MODEMS

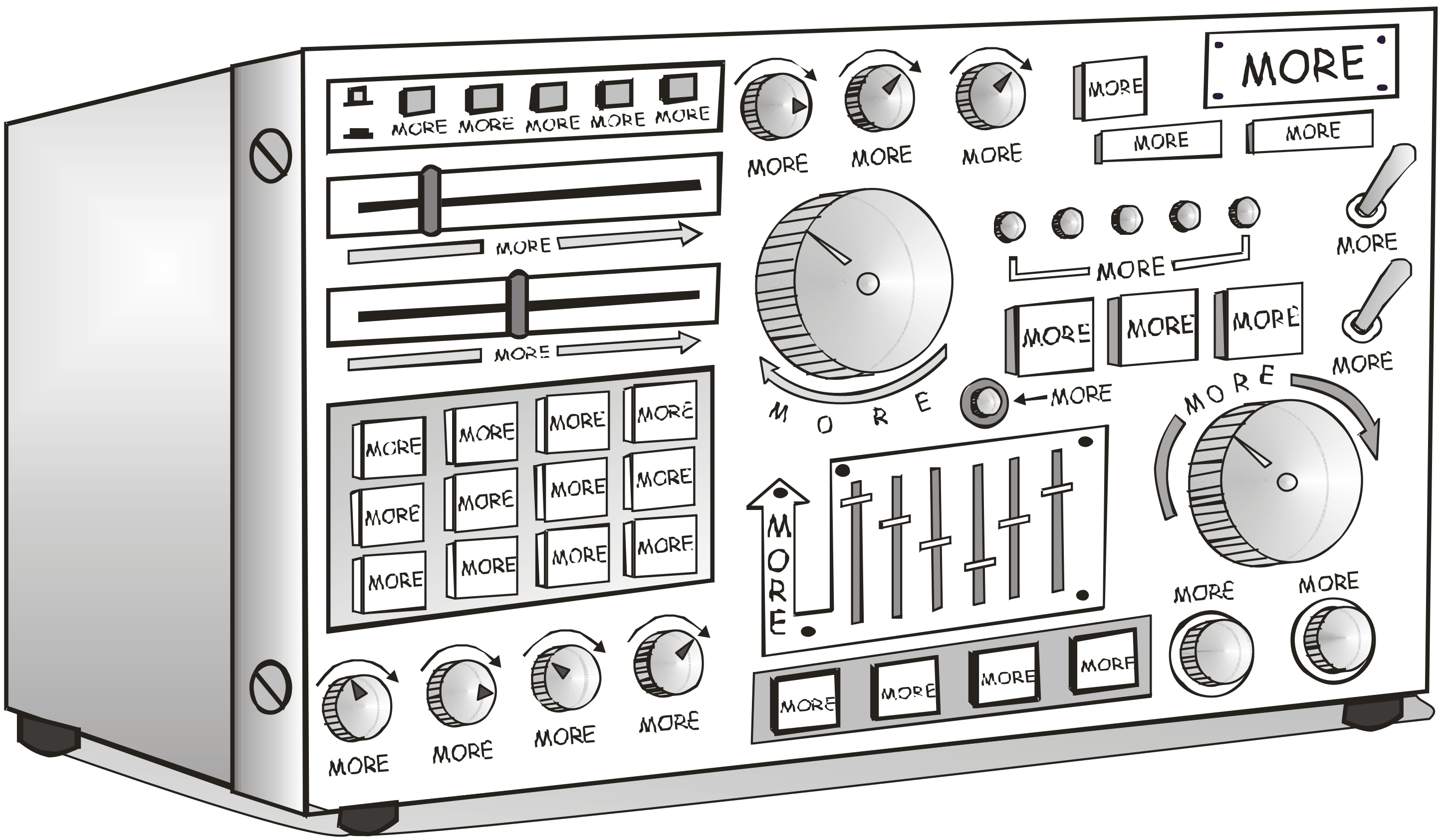
fred harris

SDR`10
Wireless Innovation Conference
and Product Exposition

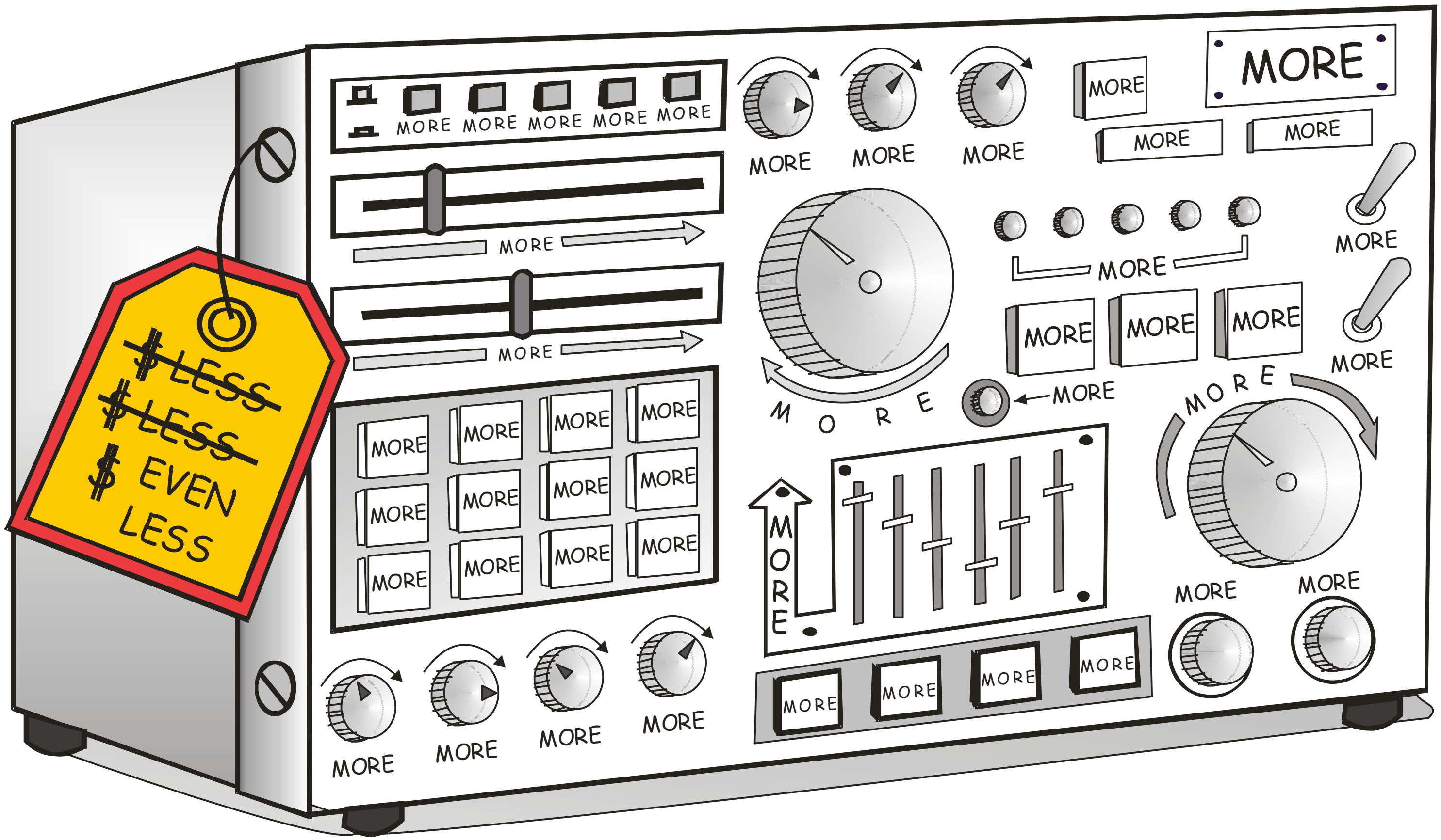
30 November - 3 December 2010

San Diego State University
College of Engineering

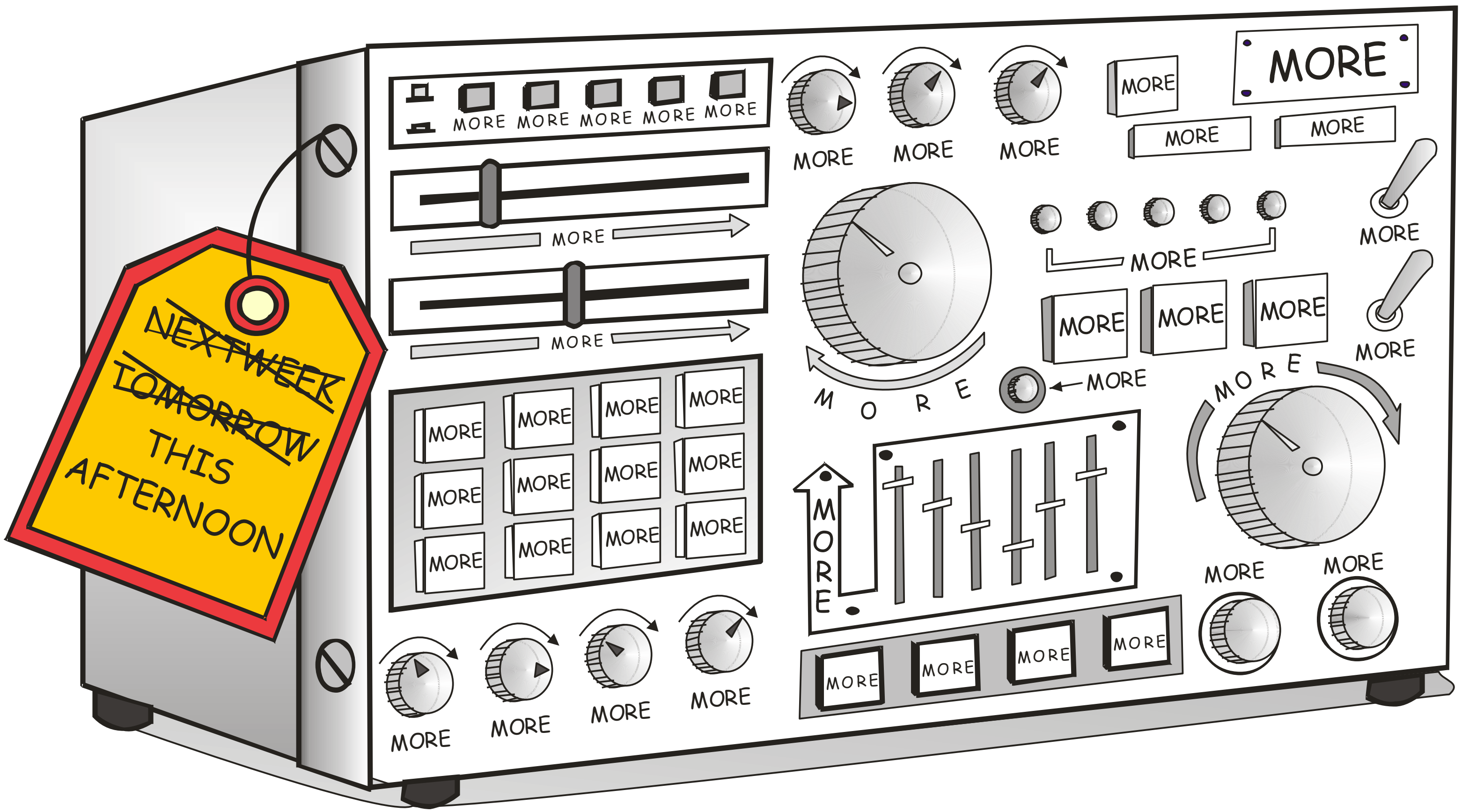
What The Customer Wants



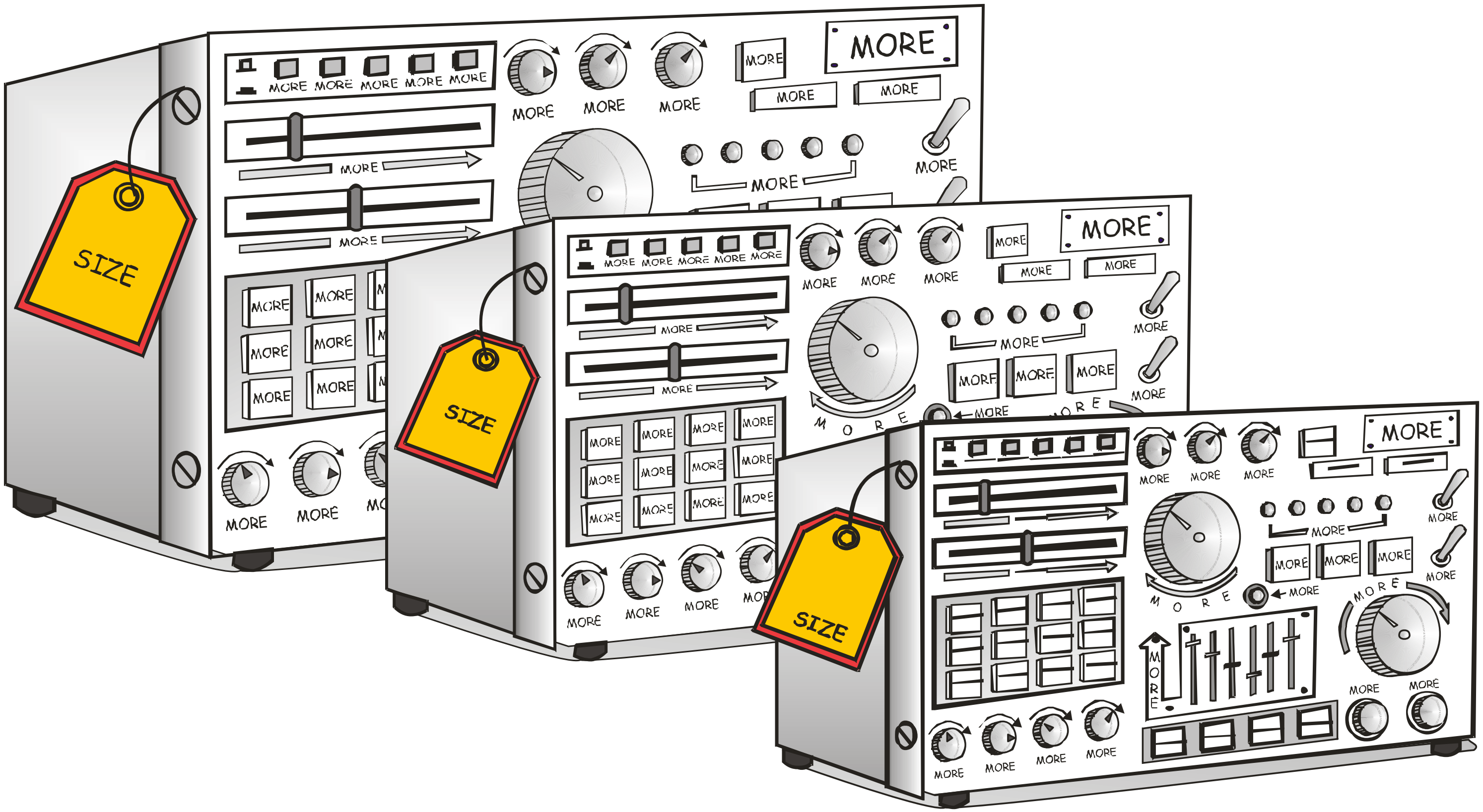
What The Customer Expects to Pay



When The Customer Wants it



What Size Customer Wants



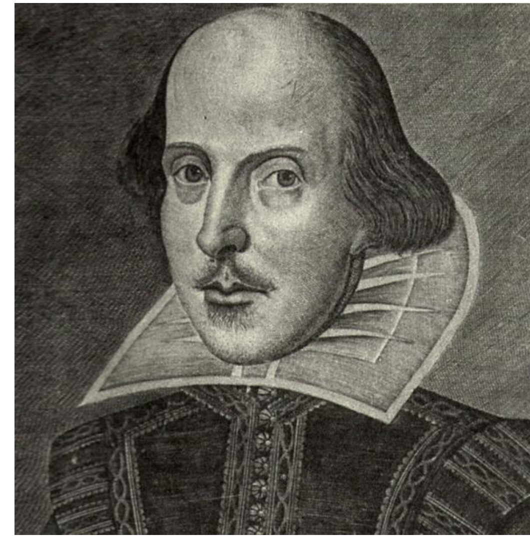
Why Digital Communications?

