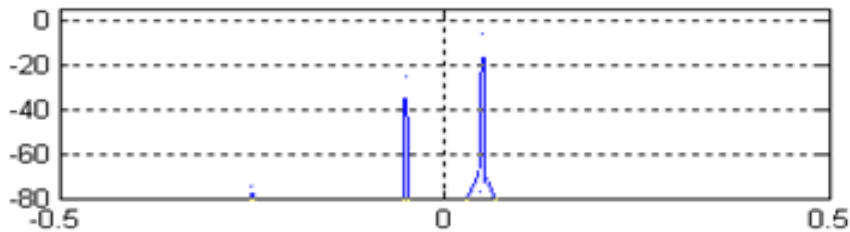
Quadrature Local Oscillator Spectrum: at $f = -0.1$



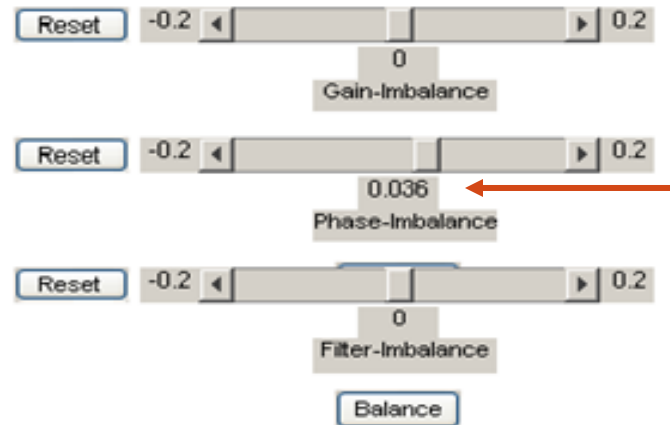
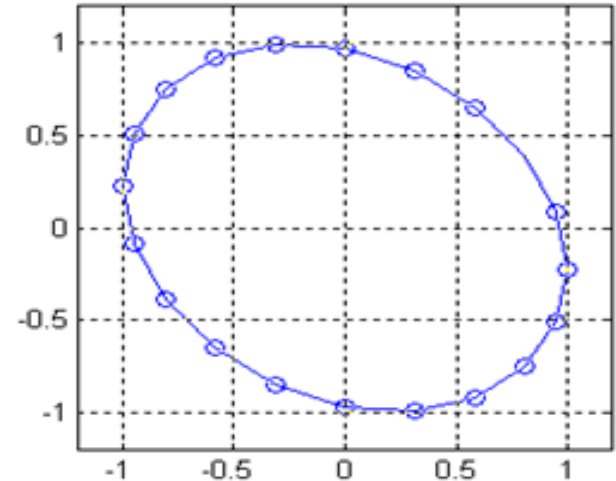
Down Converted Spectrum: Desired Signal at $f = +0.05$



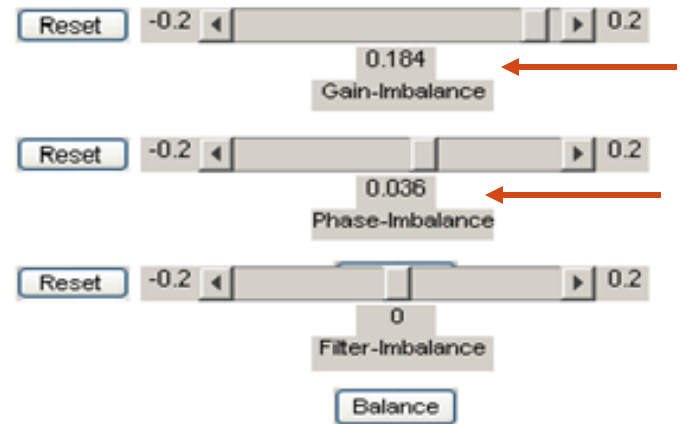
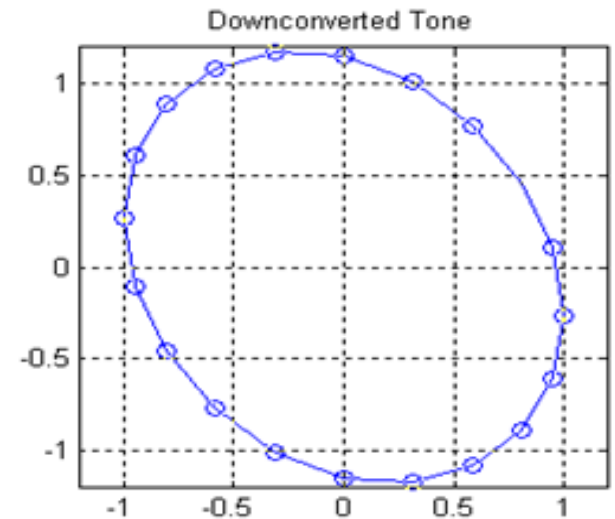
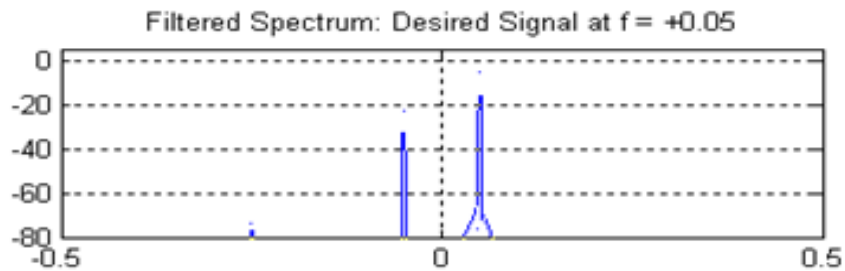
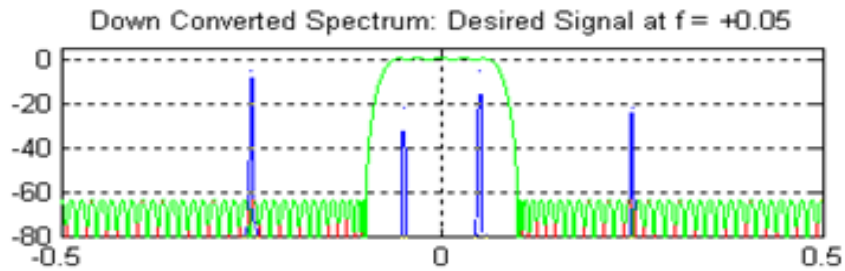
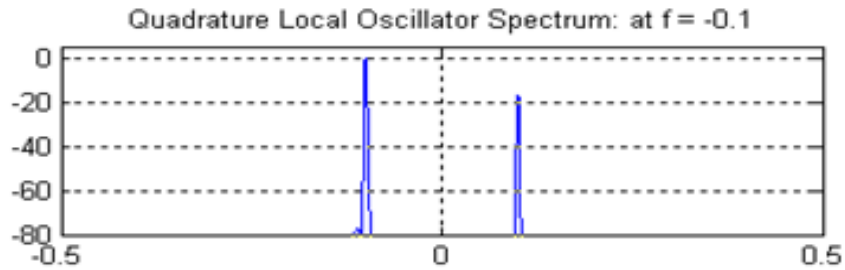
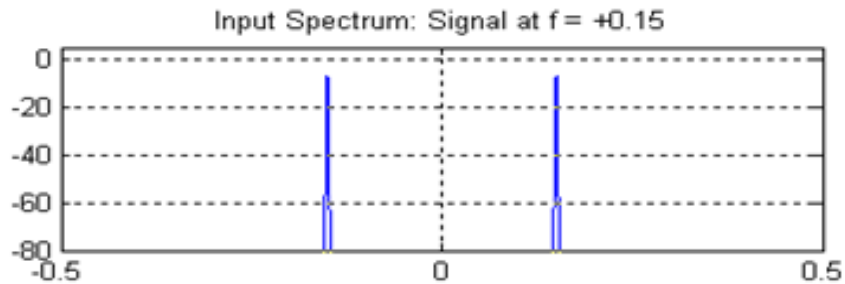
Filtered Spectrum: Desired Signal at $f = +0.05$



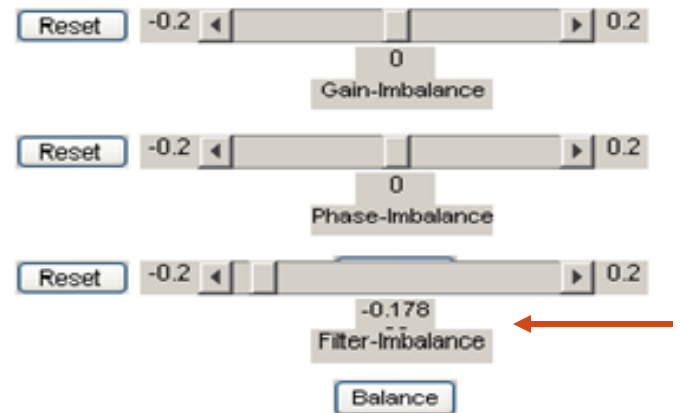
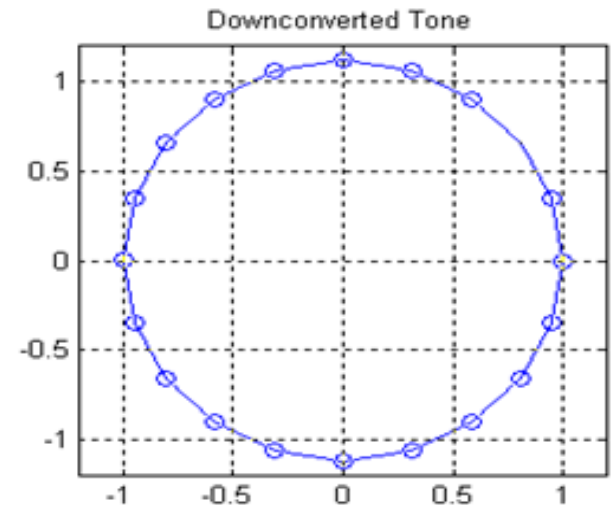
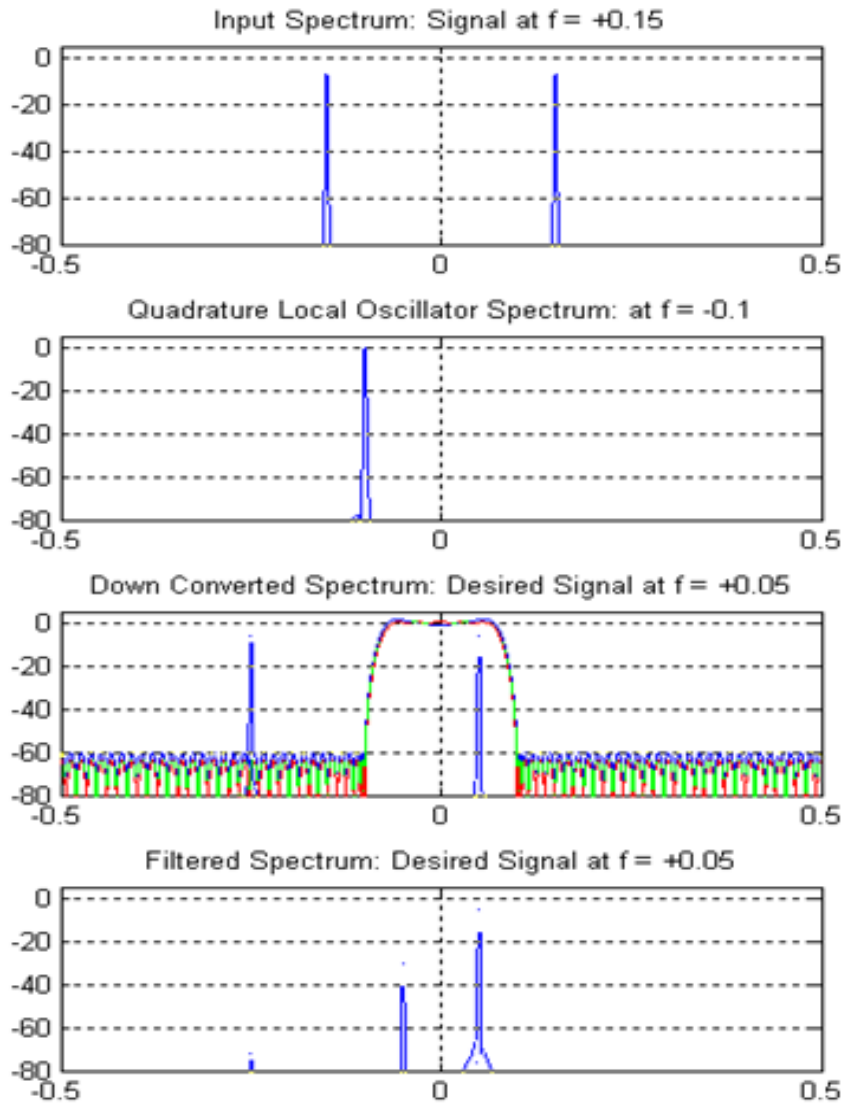
Downconverted Tone



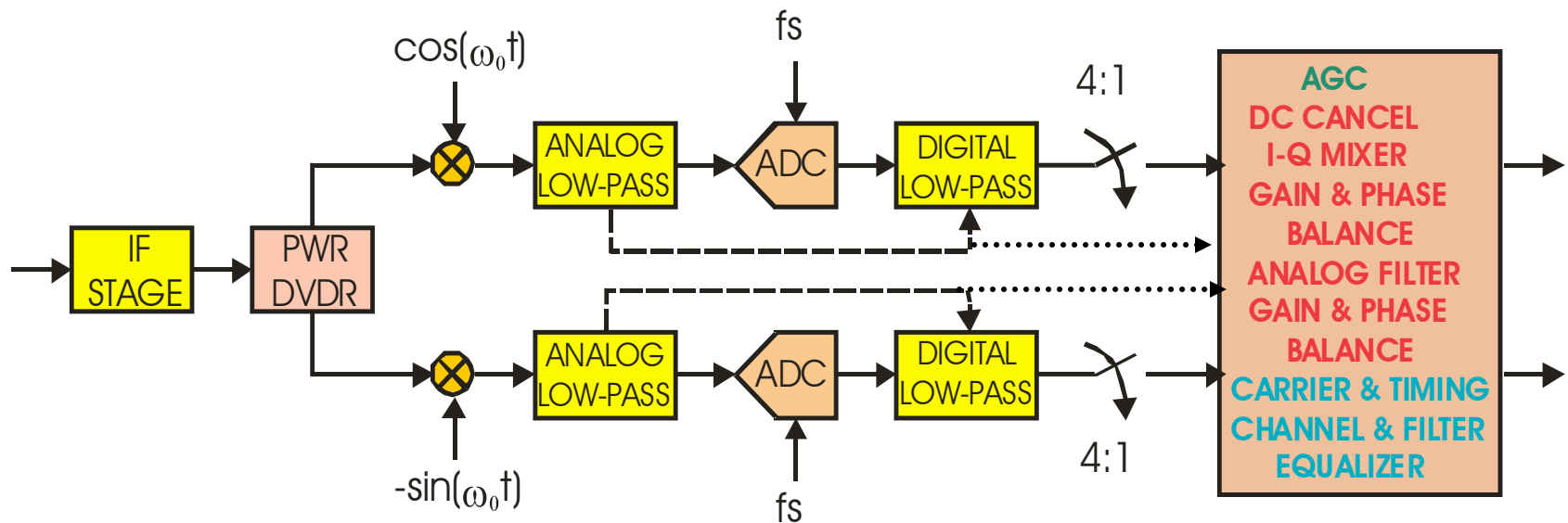
Gain and Phase Imbalance



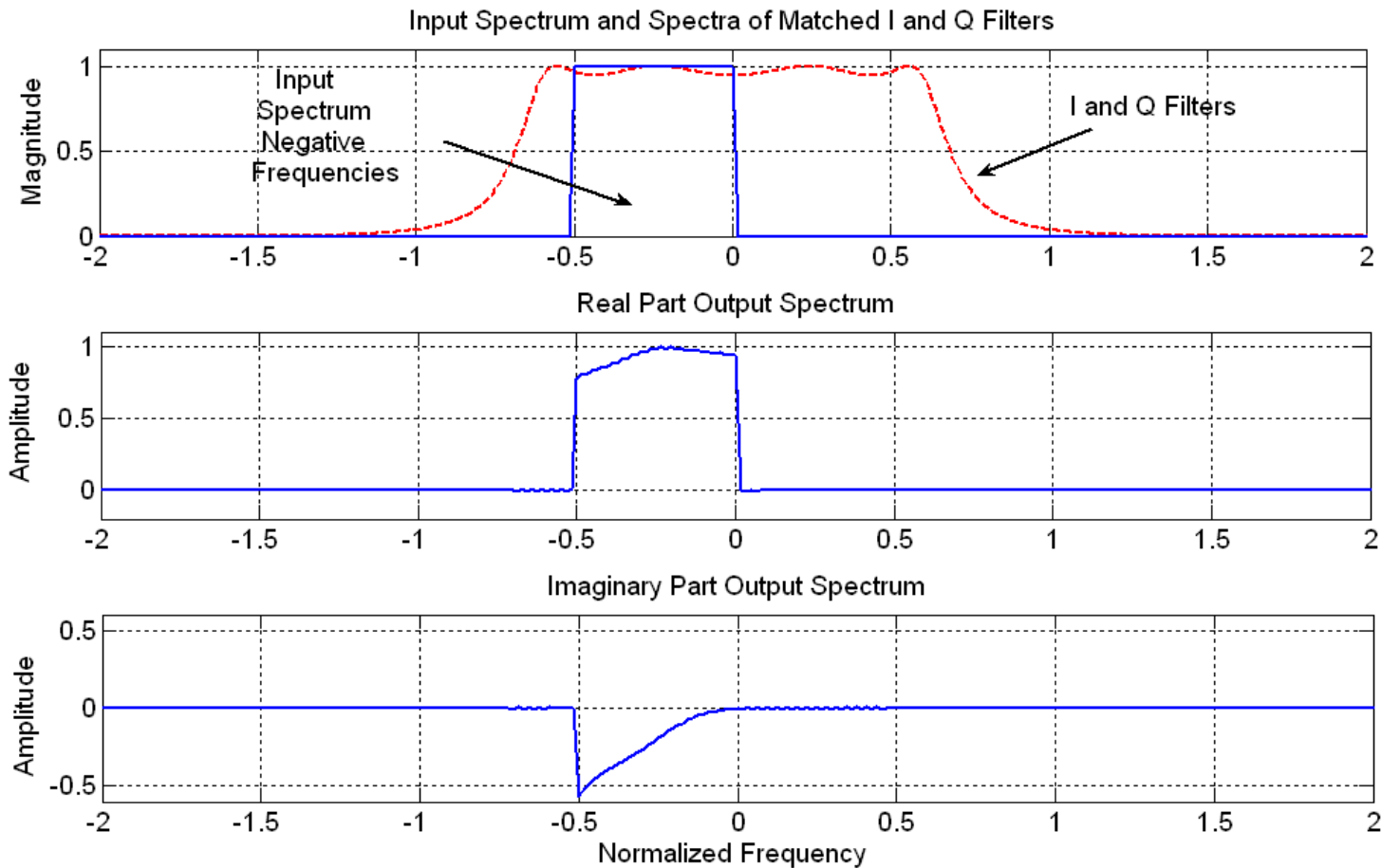
Filter Imbalance



Gain and Phase Of Mismatched Analog Low-Pass Filter

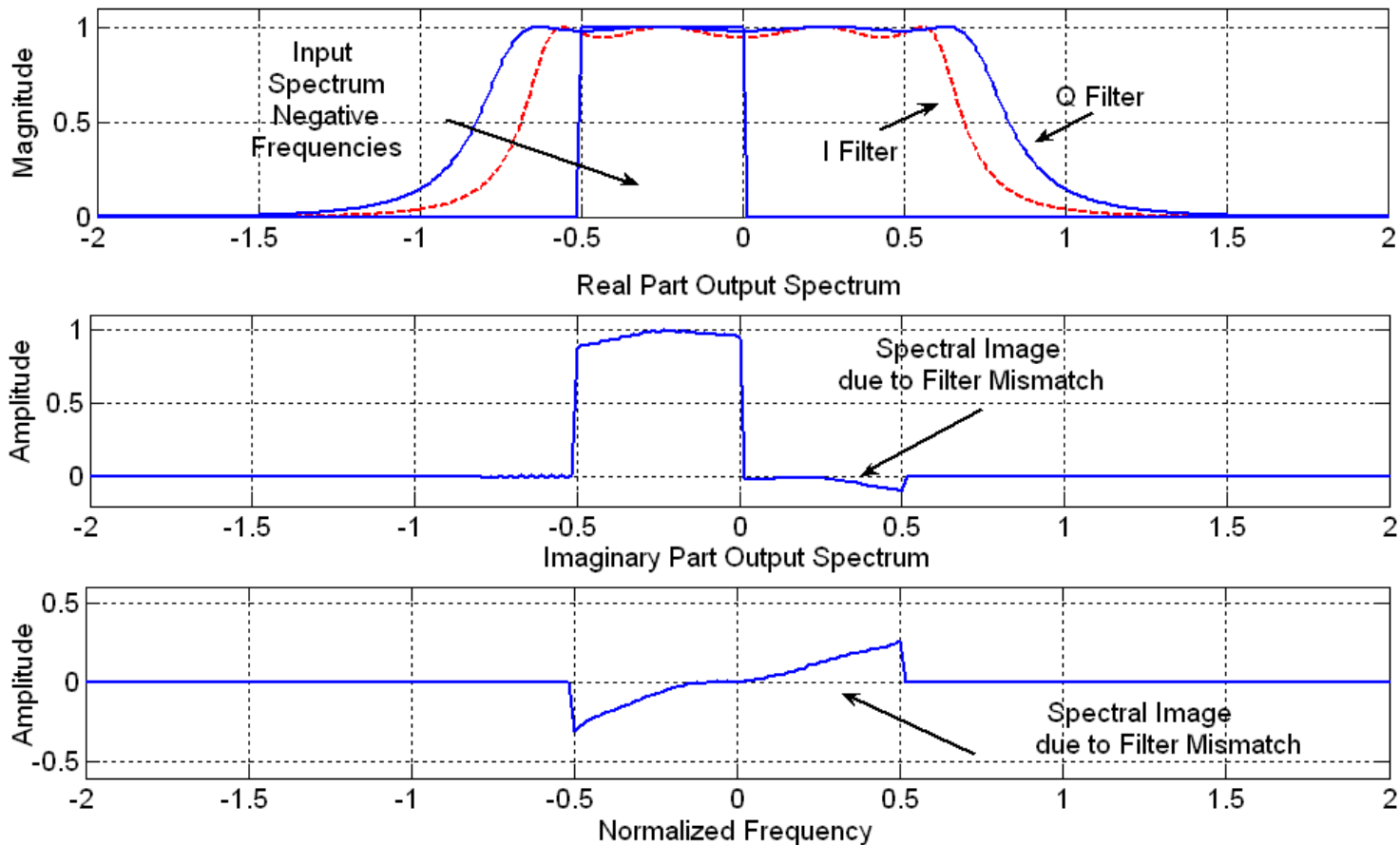


Gain and Phase Contributions of I-Q Matched Low Pass Filters

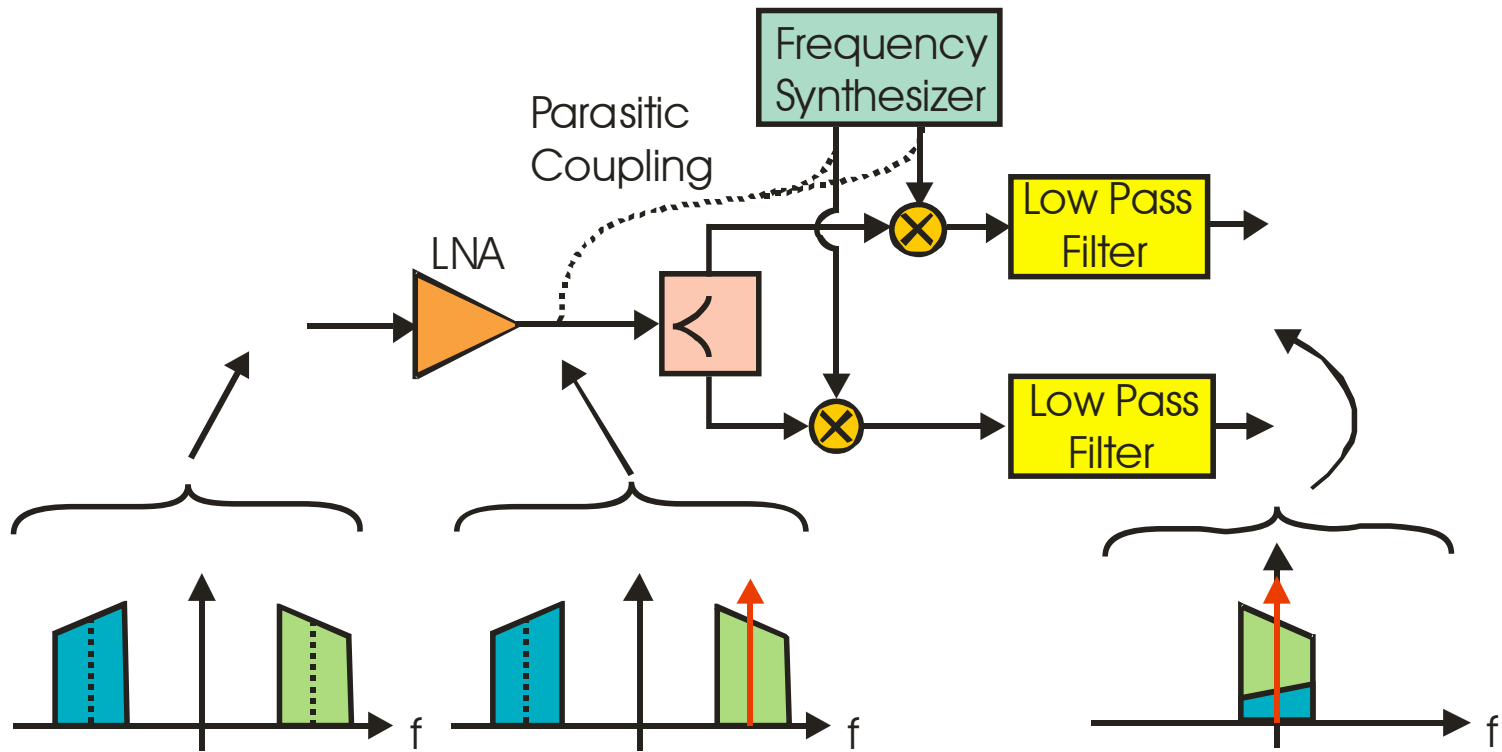


Gain and Phase Contributions of I-Q Mismatched Low Pass Filters

Input Spectrum and Spectra of Intentionally Mismatched I and Q Filters



I-Q Imbalance and Self Mixing



DC Offset:

Desired Component: Mixing

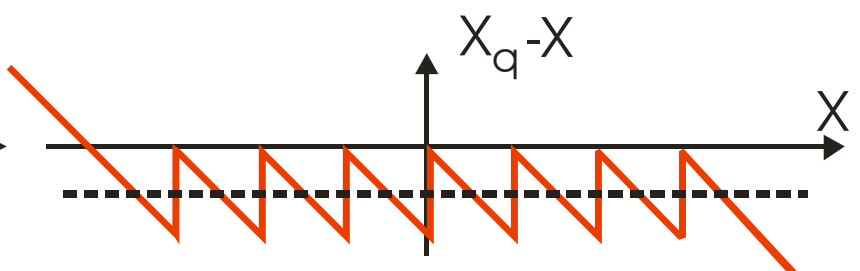
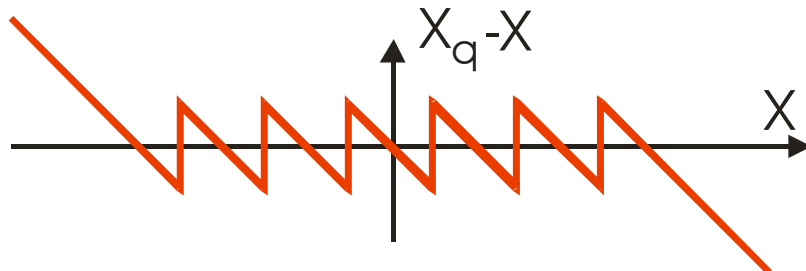
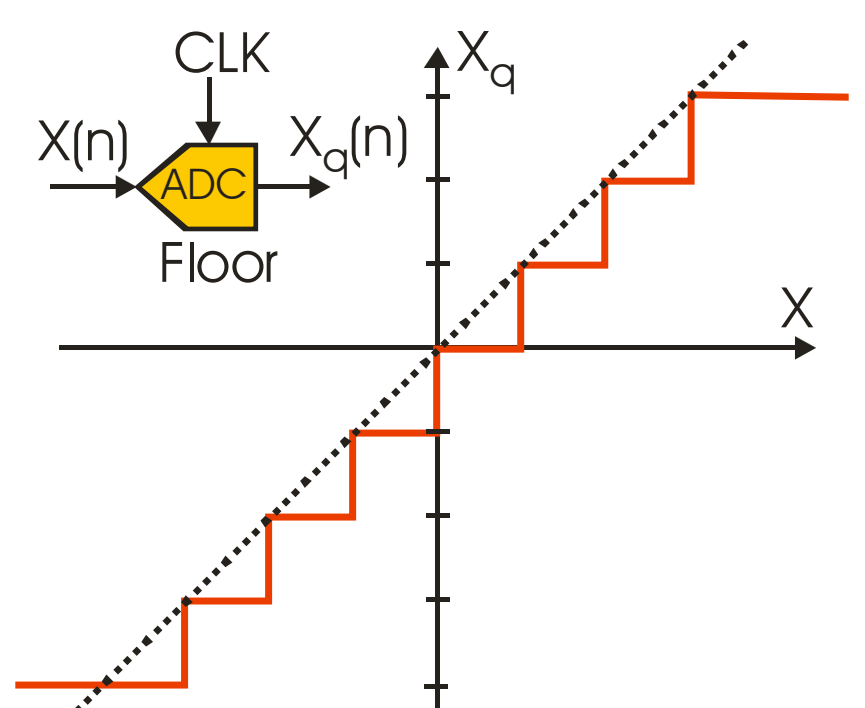
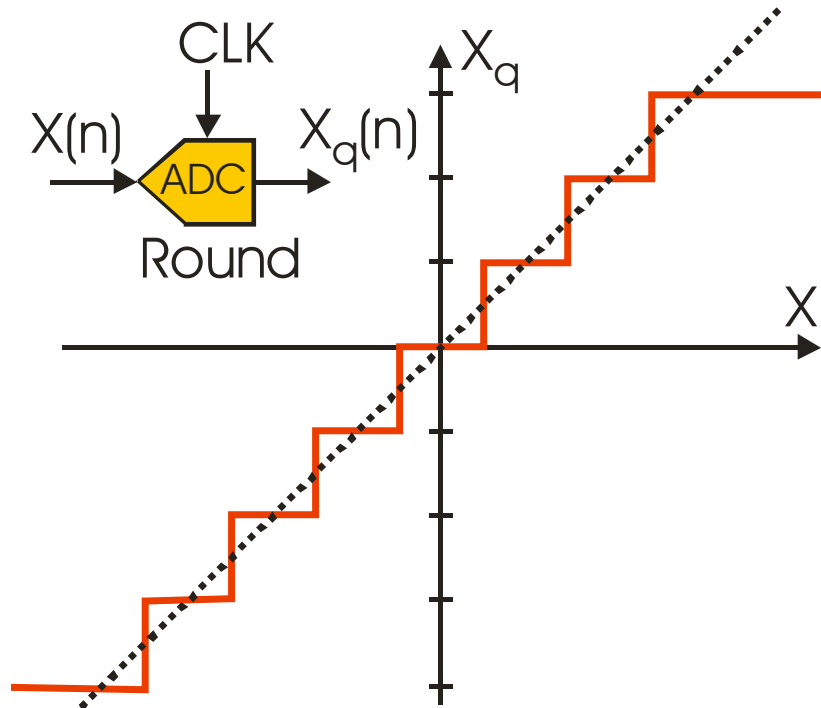
Spectral Image:

Self Mixing

Mixing

I-Q Imbalance

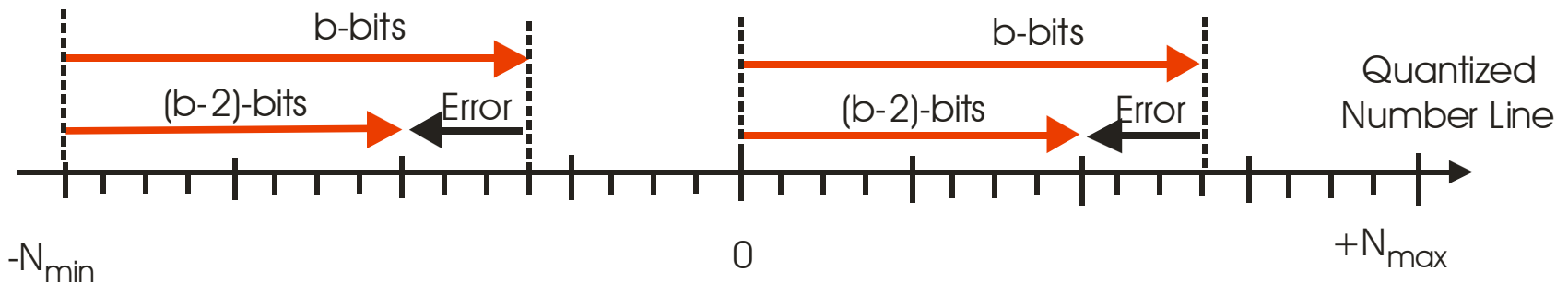
Truncating Quantizers: DC Bias



Rounding Quantizer

Truncating Quantizer

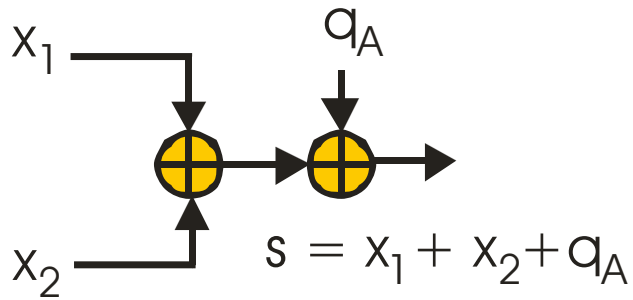
2's Complement Arithmetic; DC Bias



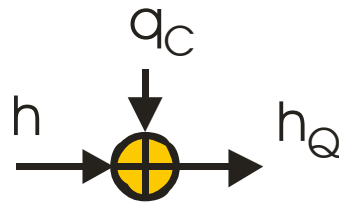
Negative numbers:
Measure displacement from reference.
Reference = $-N_{\min}$