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

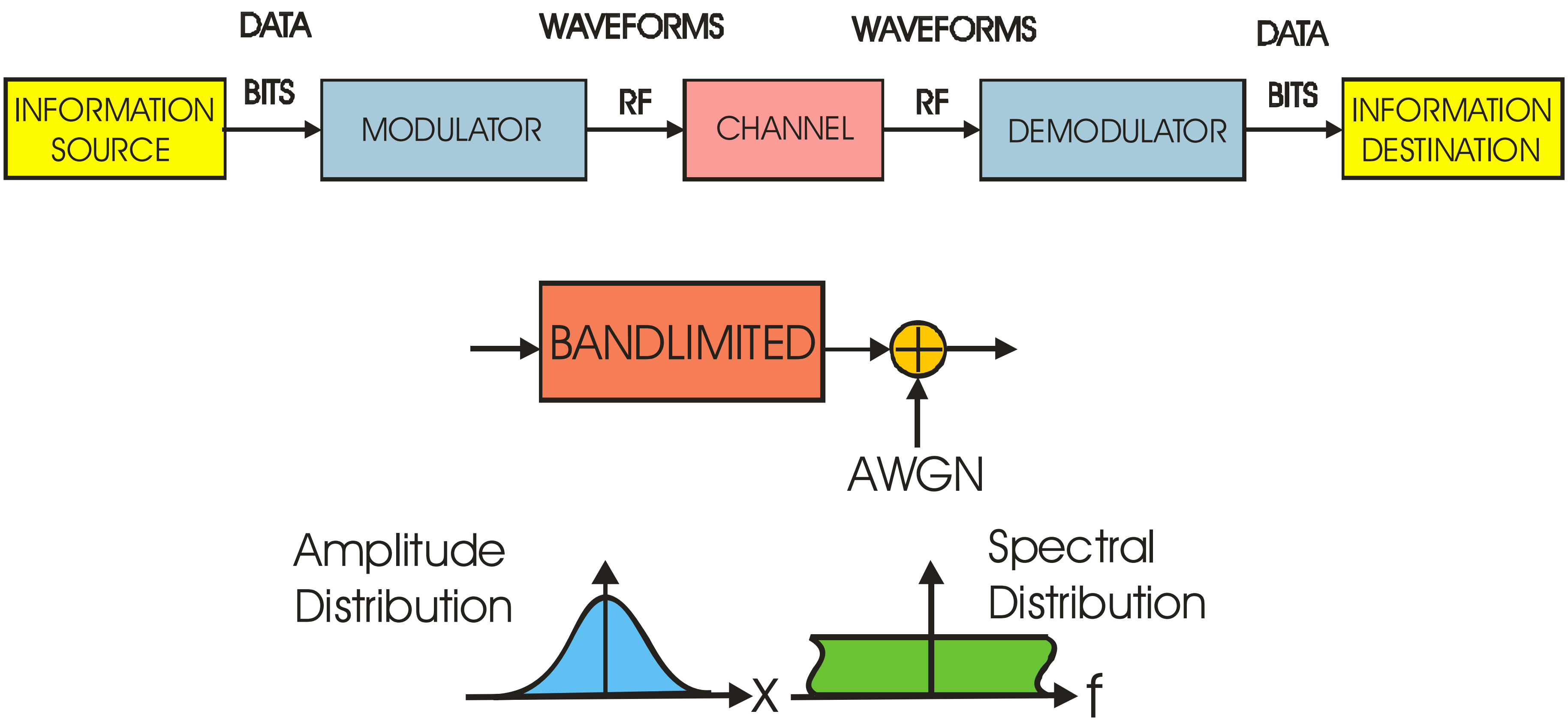


The World is an Analog Stage

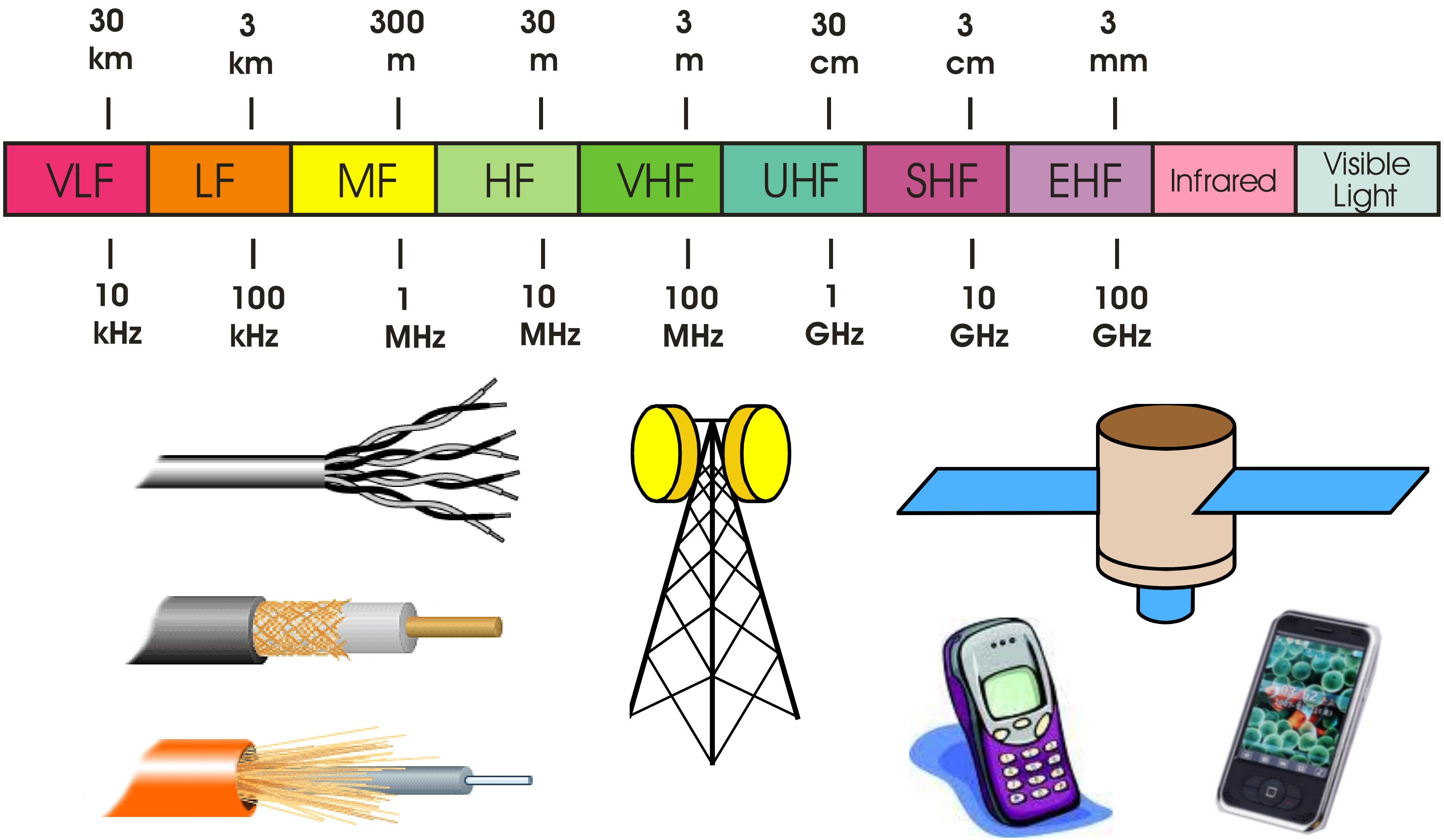
In Which Digital

Plays A Bit Part

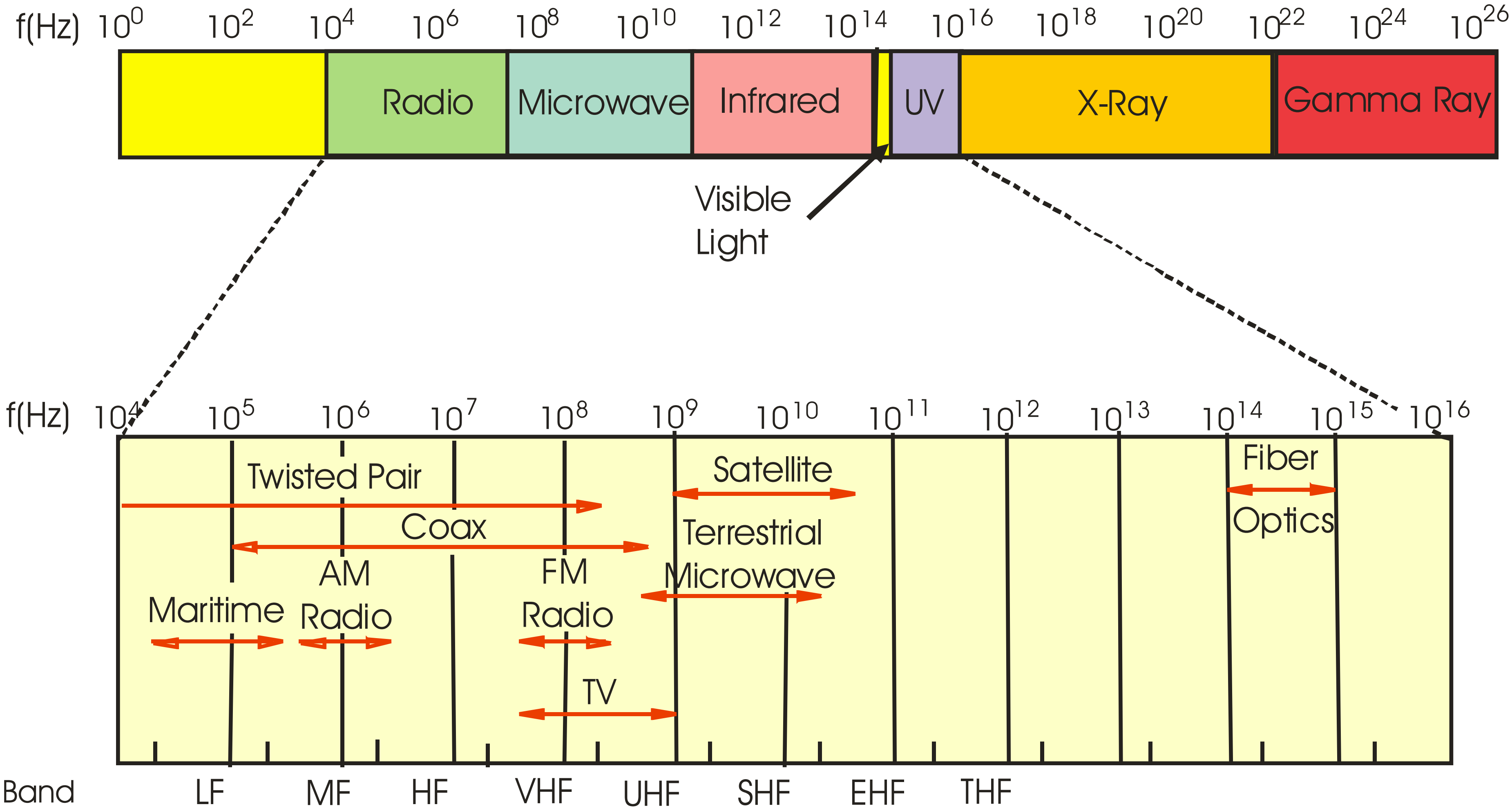
The Basic Communication System



The Radio Channel Frequency Band



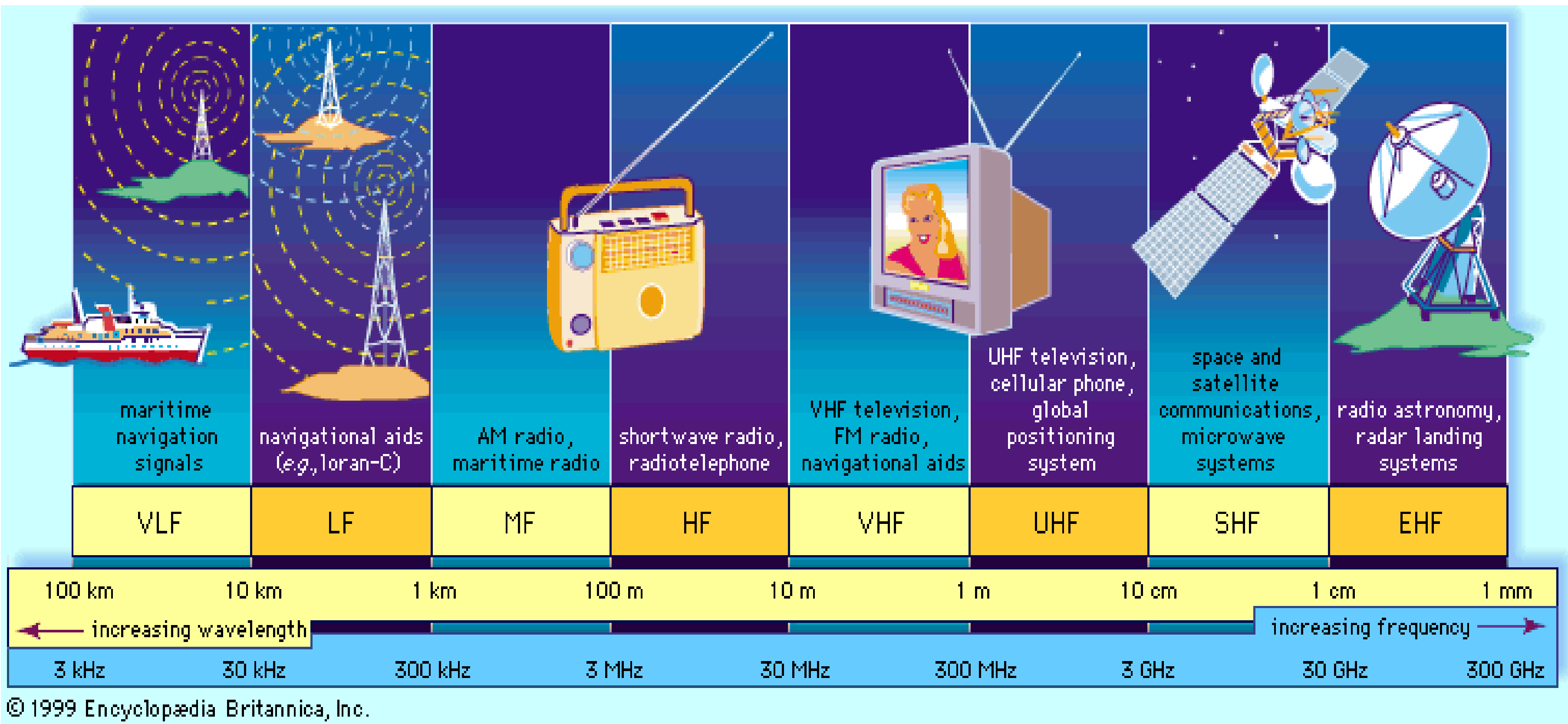
The Electromagnetic Spectrum



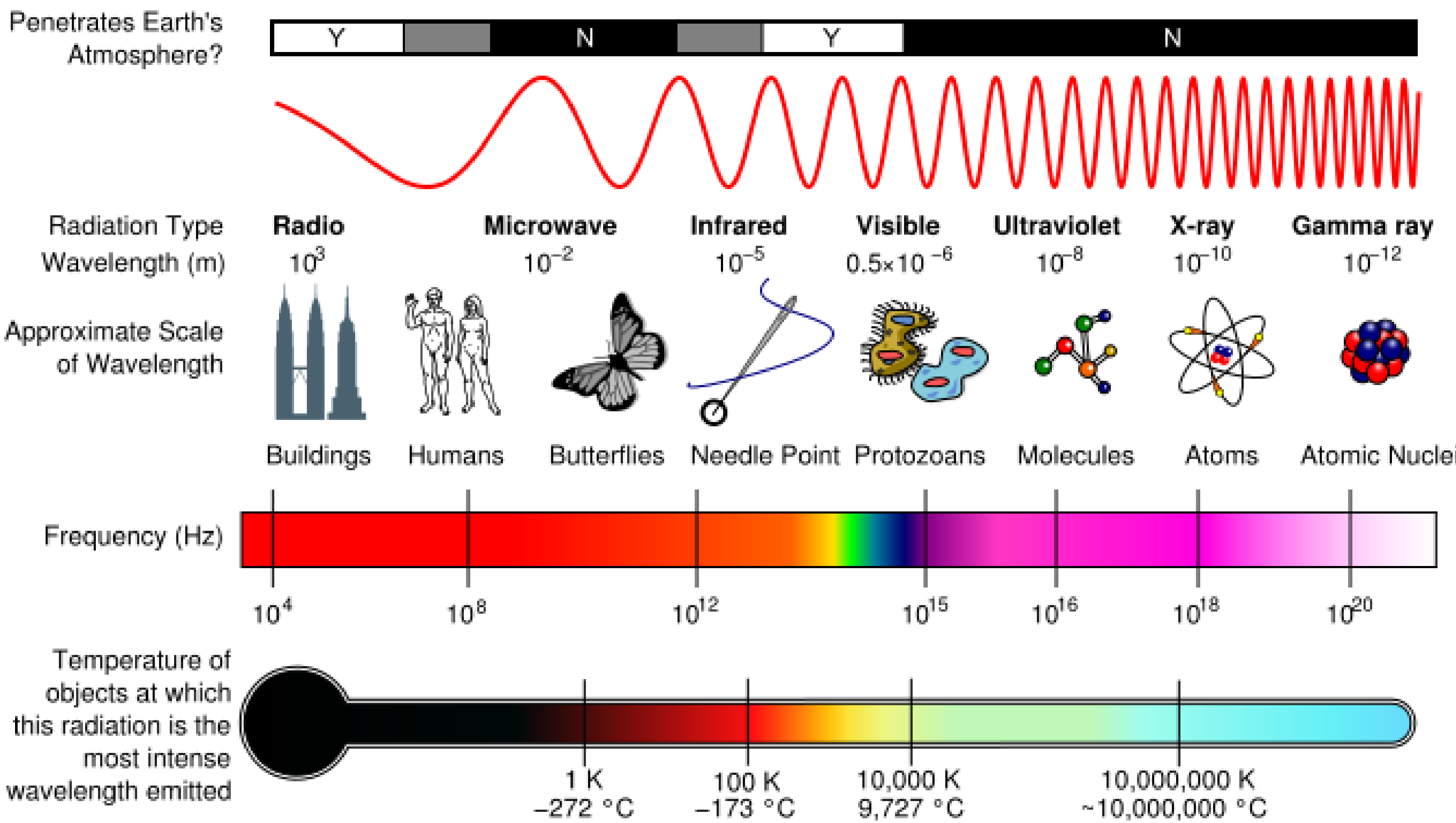
Spectral Utilization

Band	*Frequency*	*Wavelength*	*Some Uses*
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**	**UHF TV, 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**

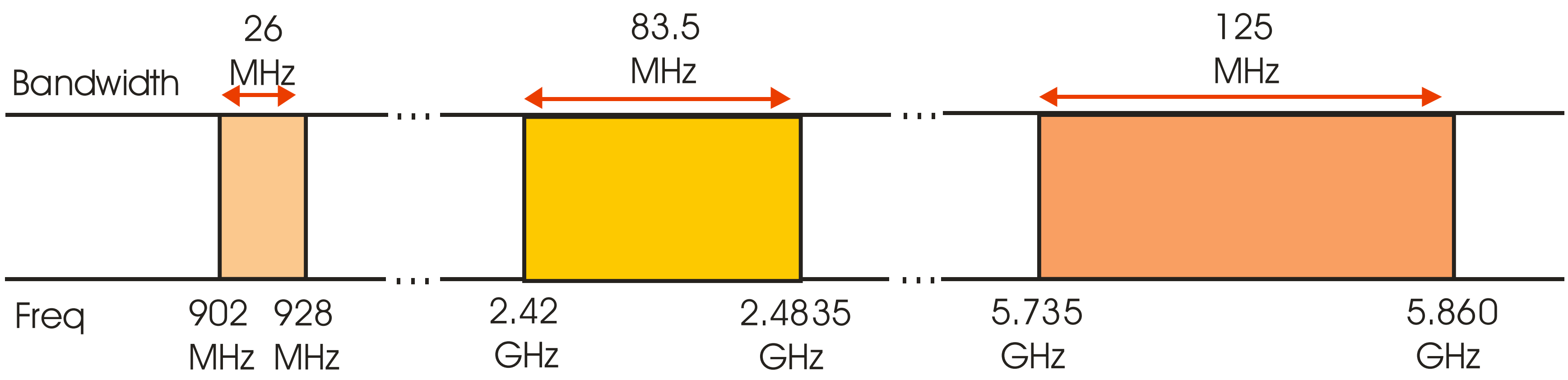
Radio Spectrum



Radio Spectrum Wavelength

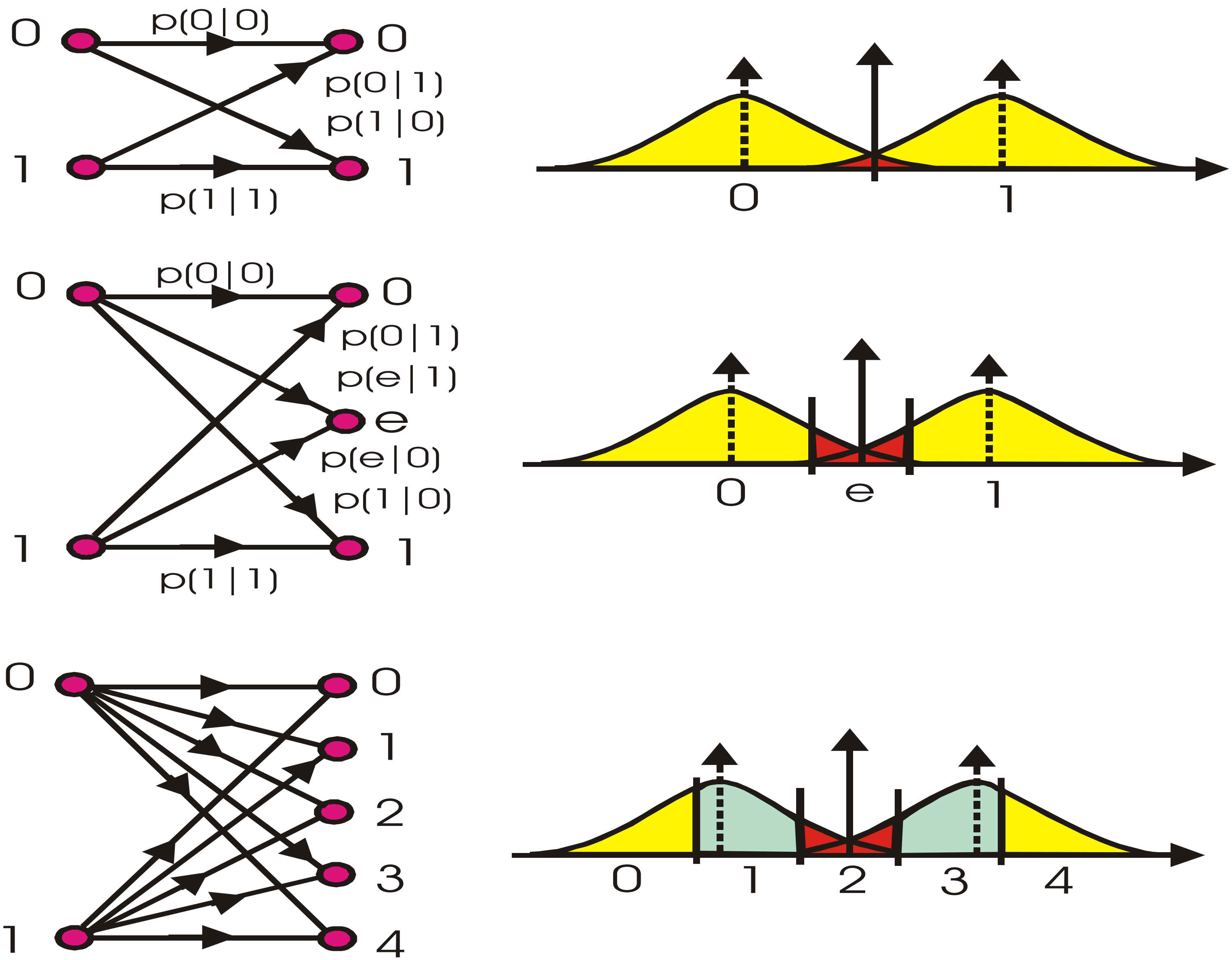


Parts of the Electromagnetic Spectrum

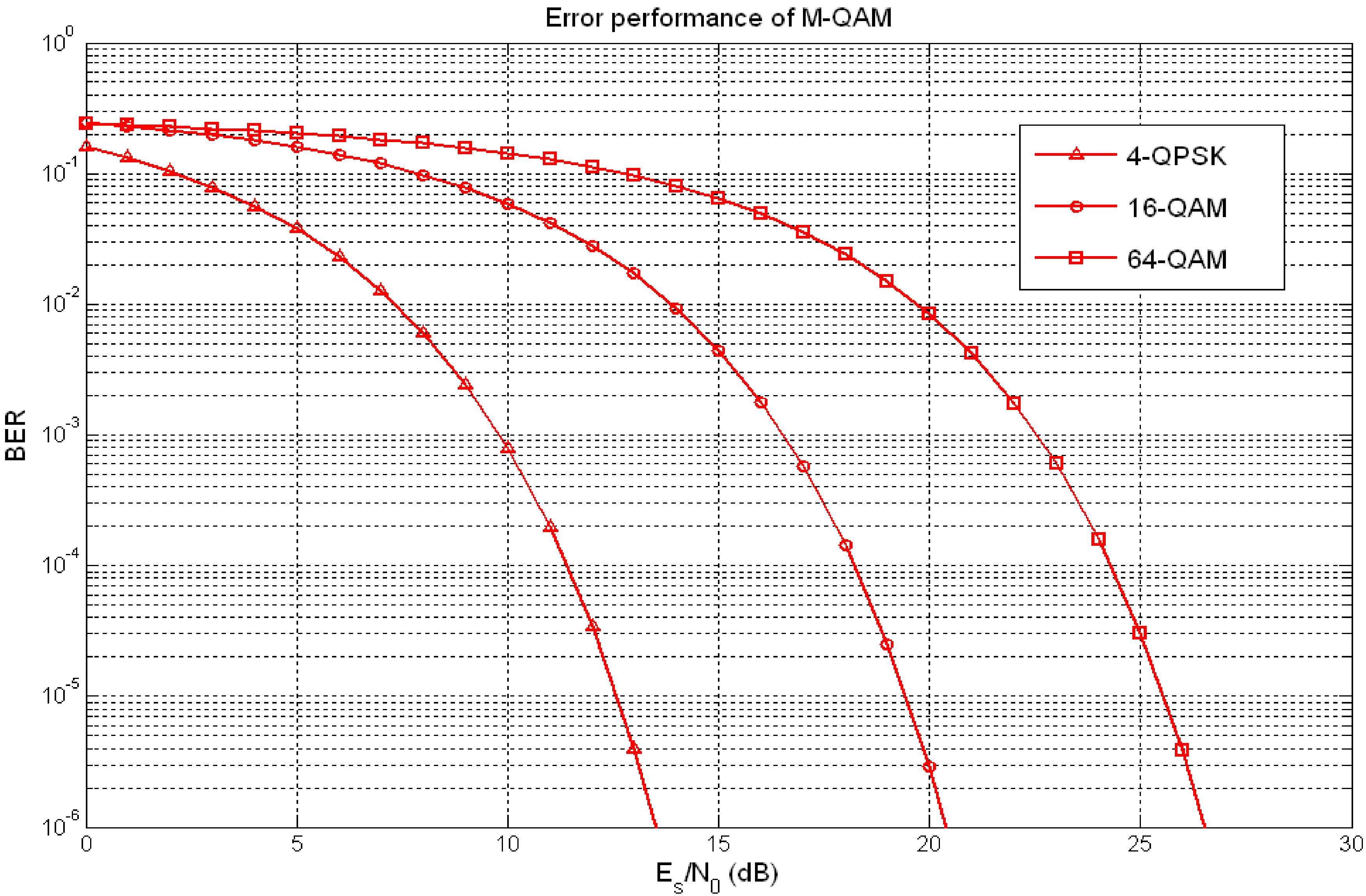


The ISM bands in the United States.