Positive numbers:
Measure displacement from reference.
Reference = 0

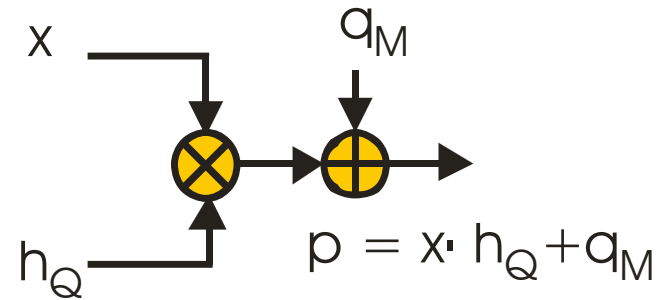
Errors Due to finite Arithmetic



Quantize Addition

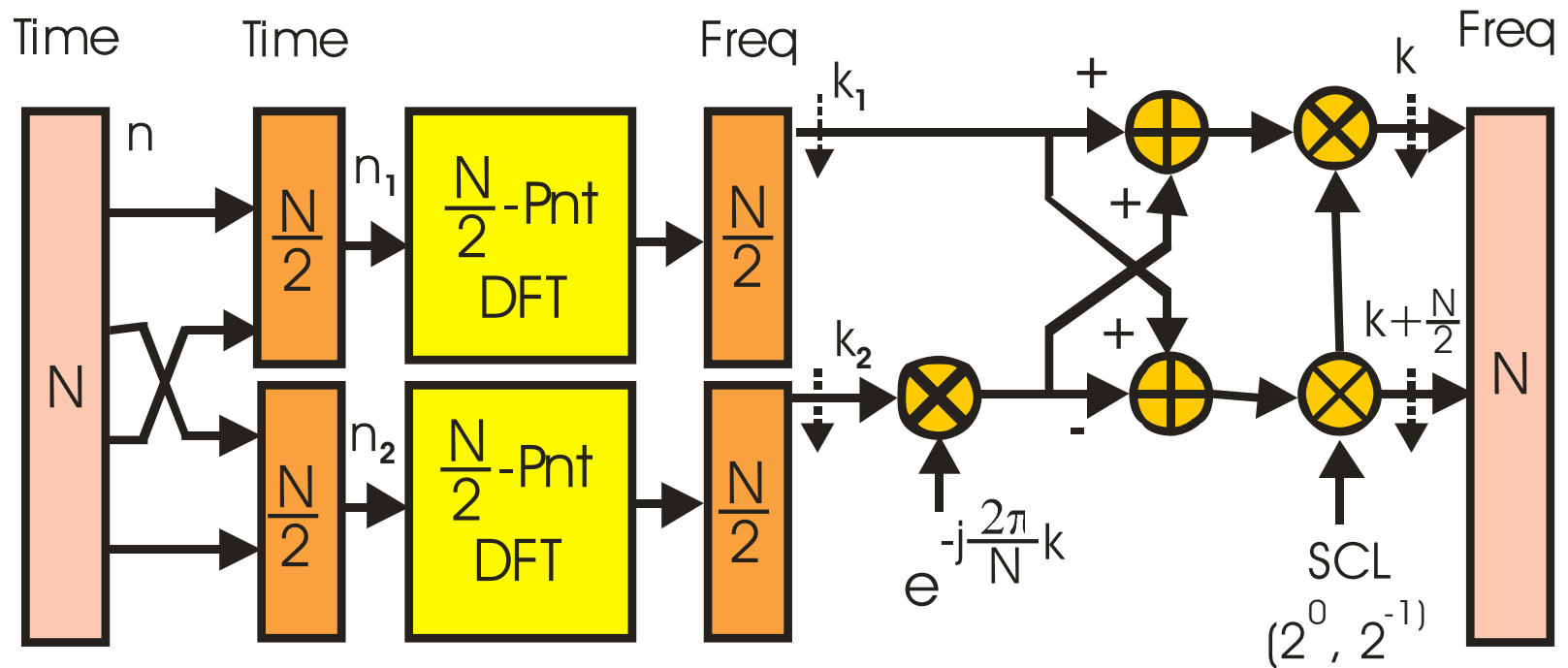


Quantize Coefficient

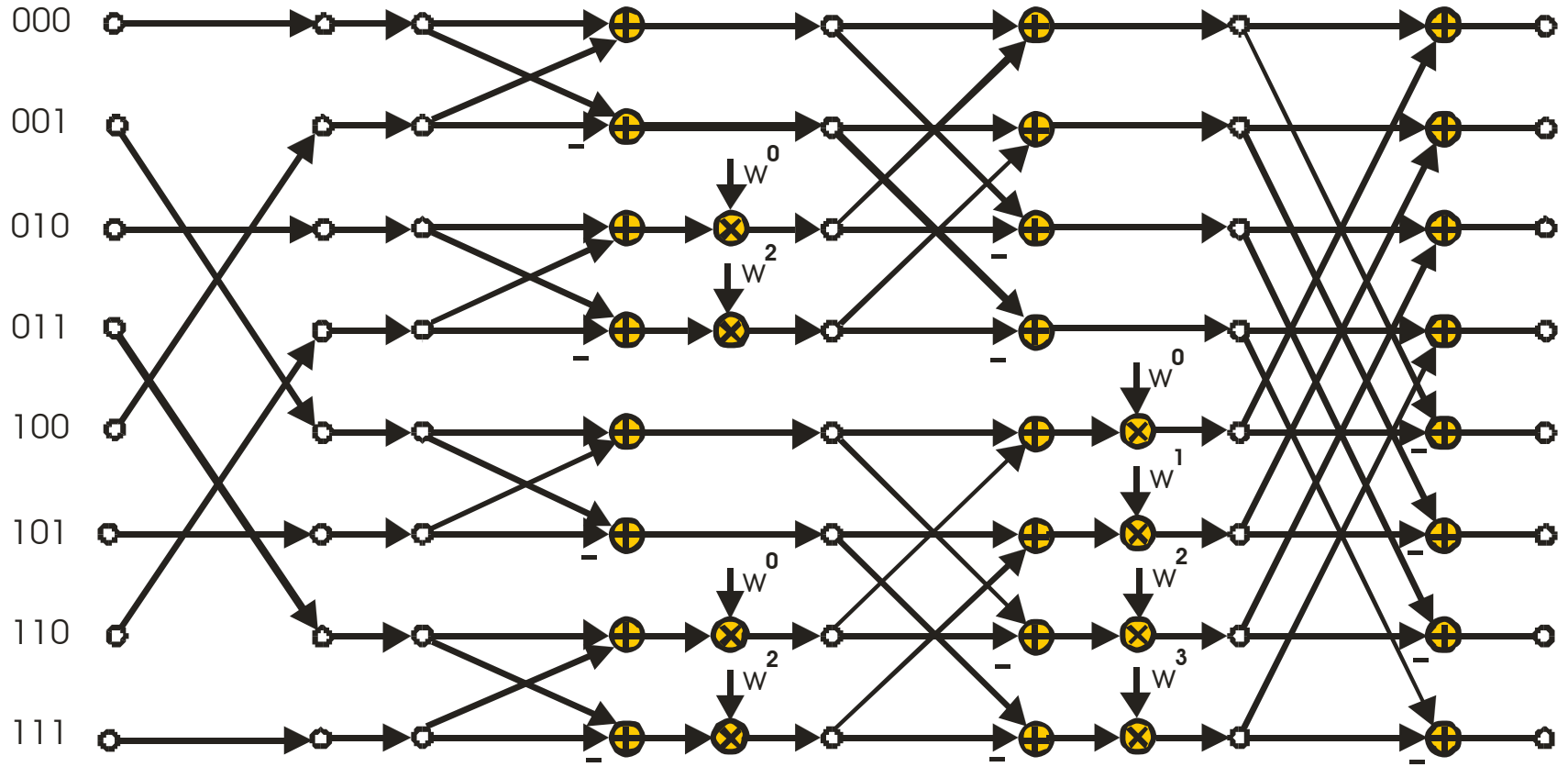


Quantize Multiplication

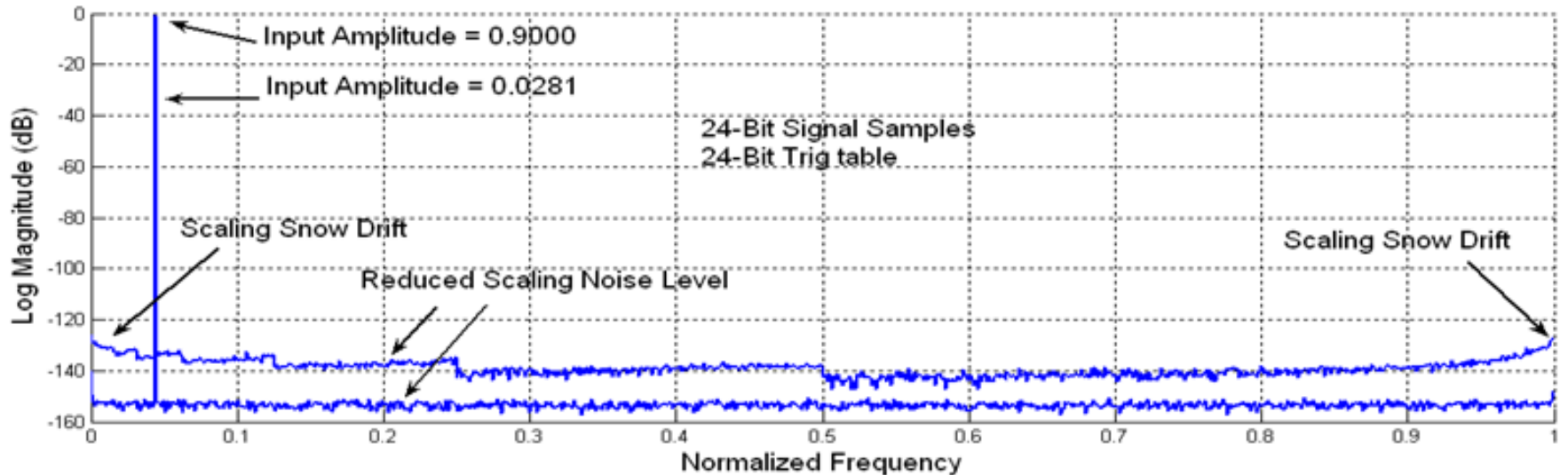
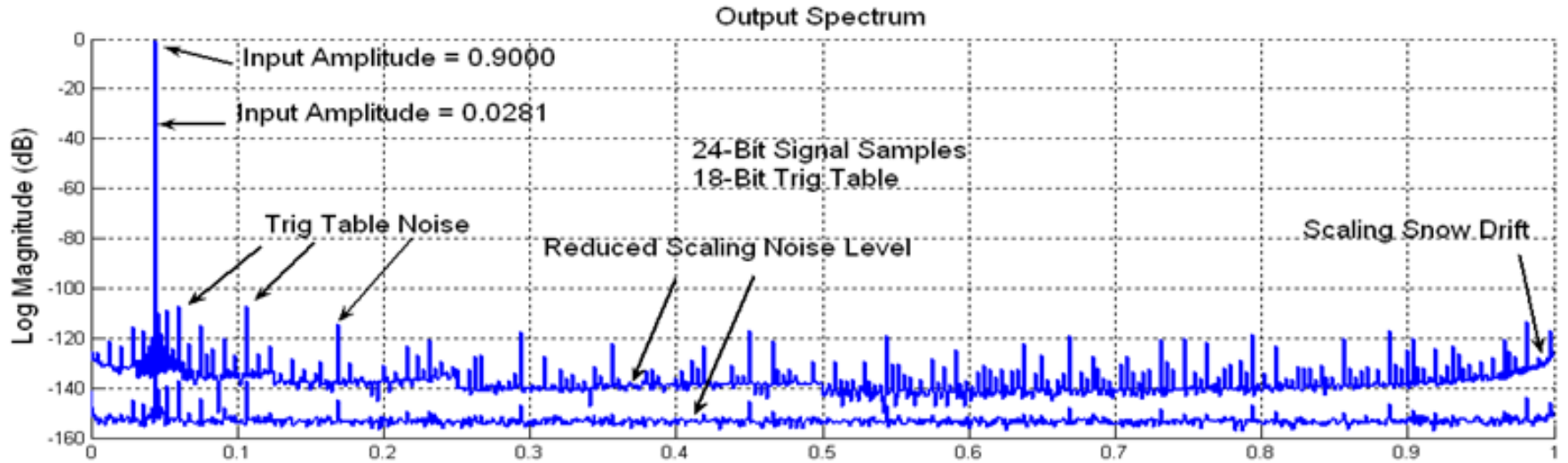
Finite Arithmetic in Radix-2 FFT Algorithm



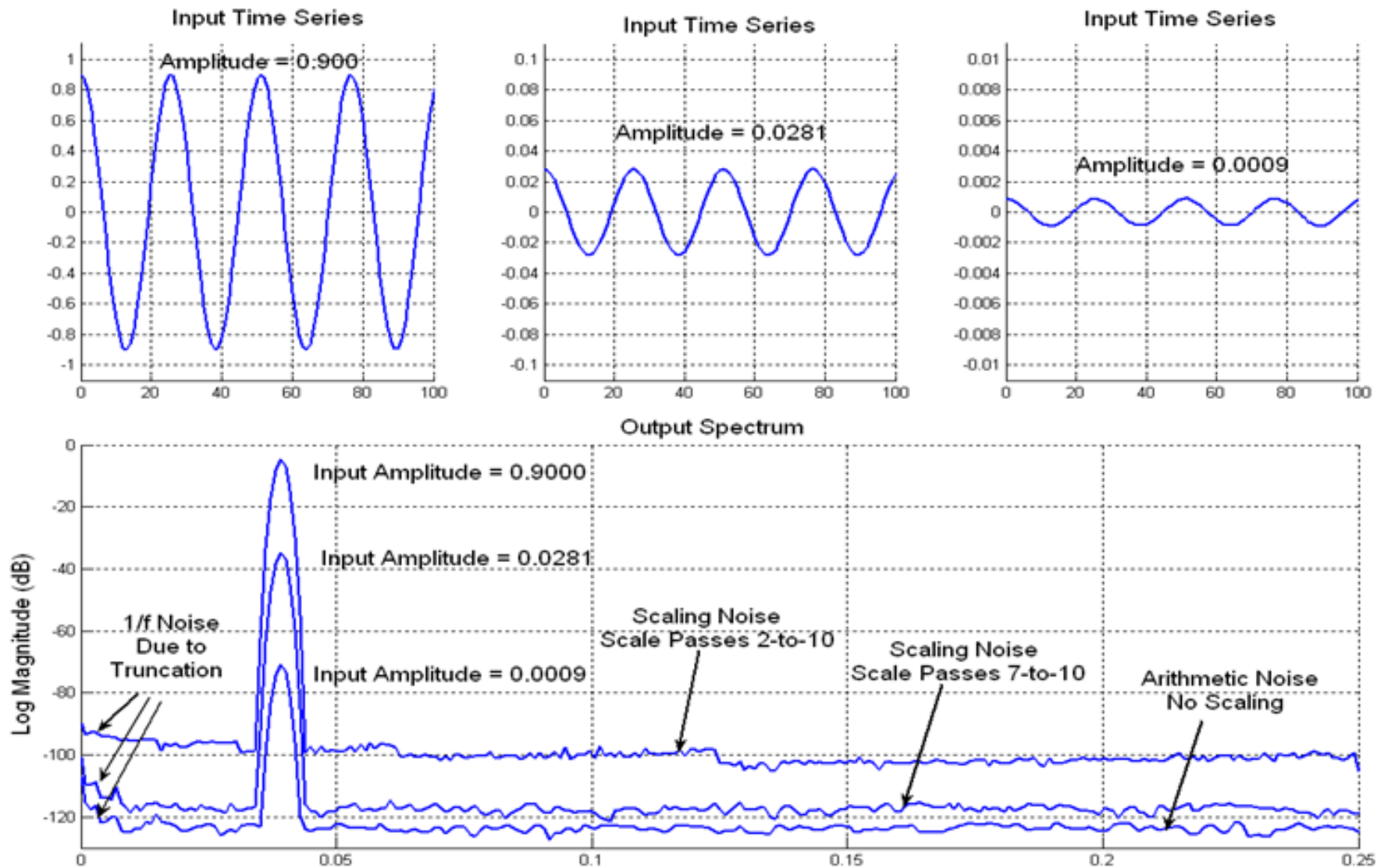
Radix-2 FFT Signal Flow Diagram



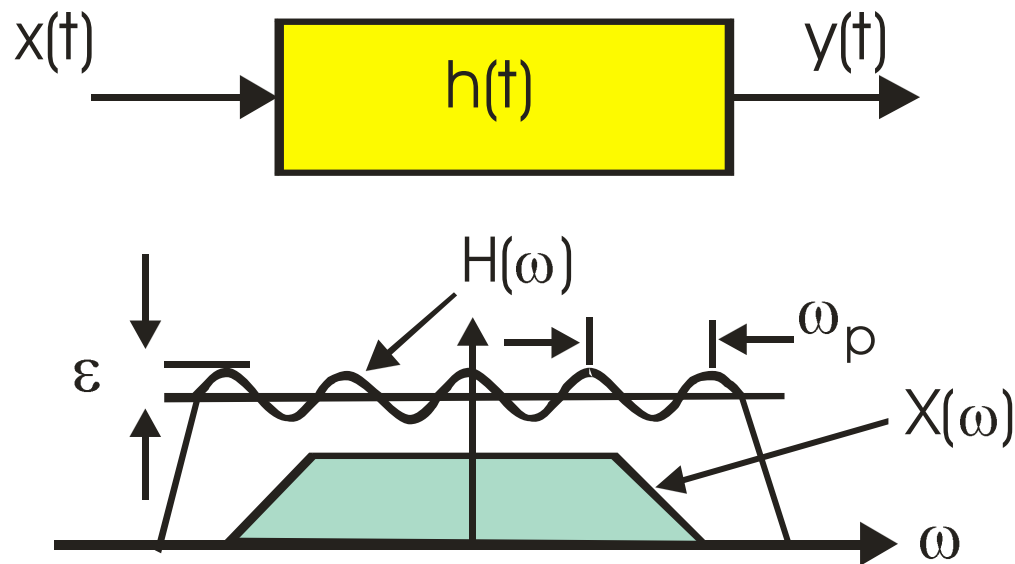
Algorithm Noise Due to Finite Arithmetic and Coefficient Noise



Algorithm Noise due to Finite Arithmetic Scaling Noise



Signal Through Filter with Gain Distortion



$$H(\omega) = 1 + \varepsilon \cos(\omega T_p)$$

Model of Gain Distortion

$$H(\omega) = 1 + \varepsilon \cos(\omega T_p)$$

$$Y(\omega) = X(\omega) H(\omega) = X(\omega) [1 + \varepsilon \cos(\omega T_p)]$$

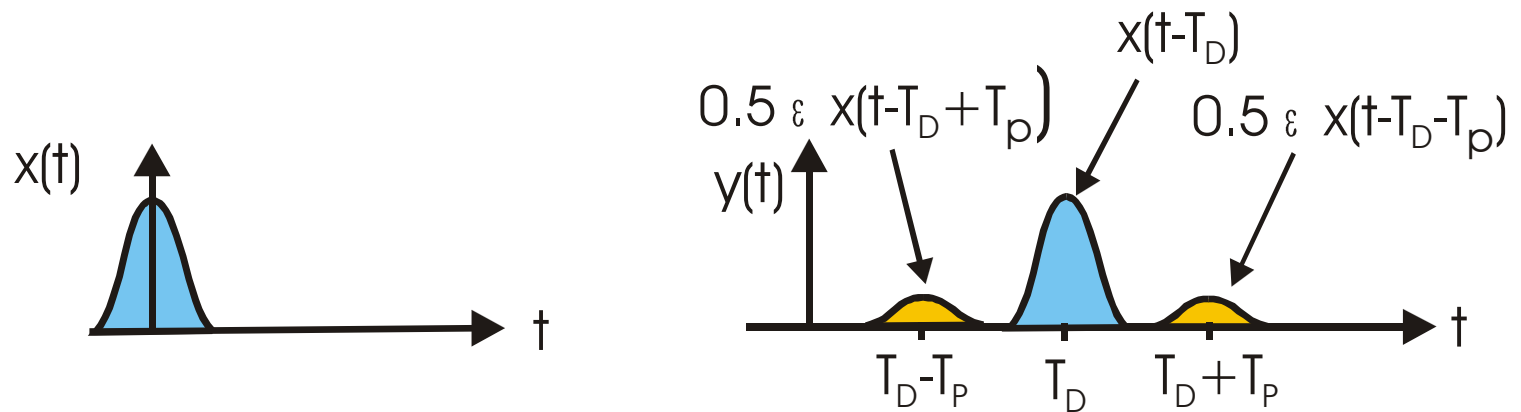
$$= X(\omega) + \varepsilon X(\omega) \cos(\omega T_p)$$

$$= X(\omega) + 0.5 \varepsilon X(\omega) \exp(j\omega T_p) + 0.5 \varepsilon X(\omega) \exp(-j\omega T_p)$$

$$y(t) = x(t) + \underbrace{0.5 \varepsilon x(t + T_p) + 0.5 \varepsilon x(t - T_p)}_{\text{Paired Echos}}$$

Paired Echos

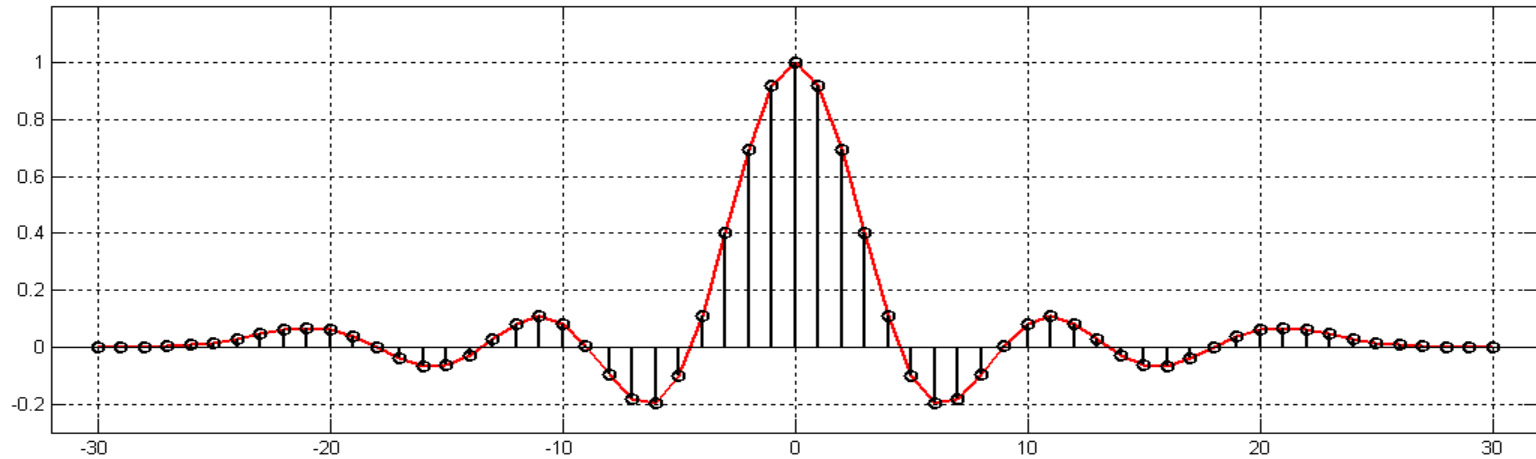
Pre-and-Post Echoes



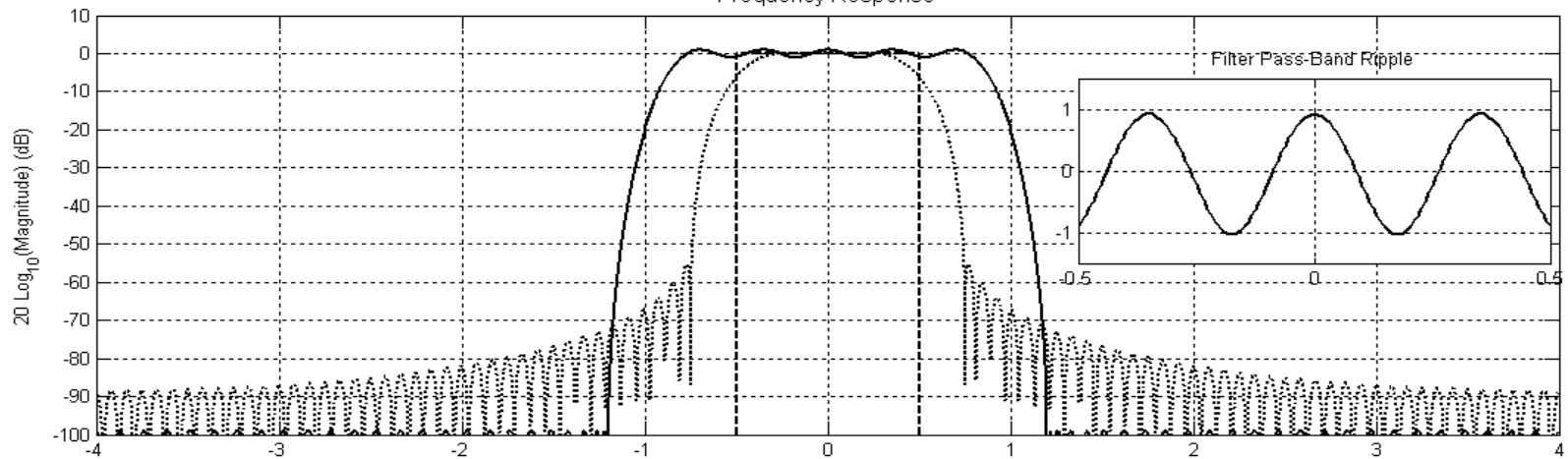
Paired Echoes: The Effect of Passband Ripple

Nyquist Pulse Time and Frequency

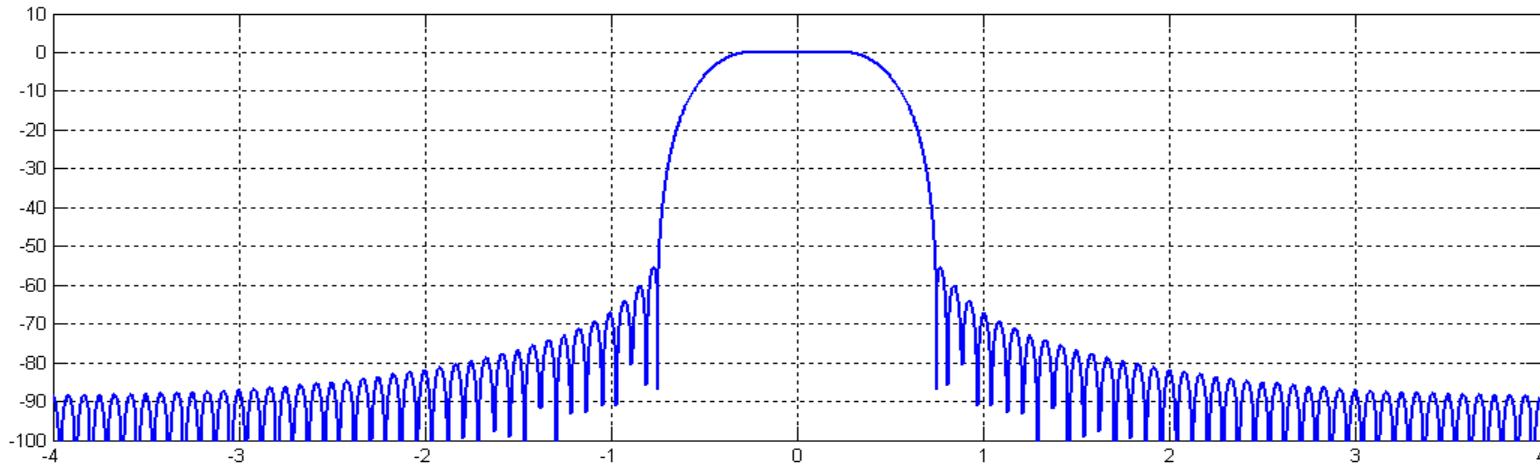
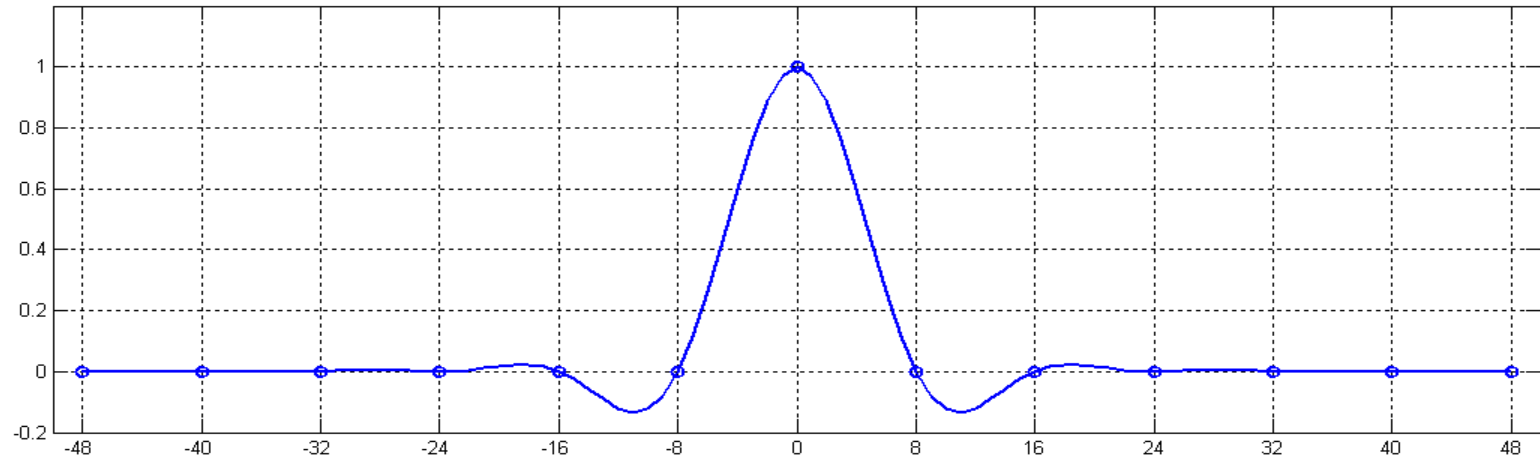
Impulse Response



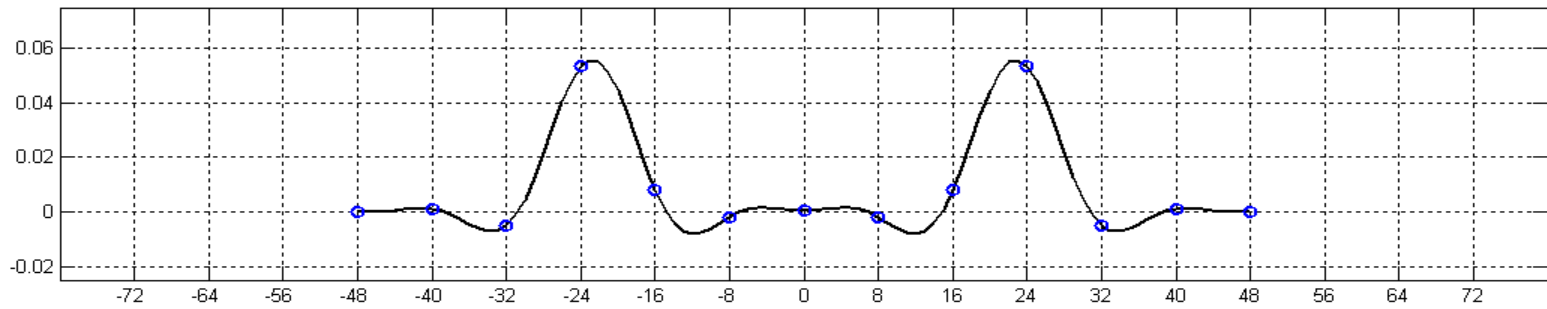
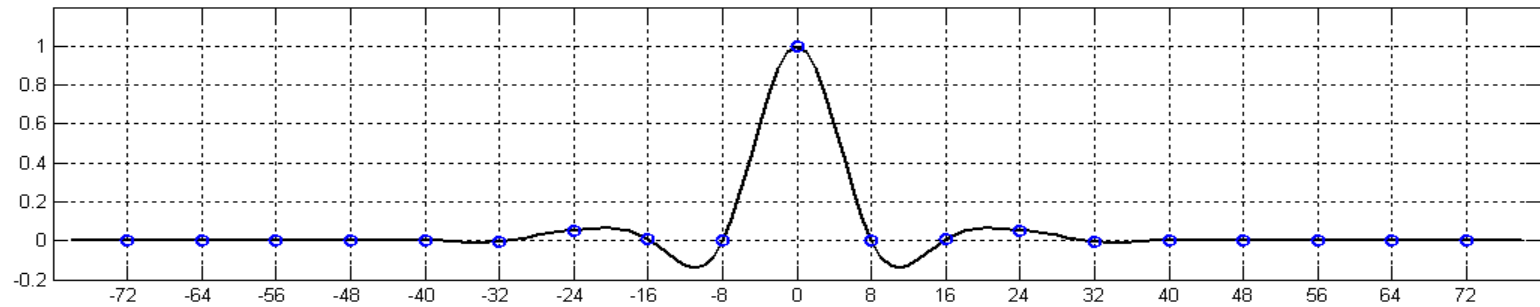
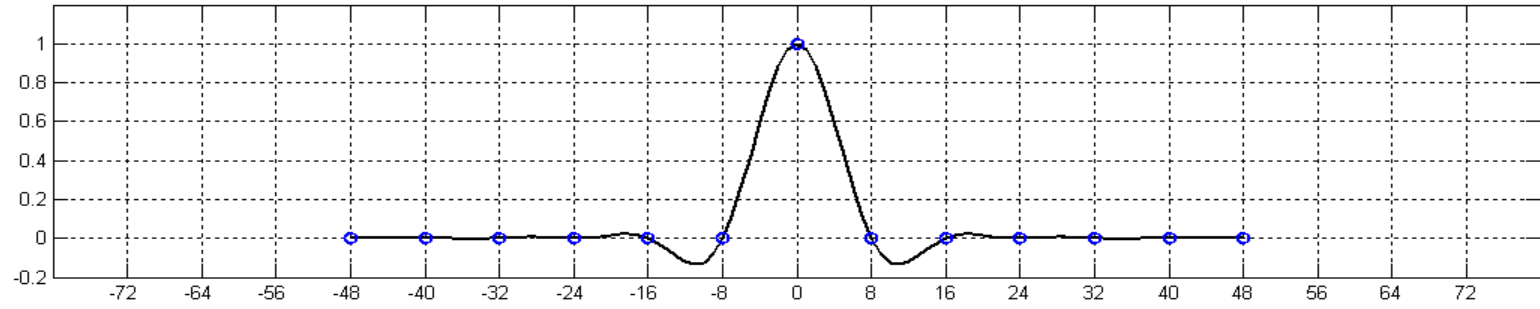
Frequency Response



Pulse: Time and Frequency

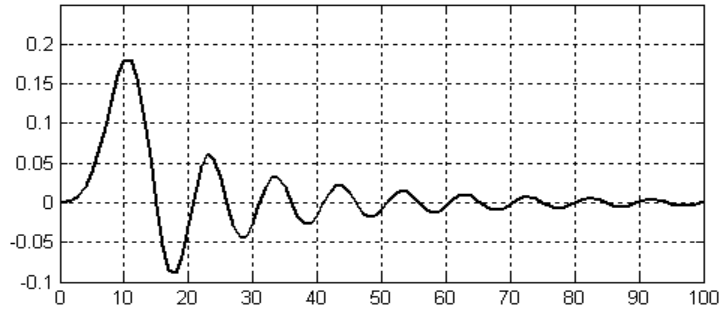


Pulse Response and ISI Component

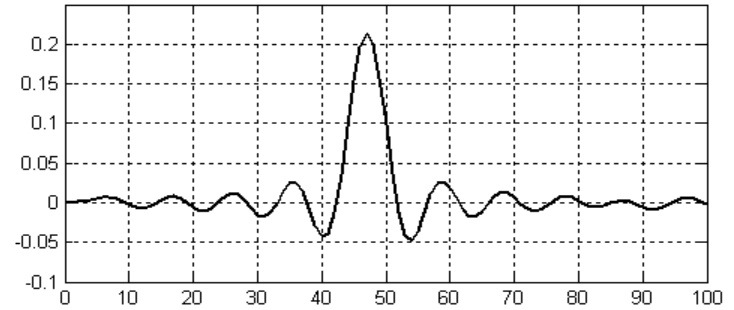


Recursive Filter Time & Frequency

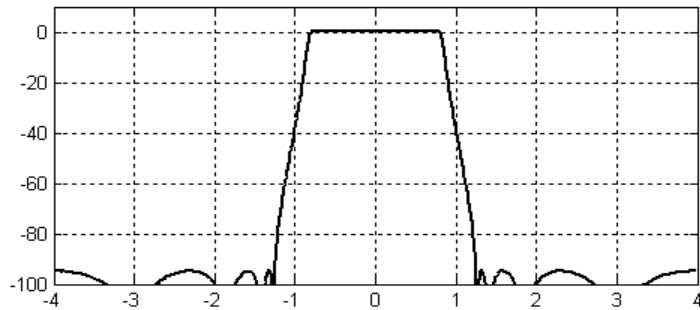
Impulse Response



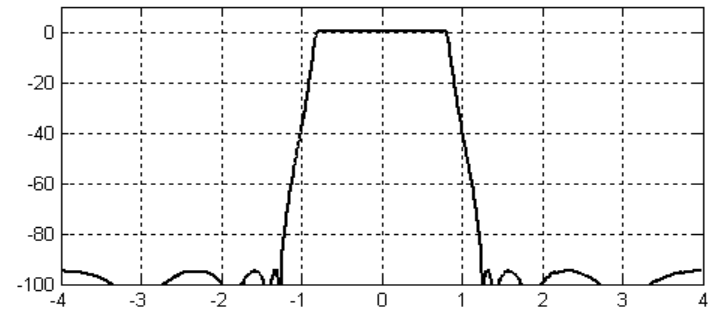
Phase Equalized Impulse Response



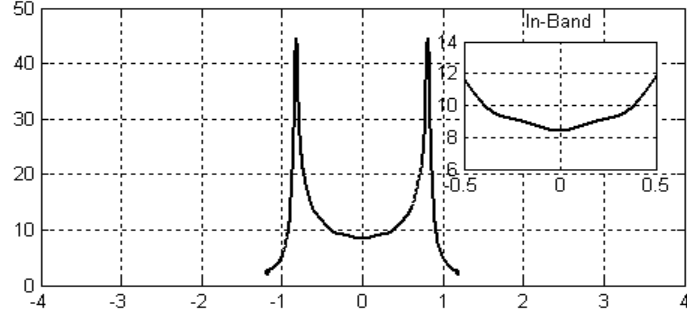
Magnitude Response



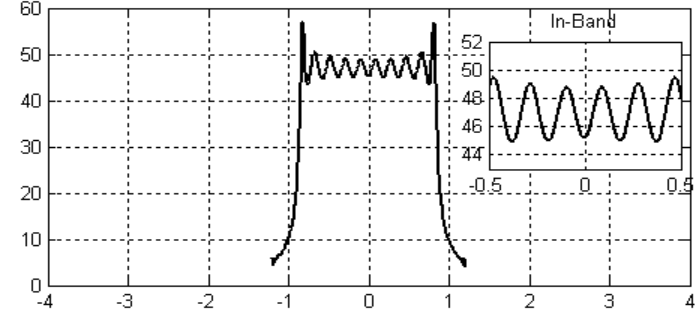
Magnitude Response



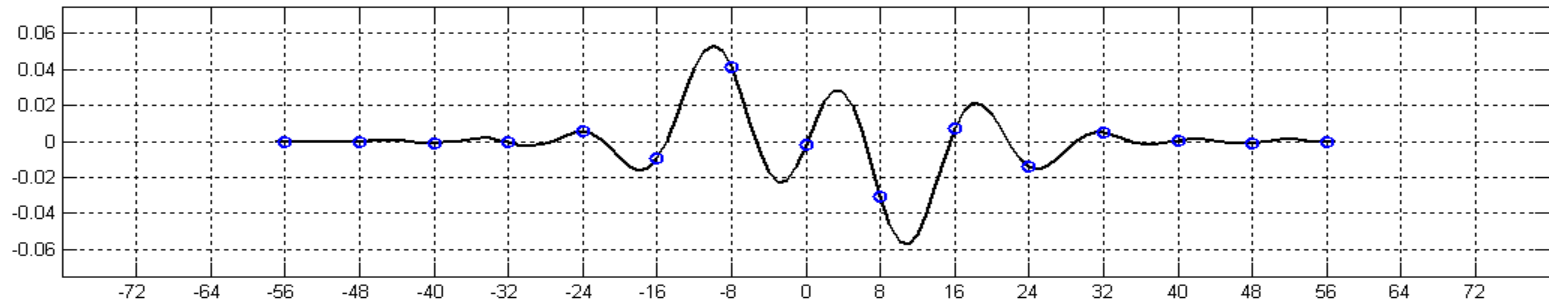
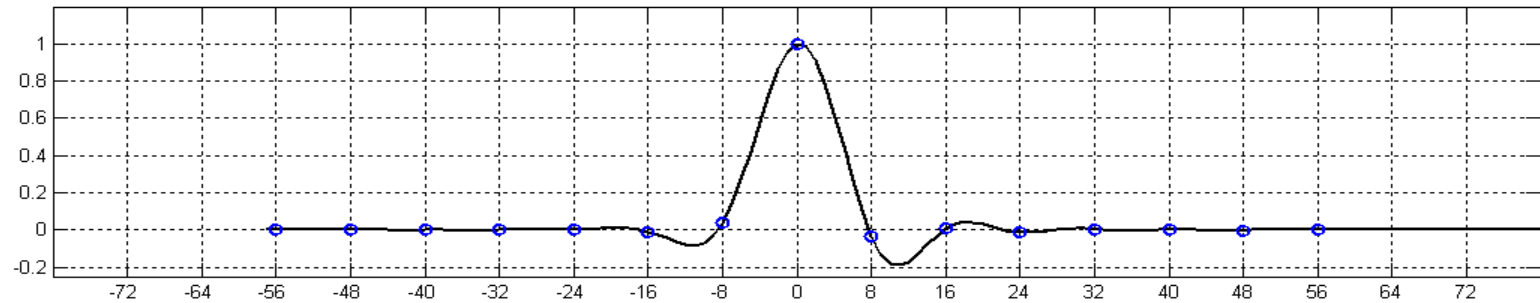
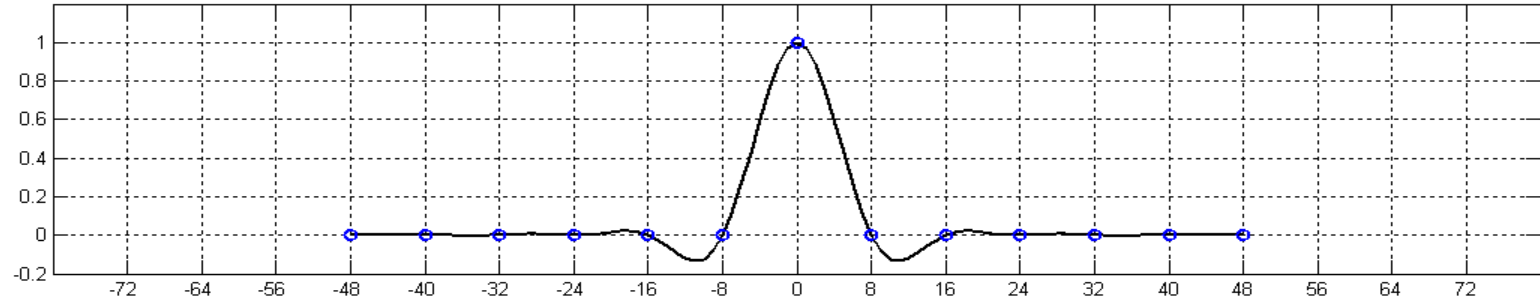
Group Delay



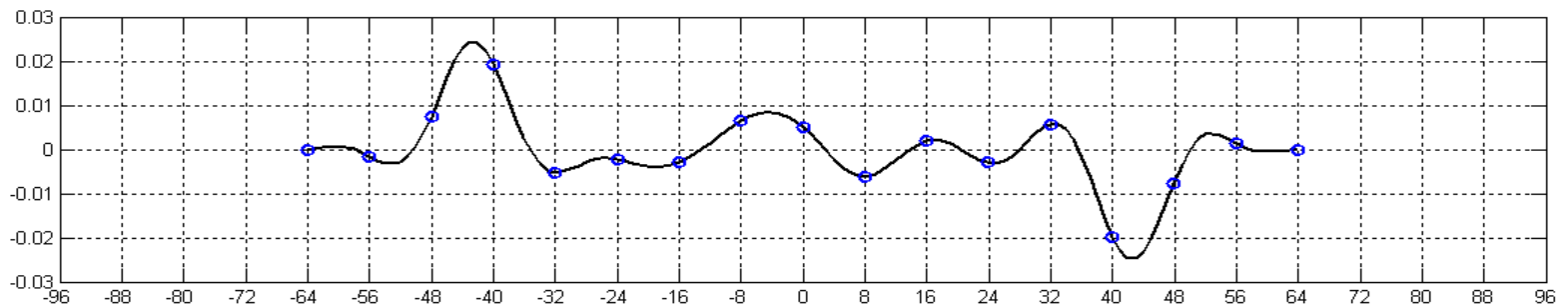
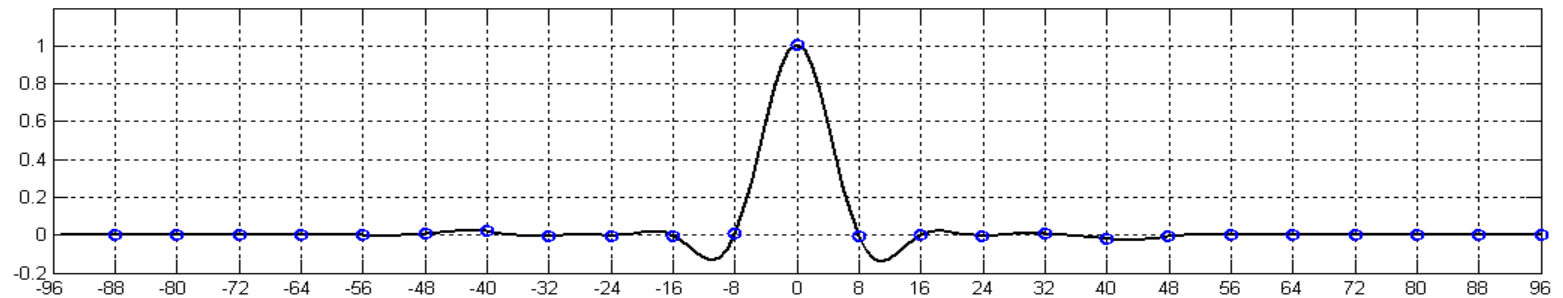
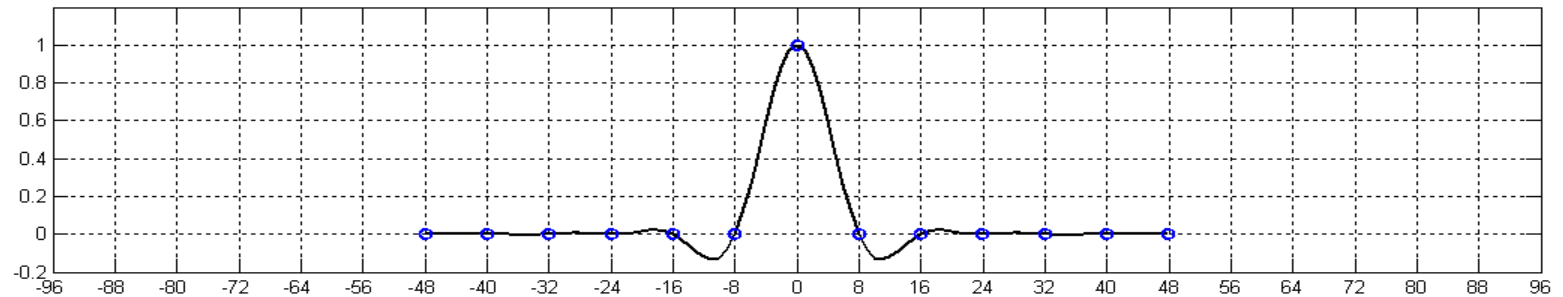
Group Delay



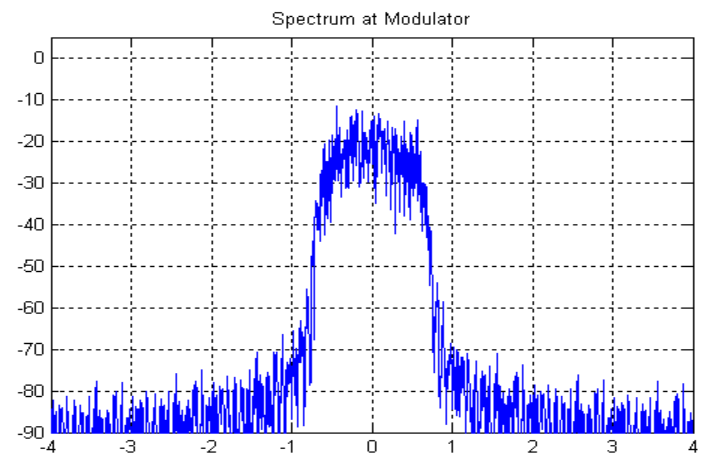
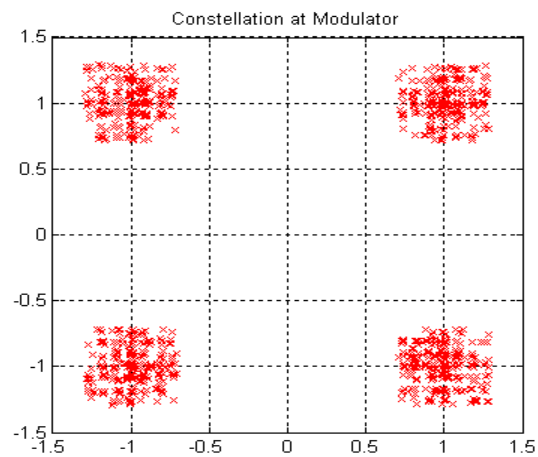
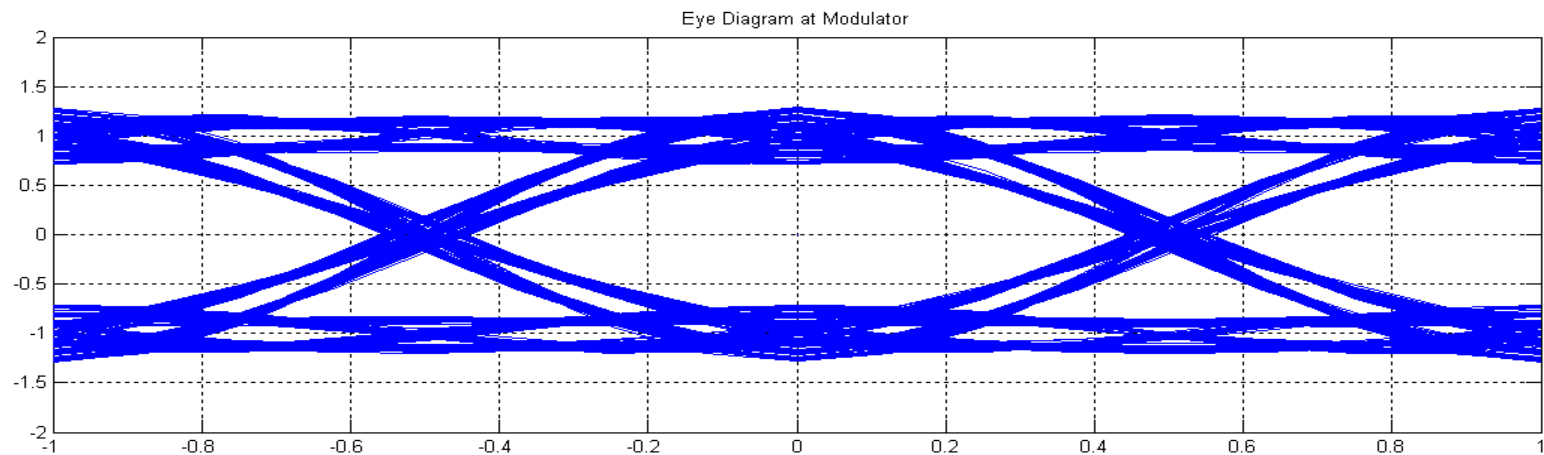
Pulse Response and ISI Component



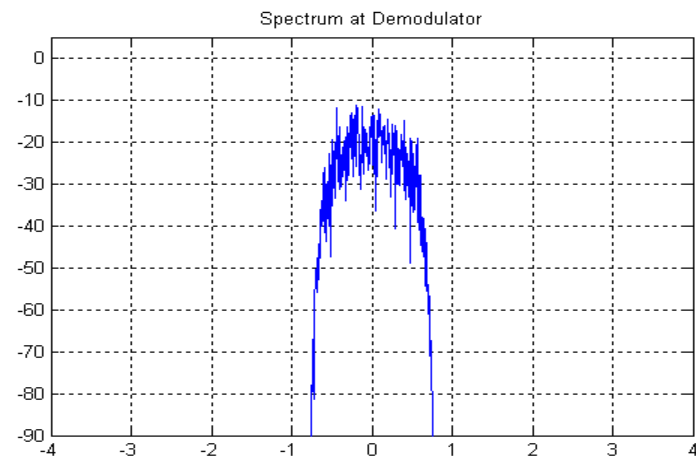
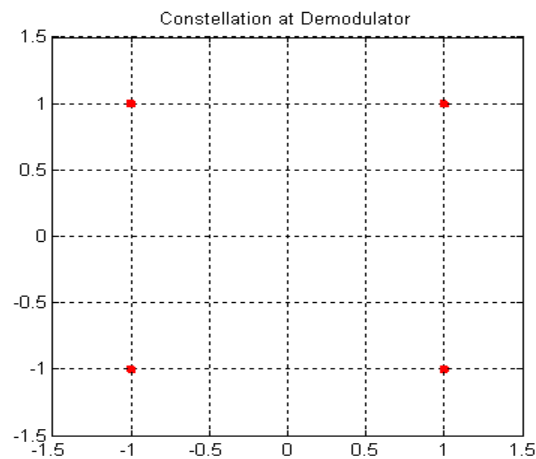
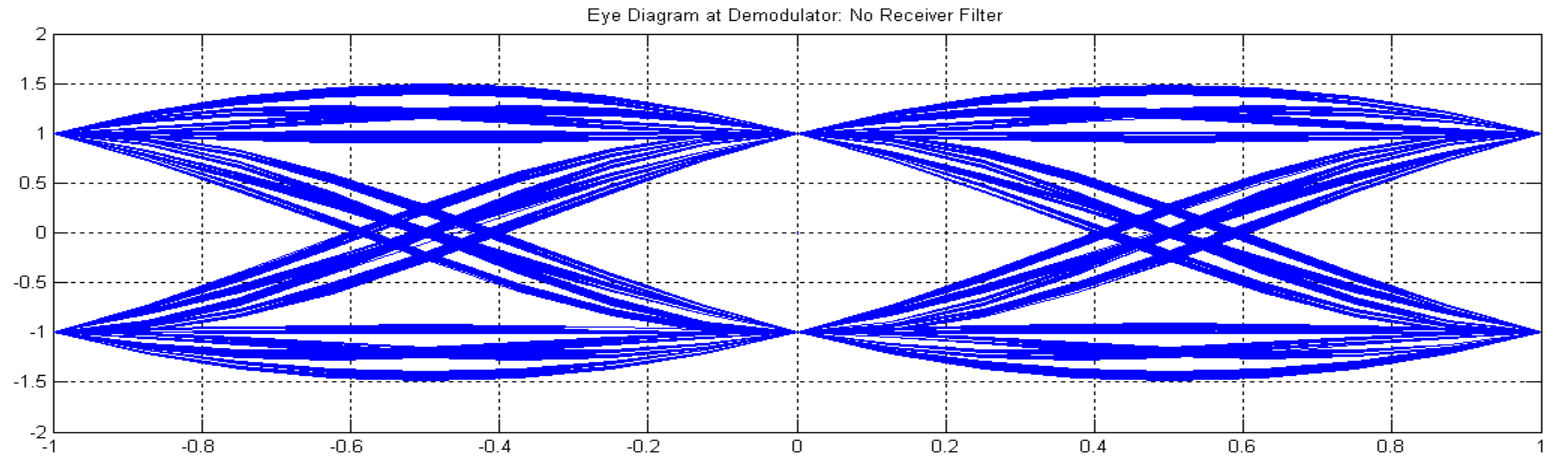
Pulse Response and ISI Component



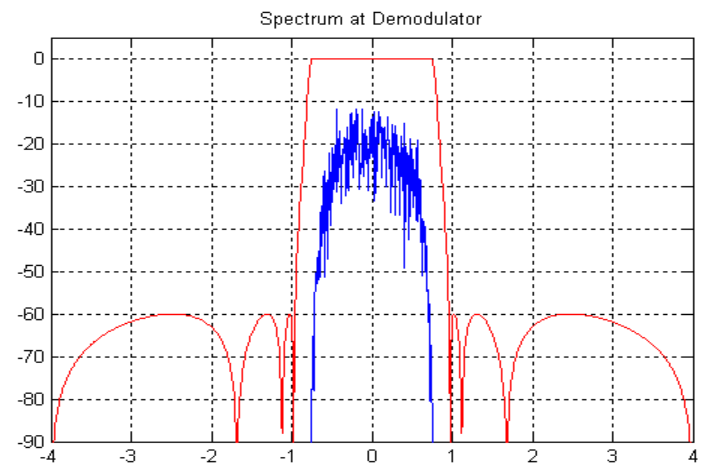
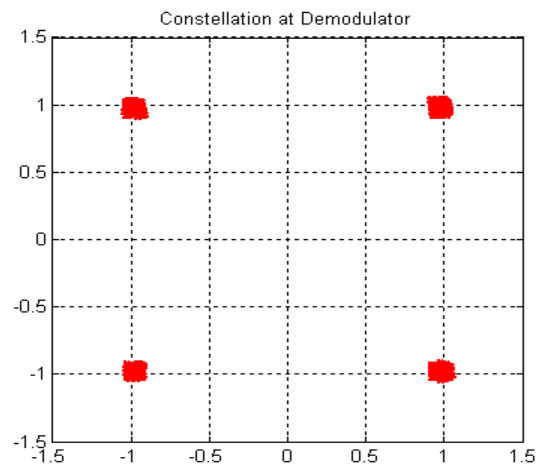
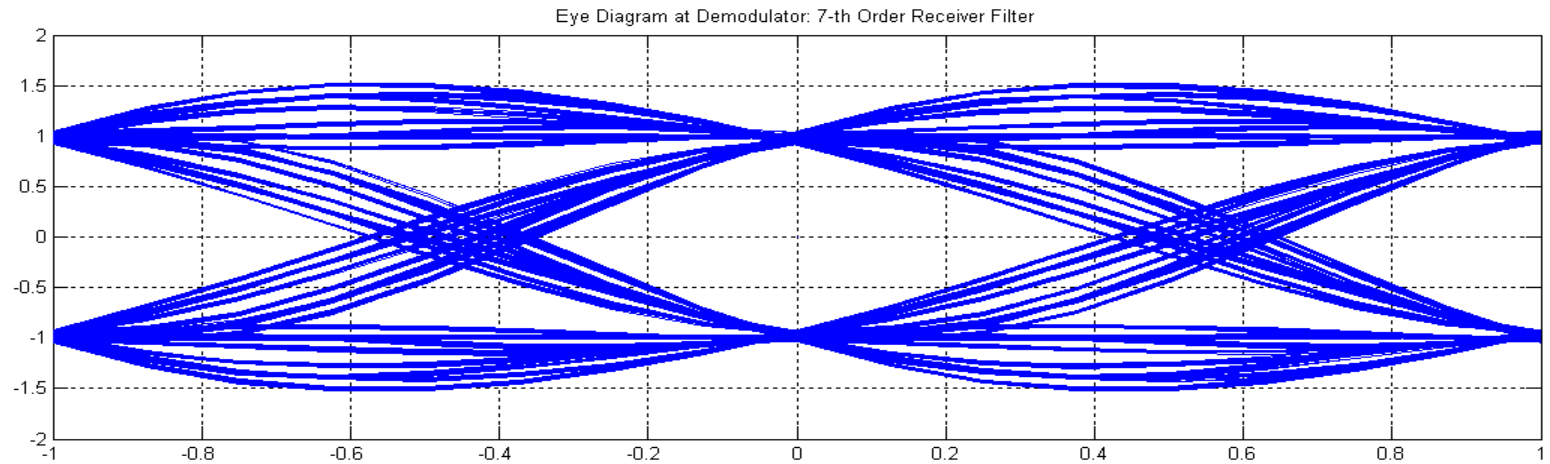
QPSK Modulator Eye-Diagram, Constellation, and Spectrum



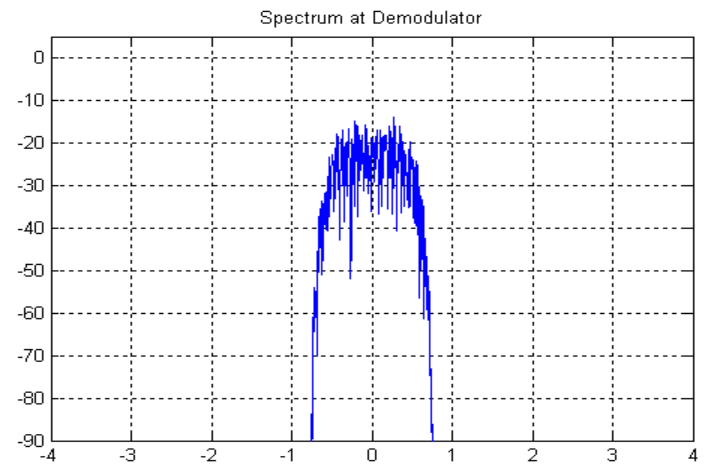
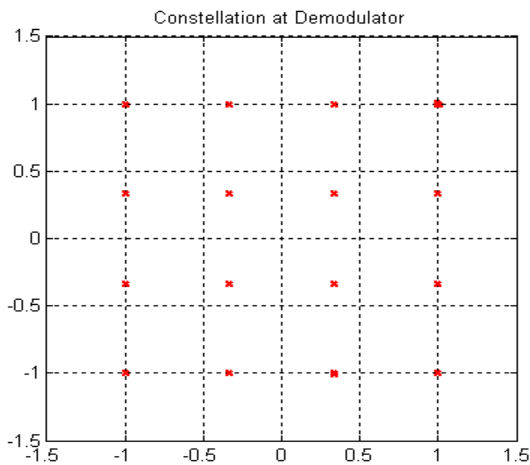
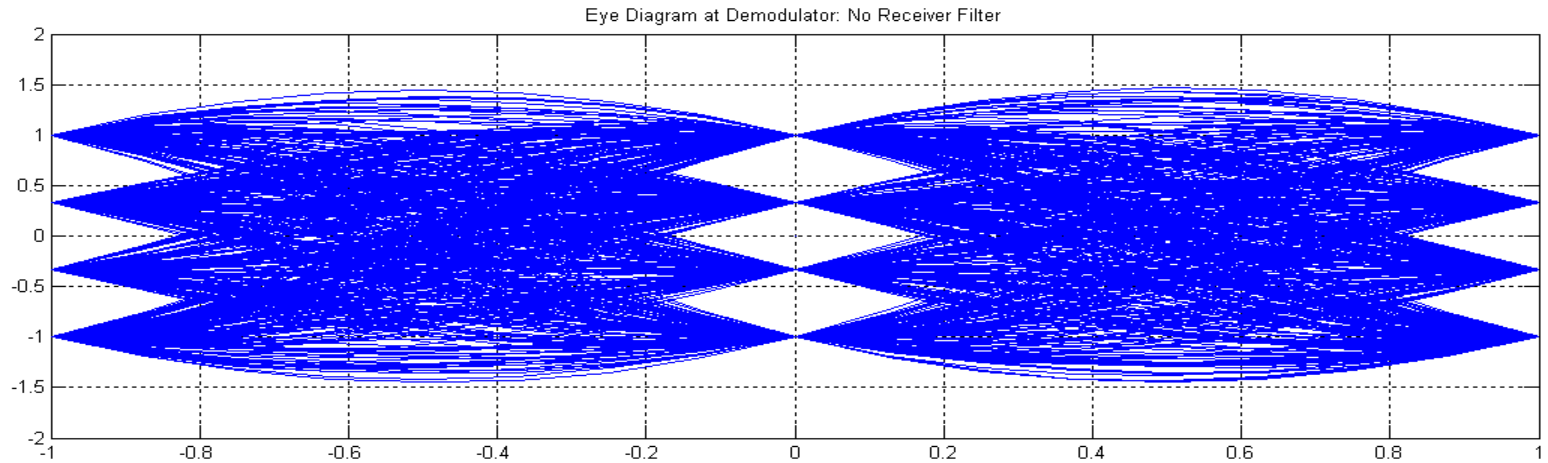
QPSK Demodulator, Eye-Diagram, Constellation, and Spectrum



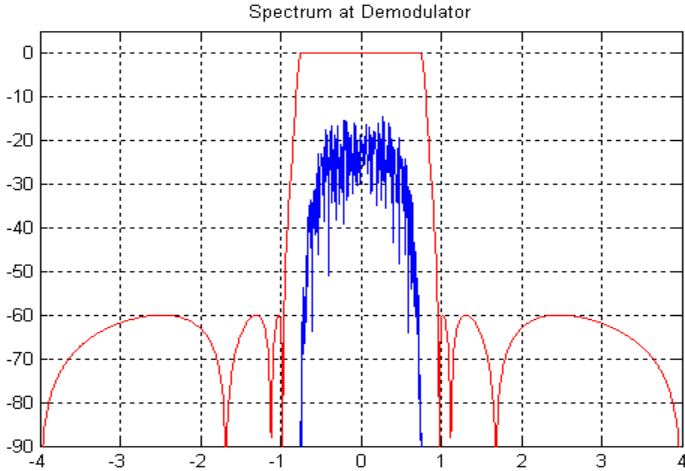
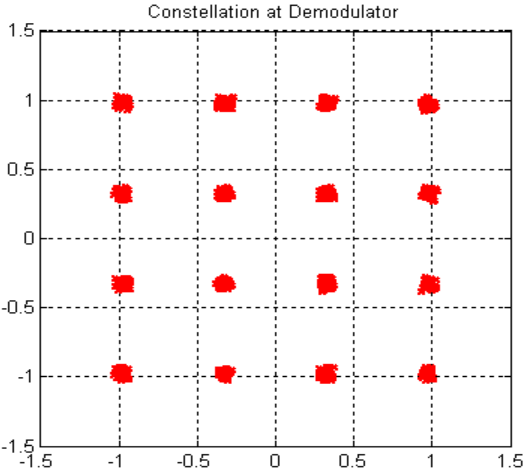
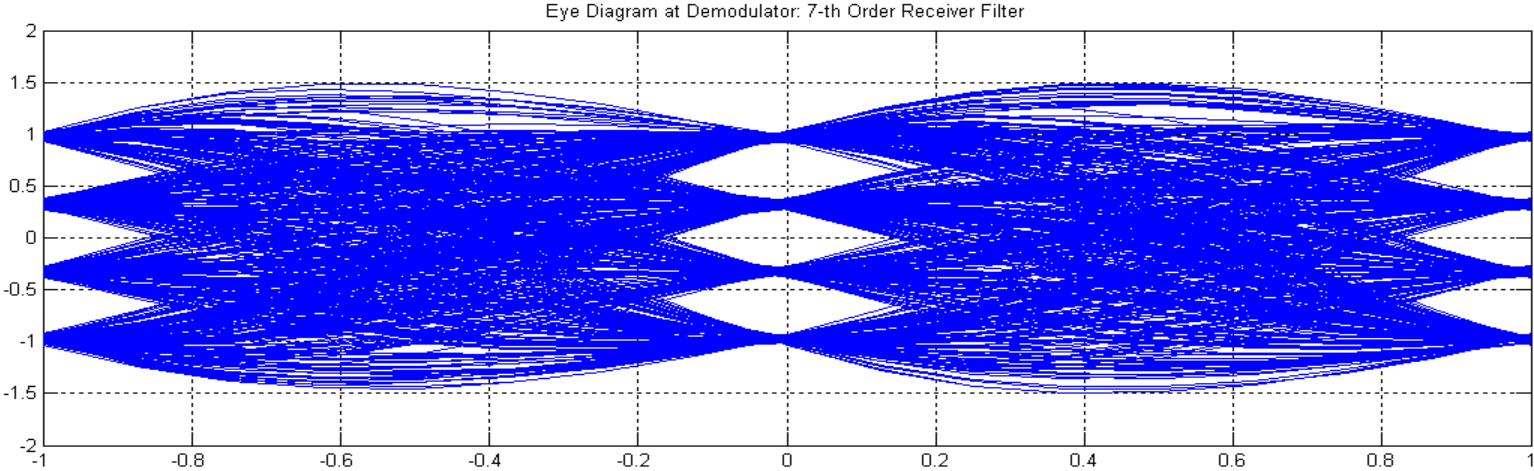
QPSK Demodulator with RCVR Filter



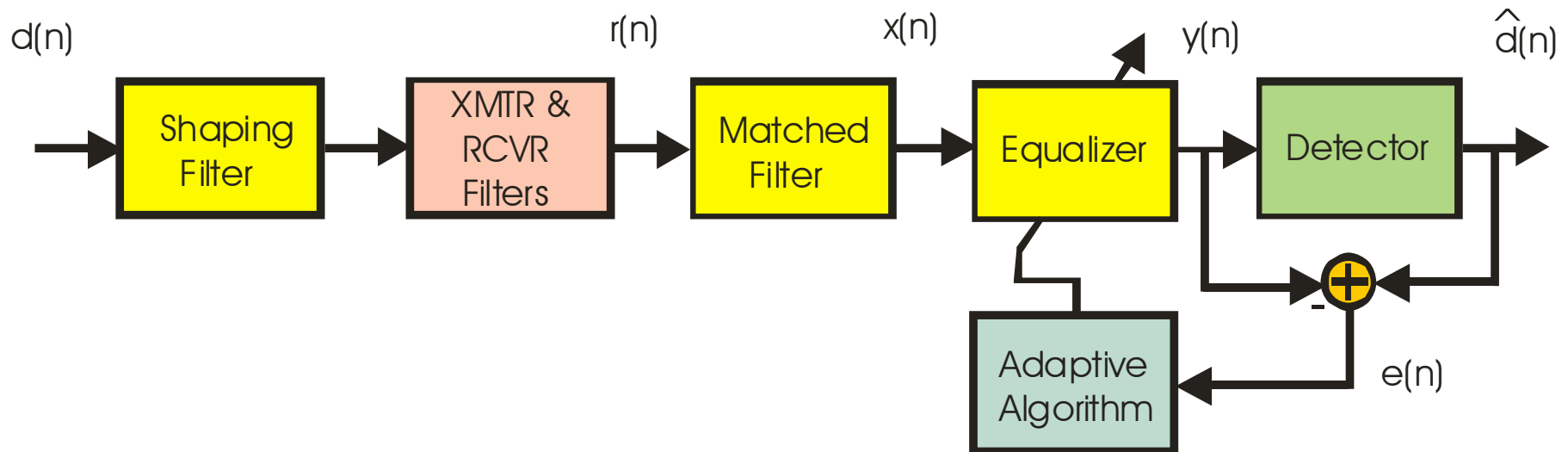
16-QAM Modulator Eye-Diagram, Constellation, and Spectrum