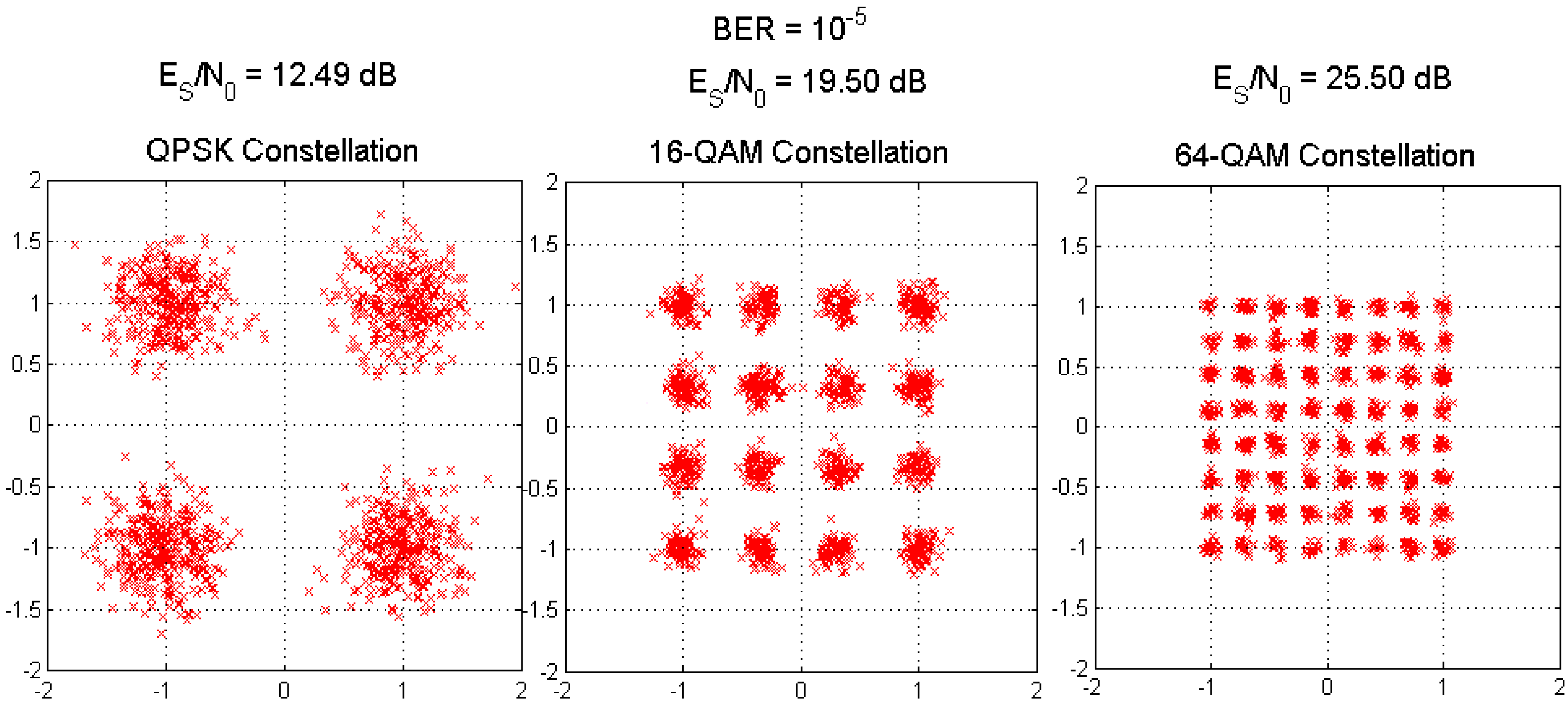
Cross-Over Probabilities



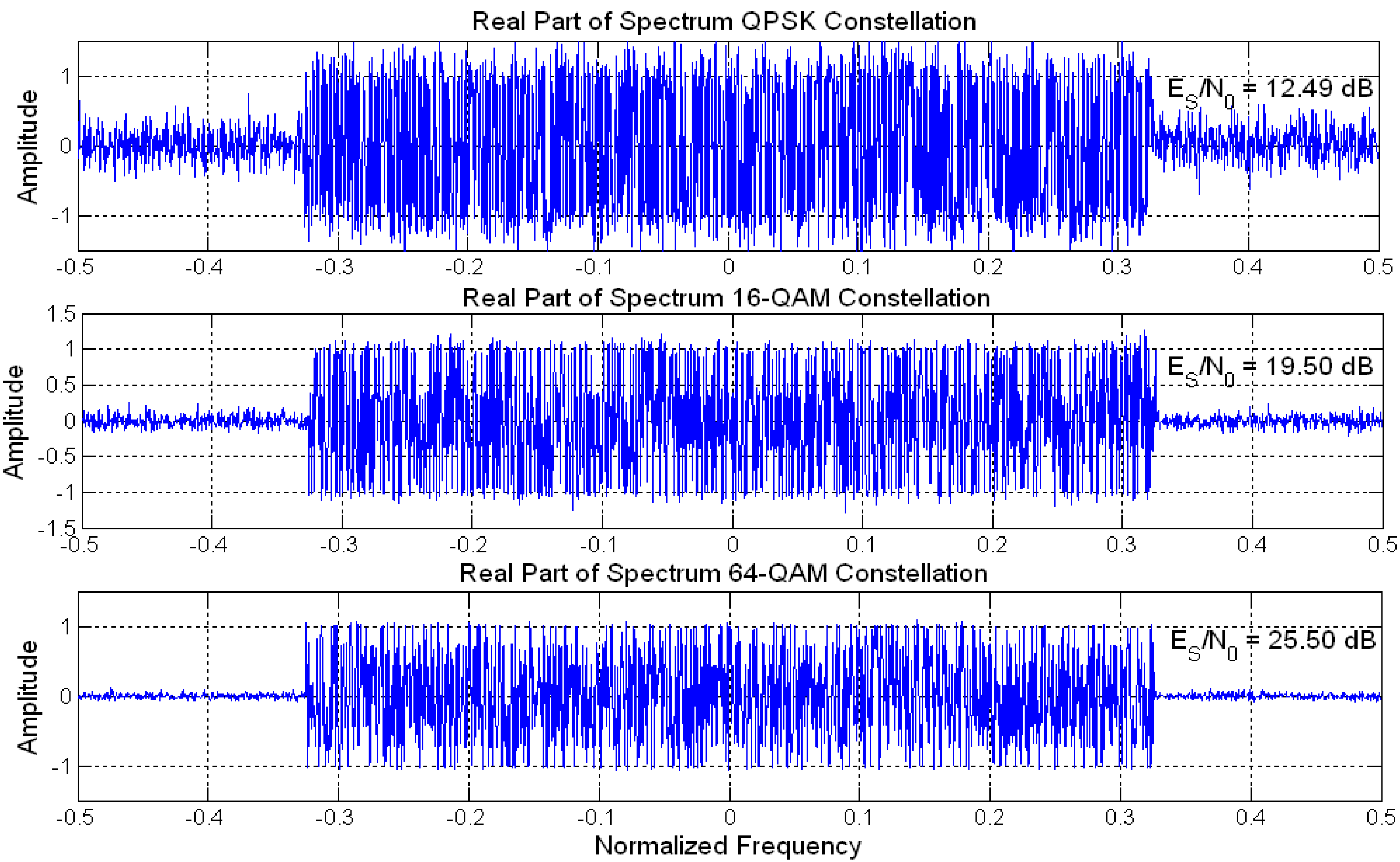
E_S/N_0 Required for Specified BER



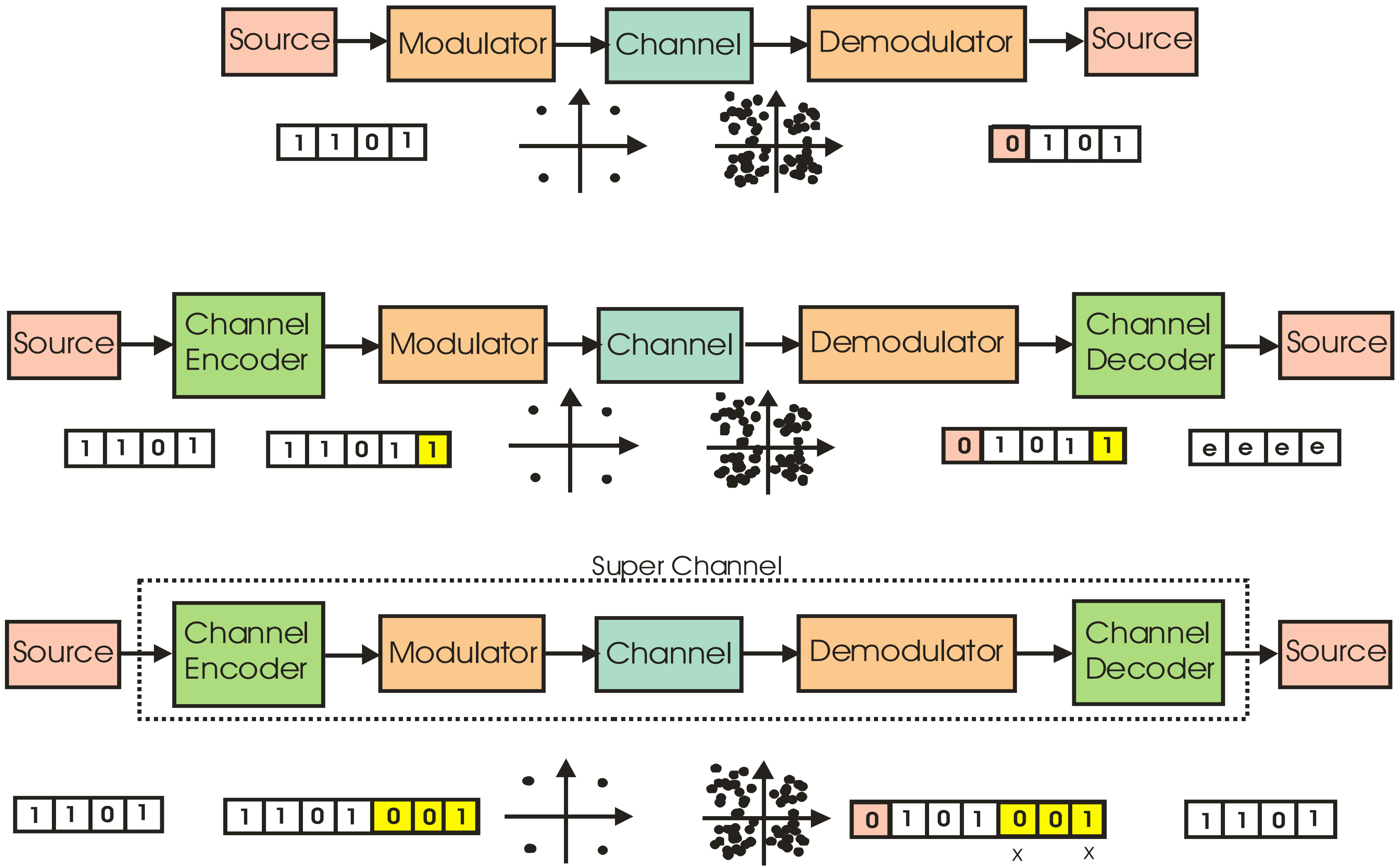
QPSK, 16-QAM, & 64-QAM Constellations for 10^{-5} BER



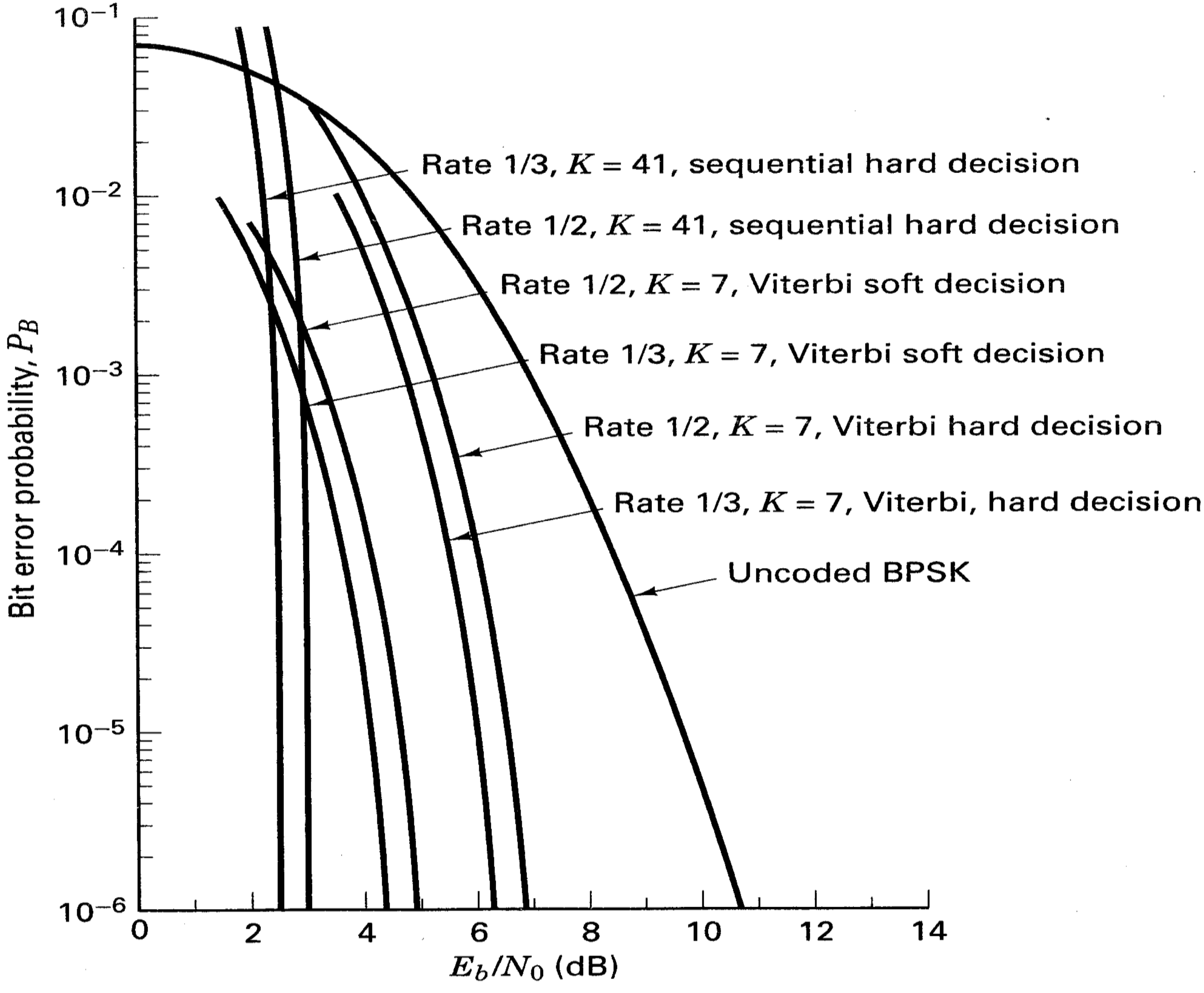
Spectral Levels of Signal and Noise for QPSK, 16-QAM, & 64-QAM for 10^{-5} BER



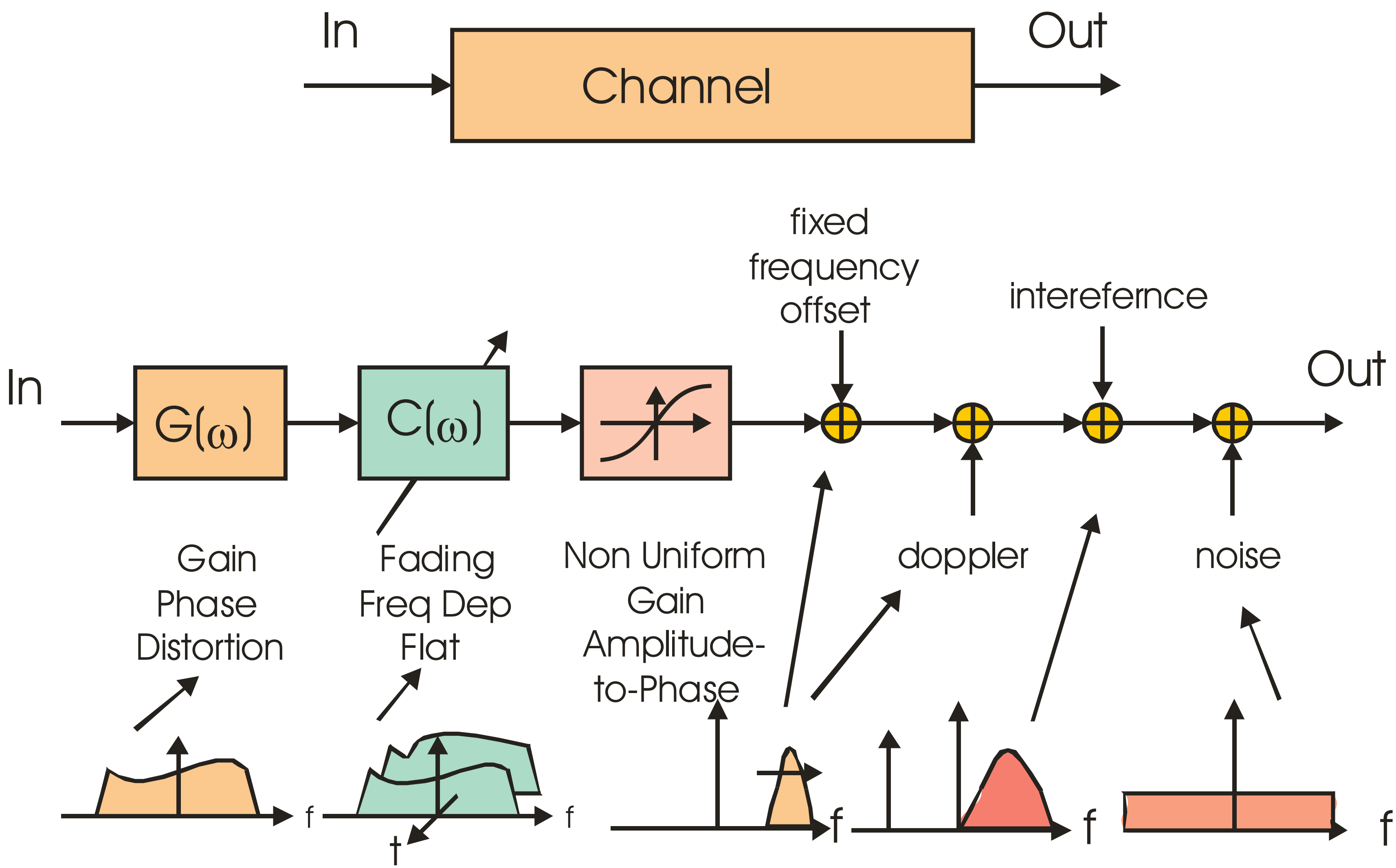
Channel Coding:
Add Structured Redundancy



Bit Error Performance Waterfall



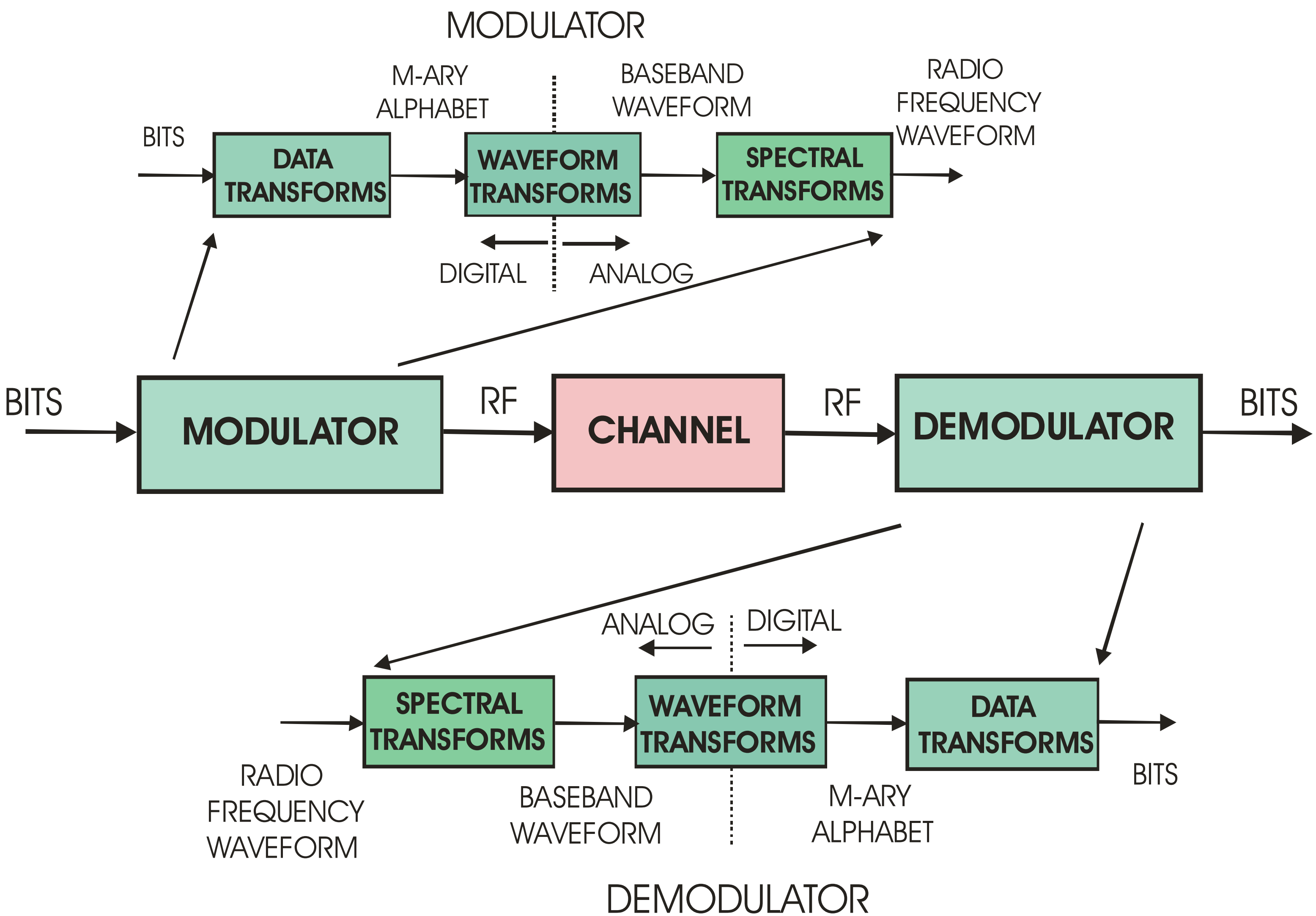
Other Channel Impairments



Modern Physical Layer Modem Recipe:
Add these Ingredients, Stir, Bake for 20 Minutes at 300º.
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



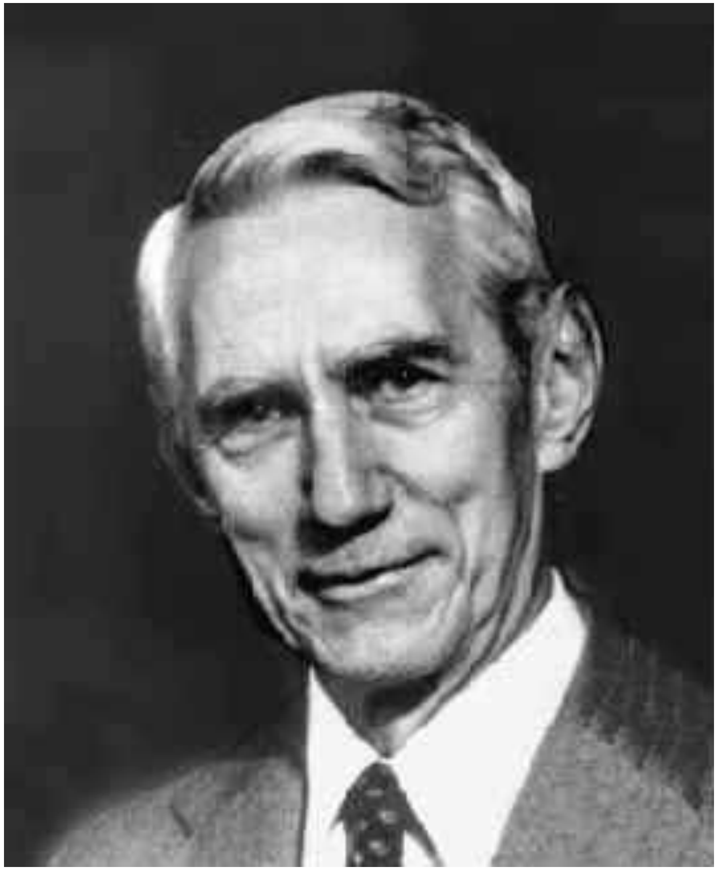
Claude Shannon

Information is measurable.