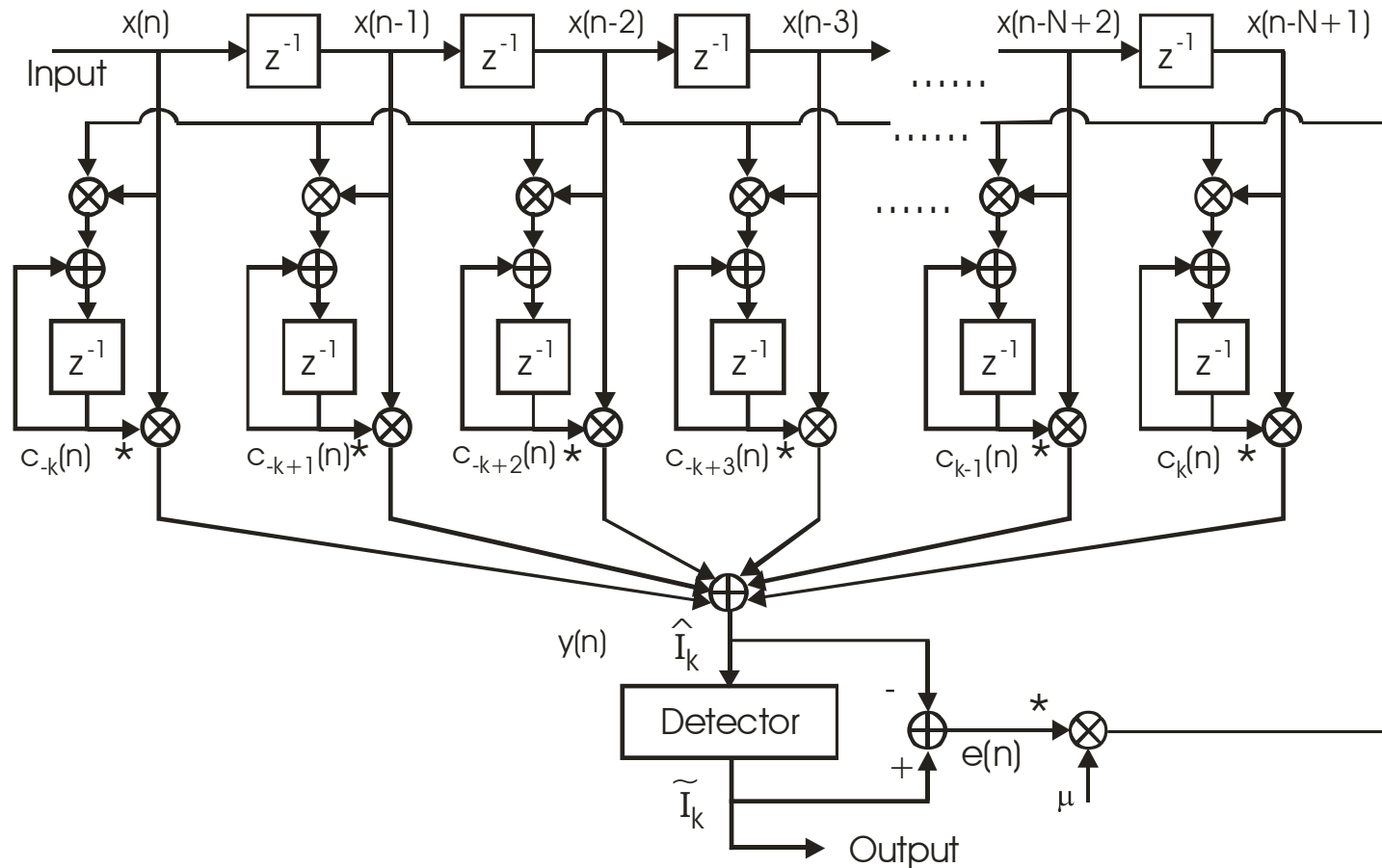
16-QAM Demodulator with RCVR Filter



Signal Flow Path in XMTR & RCVR

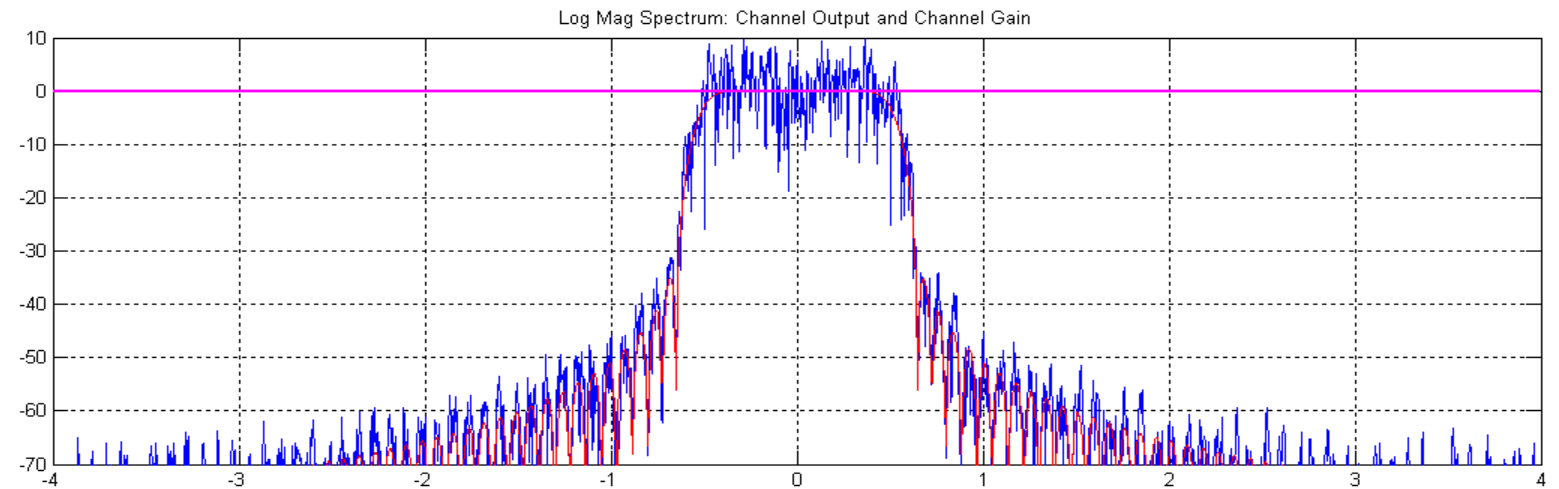
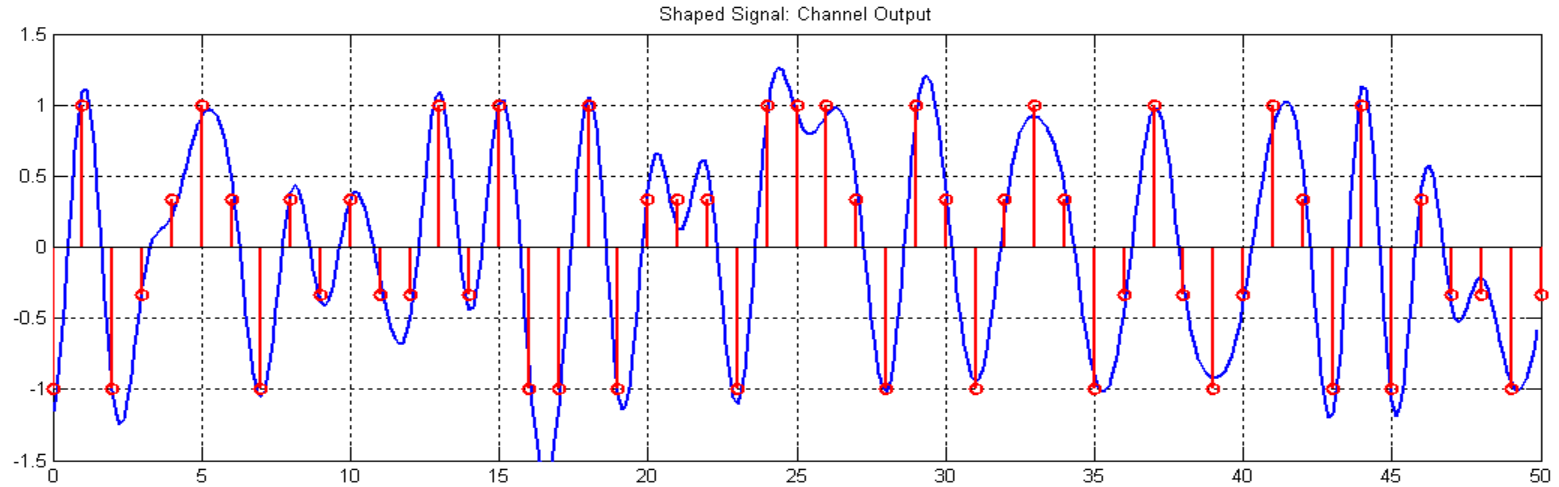


Decision Directed, Gradient Descent (LMS) Tapped Delay Line Equalizer

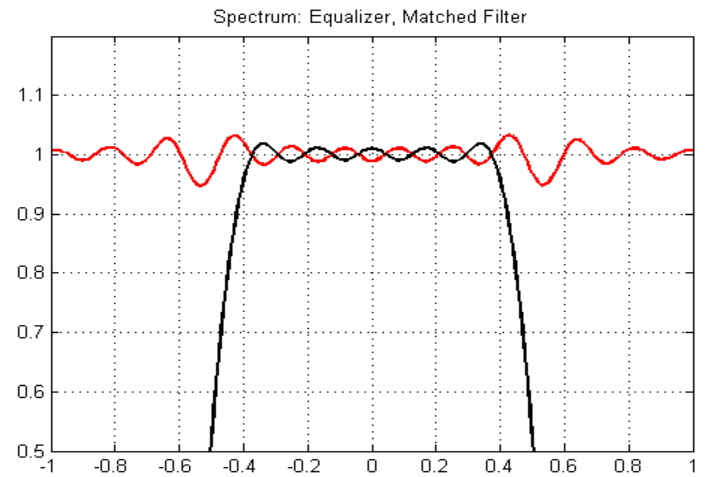
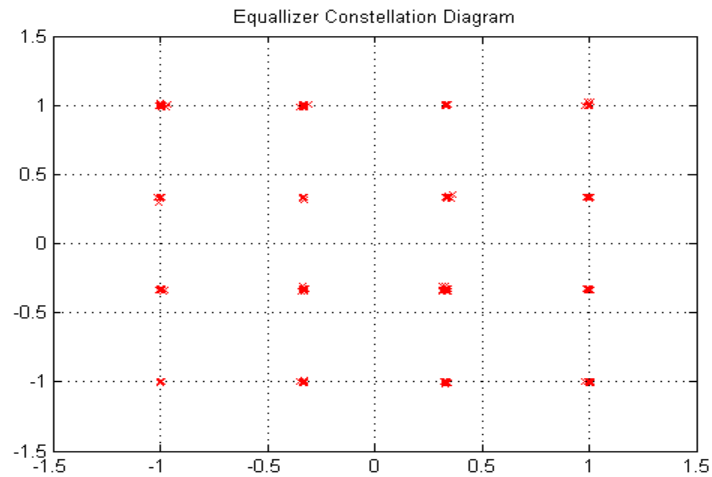
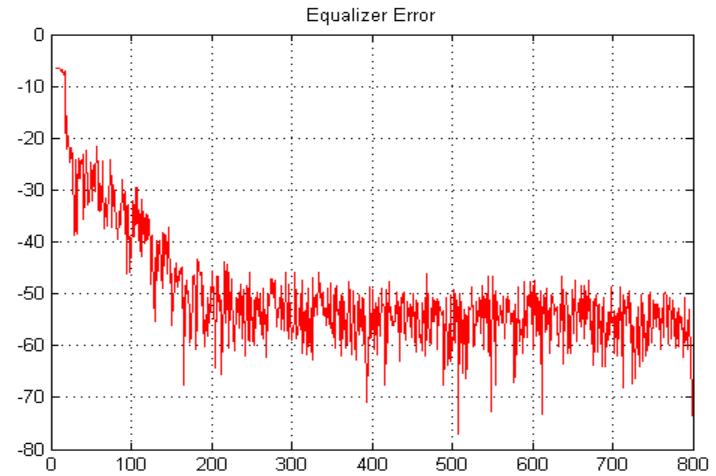
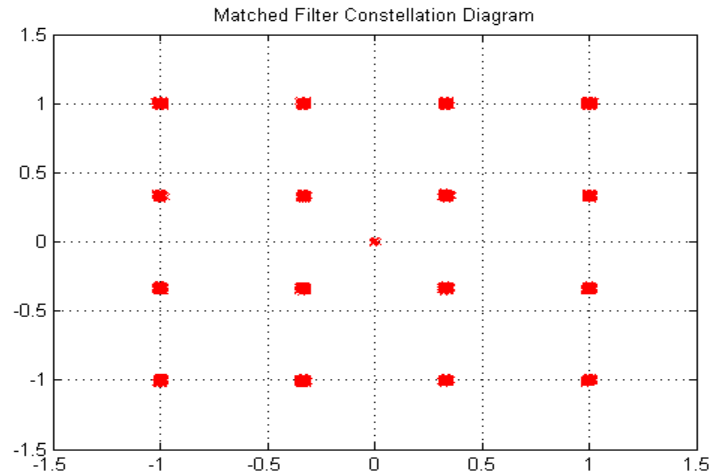


Received Signal and Spectrum

No Channel Distortion

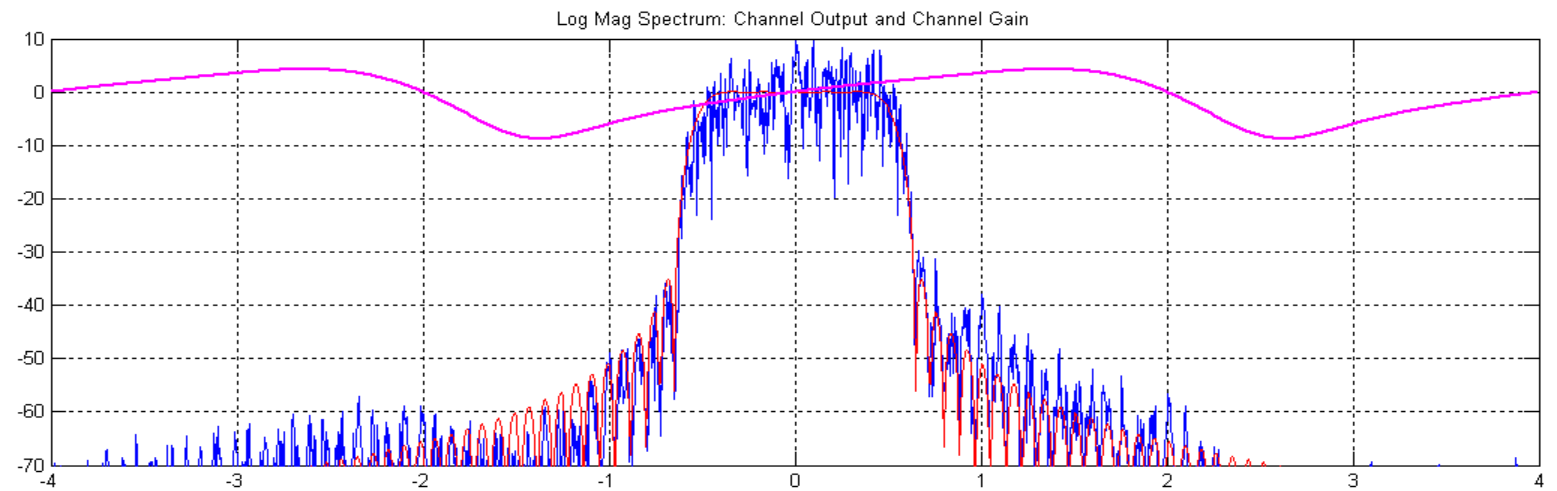
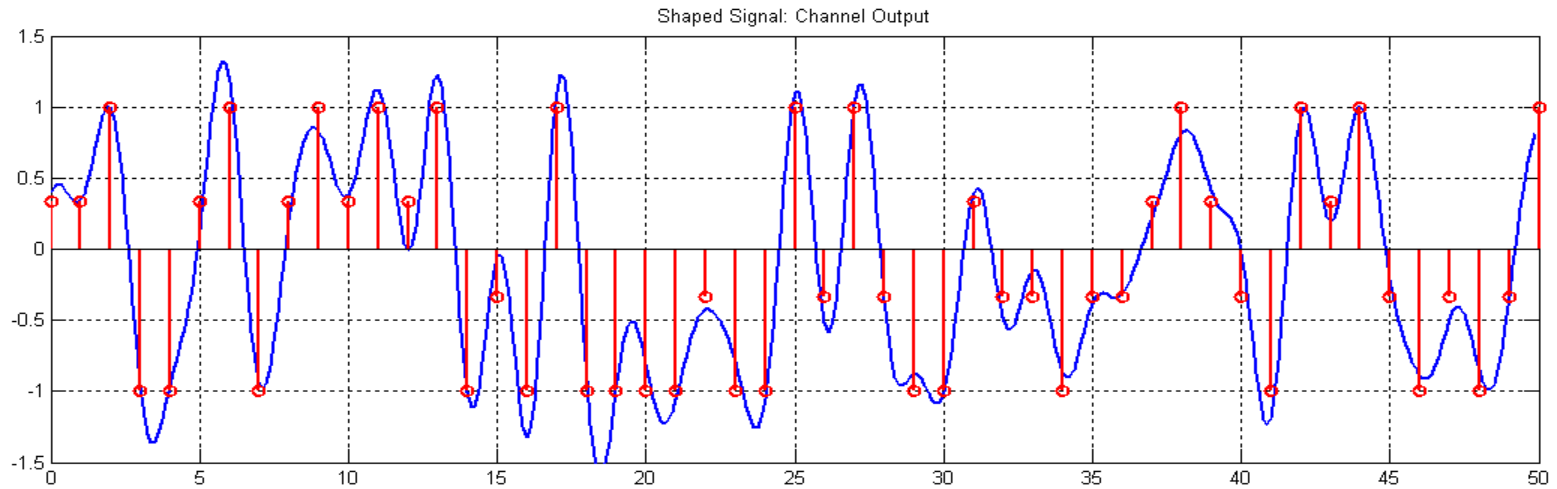


Constellation: Equalizer Input and Output

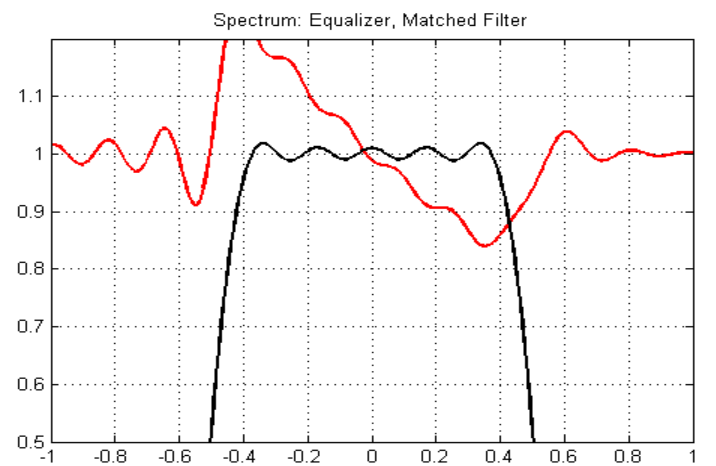
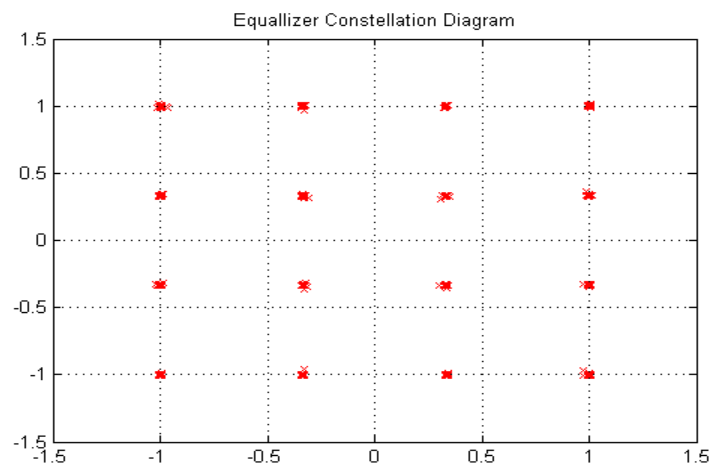
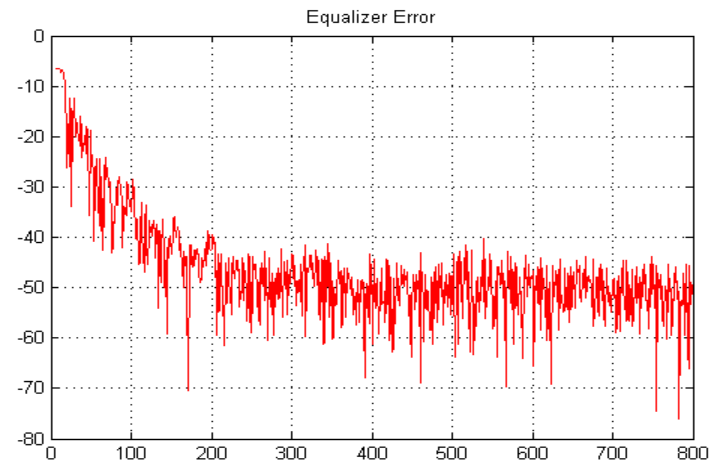
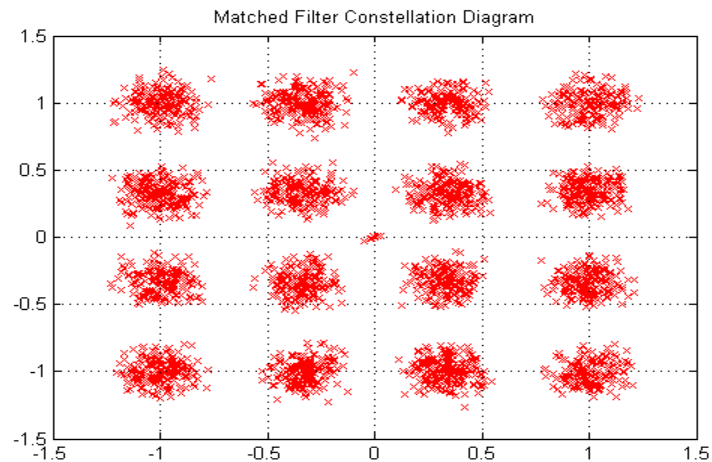


Received Signal and Spectrum

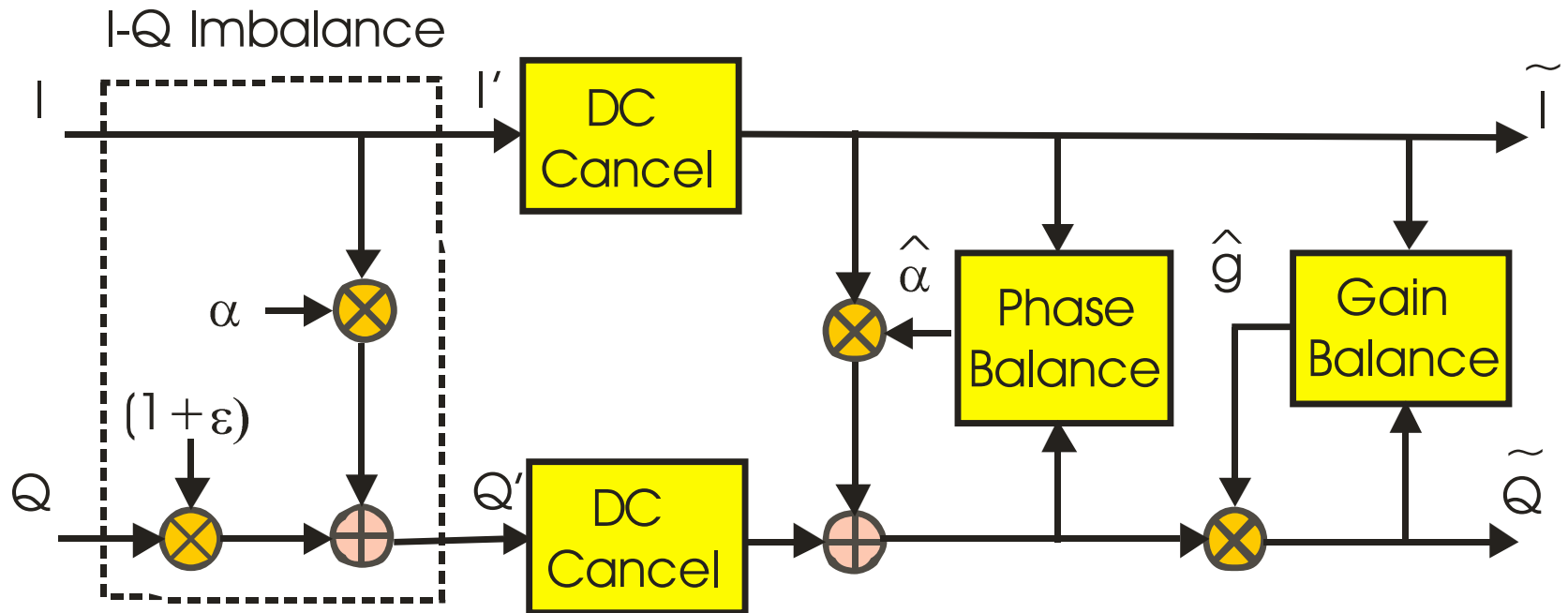
With Channel Distortion



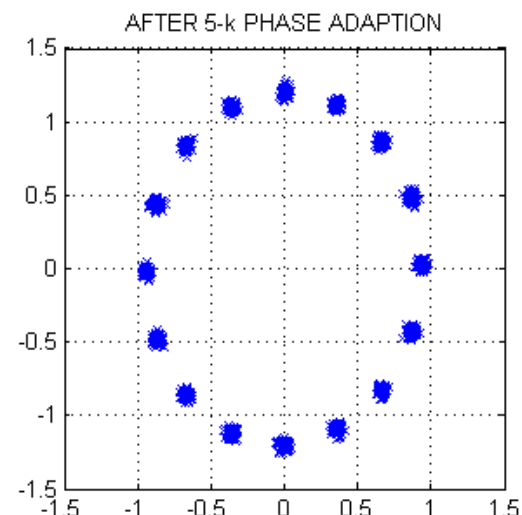
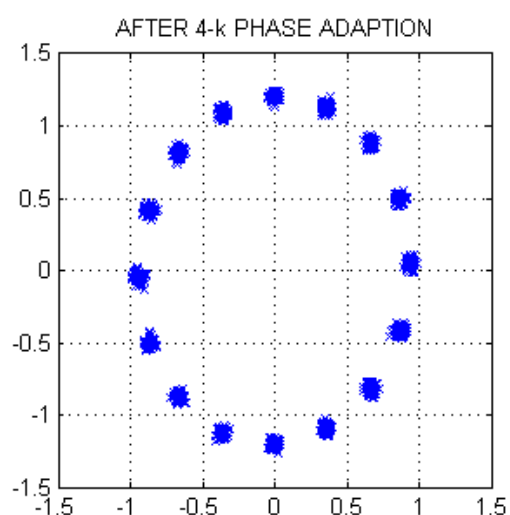
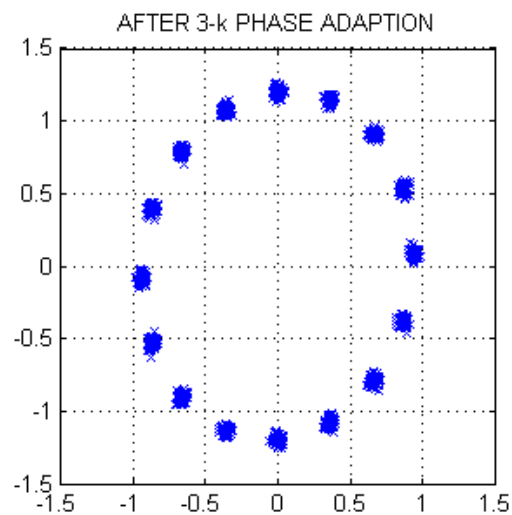
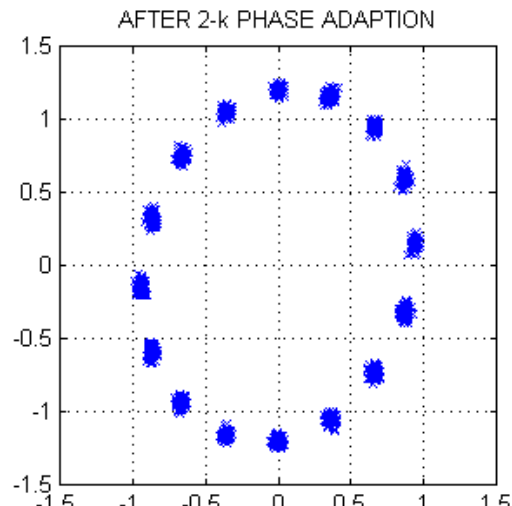
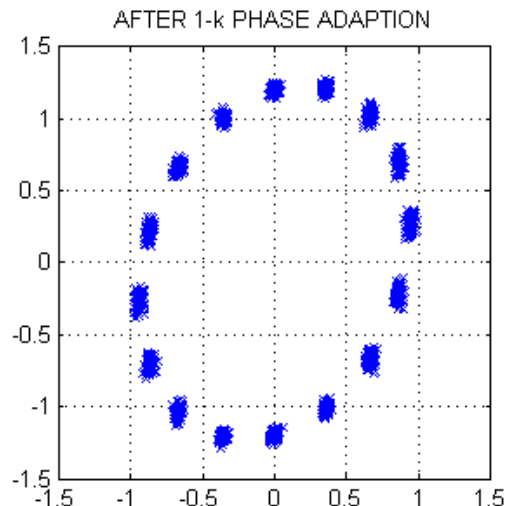
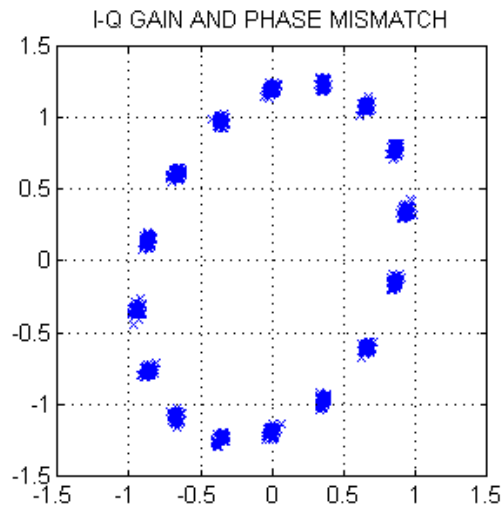
Constellation: Equalizer Input and Output



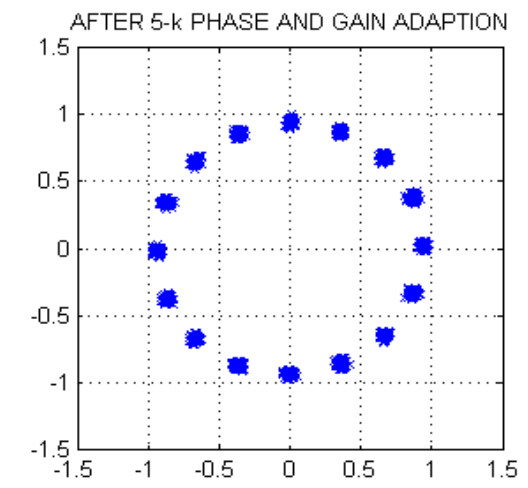
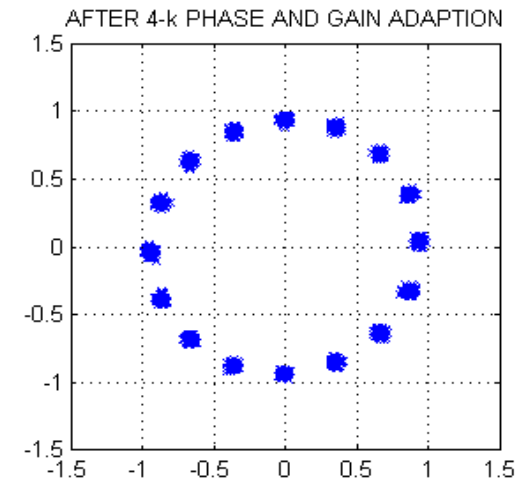
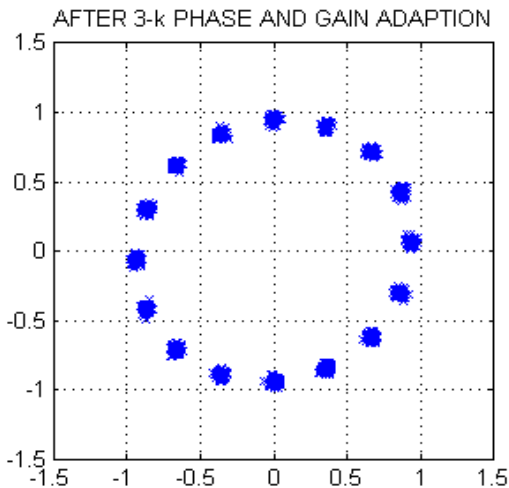
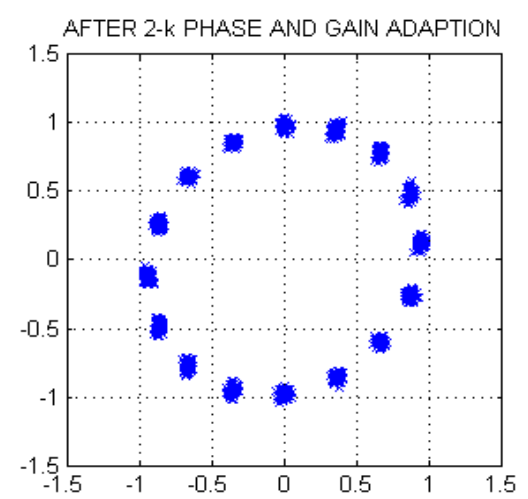
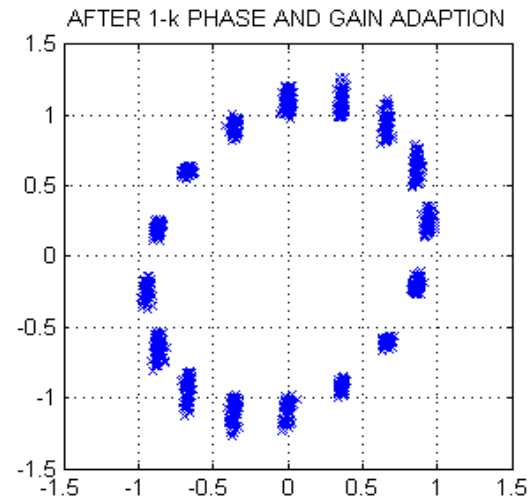
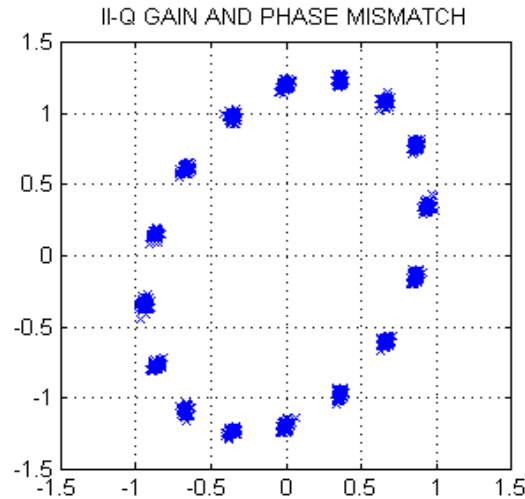
I-Q Imbalance Requires DC Cancellers



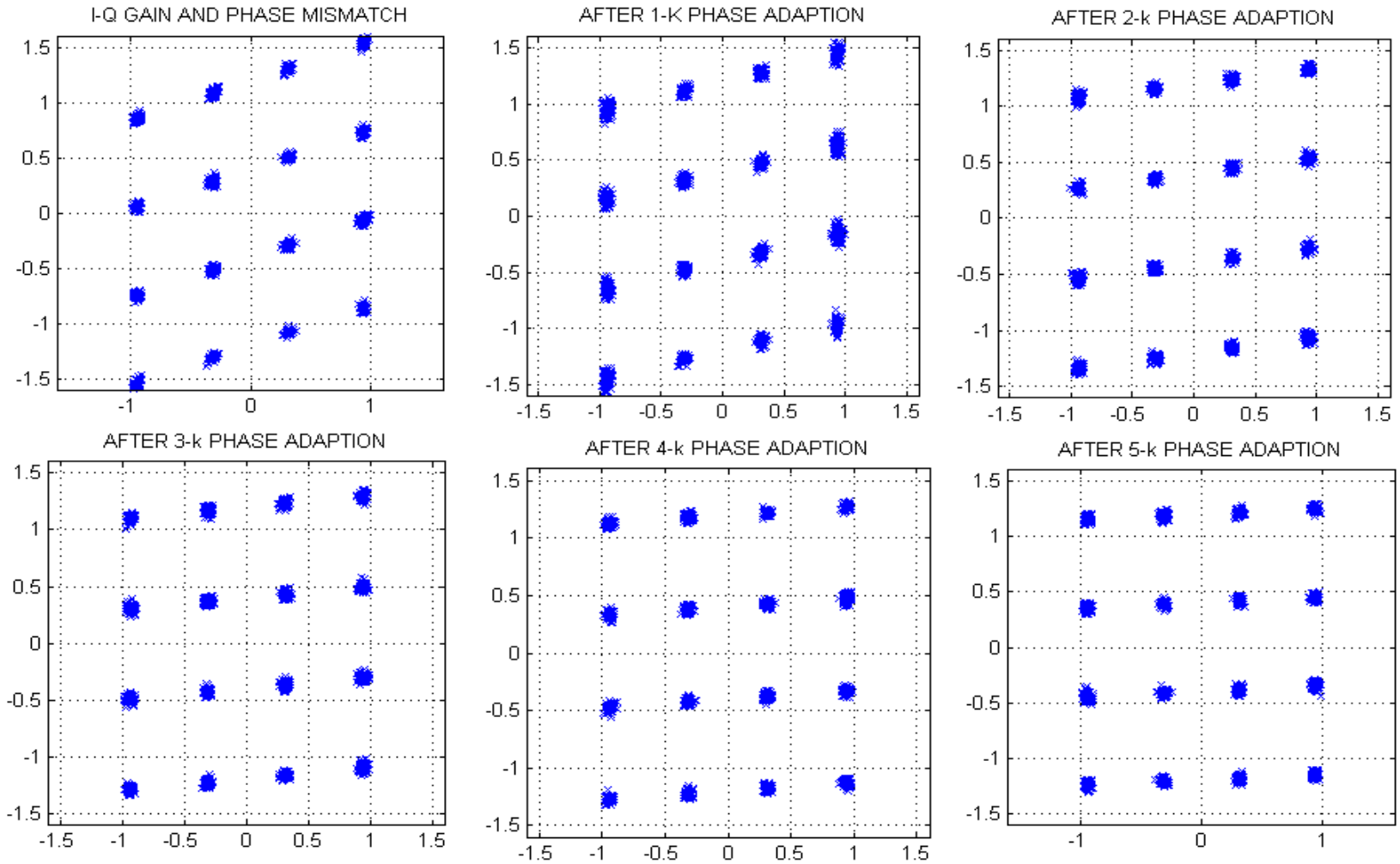
Sequence of 16-Phase Constellations During Phase Balancing



Sequence of 16-Phase Constellations During Gain and Phase Balancing

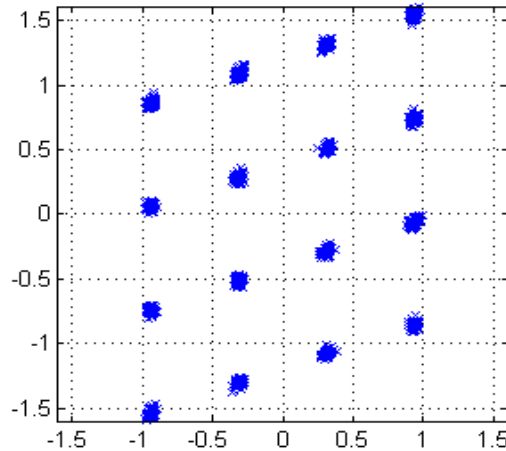


Sequence of 16-QAM Constellations During Phase Balancing

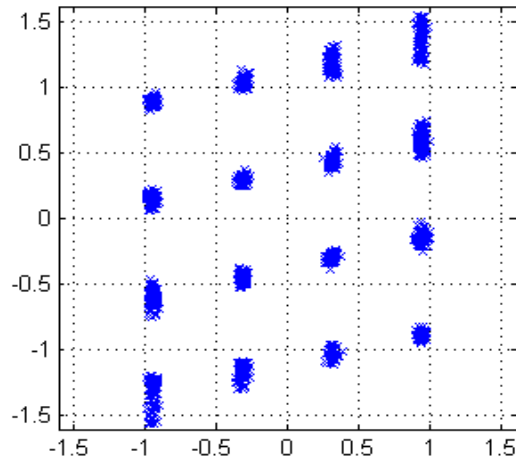


Sequence of 16-QAM Constellations During Phase and Gain Balancing

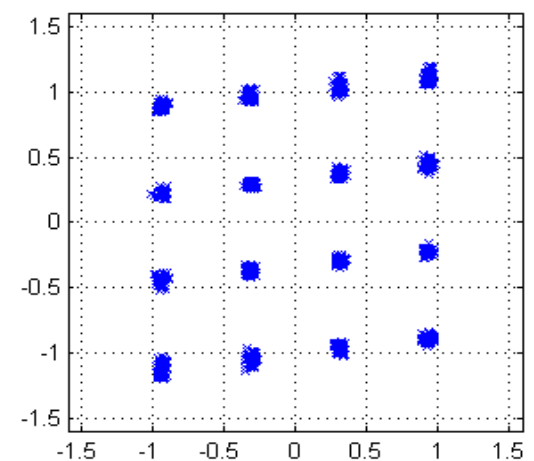
I-Q GAIN AND PHASE MISMATCH



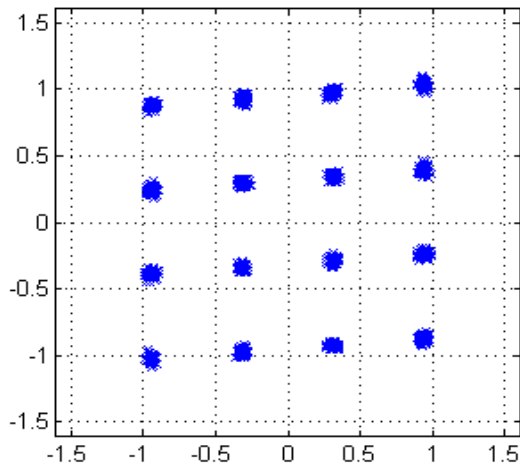
AFTER 1-k PHASE AND GAIN ADAPTION



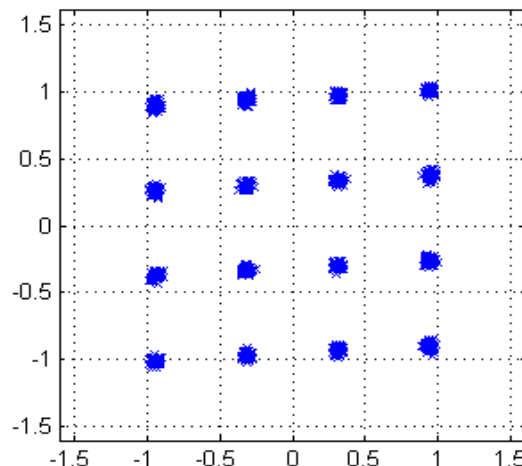
AFTER 2-k PHASE AND GAIN ADAPTION



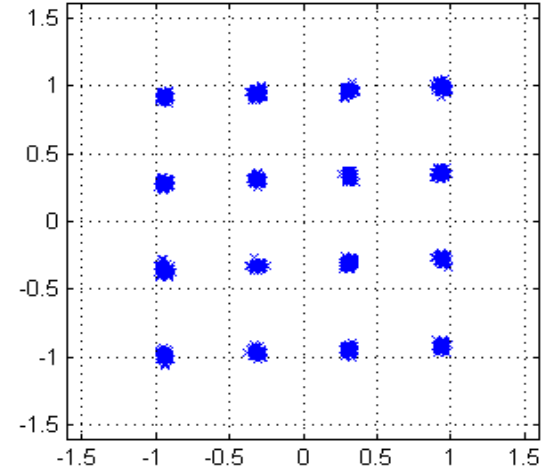
AFTER 3-k PHASE AND GAIN ADAPTION



AFTER 4-k PHASE AND GAIN ADAPTION

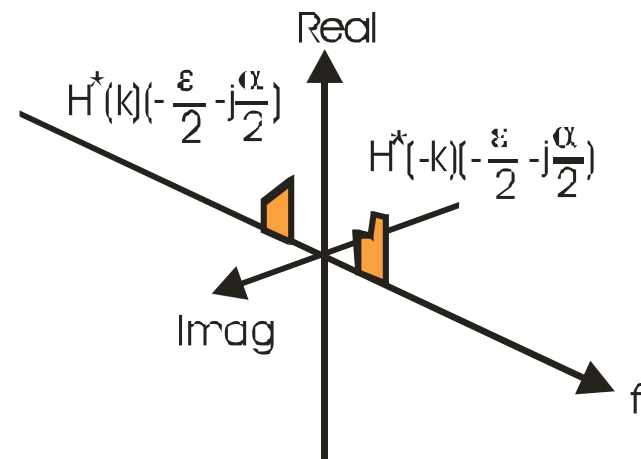
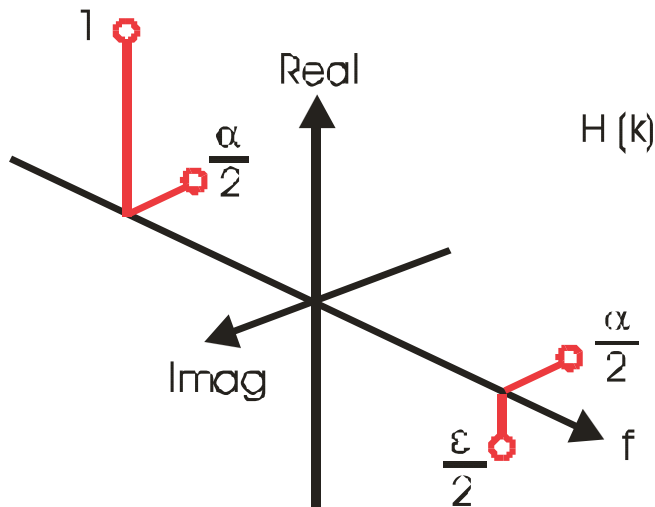
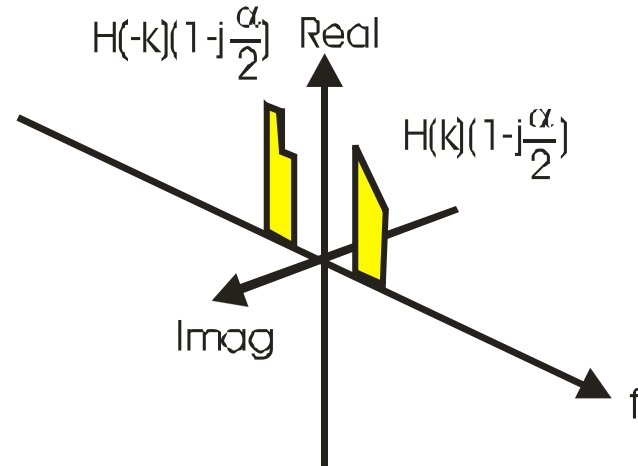
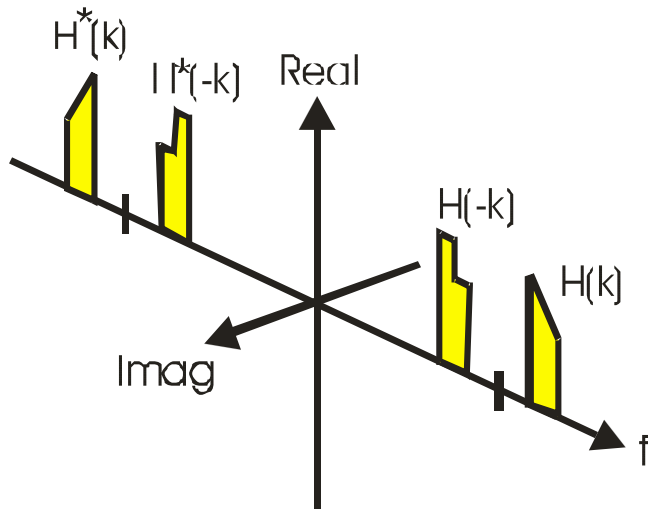


AFTER 5-k PHASE AND GAIN ADAPTION

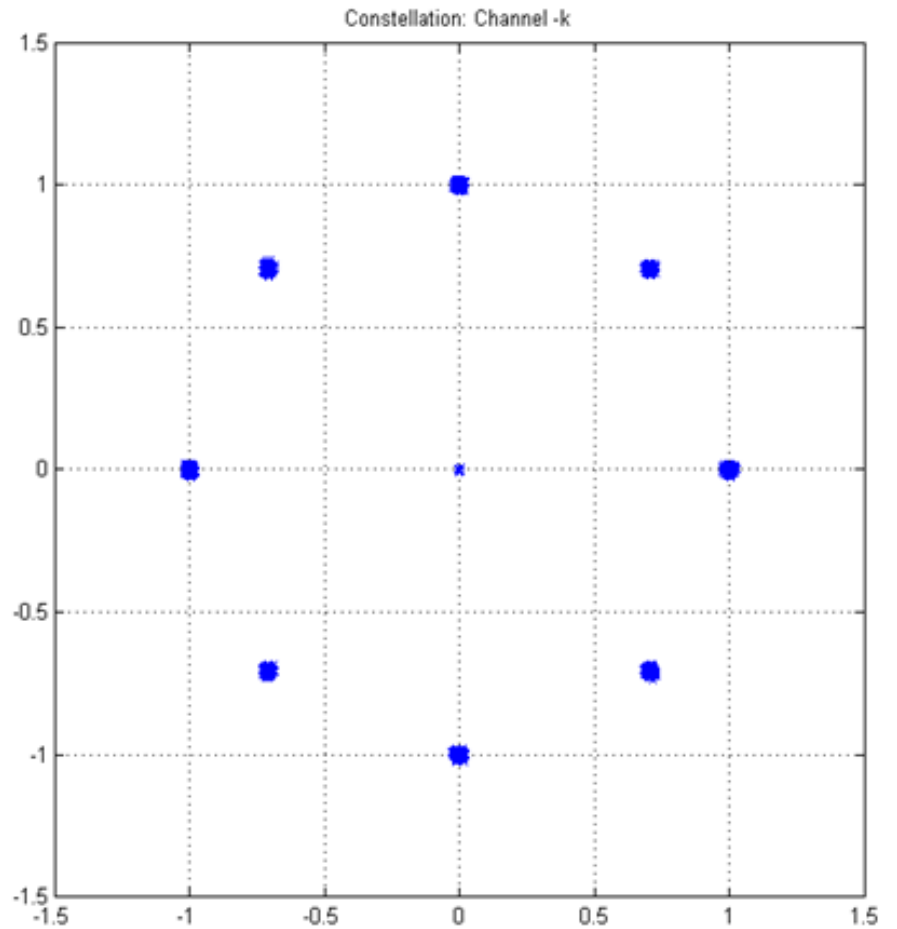
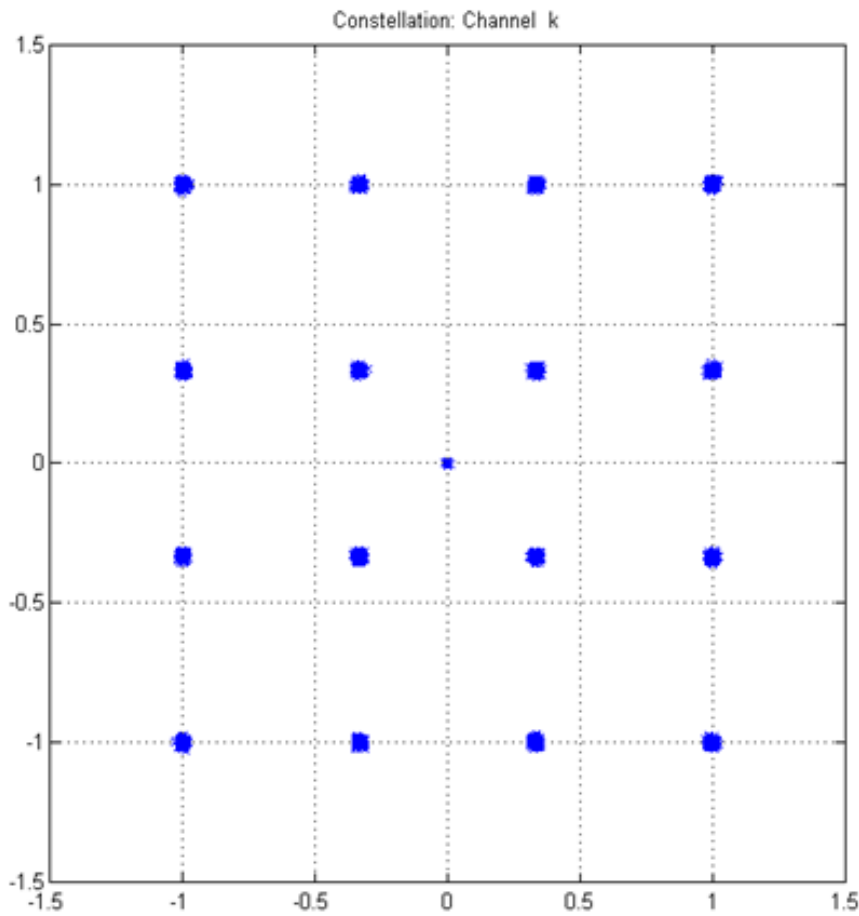


Spectral Images

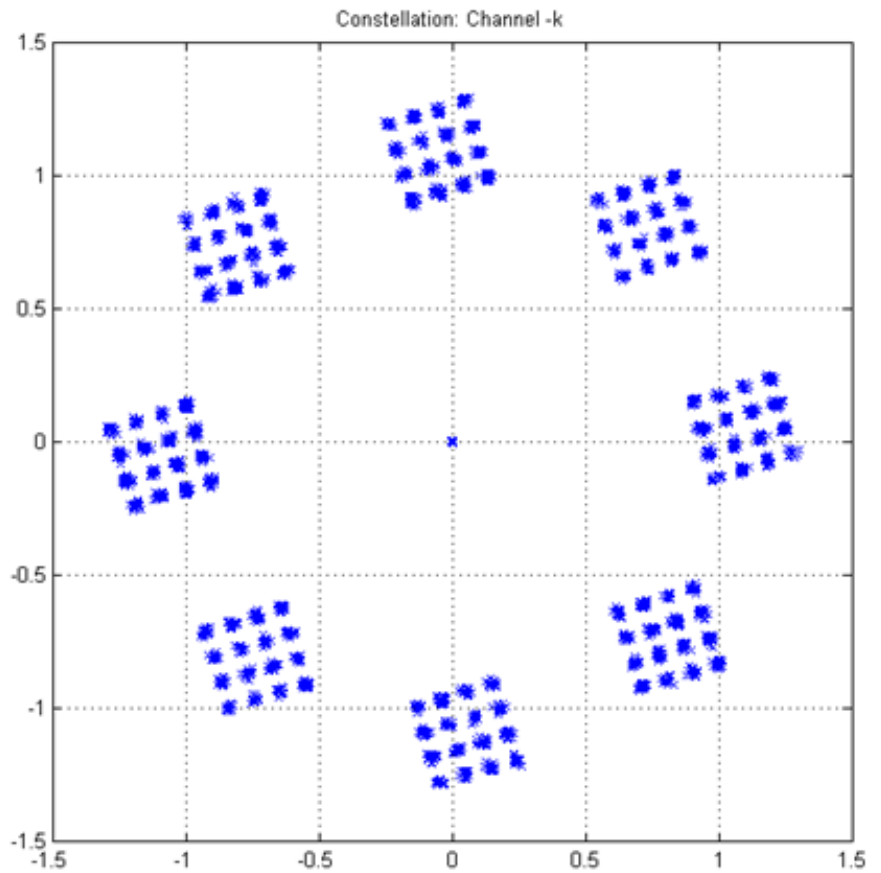
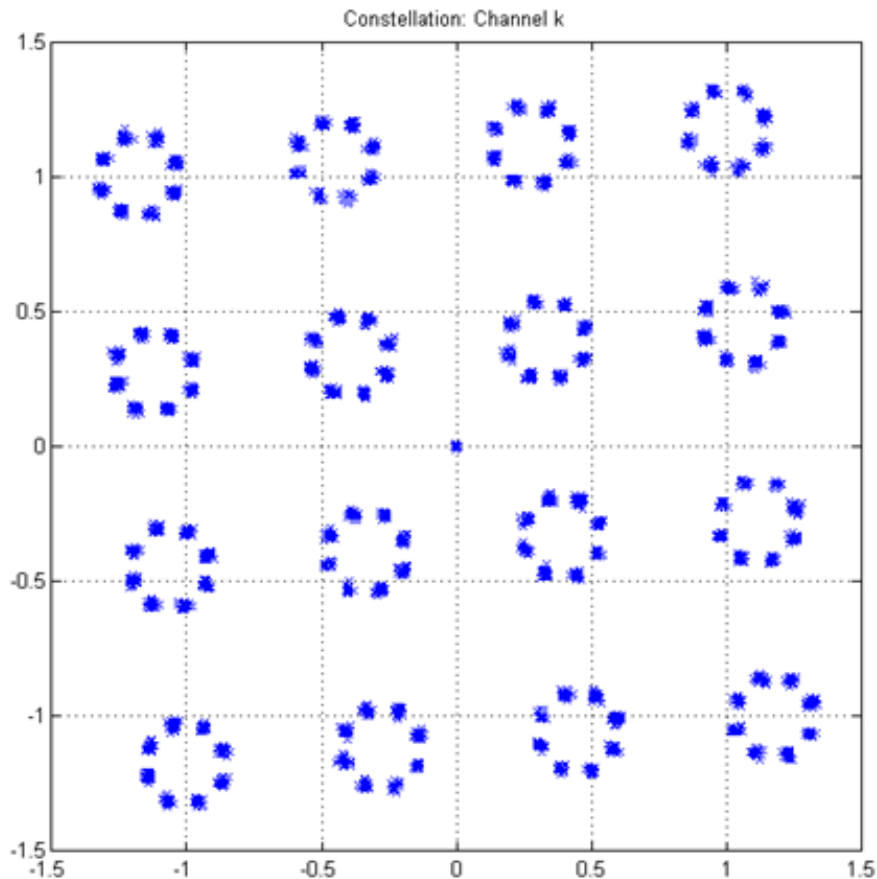
Due to I-Q Mismatch



Constellations of Channel +k and -k

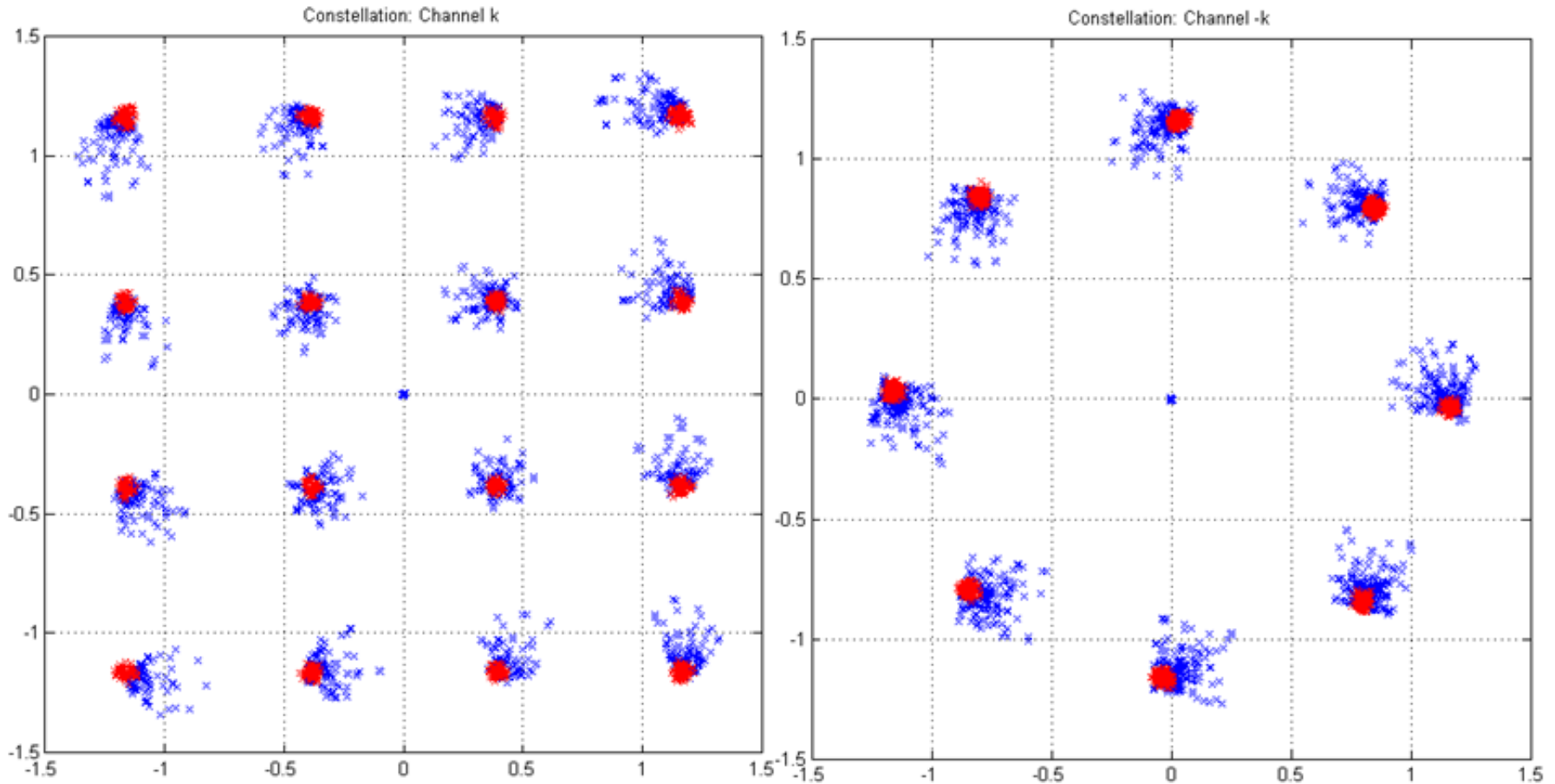


Crosstalk Between Channels k and $-k$ Due to gain and Phase Imbalance

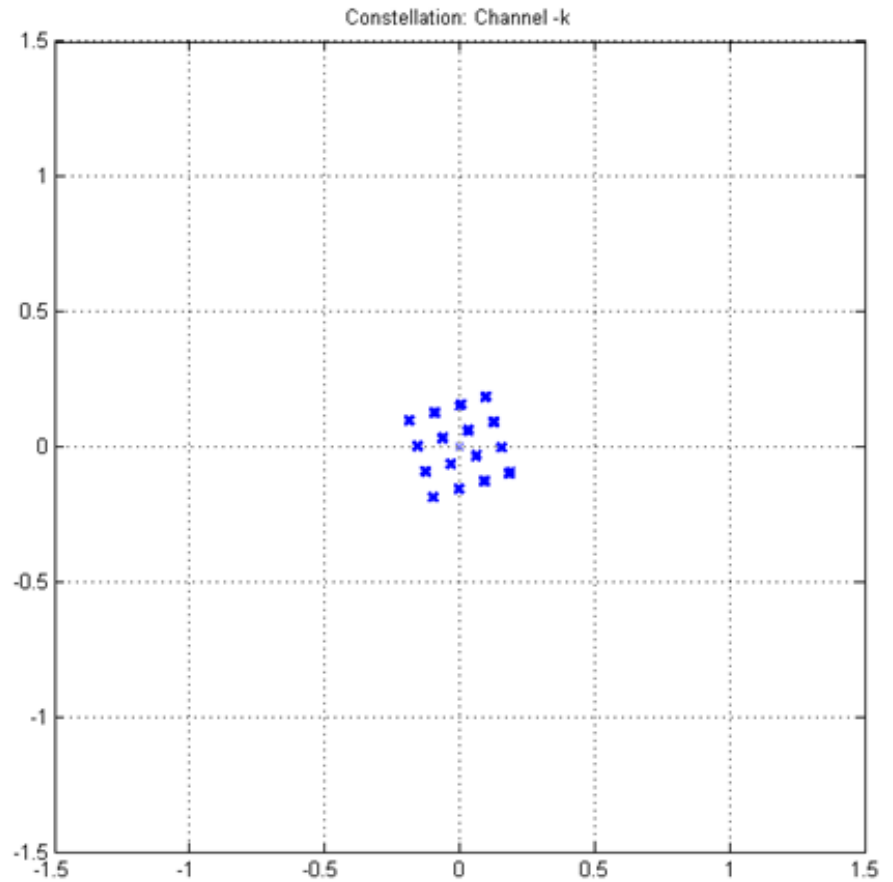
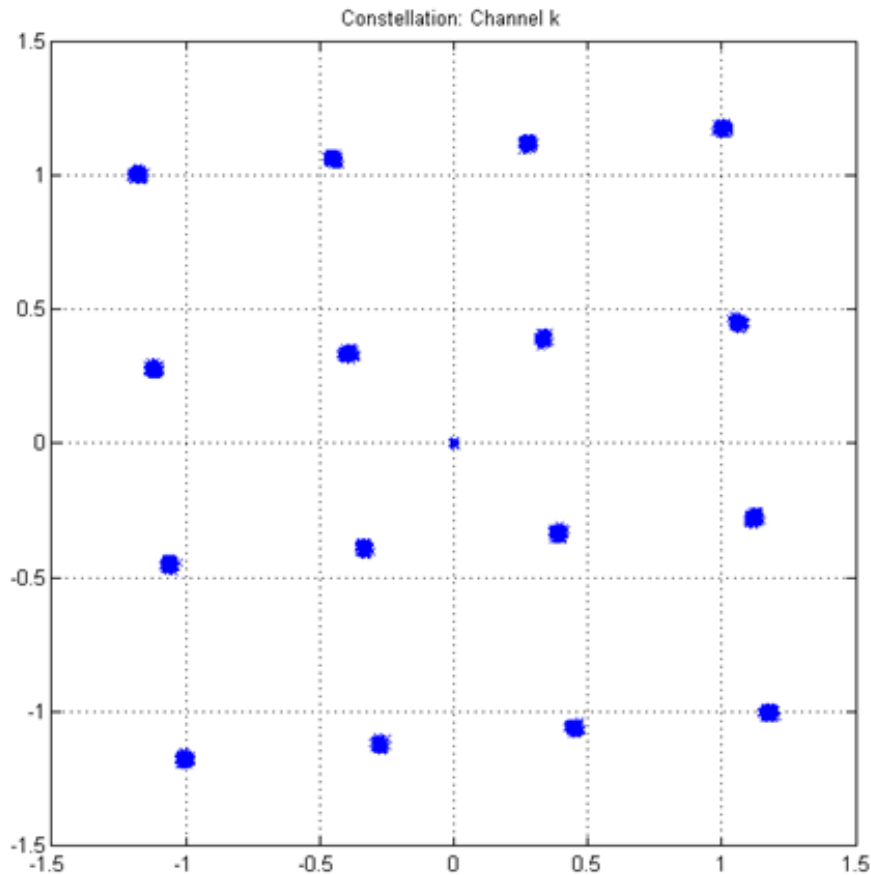


Constellation after Gradient Descent

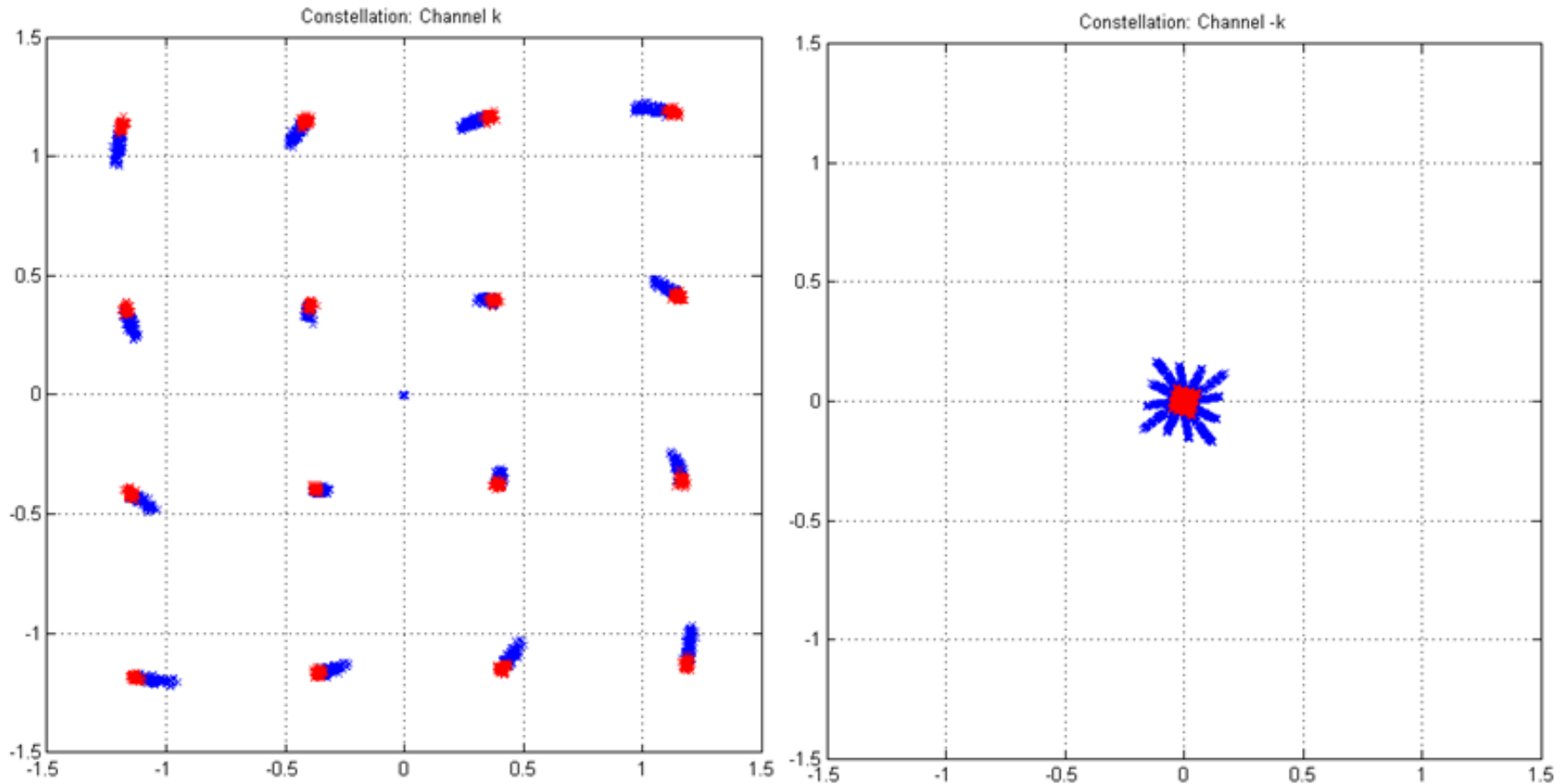
Correction of Gain and Phase Imbalance



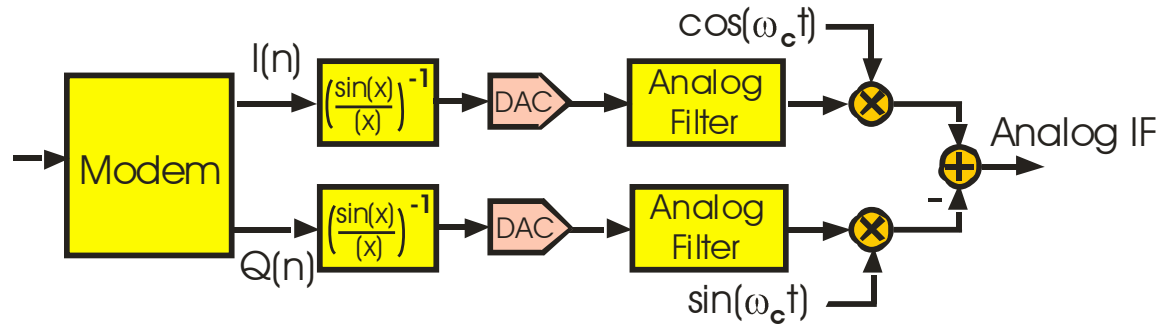
Crosstalk Between Channel k and Empty Channel $-k$



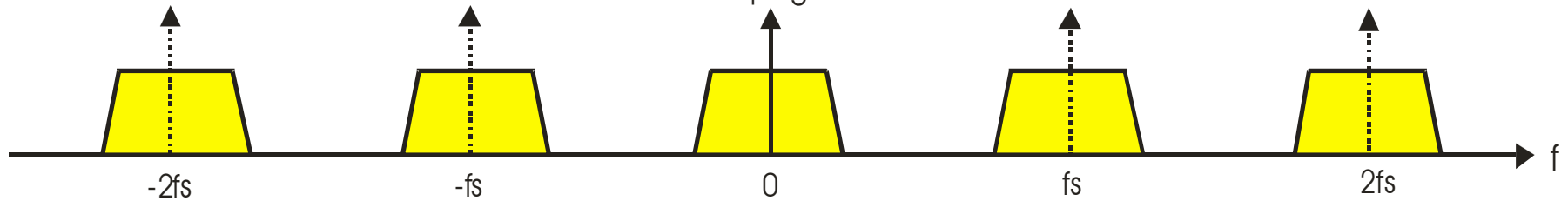
Constellation after Gradient Descent Correction of Gain and Phase Imbalance



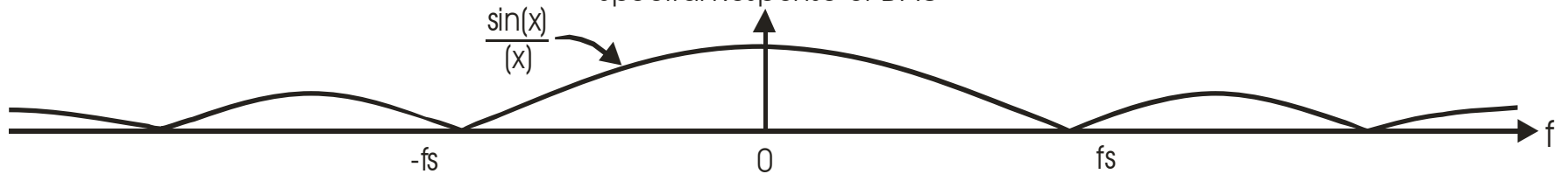
DAC $\text{Sin}(x)/x$ Baseband Distortion