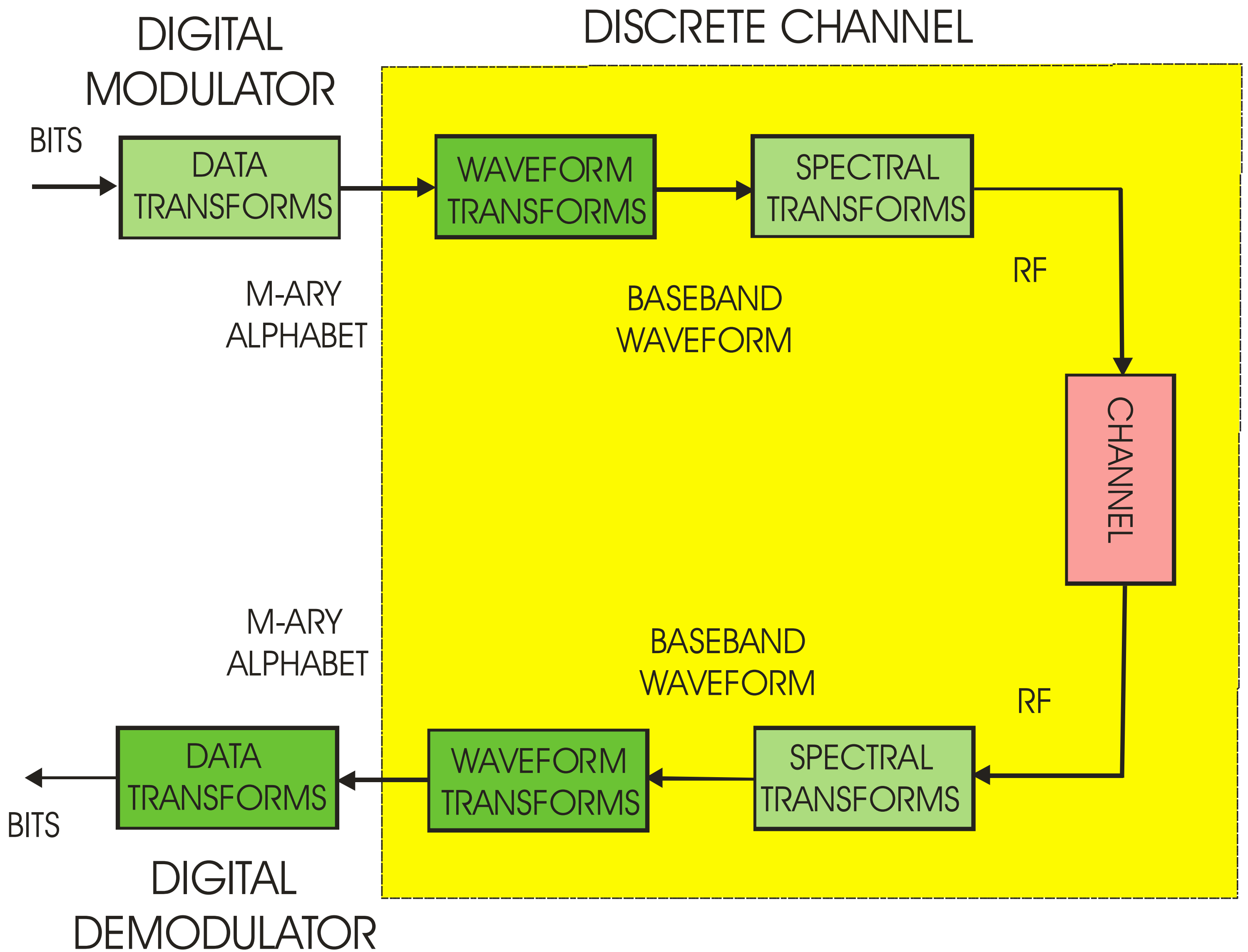
Noise Does not Limit Fidelity.

'The world has only 10
kinds of people.

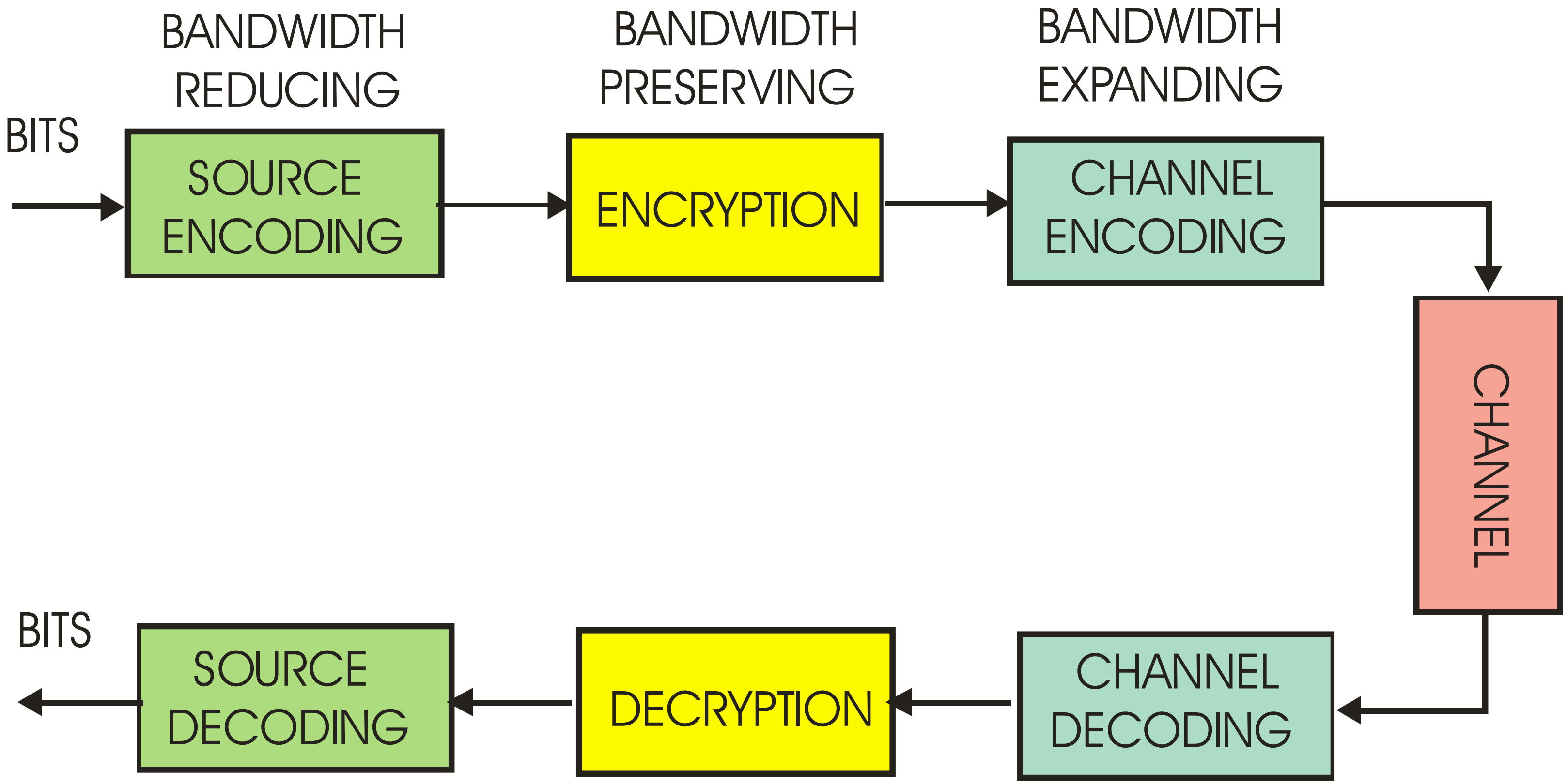
Those who get binary,
and those who don't.'



Shannon's Communication System



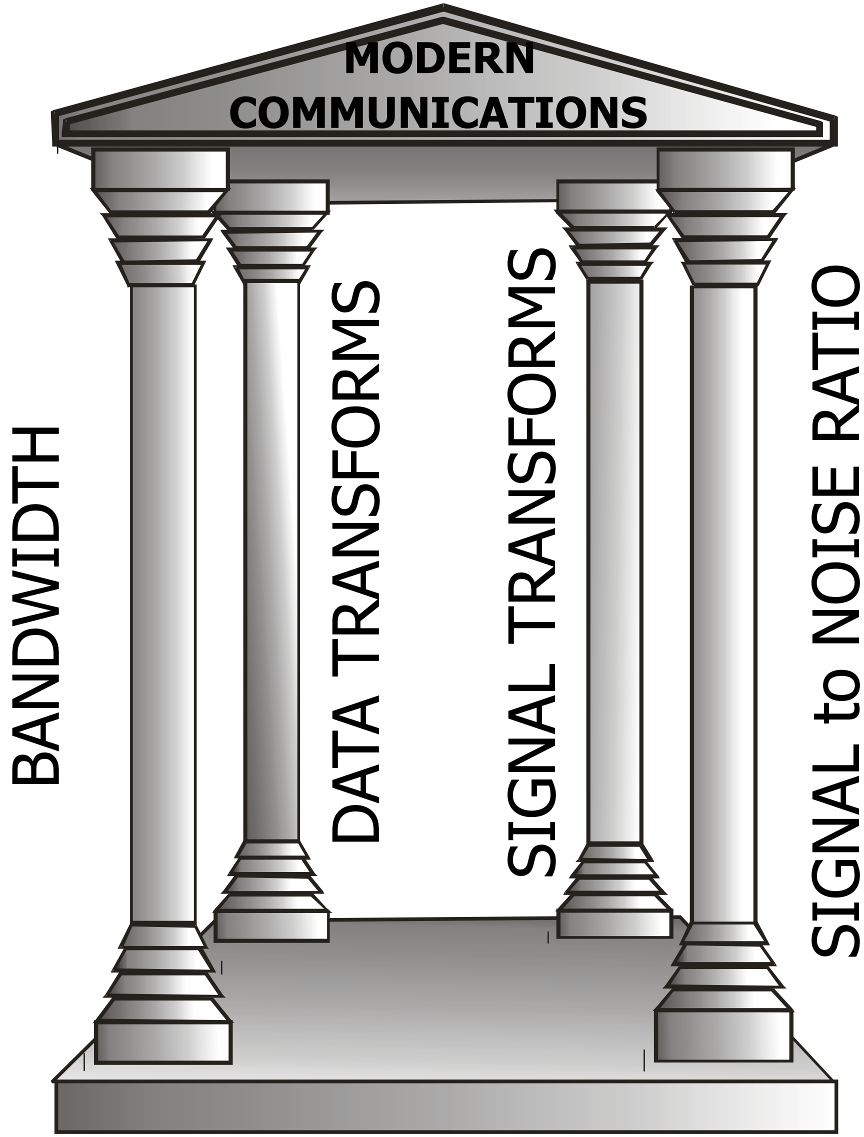
Shannon’s Model



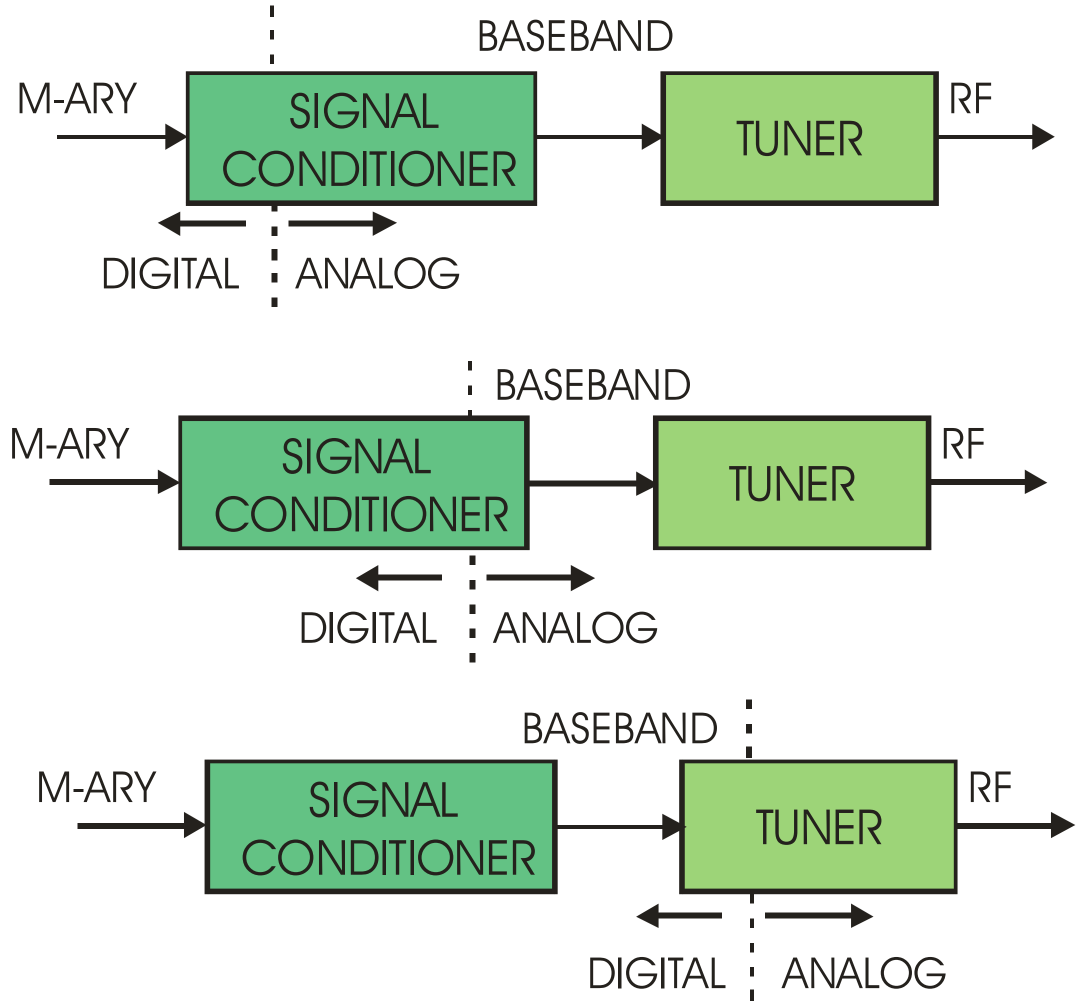
Shannon's Legacy

- ❖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!