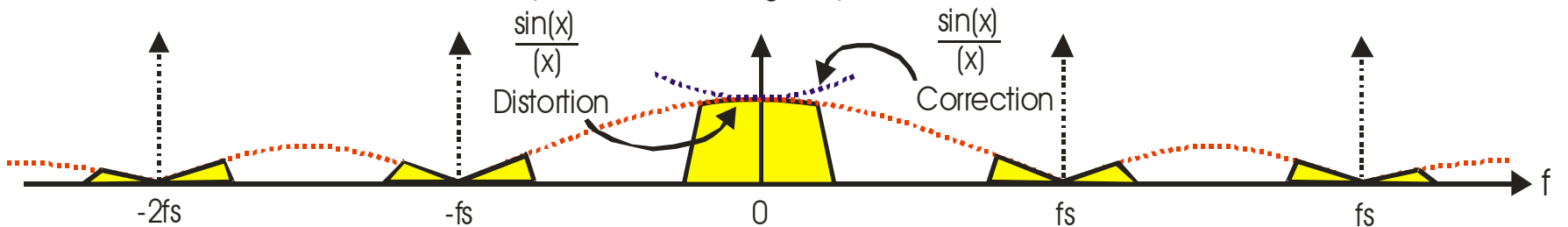
Spectrum of Sampled Data
Shaping Filter



Spectral Response of DAC

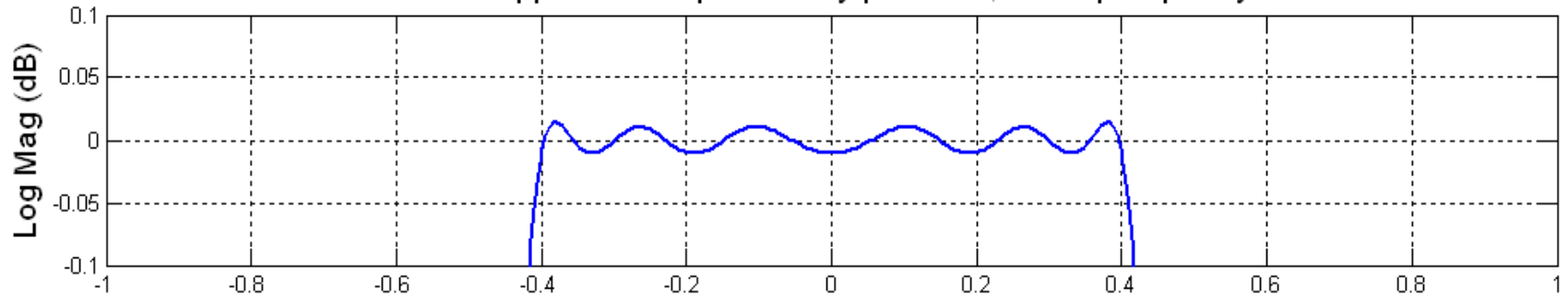


Spectrum of Analog Output from DAC

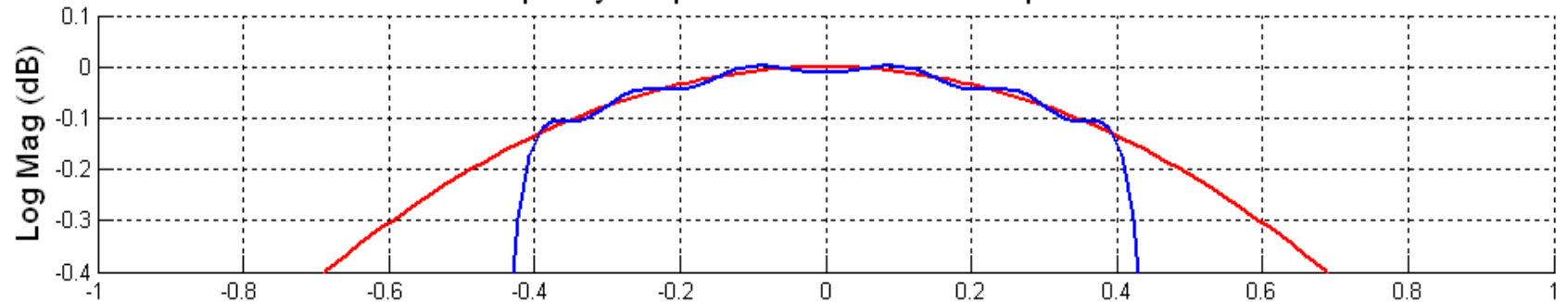


Baseband Filter DAC Predistortion

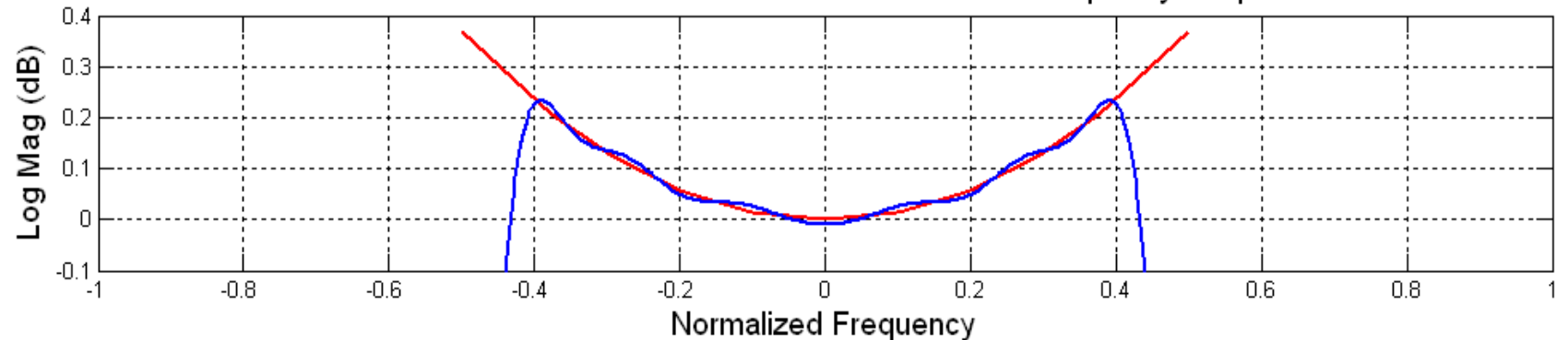
Passband Ripple of 53 Tap SQRT Nyquist Filter, 4-Samples per Symbol



DAC Frequency Response and Passband Response After DAC

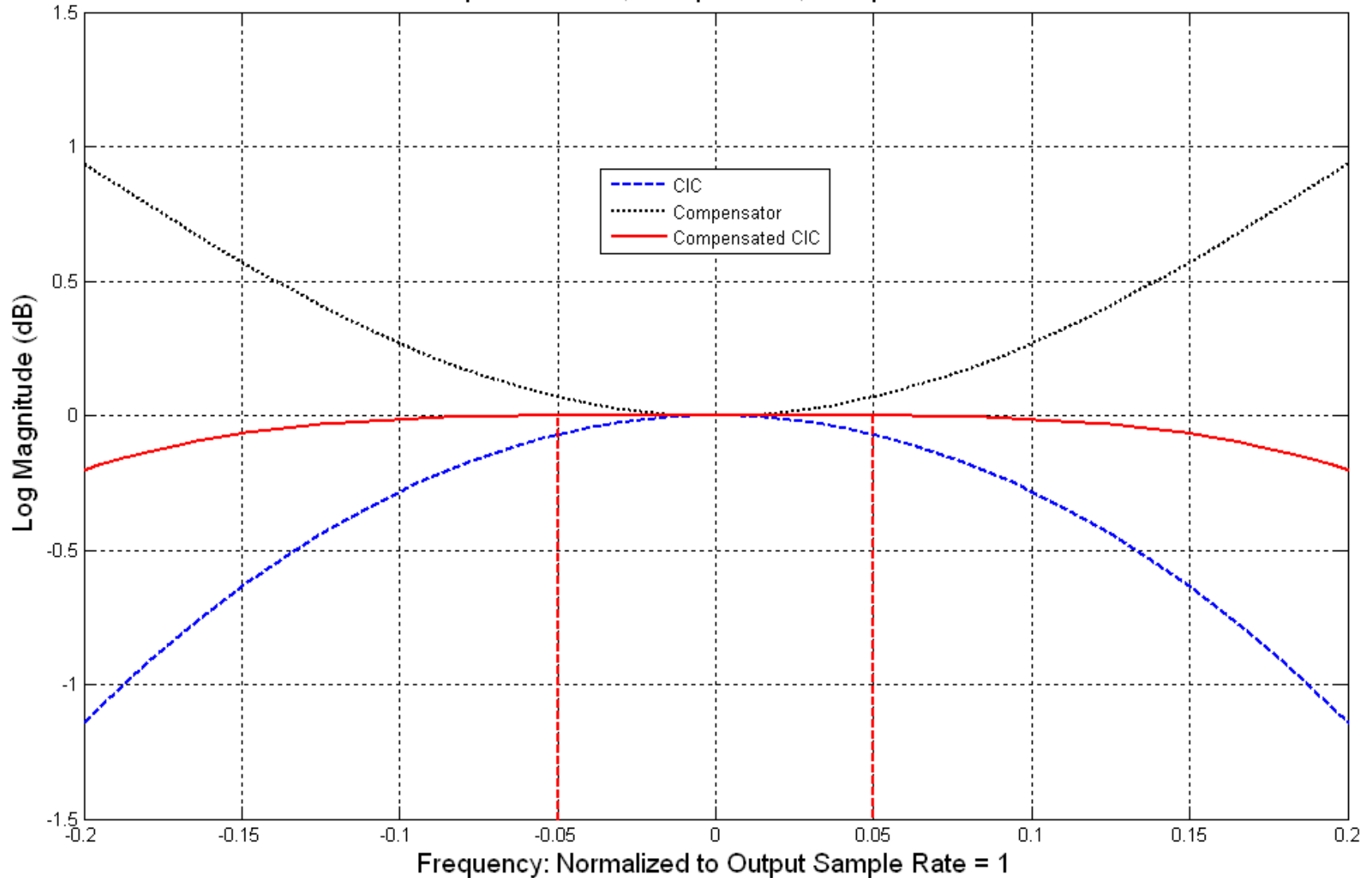


DAC Predistortion Gain and Passband Predistortion Frequency Response

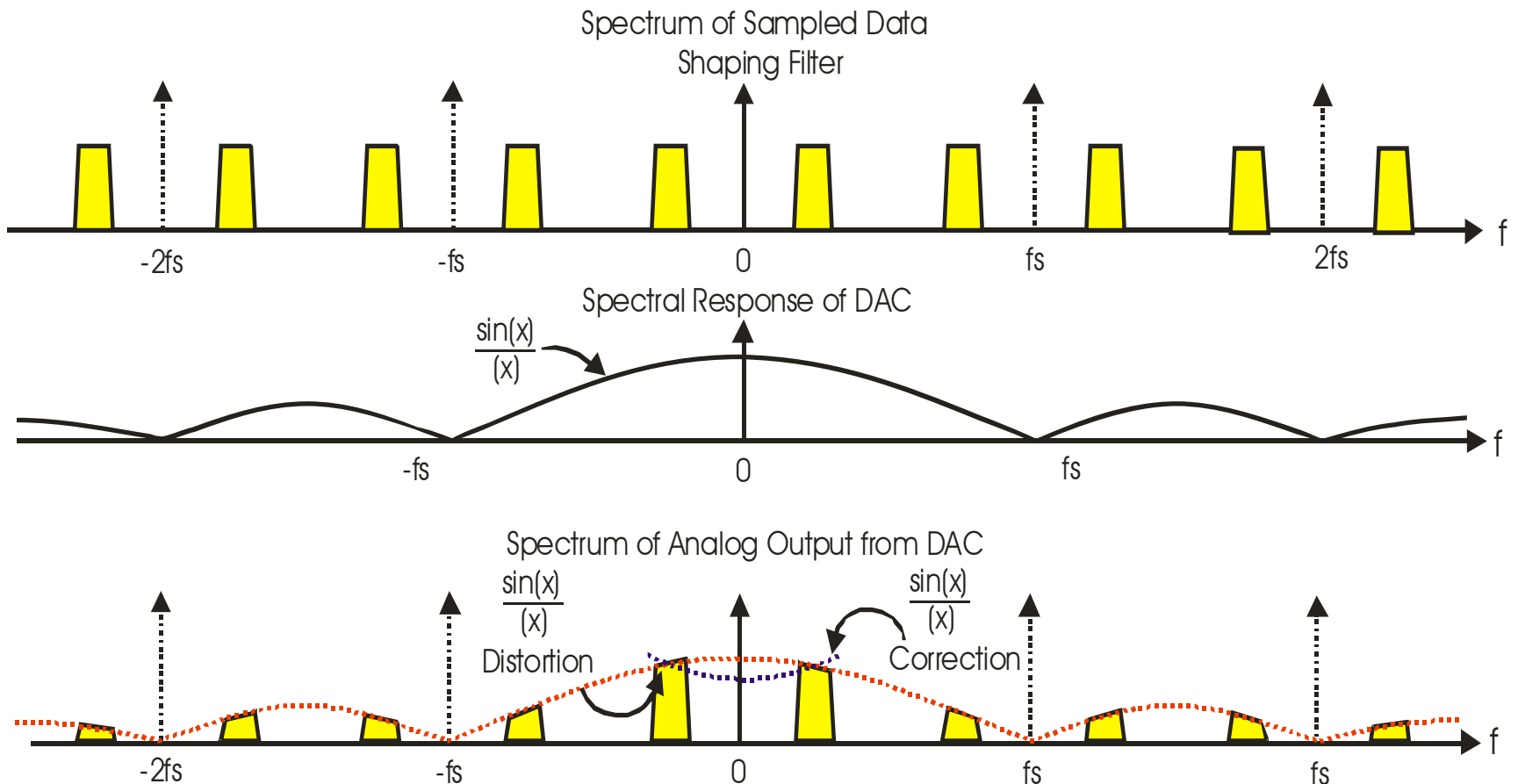
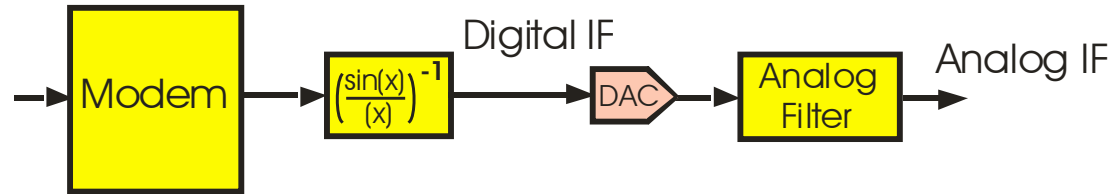


CIC [Sin(x)/(x)]^P Compensator

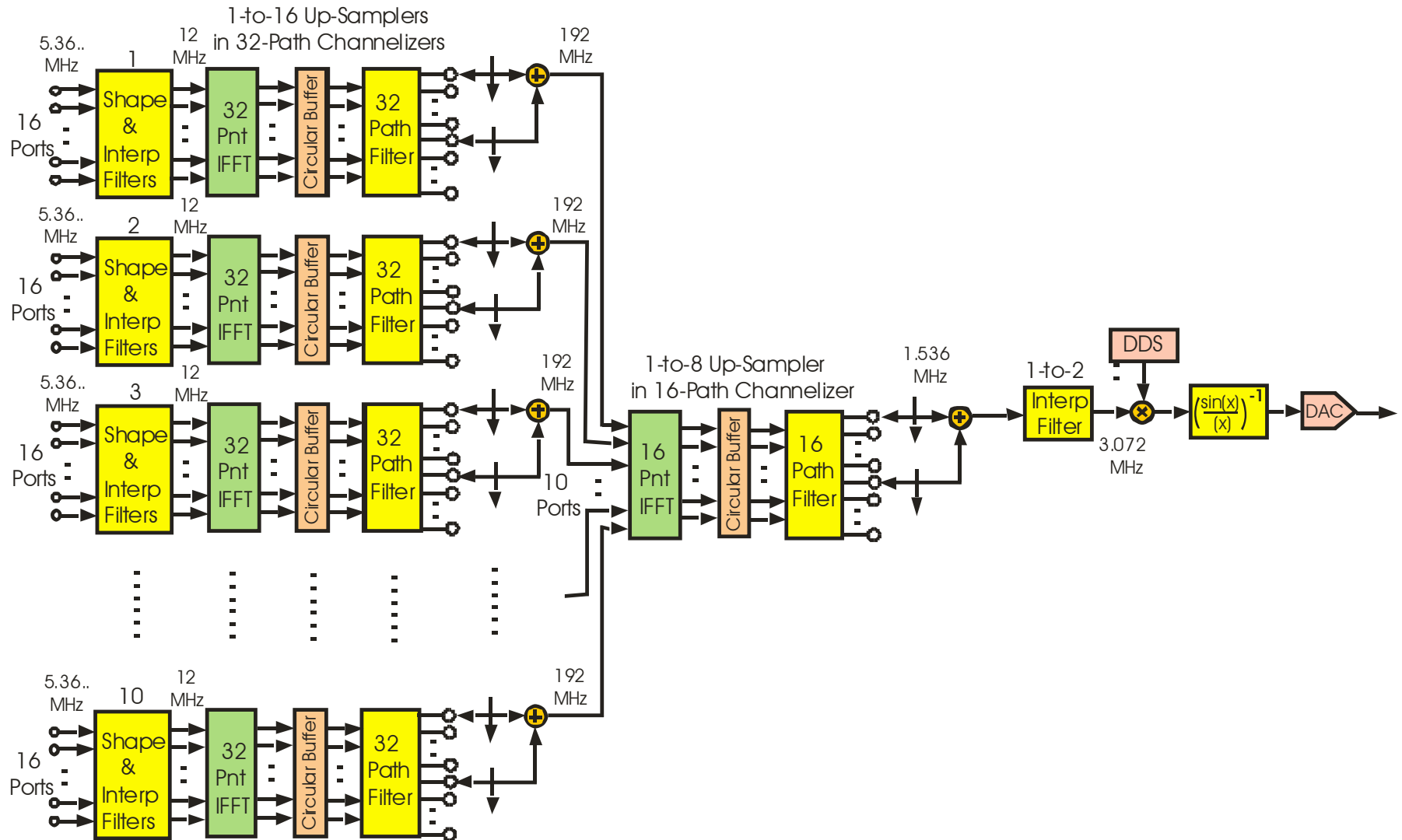
Spectrum: CIC, Compensator, Compensated



DAC $\text{Sin}(x)/x$ Digital IF Distortion

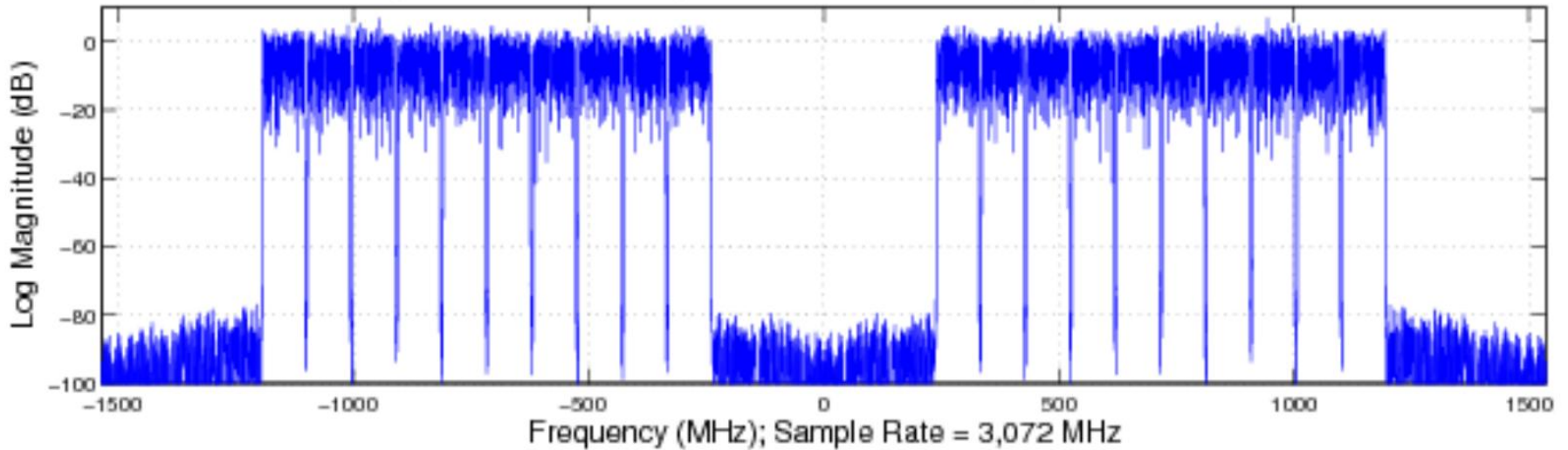


Sin(x)/(x) Predistortion

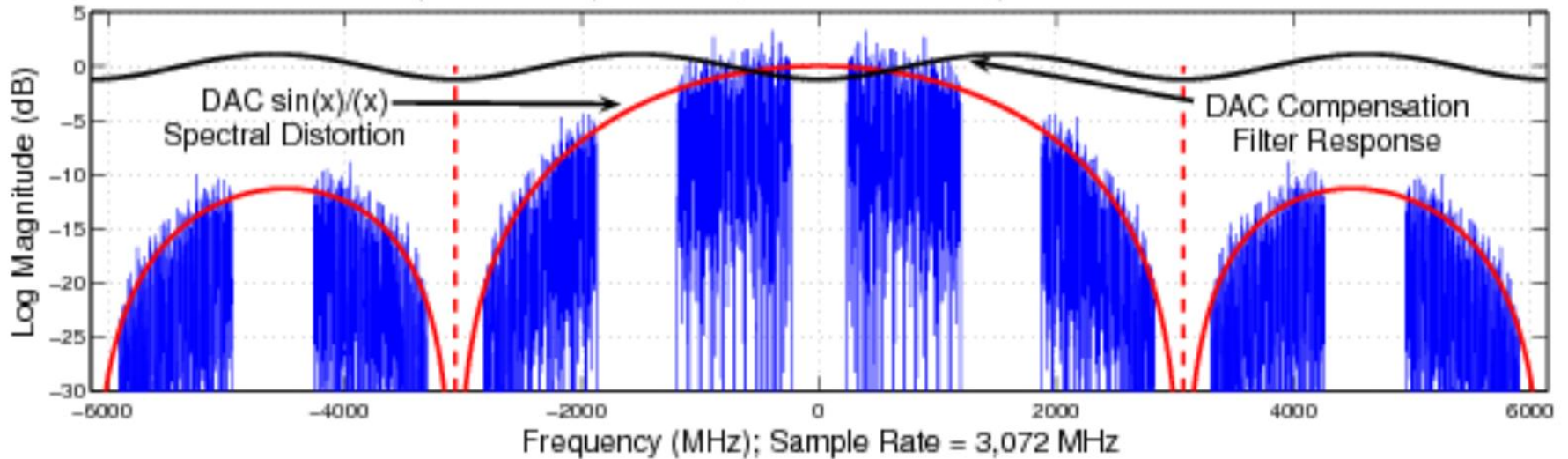


DAC SIN(X)/X CORRECTION

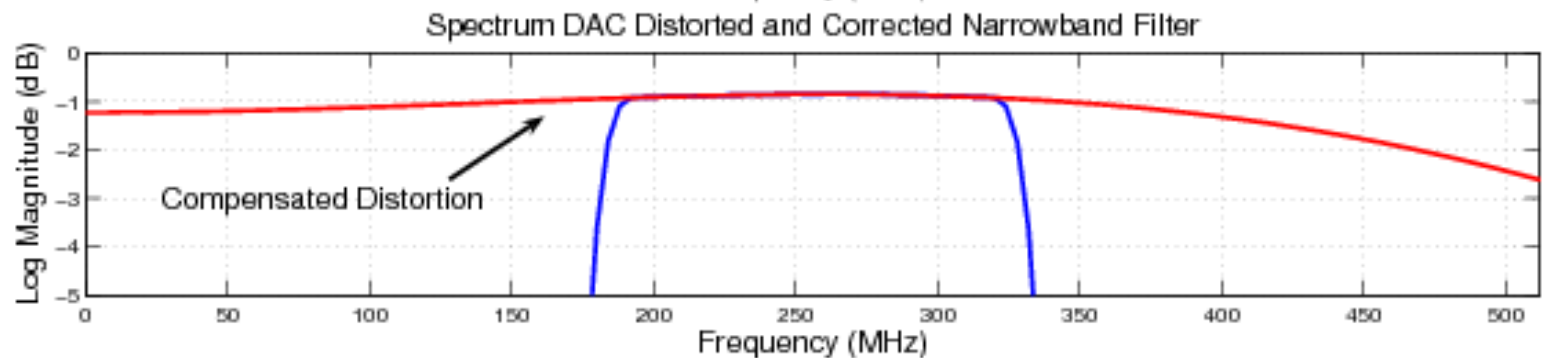
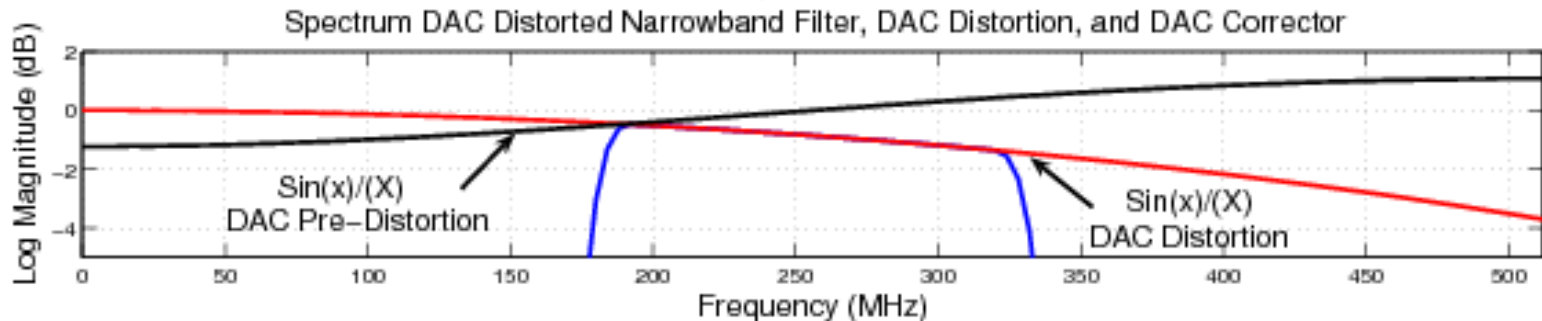
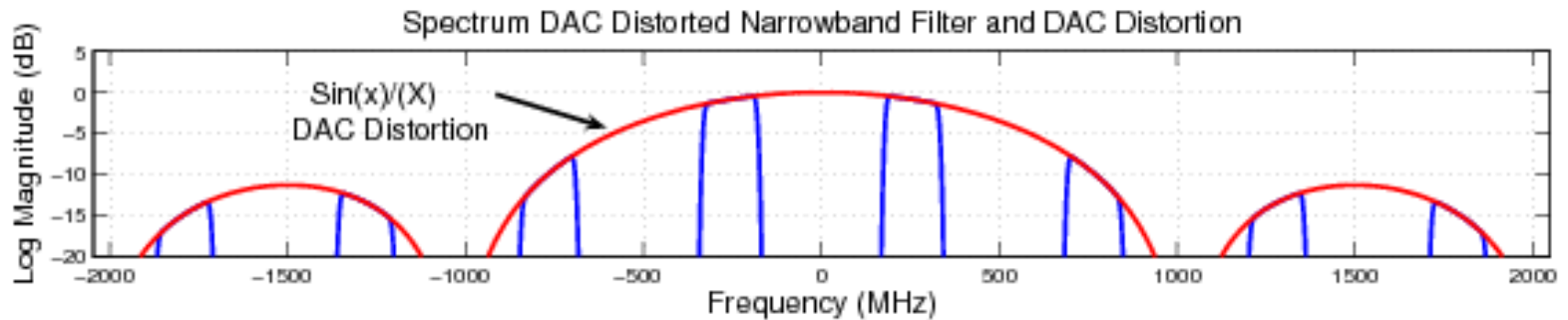
Spectrum: 1-to-2 Interpolated 160-Channel Polyphase Channelizer



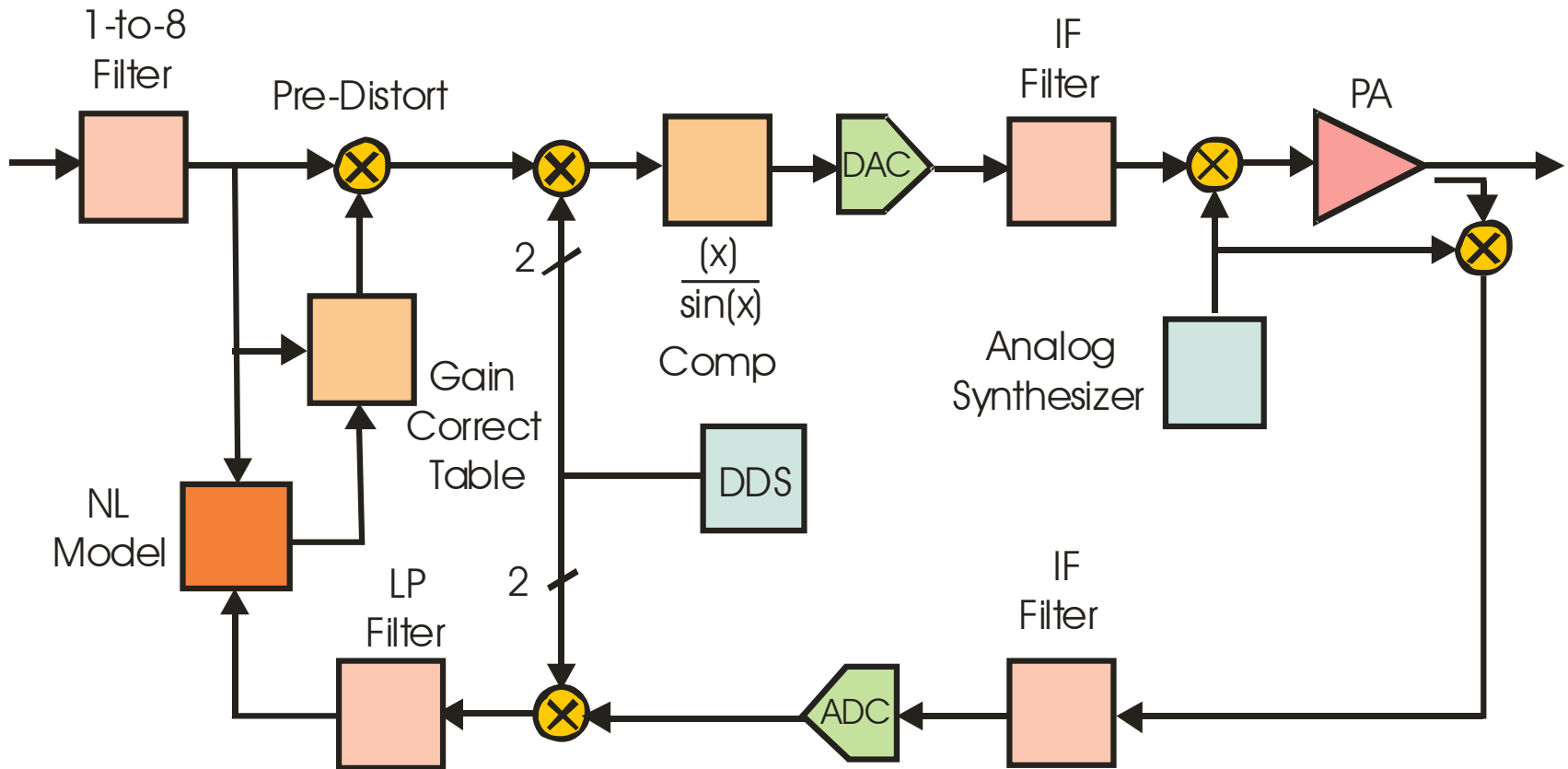
Spectrum: Output of DAC, 160-Channel Polyphase Channelizer



DAC $\text{Sin}(x)/x$ IF Predistortion

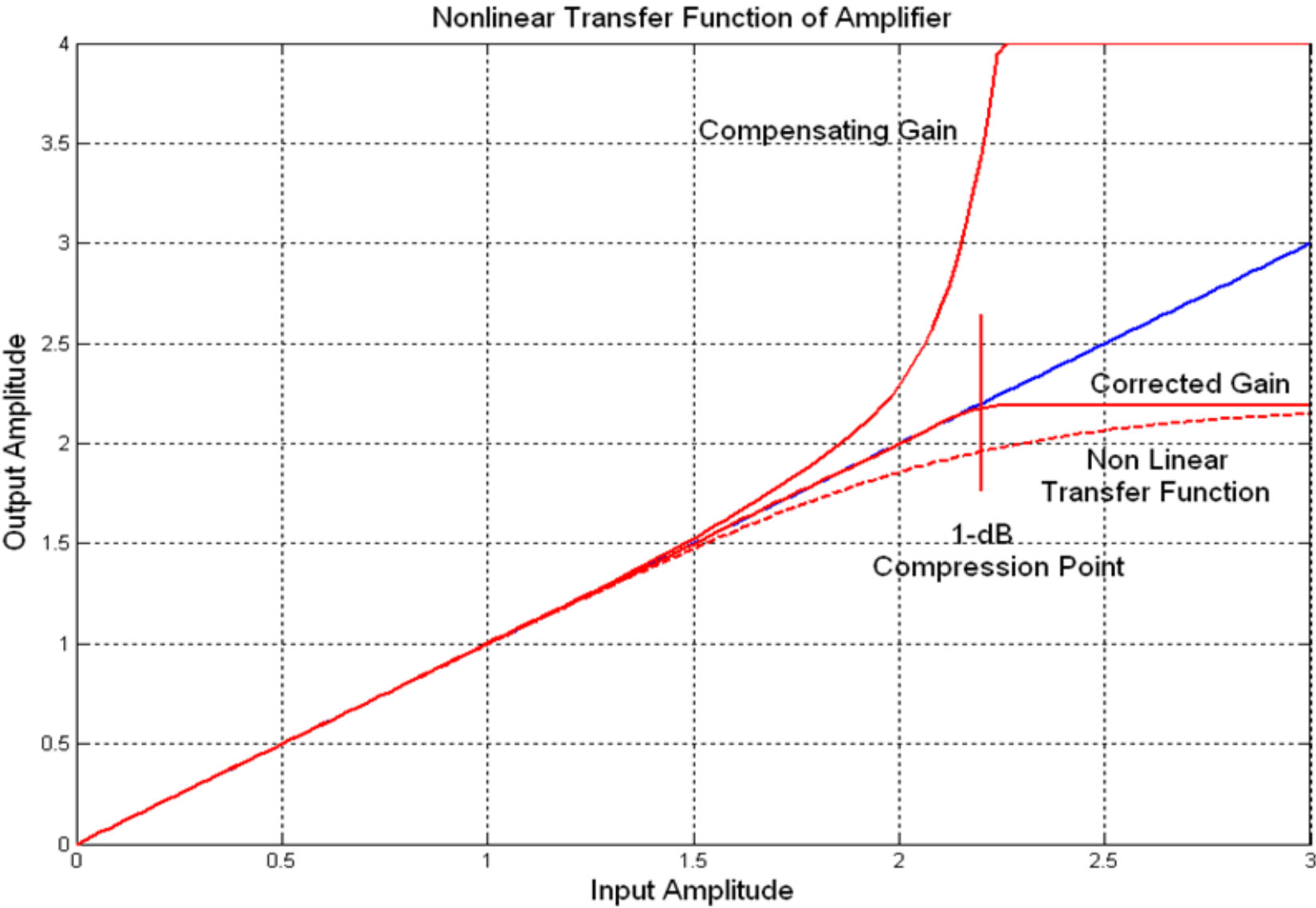


Power Amplifier Linearization

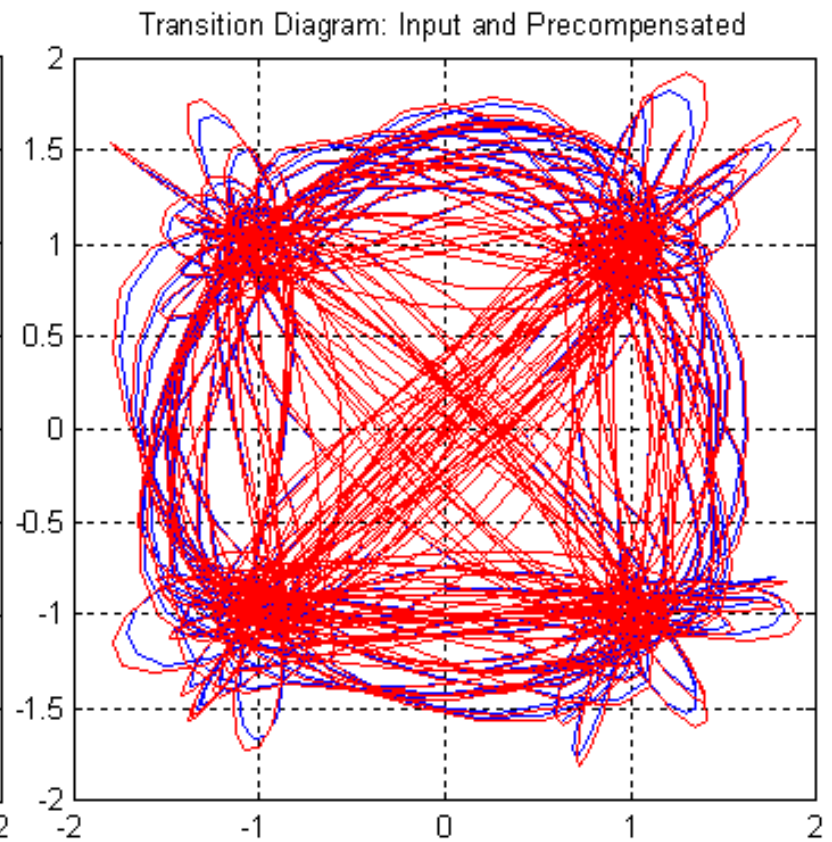
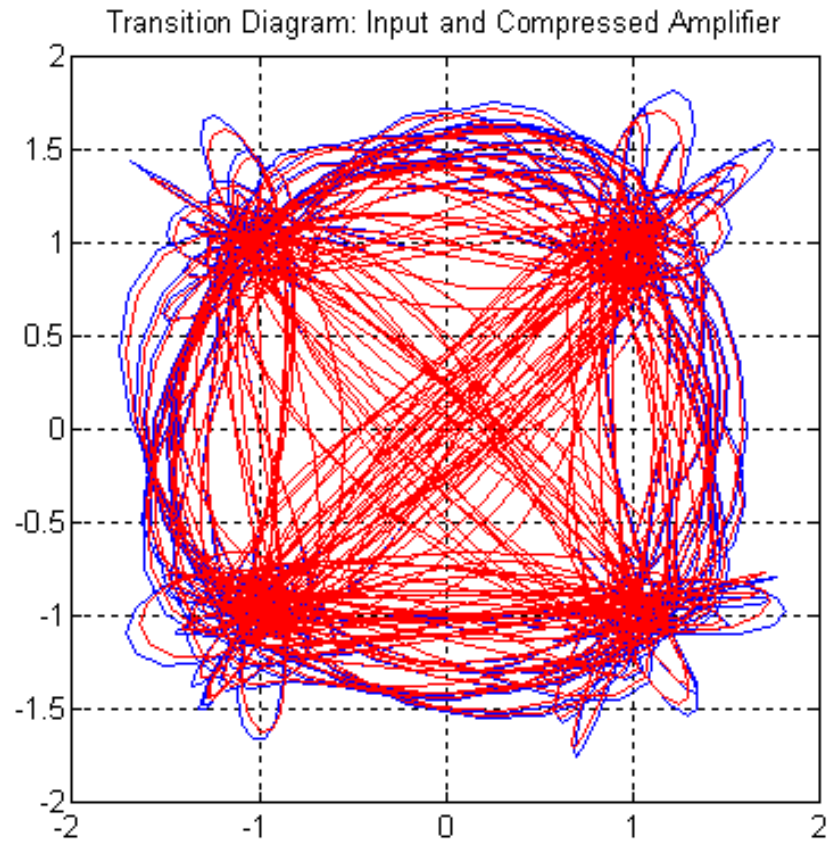


PA Linearization
Peak-to-Average Ratio Control

Non Linear Amplifier and Pre-Compensating Gain

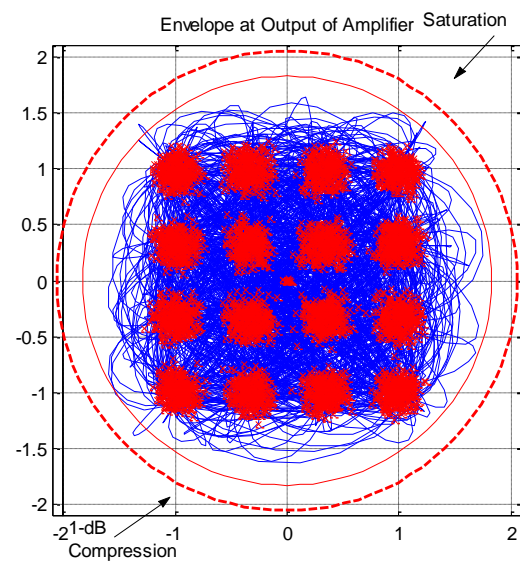
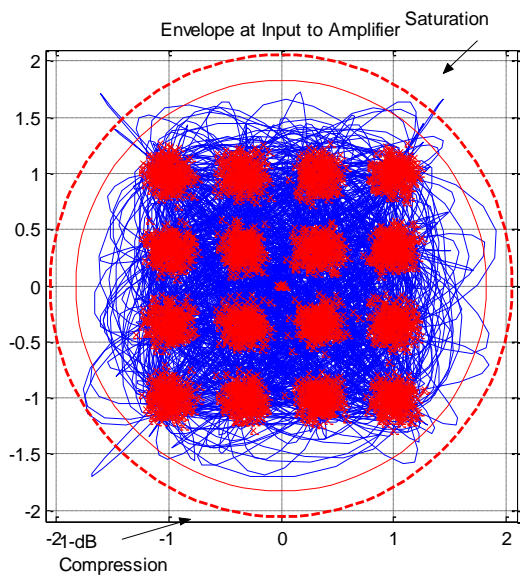


Transition Diagram Input and Output of Amplifier and Input and Output of Precompensator

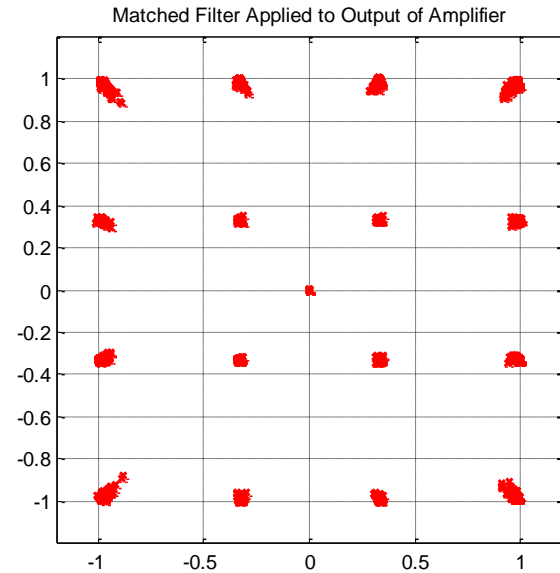
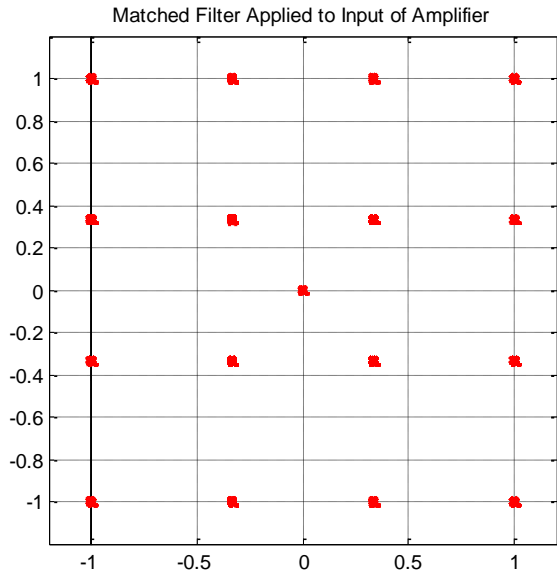


16-QAM Input and Output Envelopes. Saturation and 1-dB Compression Circles

Saturation at 2-Times RMS Signal Level

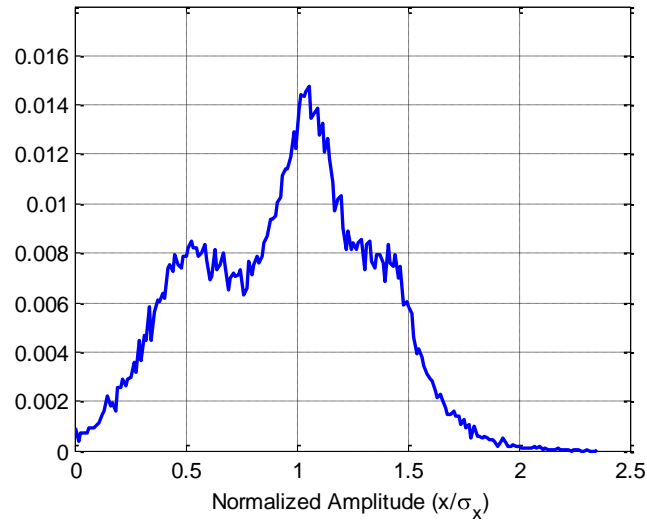


Limiting Amplifier Effect on Received QAM Constellation

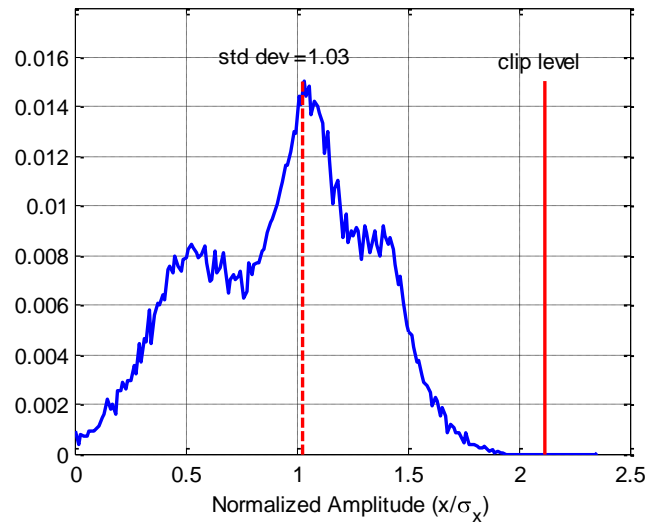


16-QAM ($\alpha=0.2$) Envelope Statistics

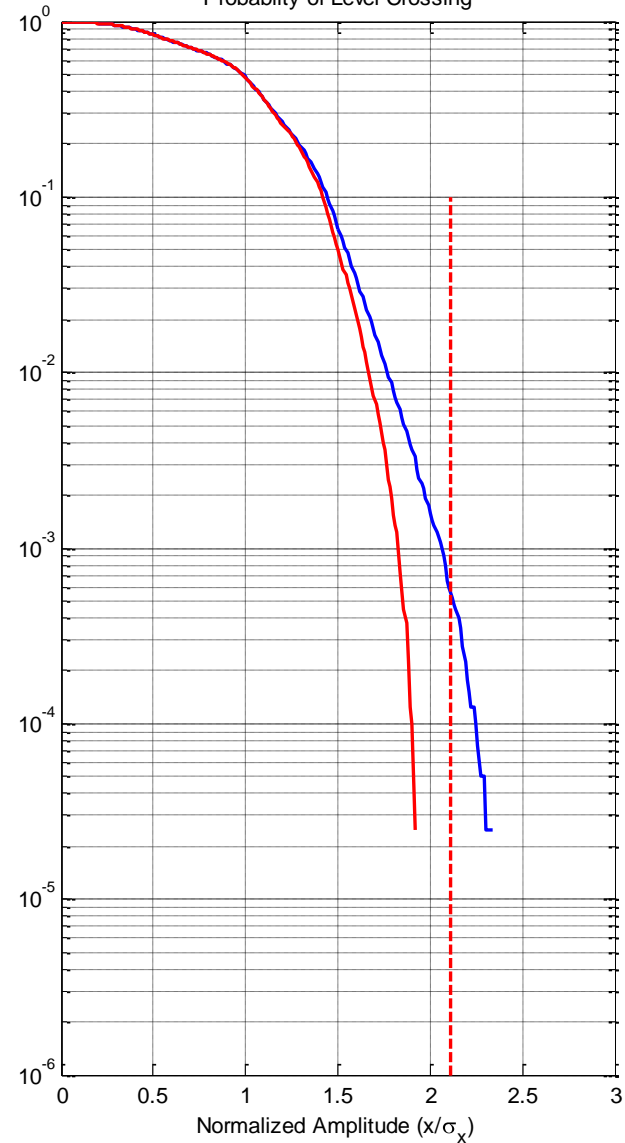
16-QAM Histogram at Amplifier Input



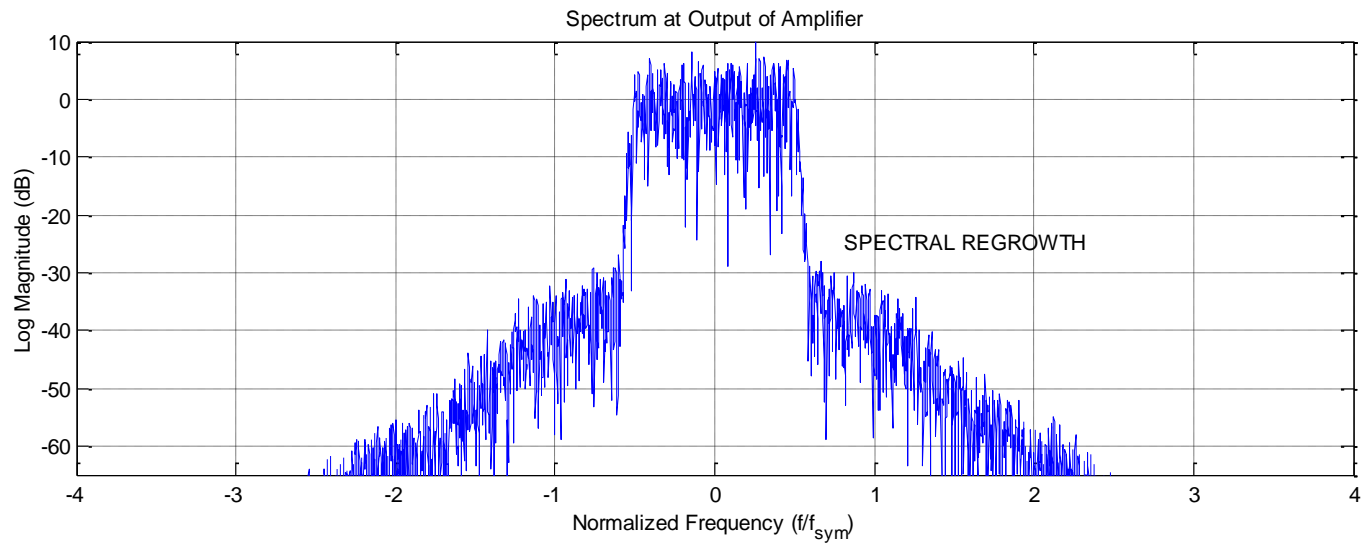
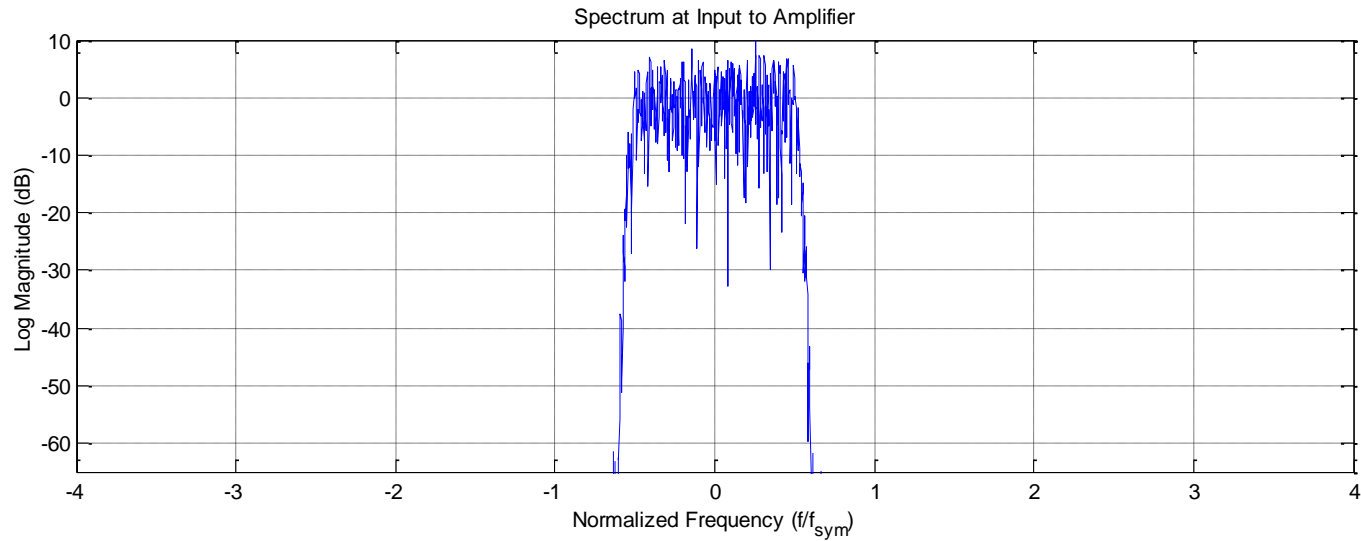
16-QAM Histogram at Amplifier Output



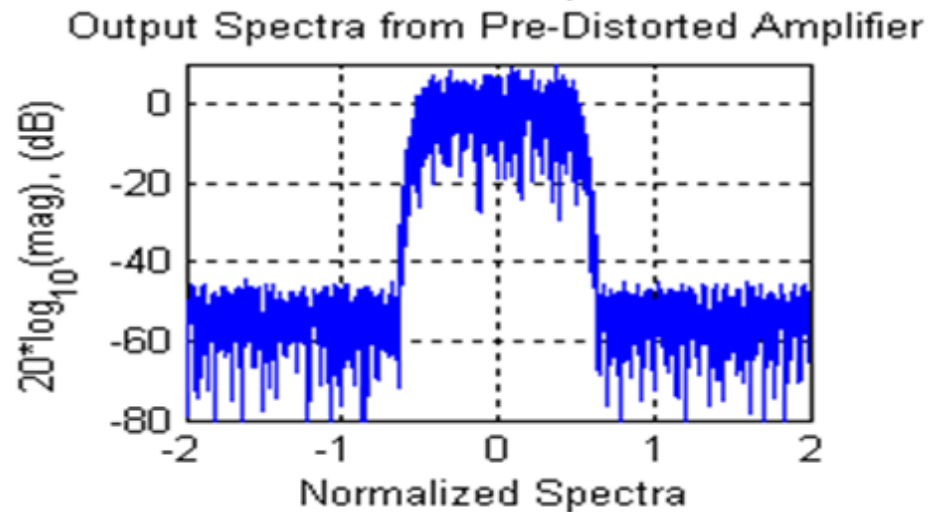
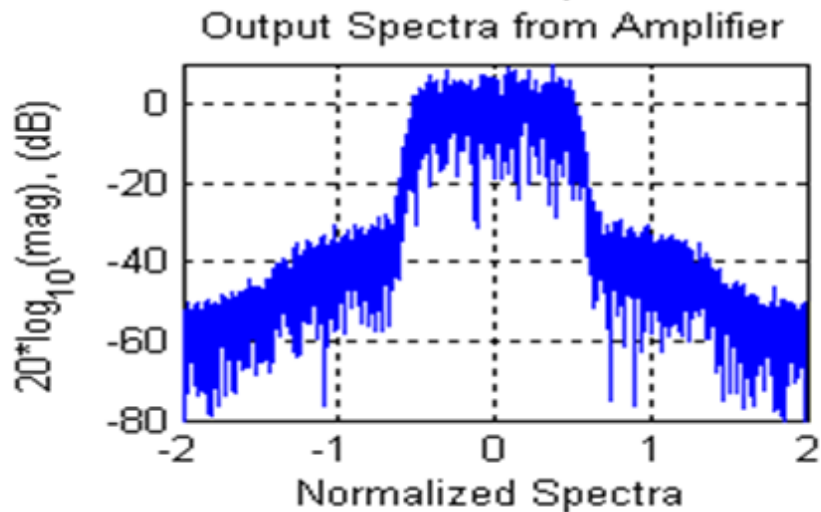
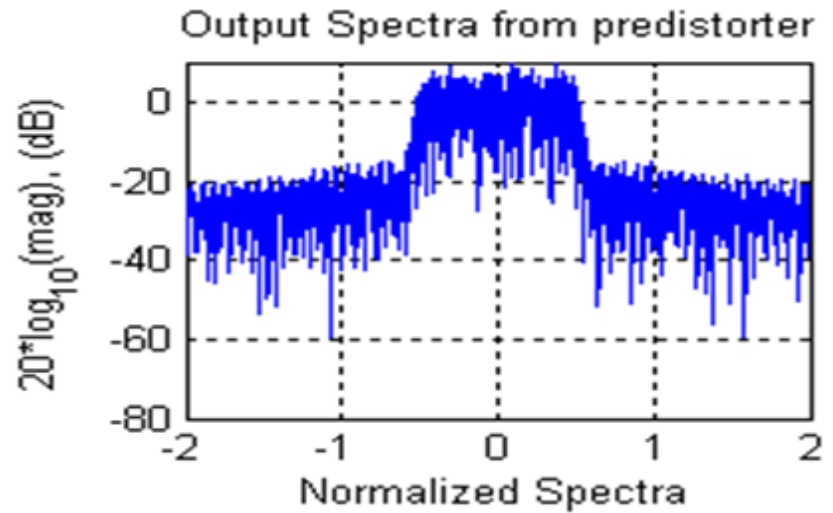
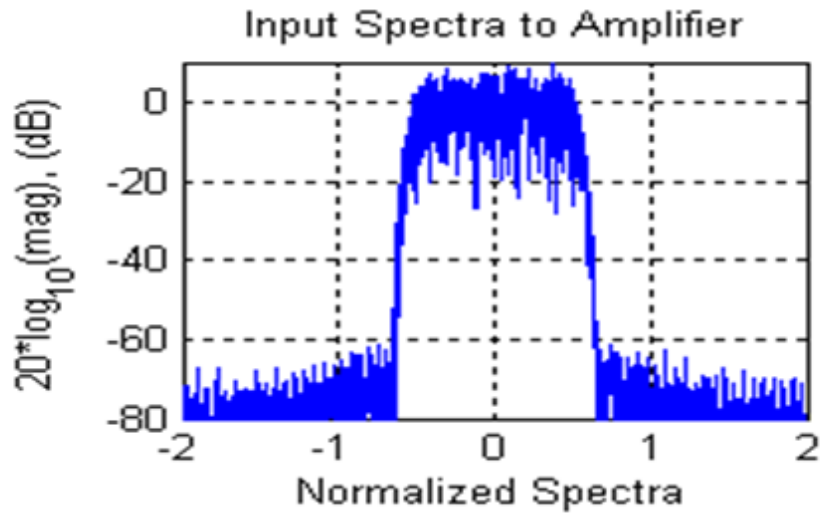
Probability of Level Crossing



Limiting Amplifier Effect on Signal Spectra

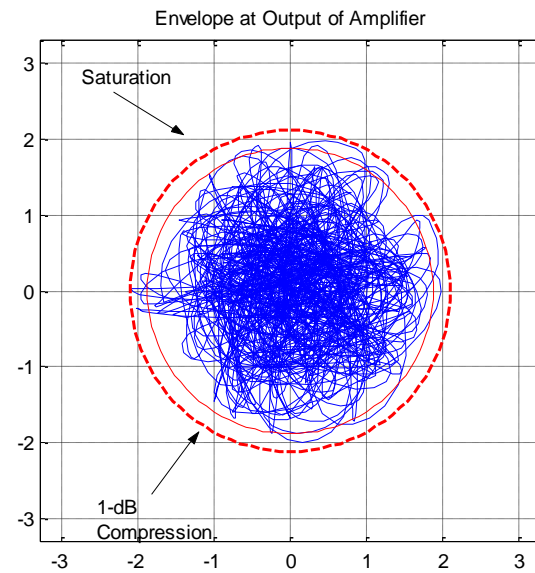
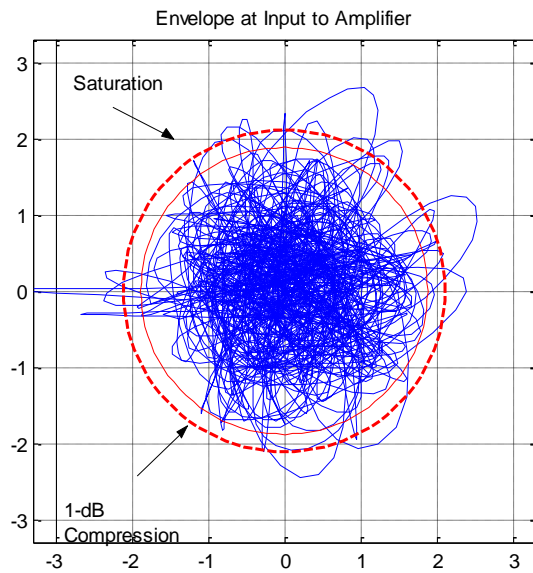


Spectra: Input and Output of Amplifier and Output of Pre-Compensator and Pre-Compensated Amplifier

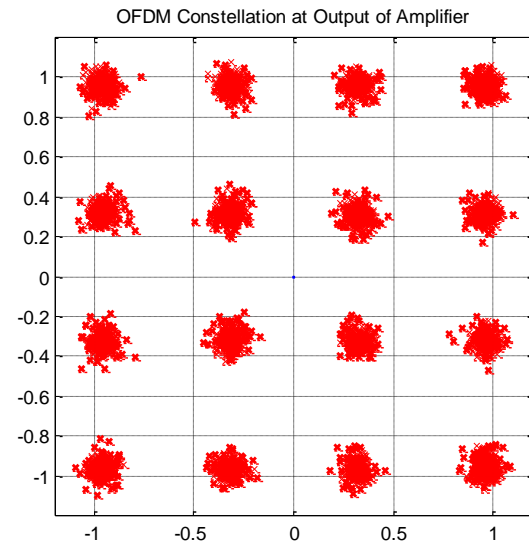
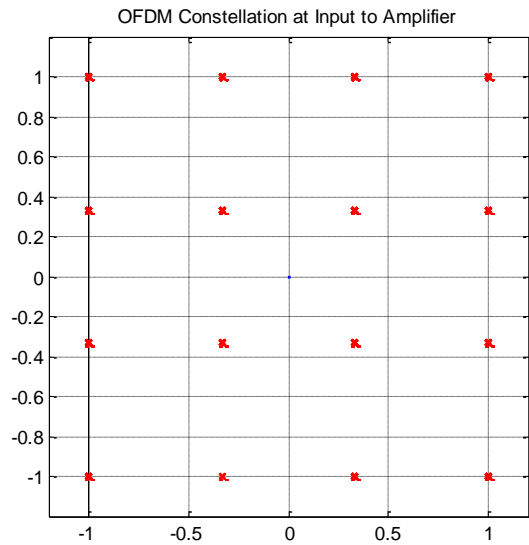


OFDM Input and Output Envelopes: Saturation and 1-dB Compression Circles

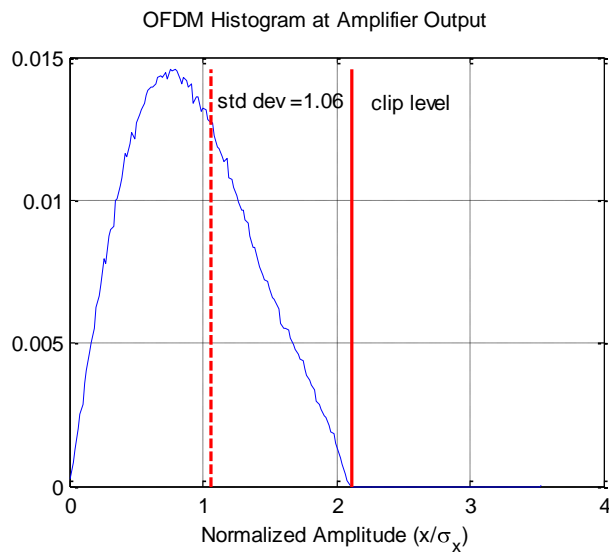
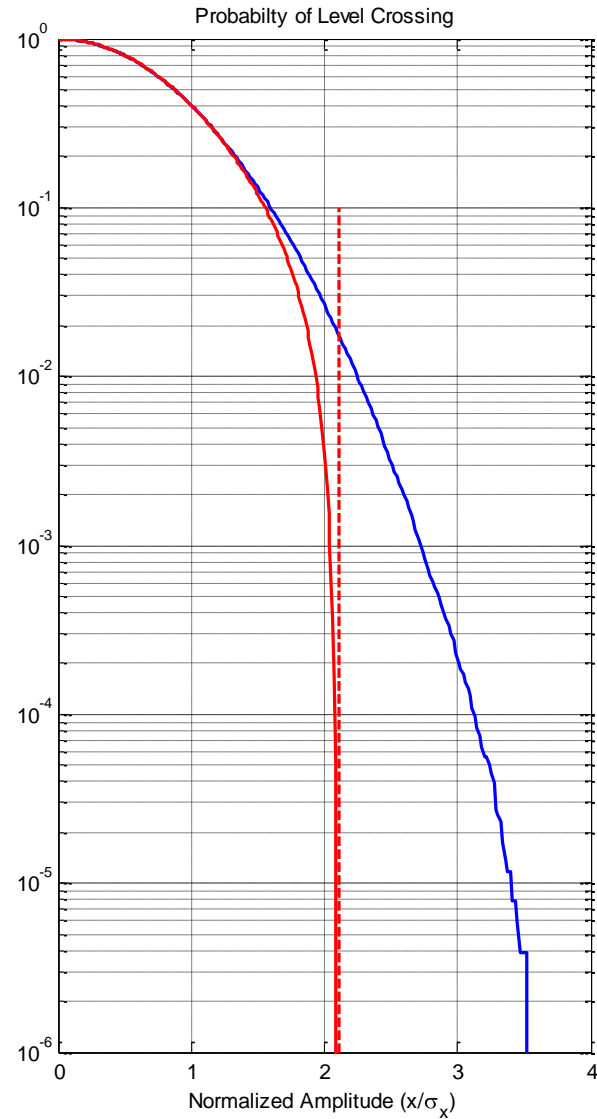
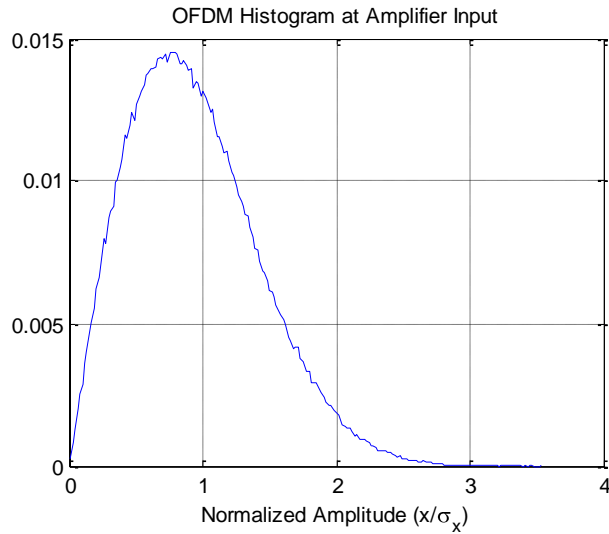
Saturation at 2-Times RMS Signal Level



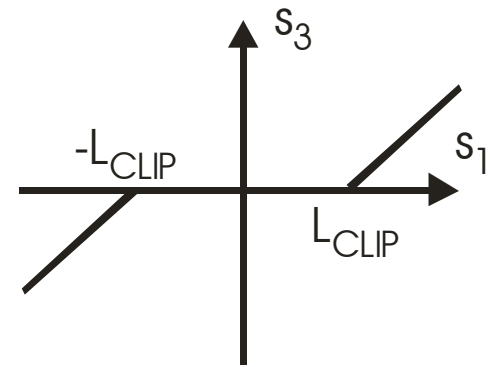
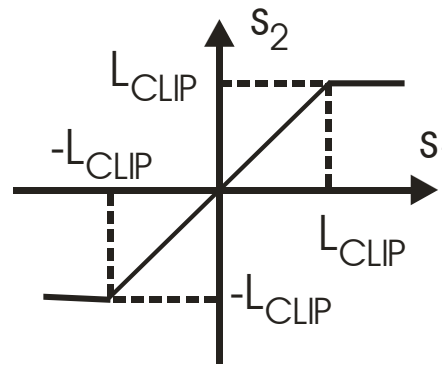
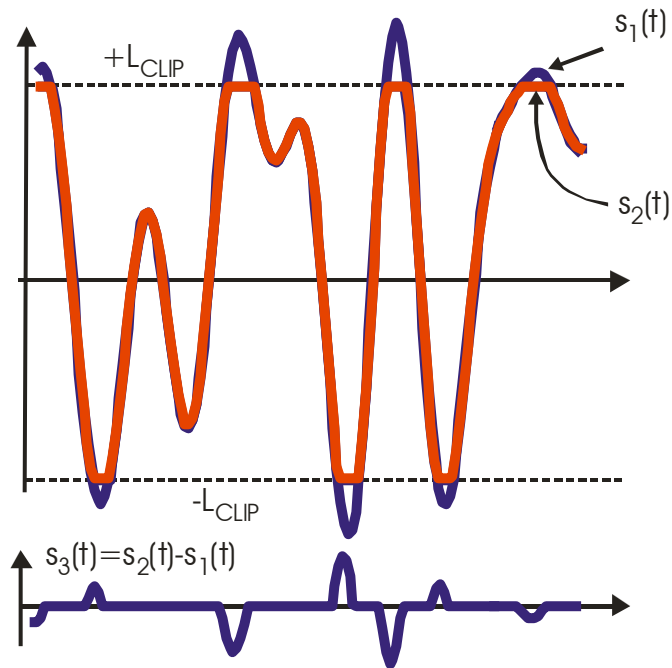
Limiting Amplifier Effect on OFDM Constellation



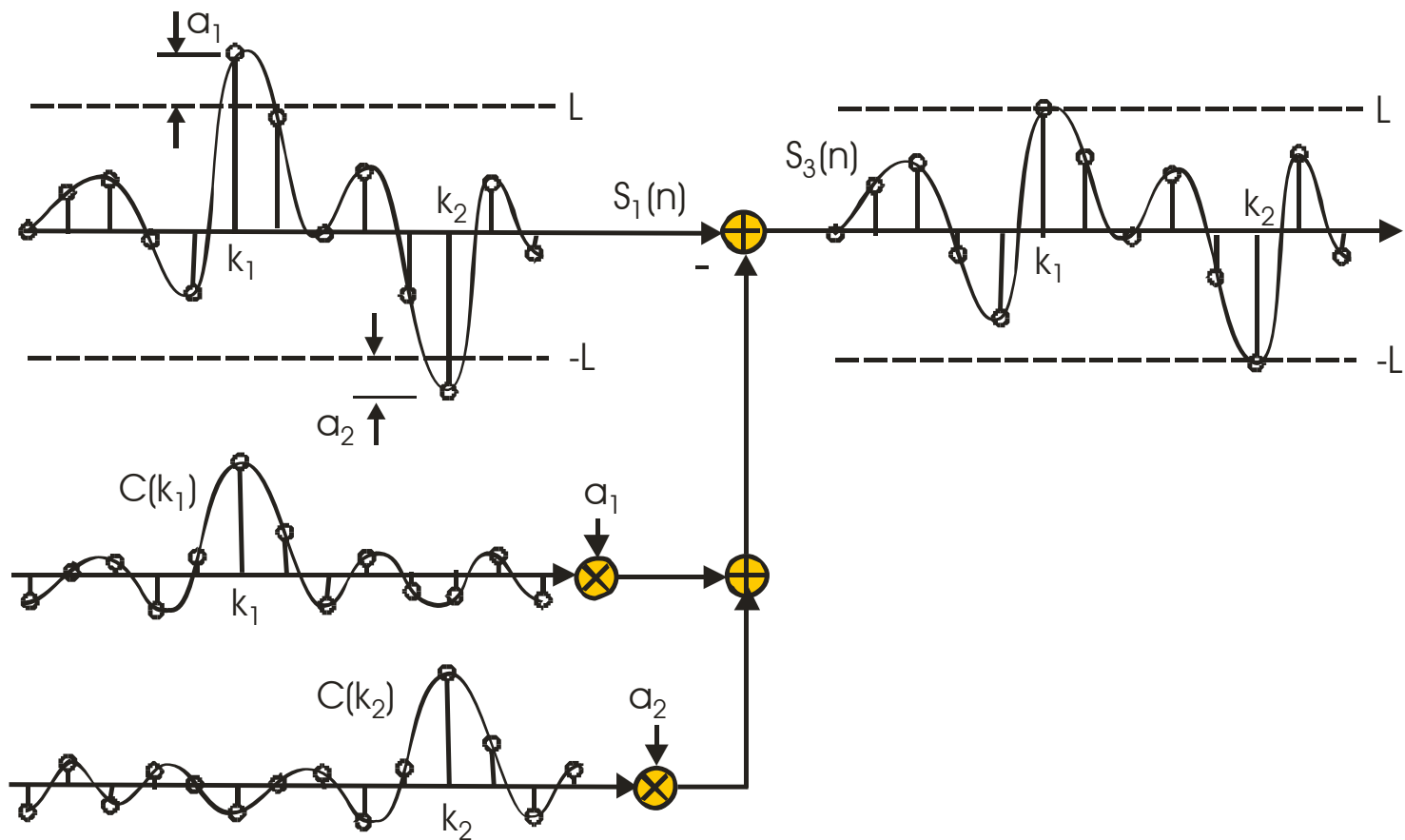
OFDM Envelope Statistics



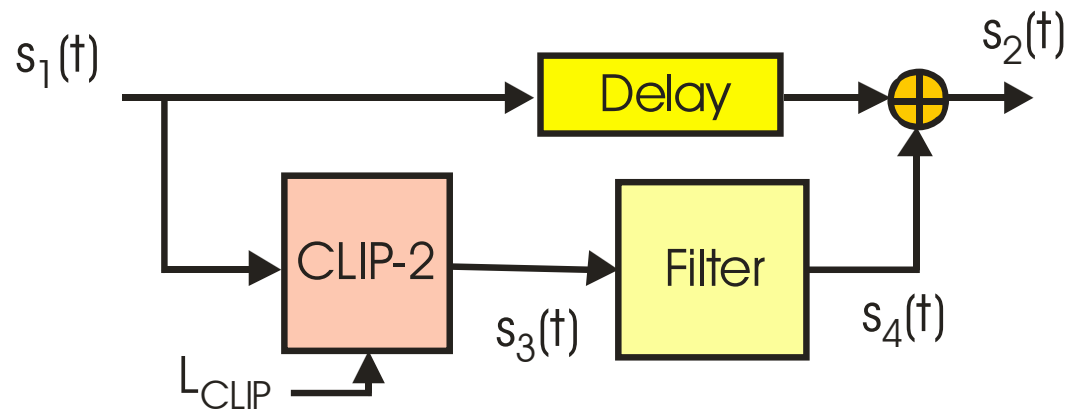
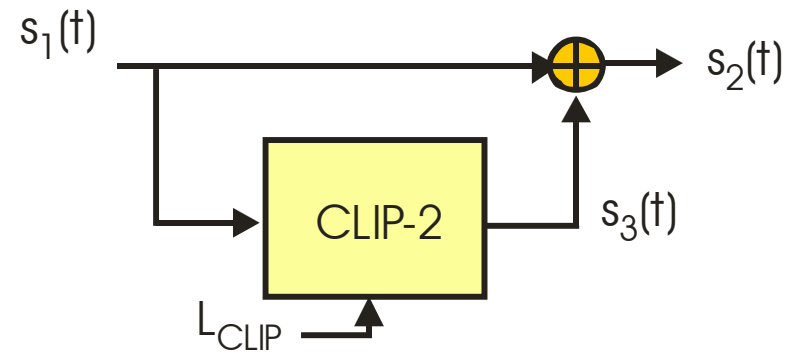
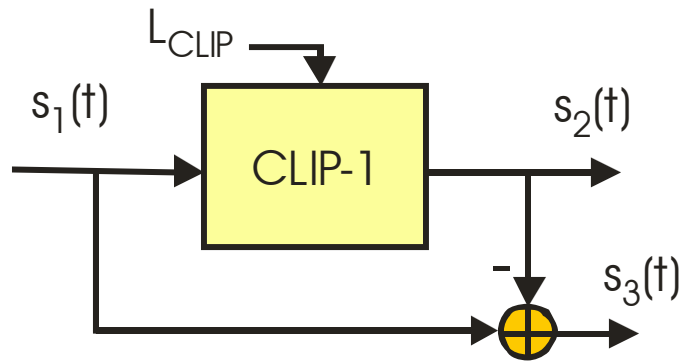
To Clip or Not to Clip: That is the Question!