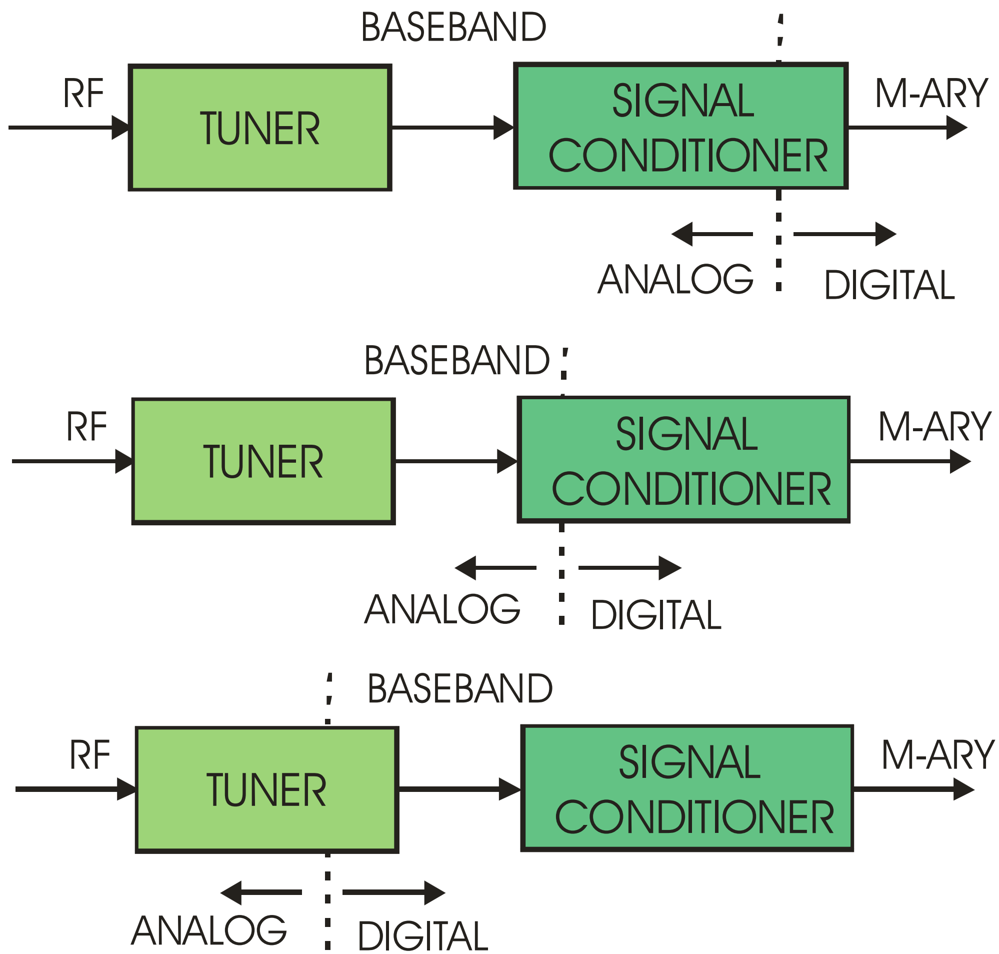
Four Pillars of Modern Communications



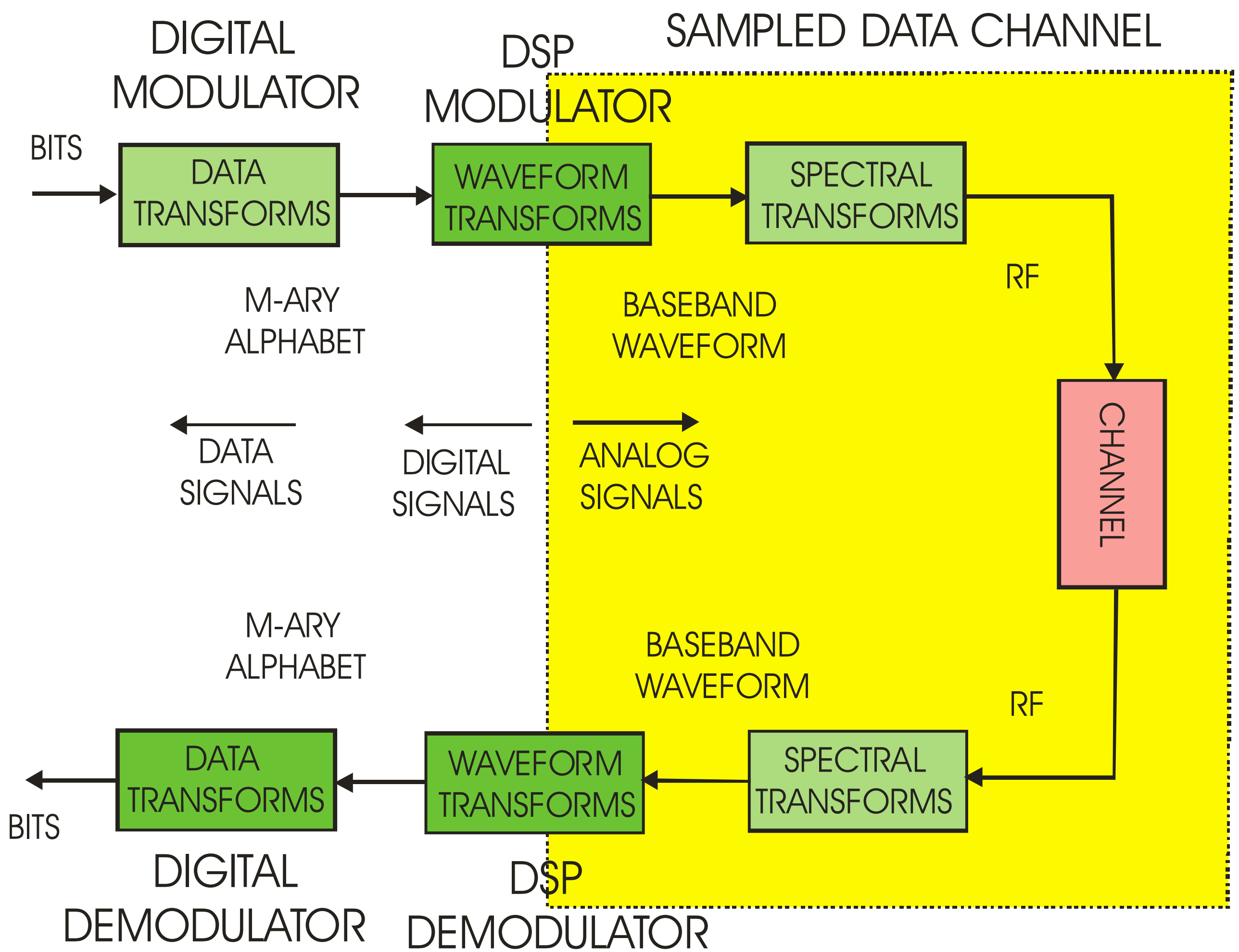
The Modulator Digital to Analog Interface Moves Towards the RF



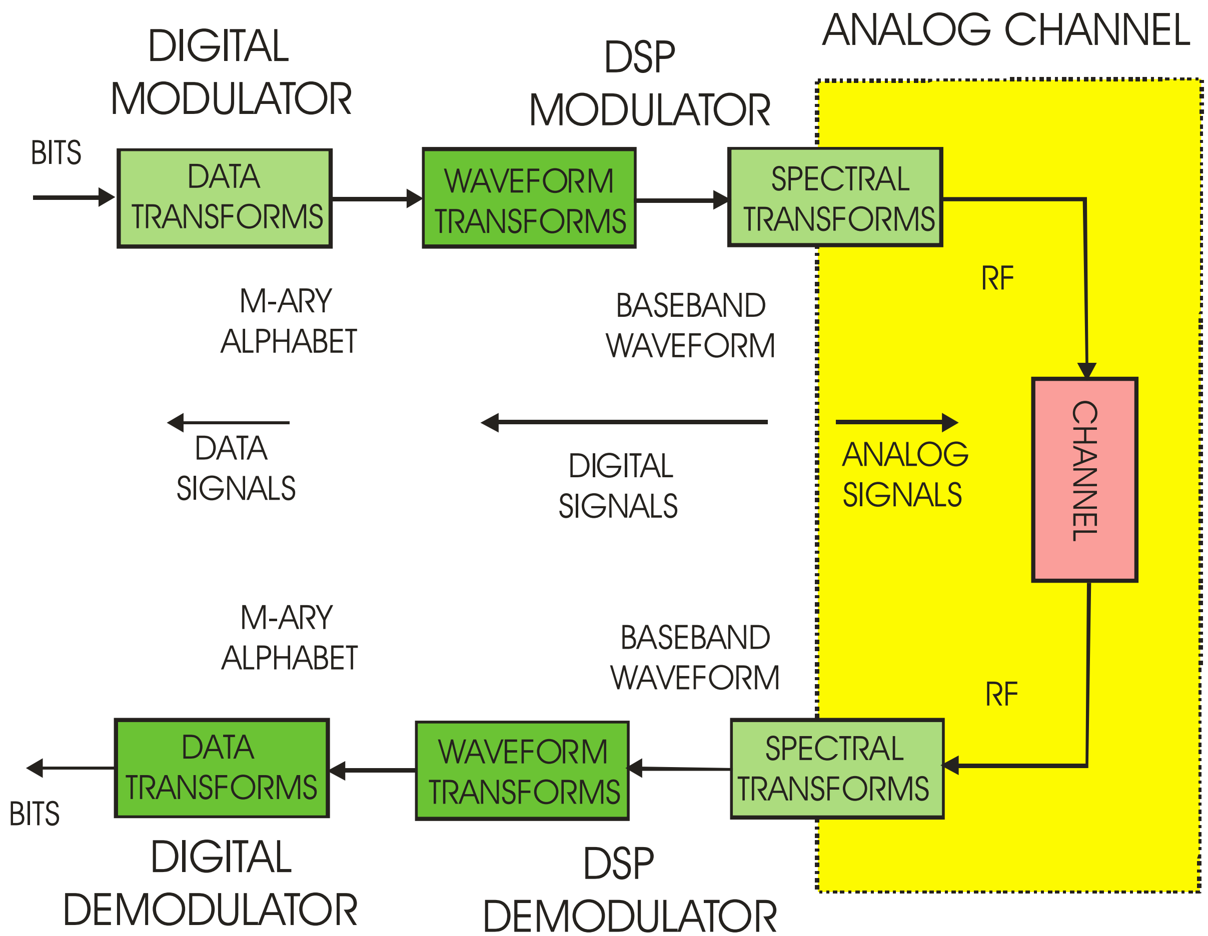
The Demodulator Analog to Digital Interface Moves Towards the RF



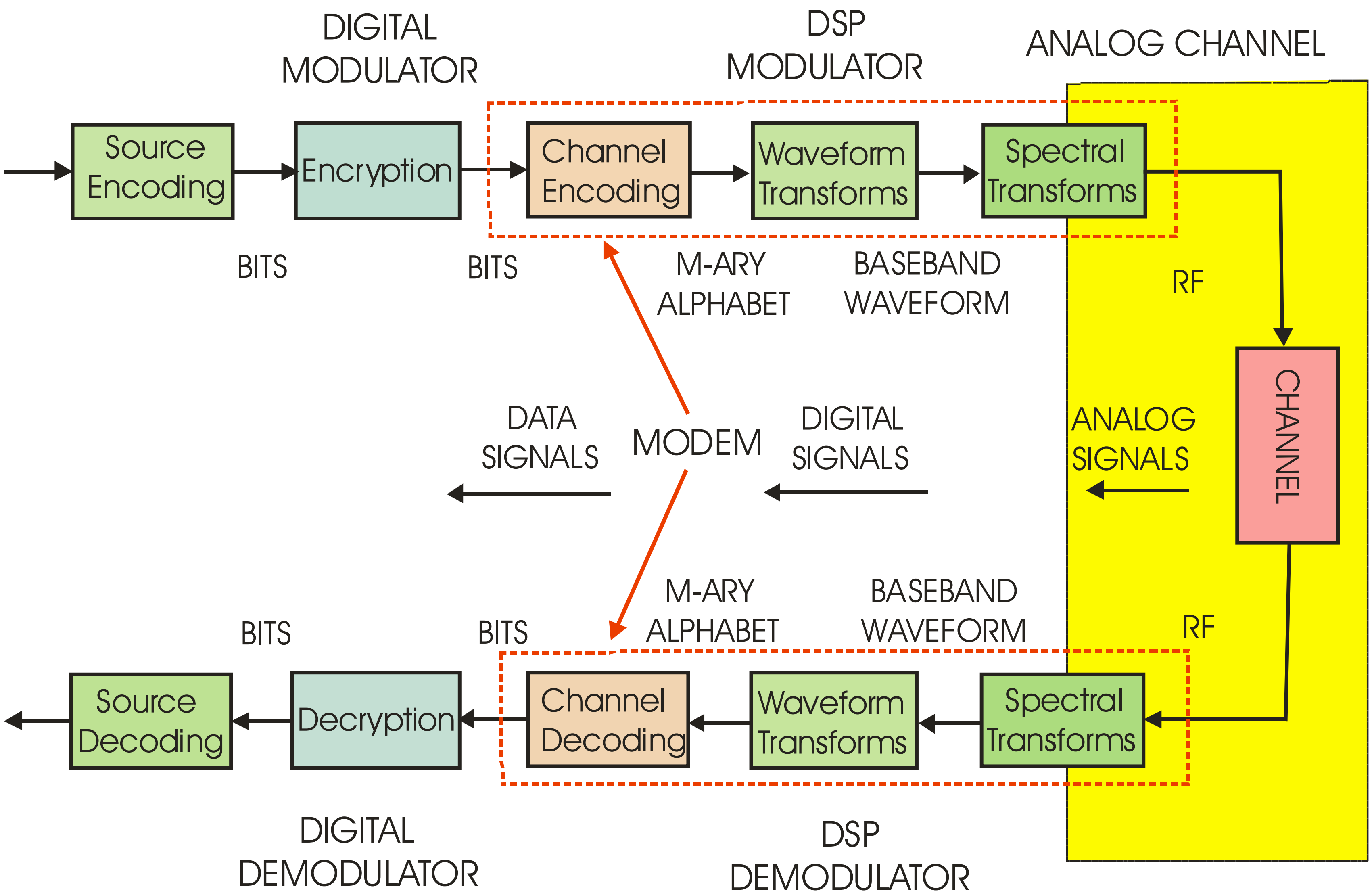
SECOND GENERATION DSP CENTRIC MODEL



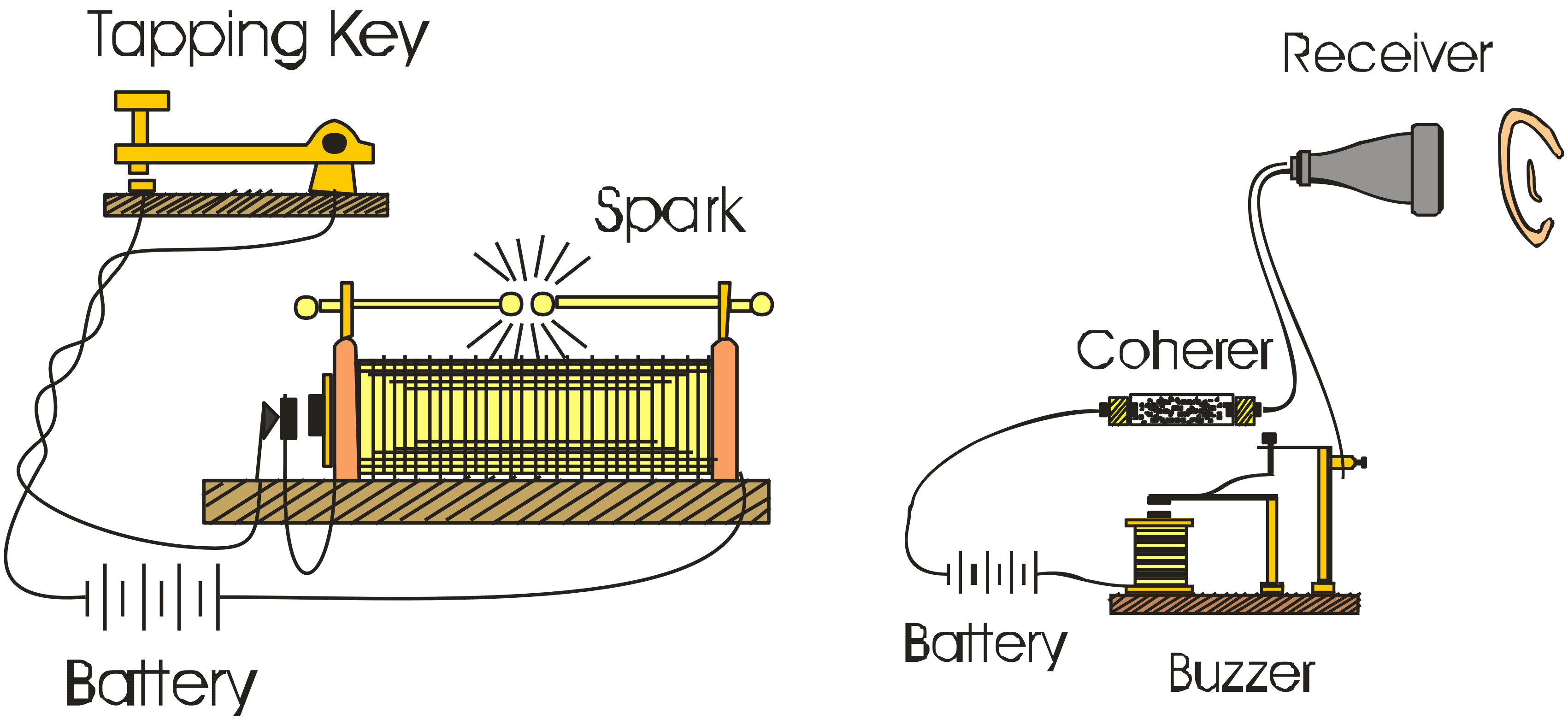
THIRD GENERATION DSP CENTRIC MODEL



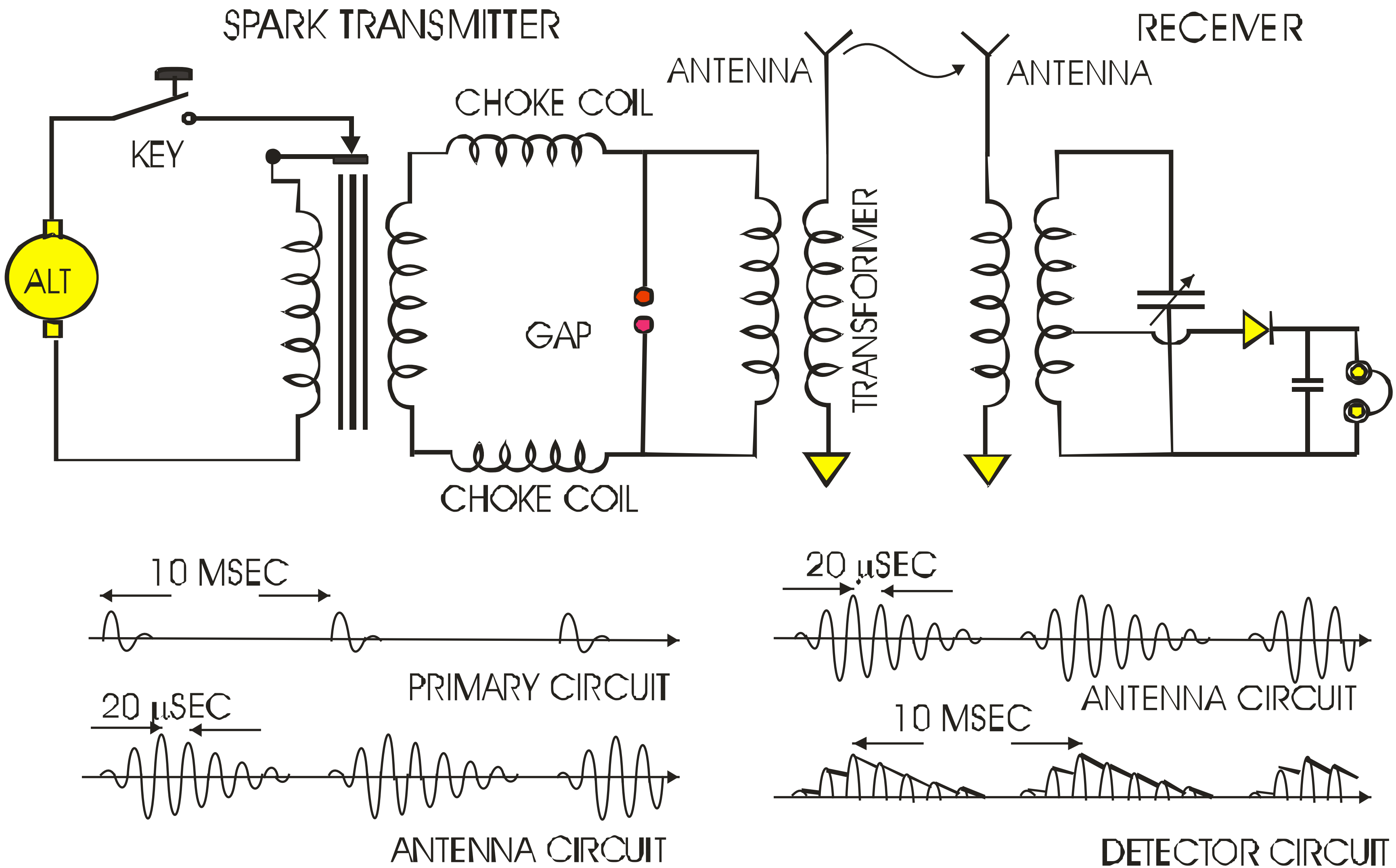
Modem: Bits In - RF Out, RF In - Bits Out



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

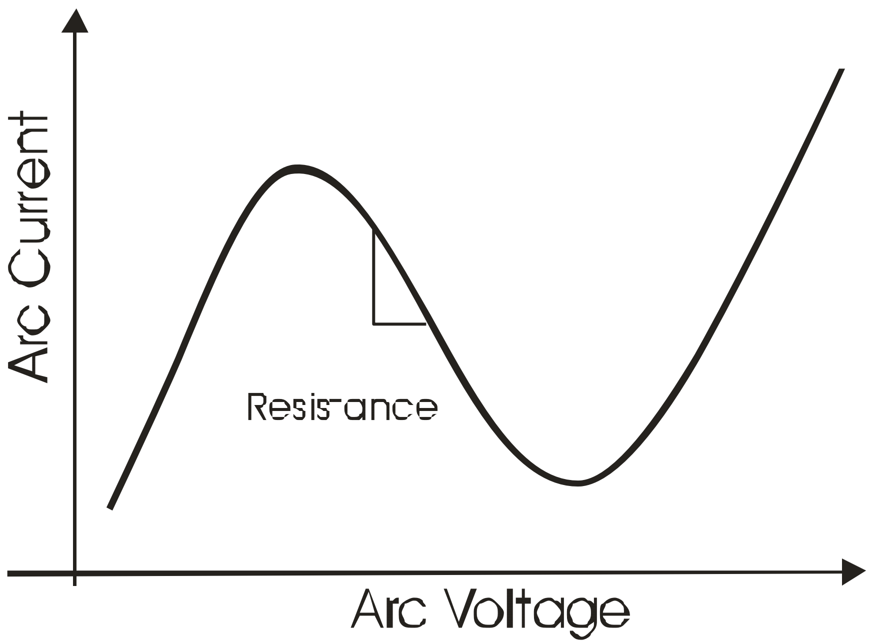


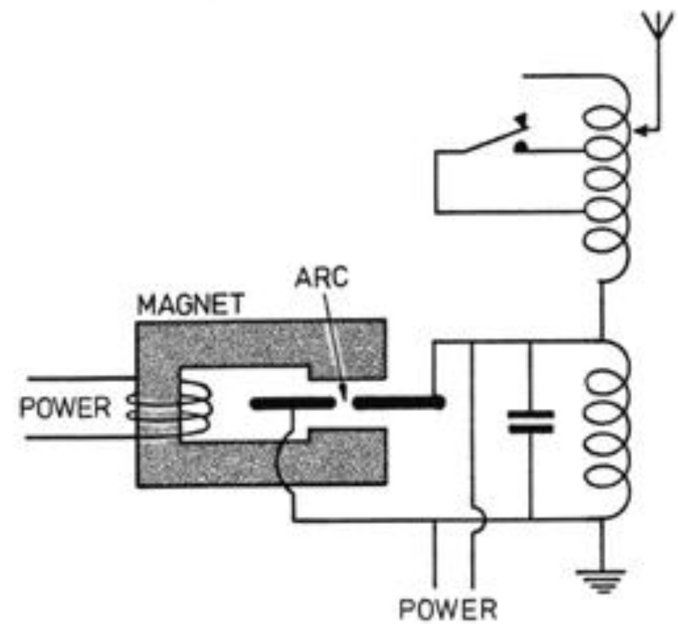
Spark Transmitter: Damped Oscillations



Arc Transmitter: Continuous Oscillation

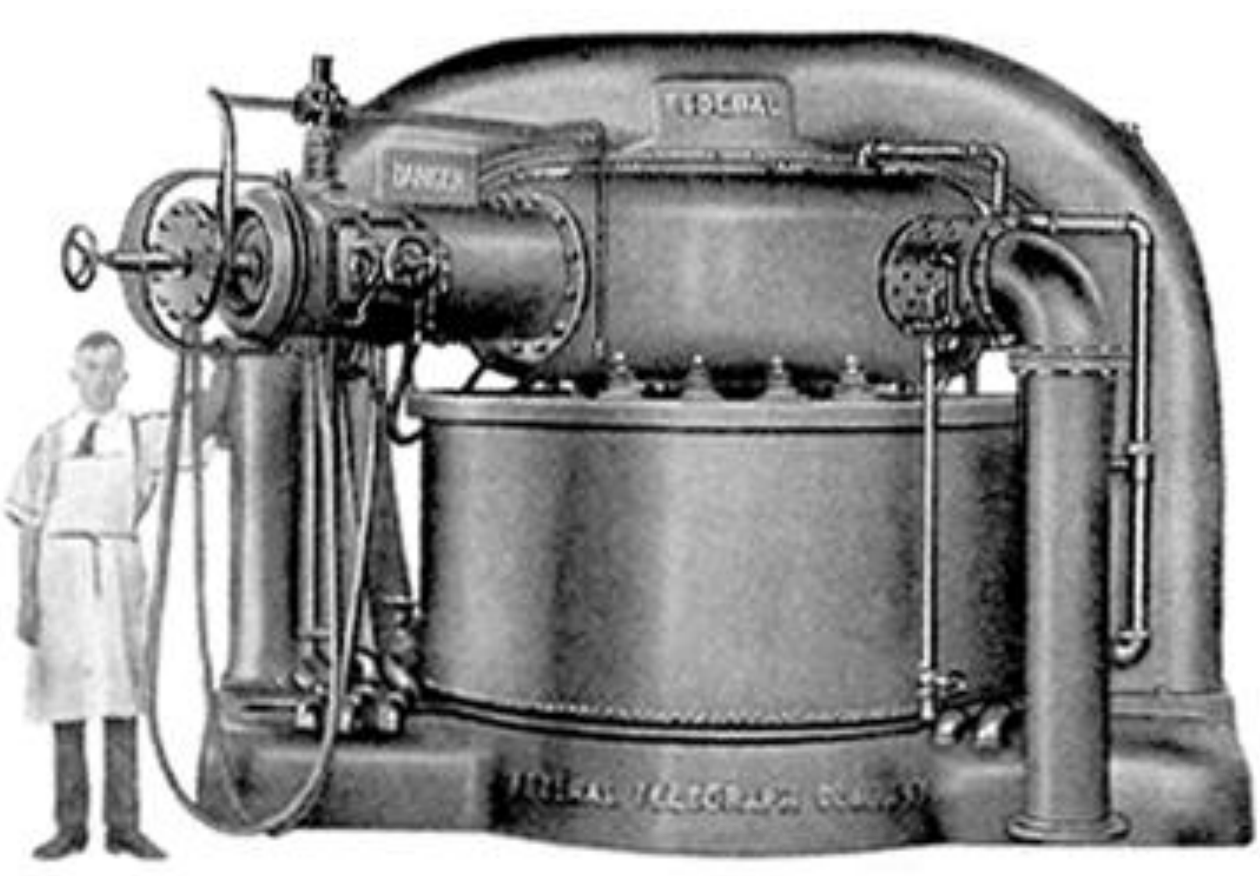
Replace Sparks with an Arc
Negative Resistance Injects Energy
As Opposed to Dissipates Energy



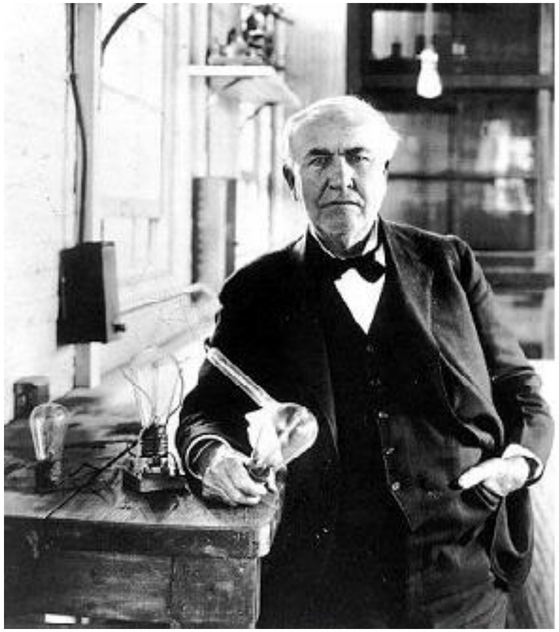


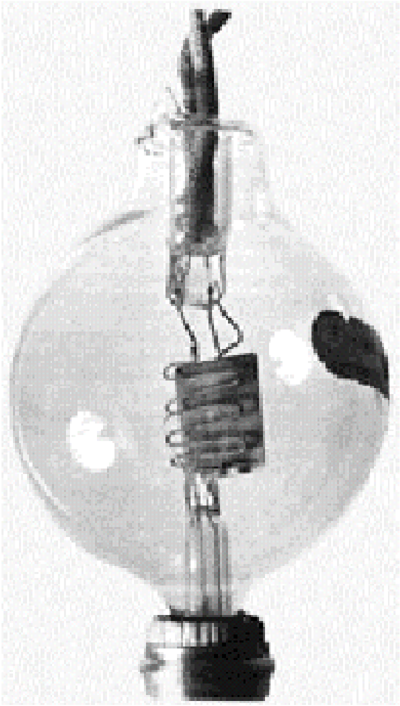
Valdemar Poulsen, 1869-1942

Poulsen 100 KW Arc Transmitter

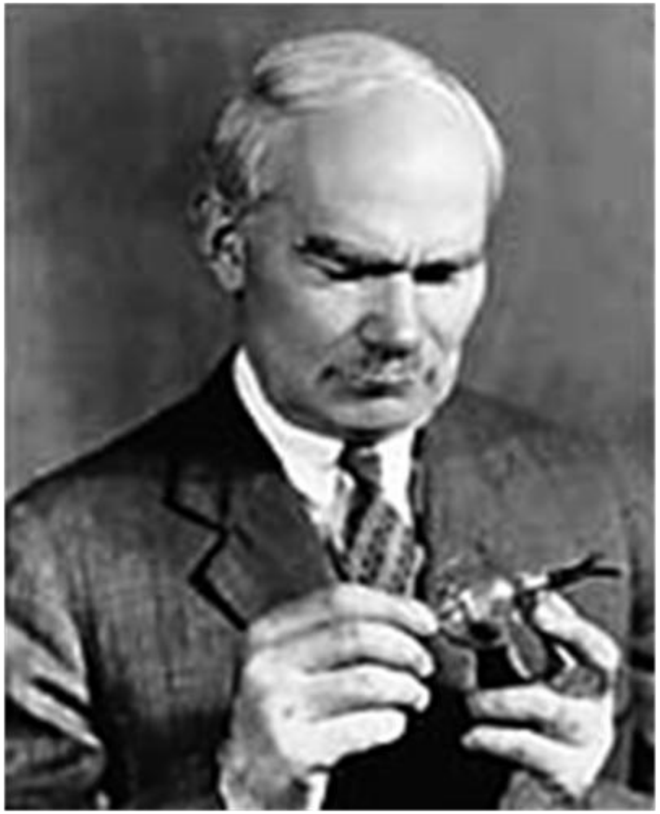


The path to the Triode Thermonic Valve, Thomas Edison, John Fleming, Lee de Forest





Lee De Forest, 1877-1961



Patent No. 879532

Put those sparks to rest!

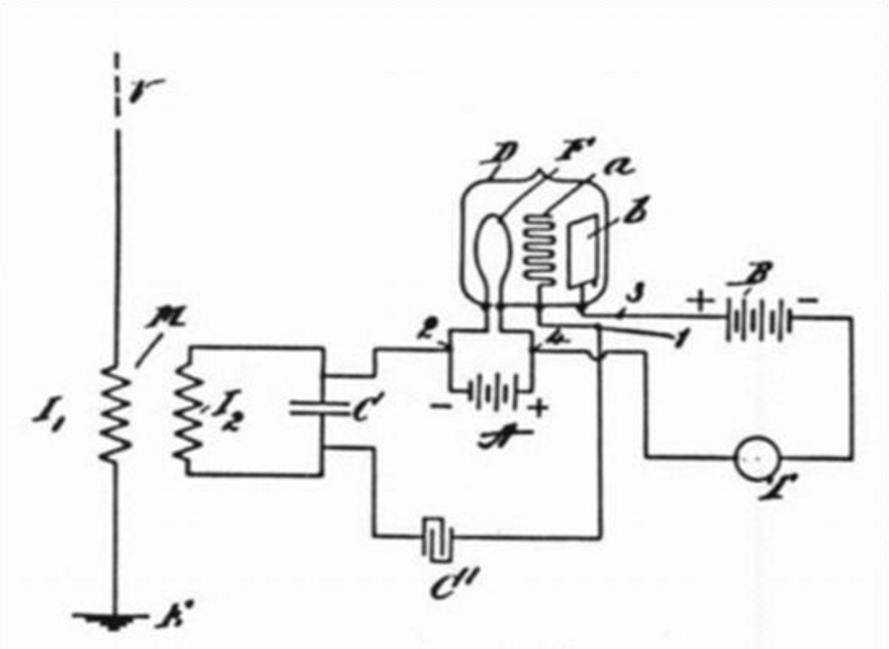
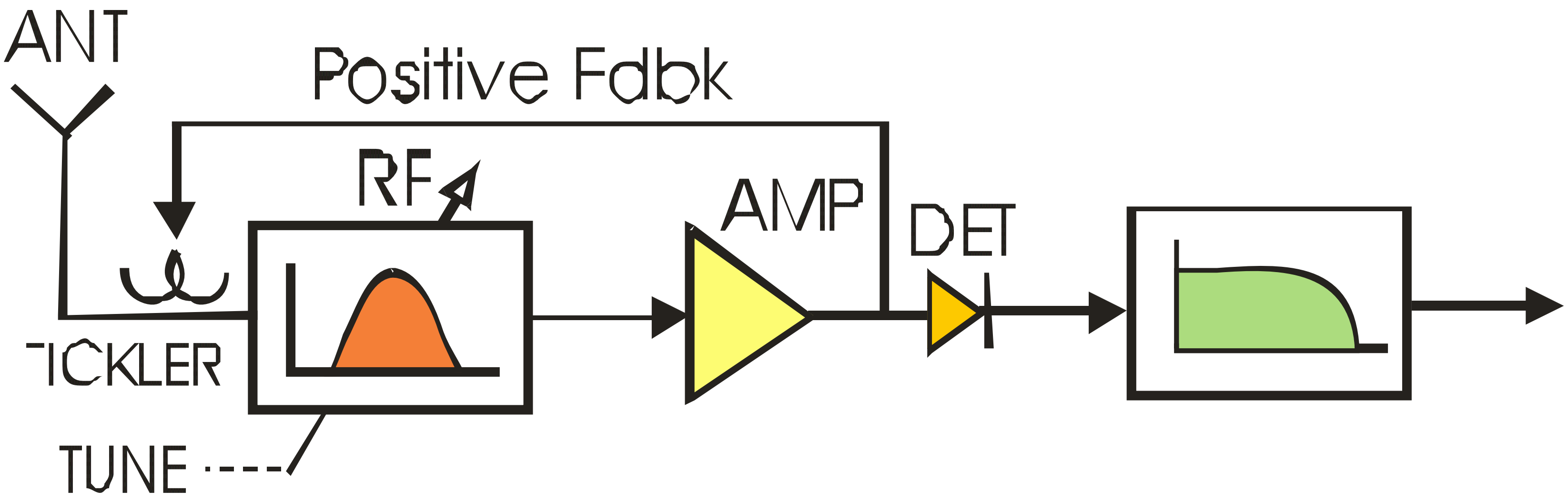
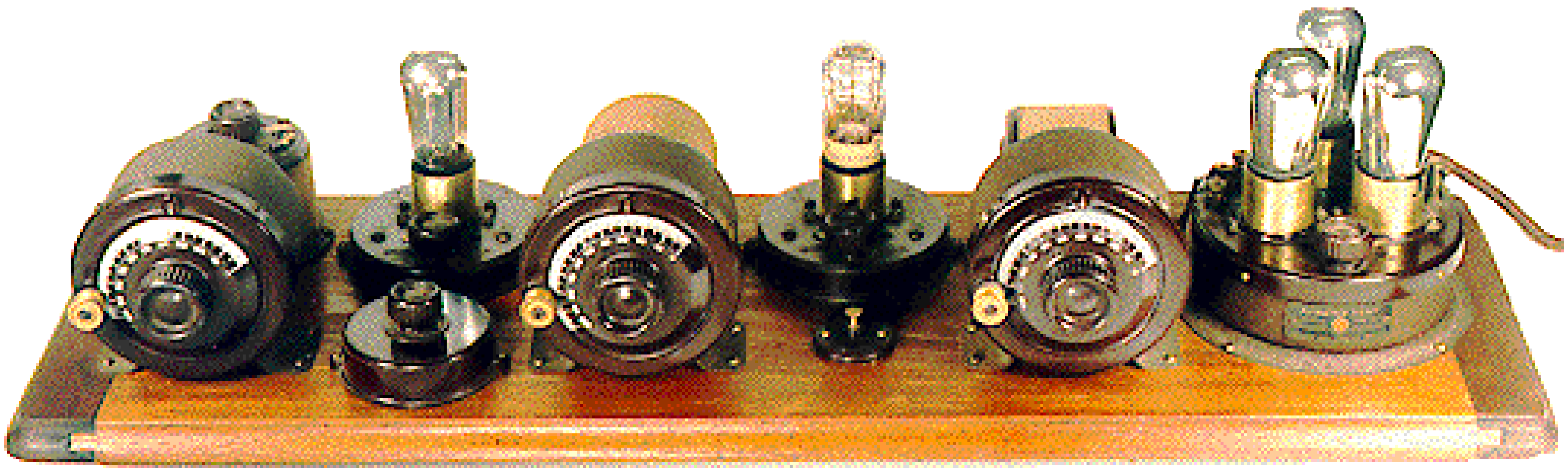


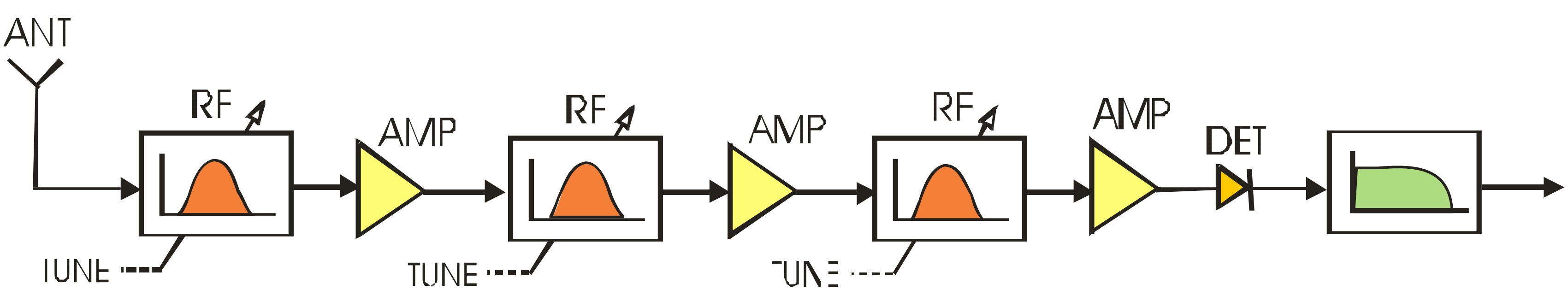
Fig. 1.