Band Limited Subtractive Clipping

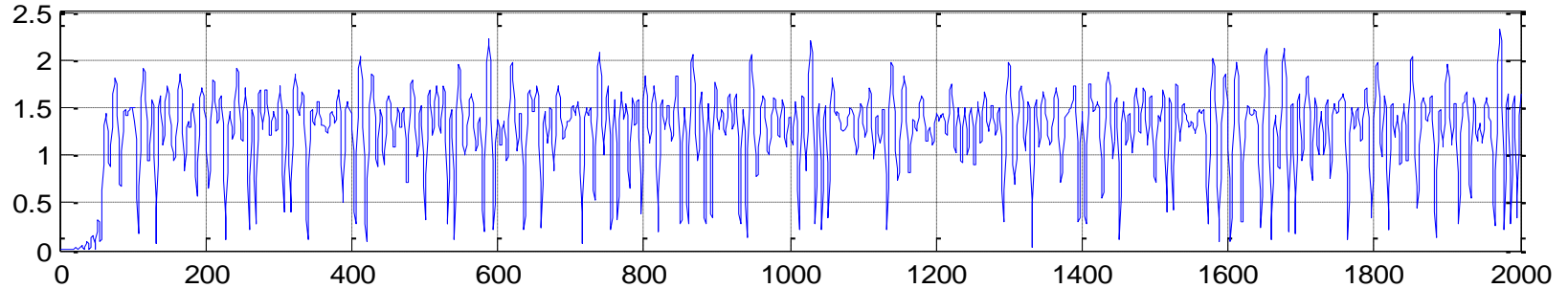


Band-Limited Clipping

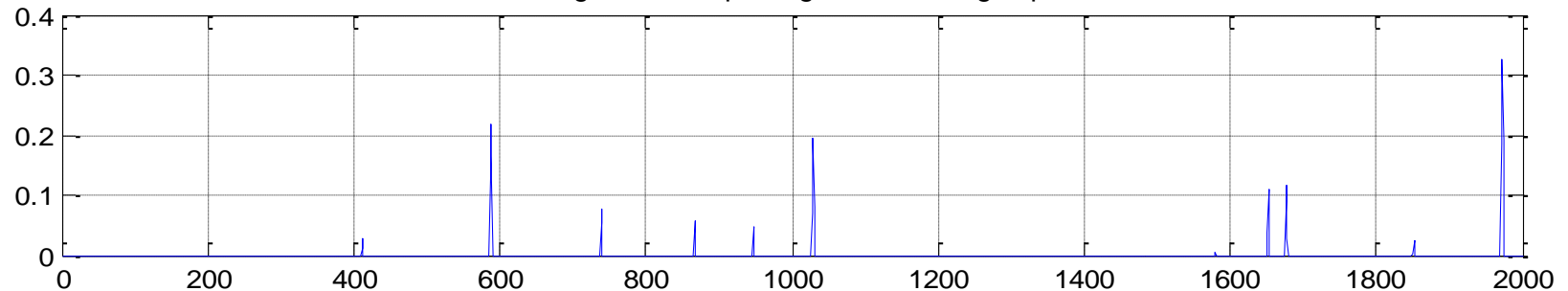


Input Signal, Clipping Component and Clipped Signal

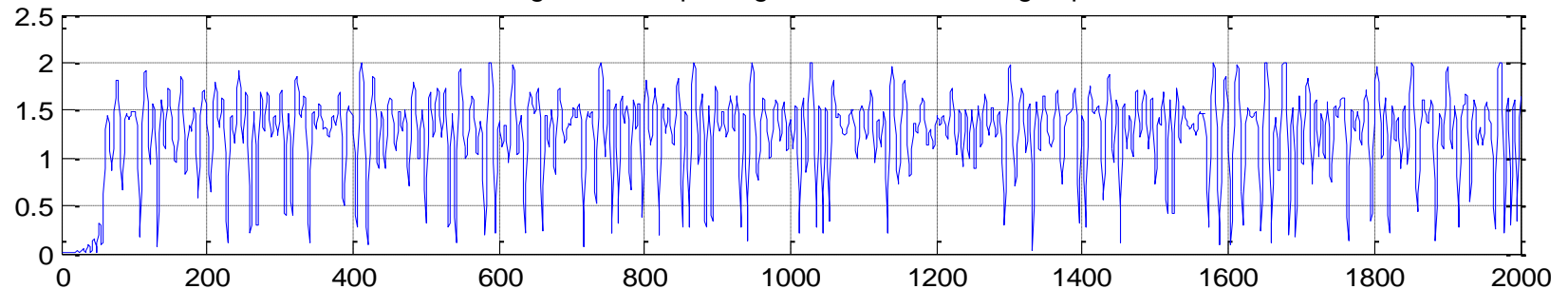
Magnitude of Input Signal



Magnitude of Input Signal Exceeding Top

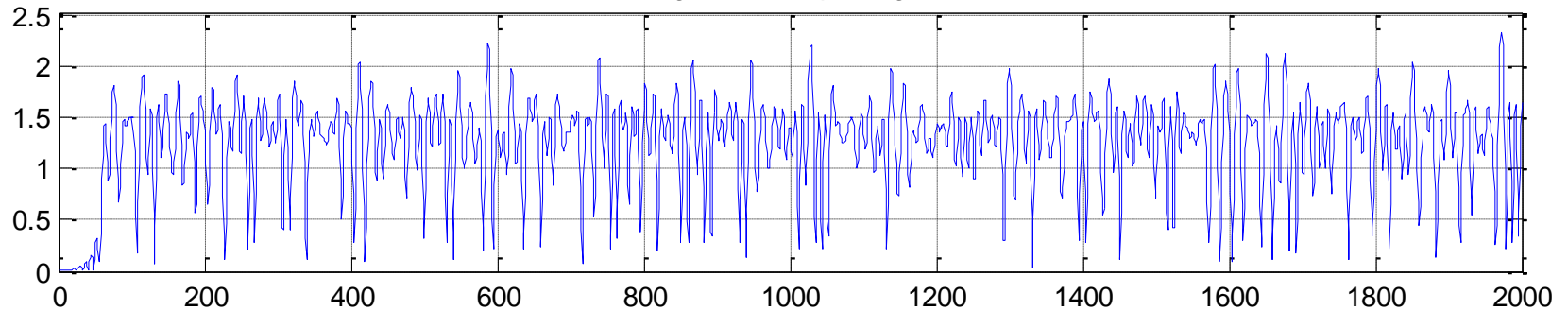


Magnitude of Input Signal - Level Exceeding Top

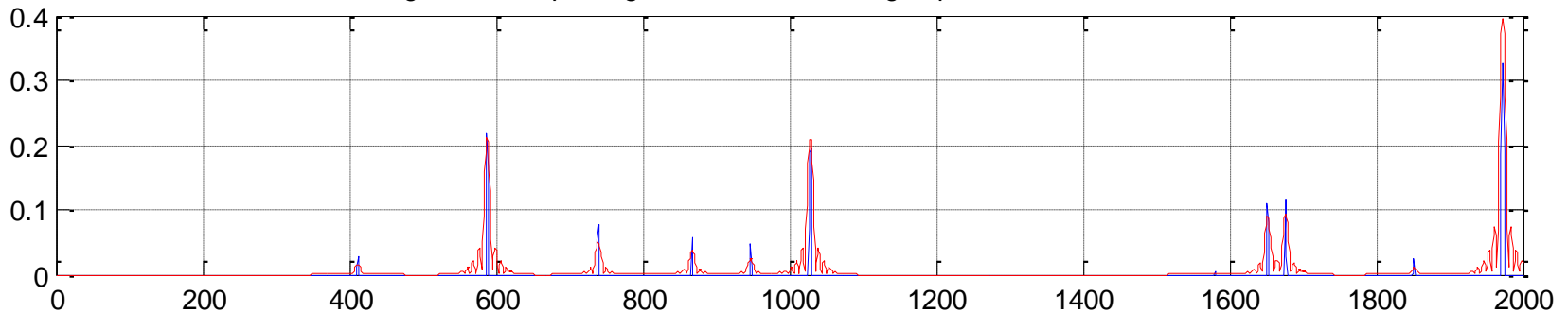


Spectra: Input Signal, Band Limited Clipping Component and Clipped Signal

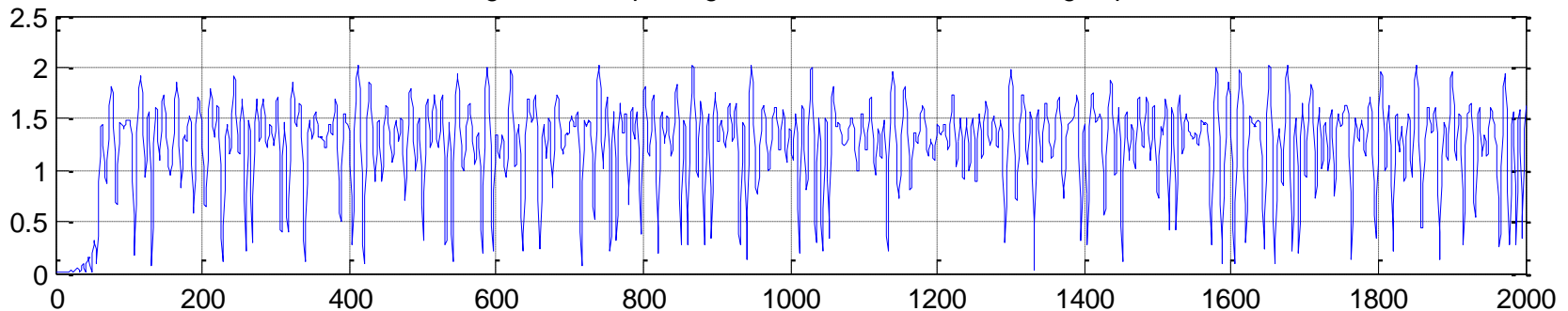
Magnitude of Input Signal



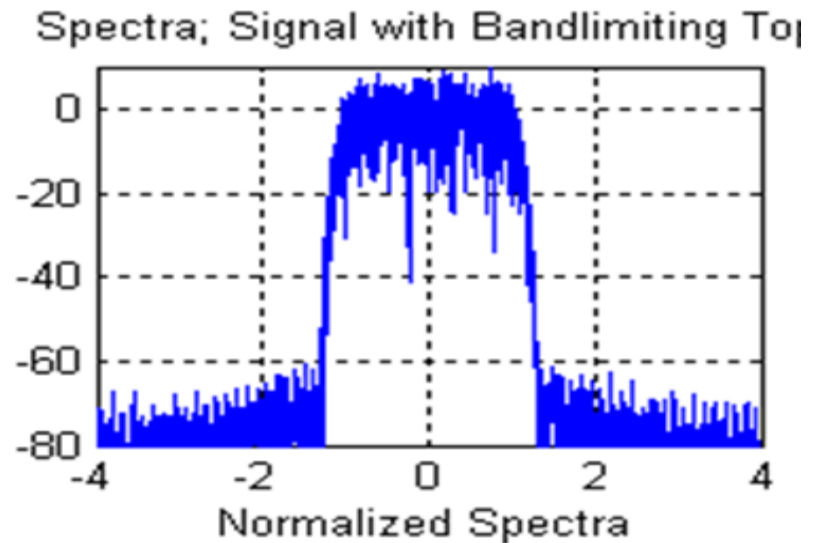
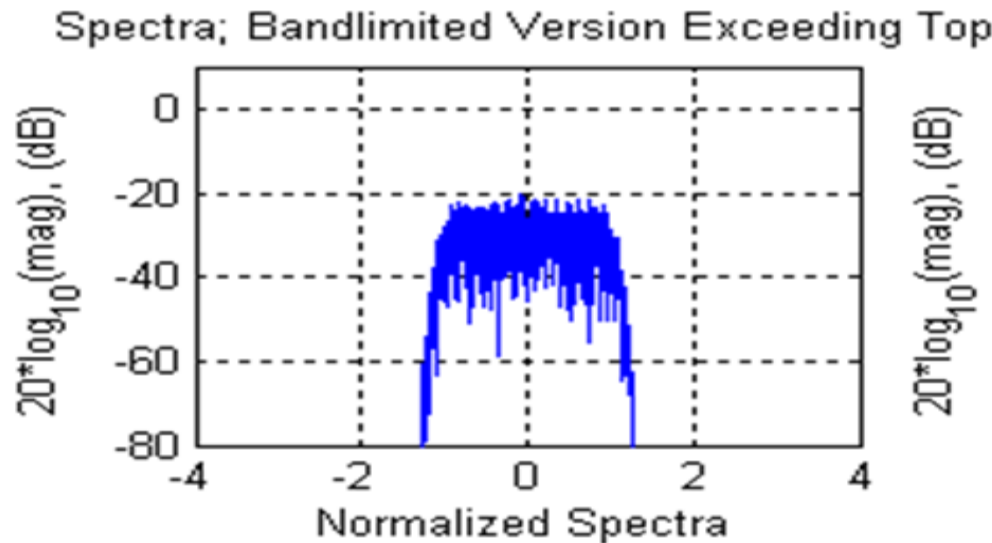
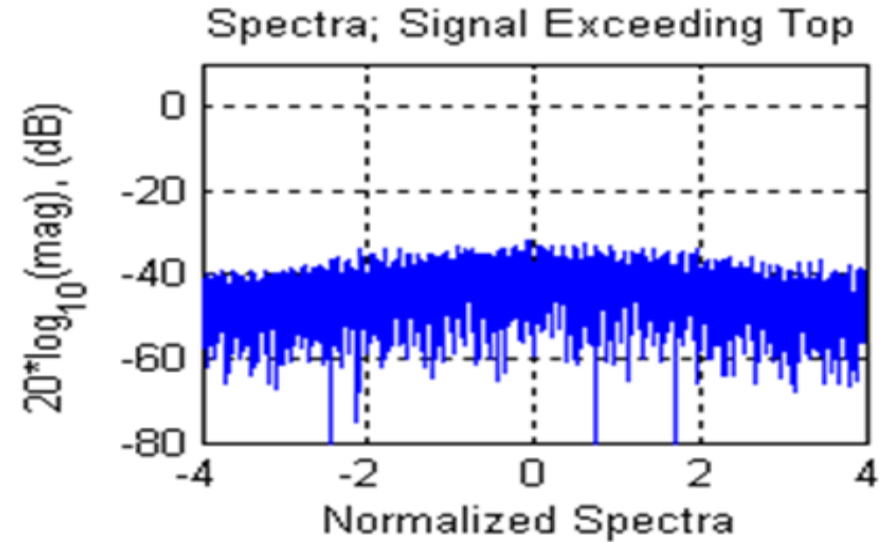
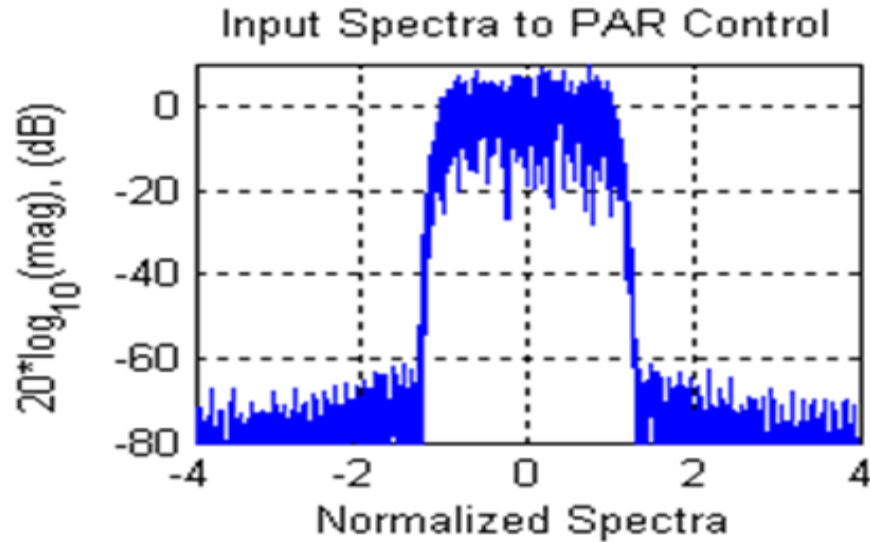
Magnitude of Input Signal - Level Exceeding Top and Filtered Version



Magnitude of Input Signal - Filtered Level Exceeding Top

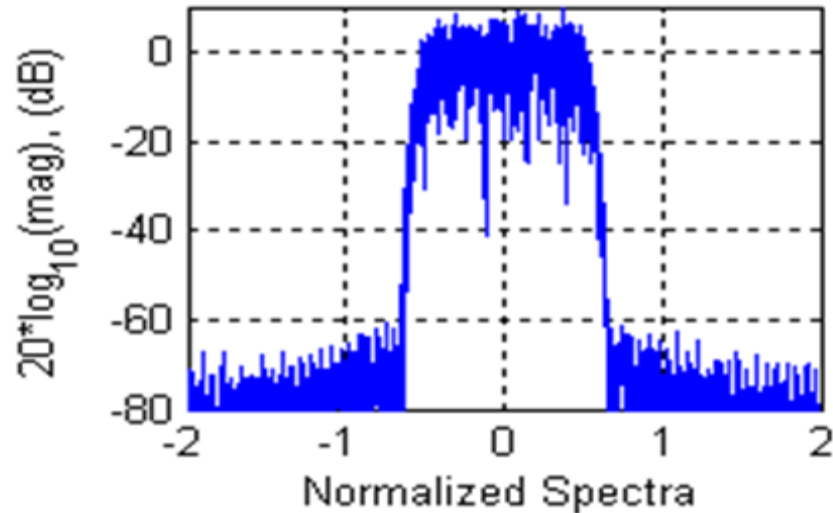


Spectra: Input, Clip Component, Band Limited Clip, and Band Limited Clip

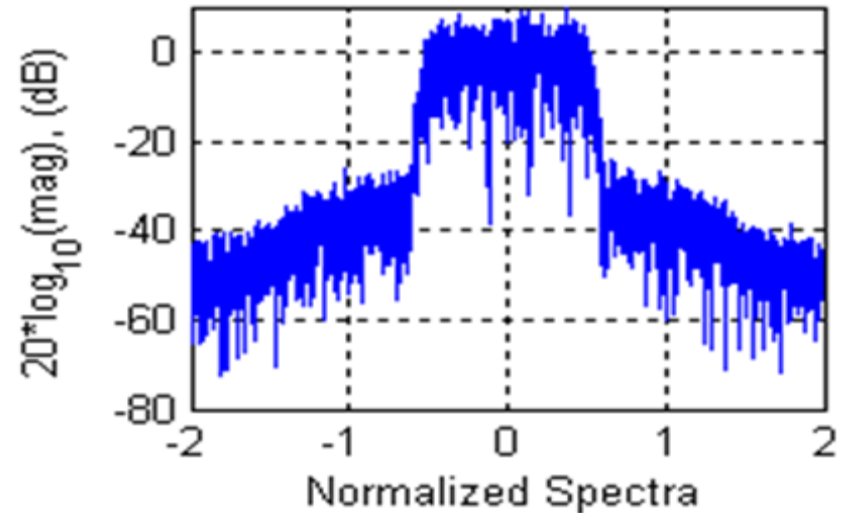


Spectra: Input and Output of Amplifier and Output of PAPR Controlled and Pre-Compensator and Pre-Compensated Amplifier

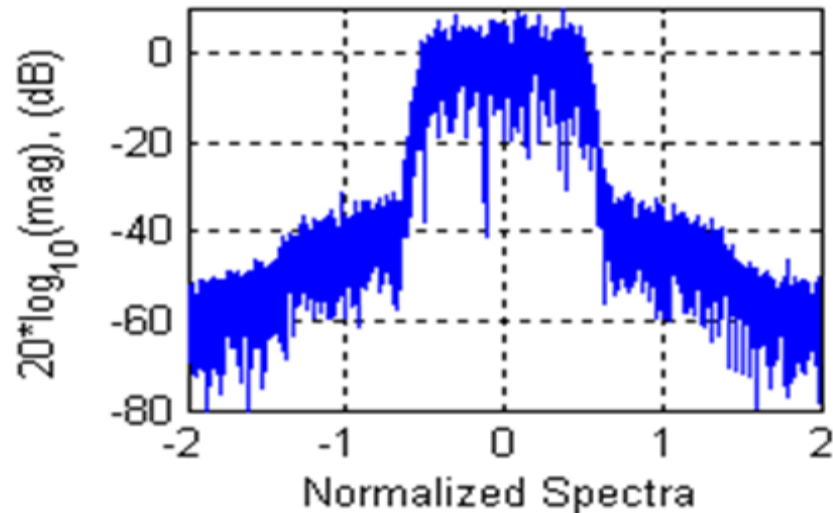
PAPR processed Input Spectra to Amplifier



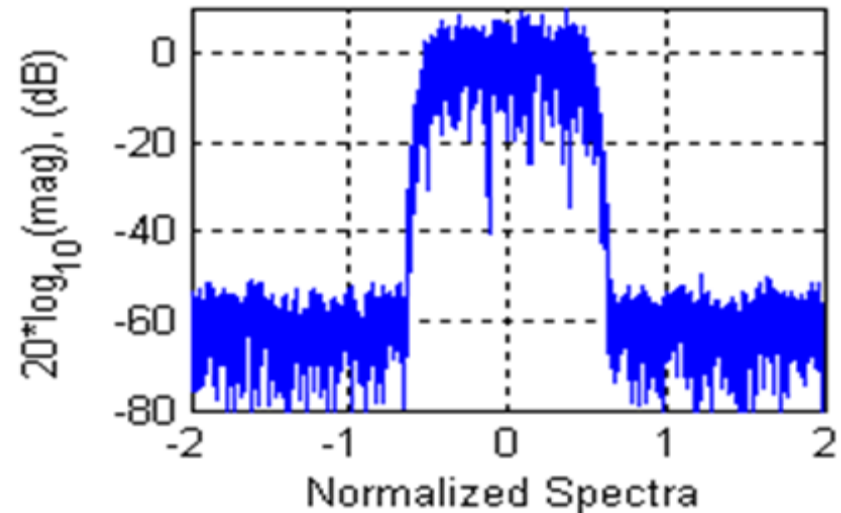
Output Spectra from predistorter



Output Spectra from Amplifier

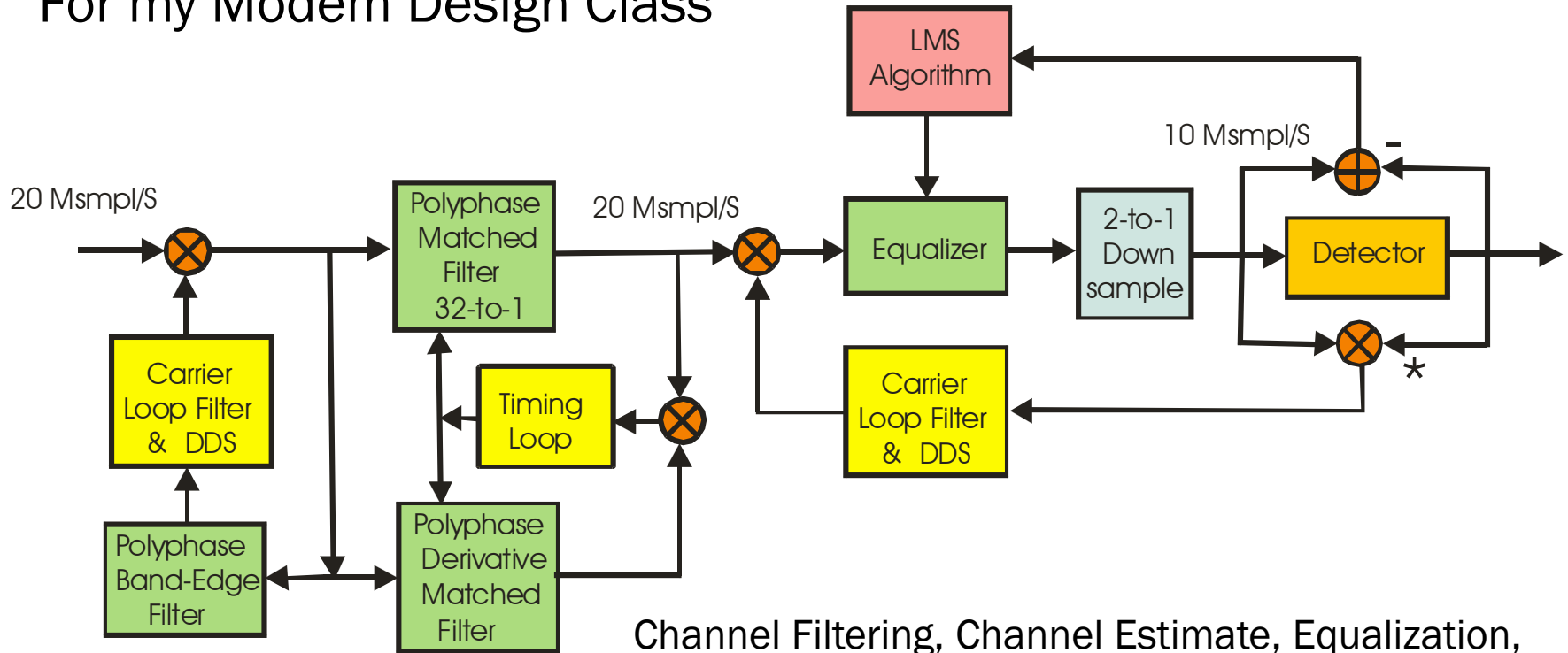


Output Spectra from Pre-Distorted Amplifier

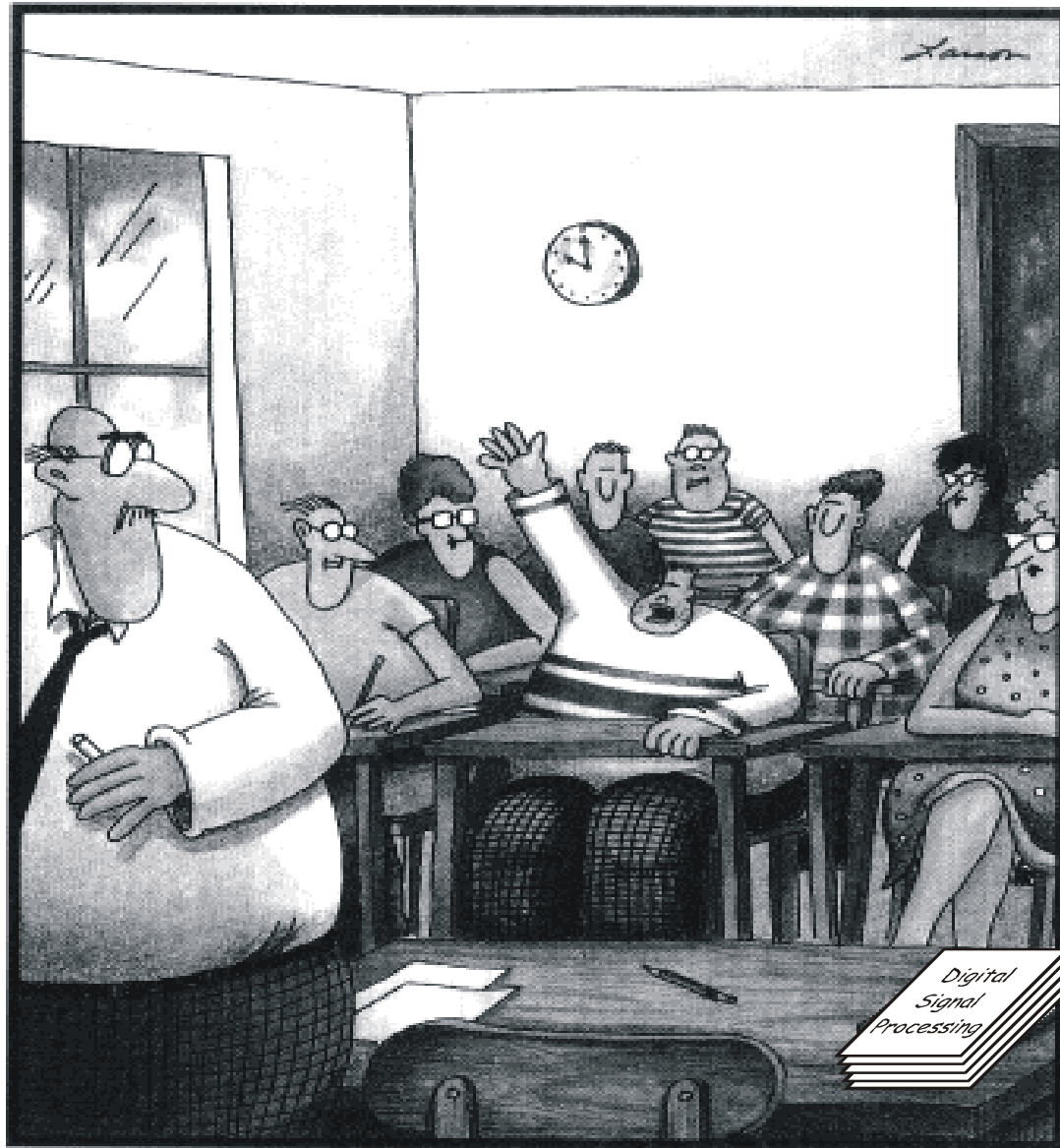


DSP Radio (DSP Everywhere!)

Actually, A design Project
For my Modem Design Class



Channel Filtering, Channel Estimate, Equalization, AGC, DC-Cancelling, I-Q Balance, Line Canceller, Interference Canceller, Matched Filter, SNR Estimate, Band Edge Filter, Frequency Lock Loop, Carrier Lock Loop, Interpolator, Timing Lock Loop

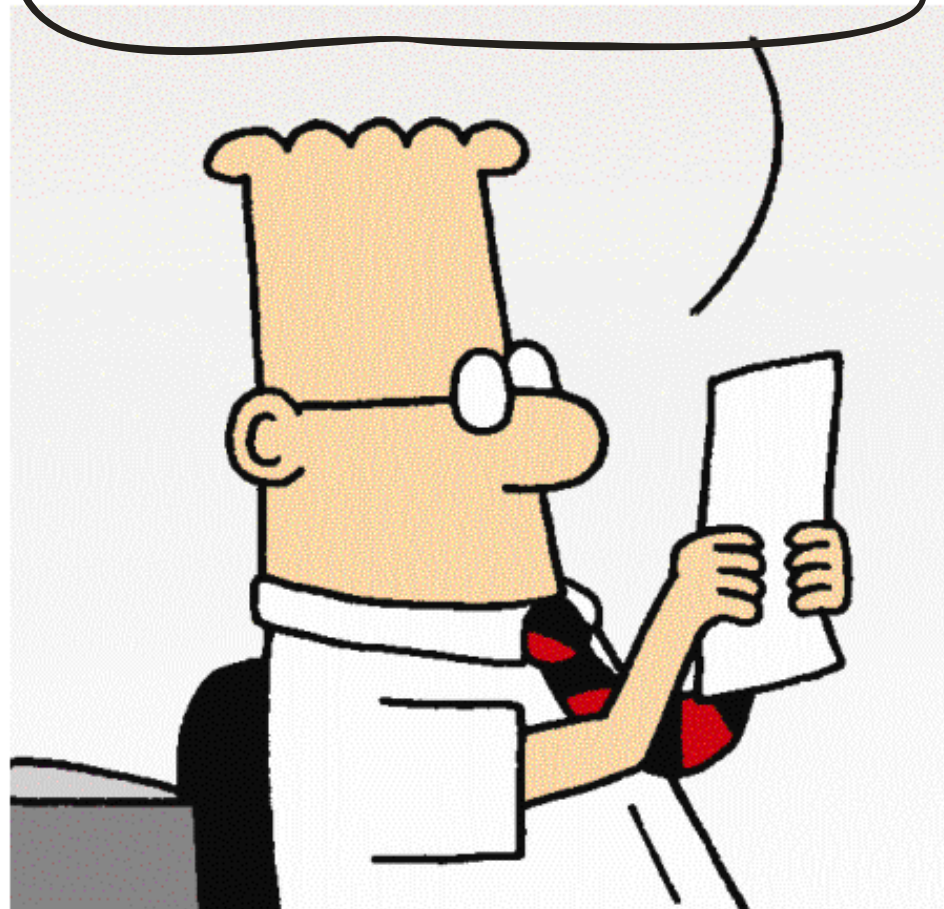


Professor harris, may I be excused?
My brain is full.

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



Yes: That is True!





SOFTWARE DEFINED RADIO MAN

Is Open For Questions