Regenerative Receiver:
A Little Feedback Goes a Long Way

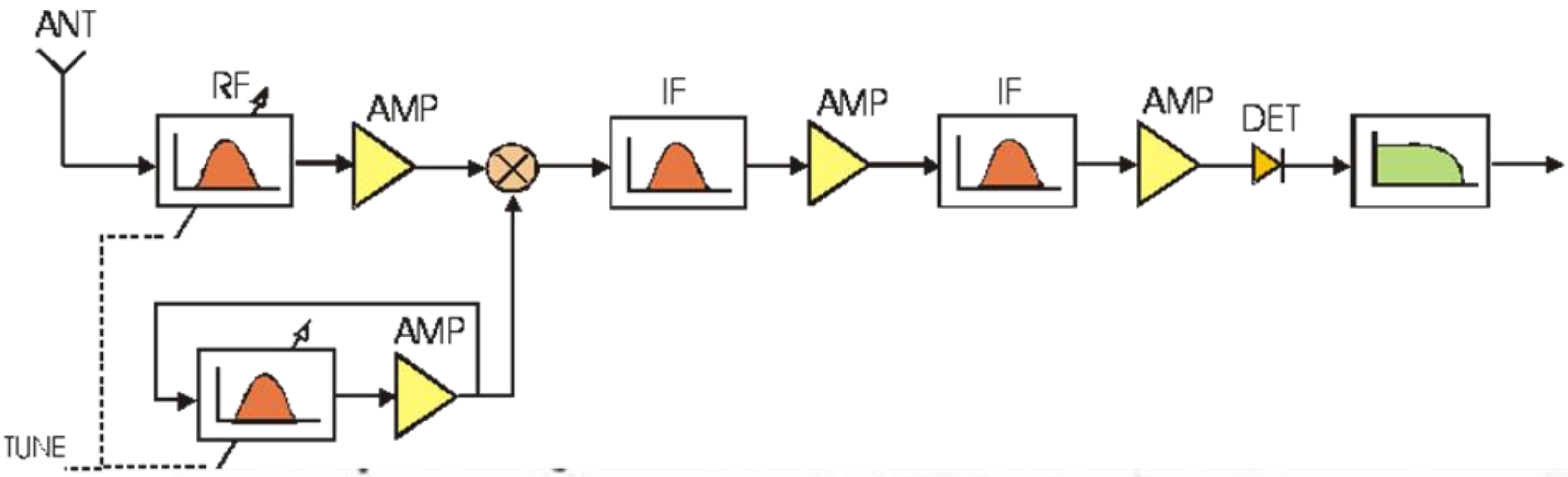


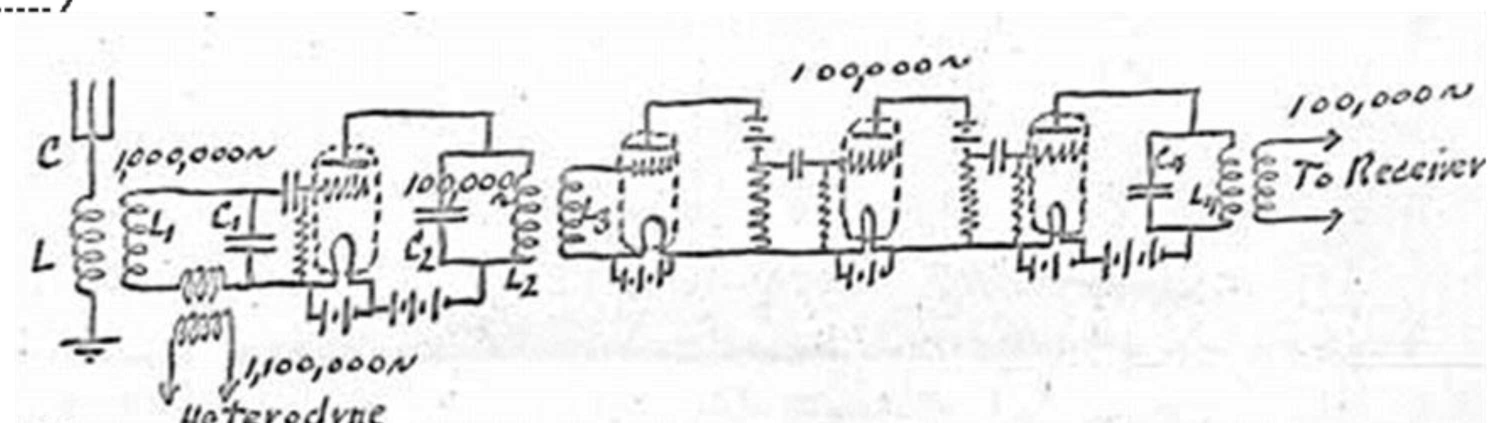
Tuned RF (TRF) Radio





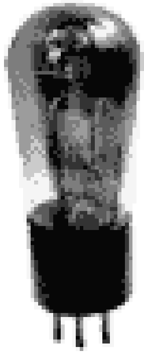
Edwin Armstrong's Super Heterodyne Receiver





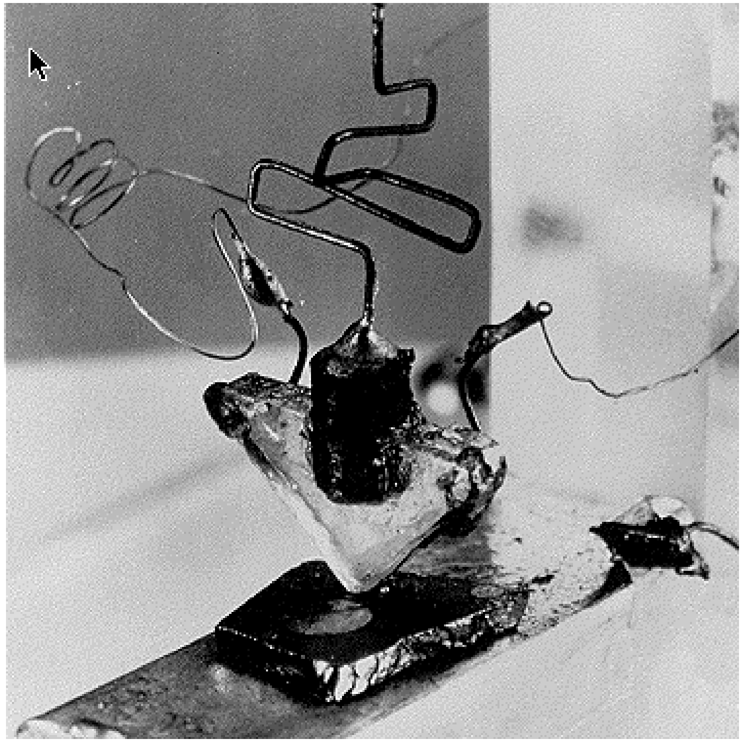
From Disclosure: June 3, 1918

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

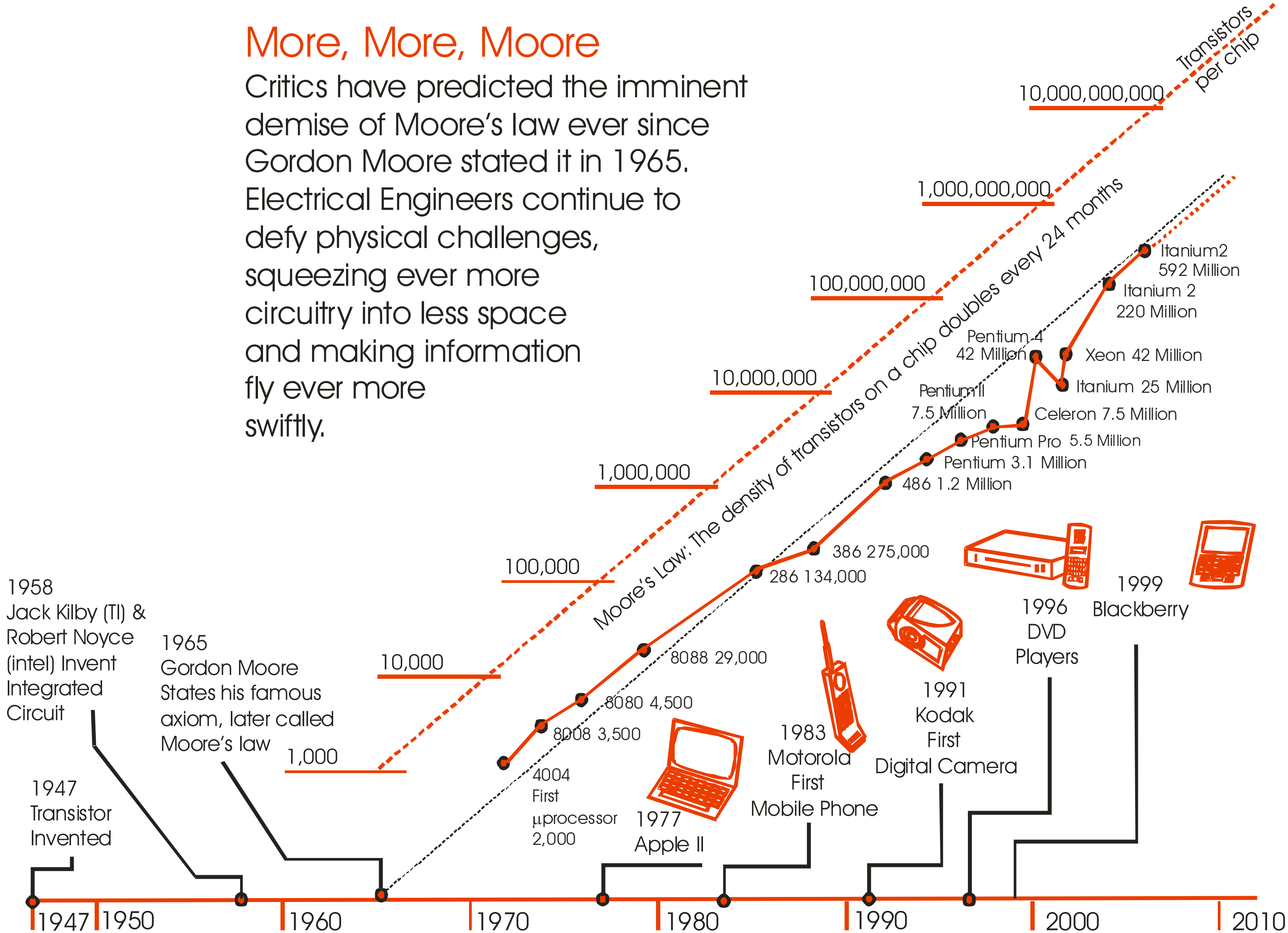
Robert Noyce,
Intel

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

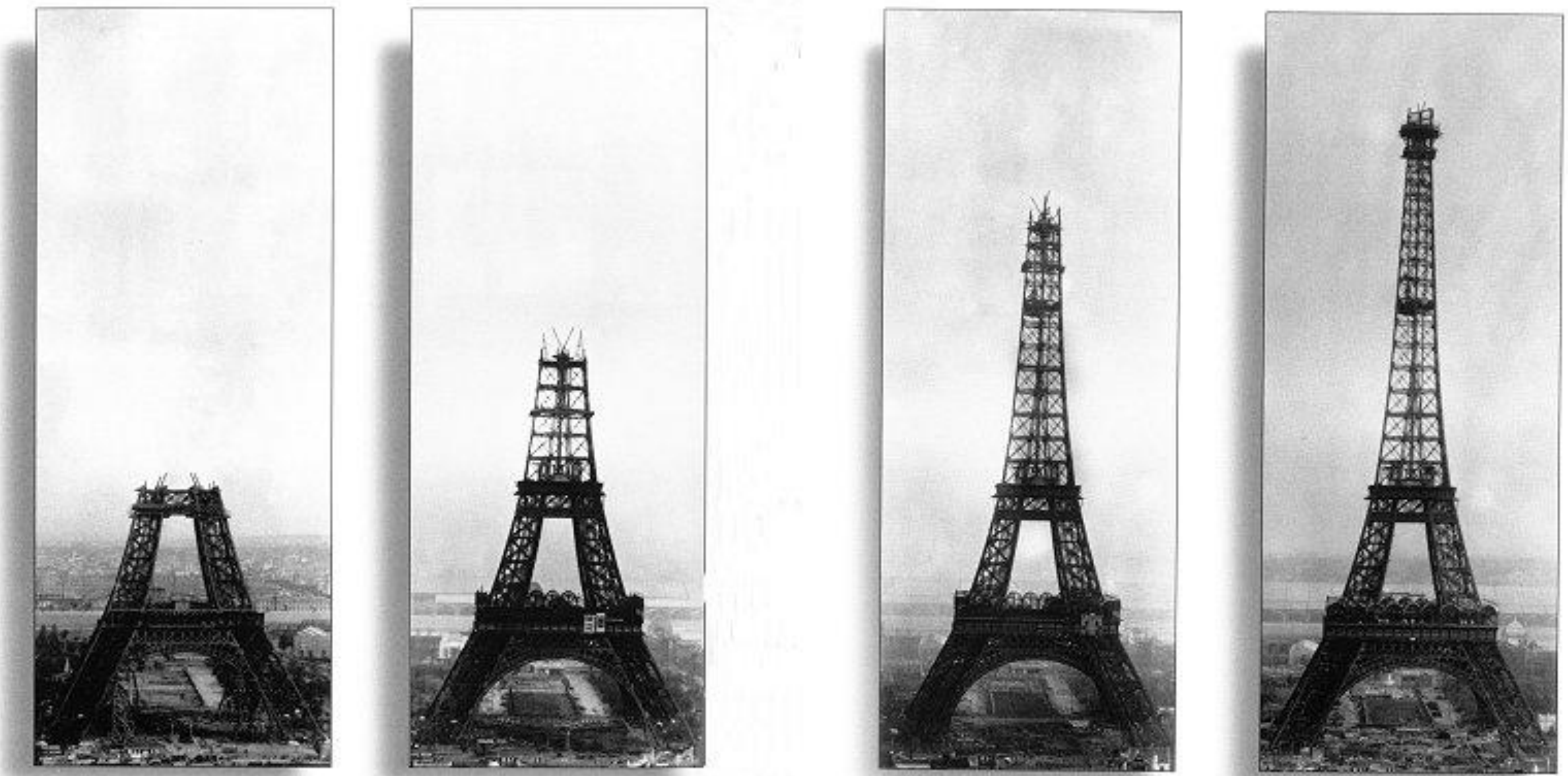
We have an amazing wealth of resources at our disposal!

Just how big is a Billion?

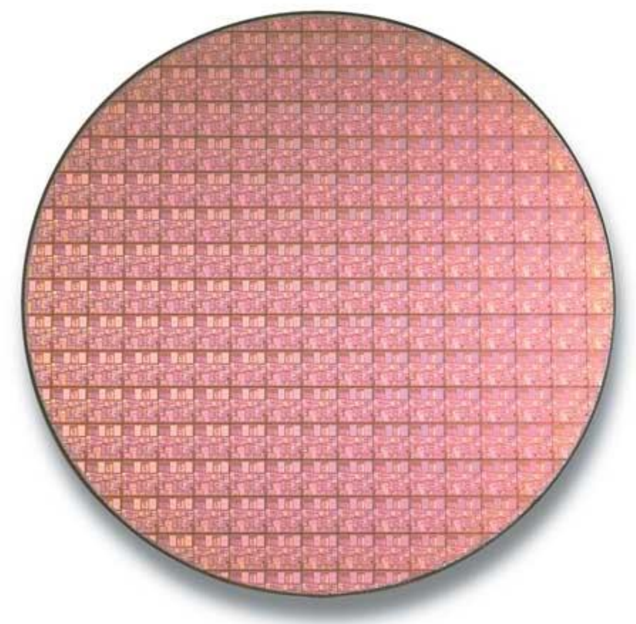
A stack of a billion bank notes would be 76.2 kilometers High.

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.



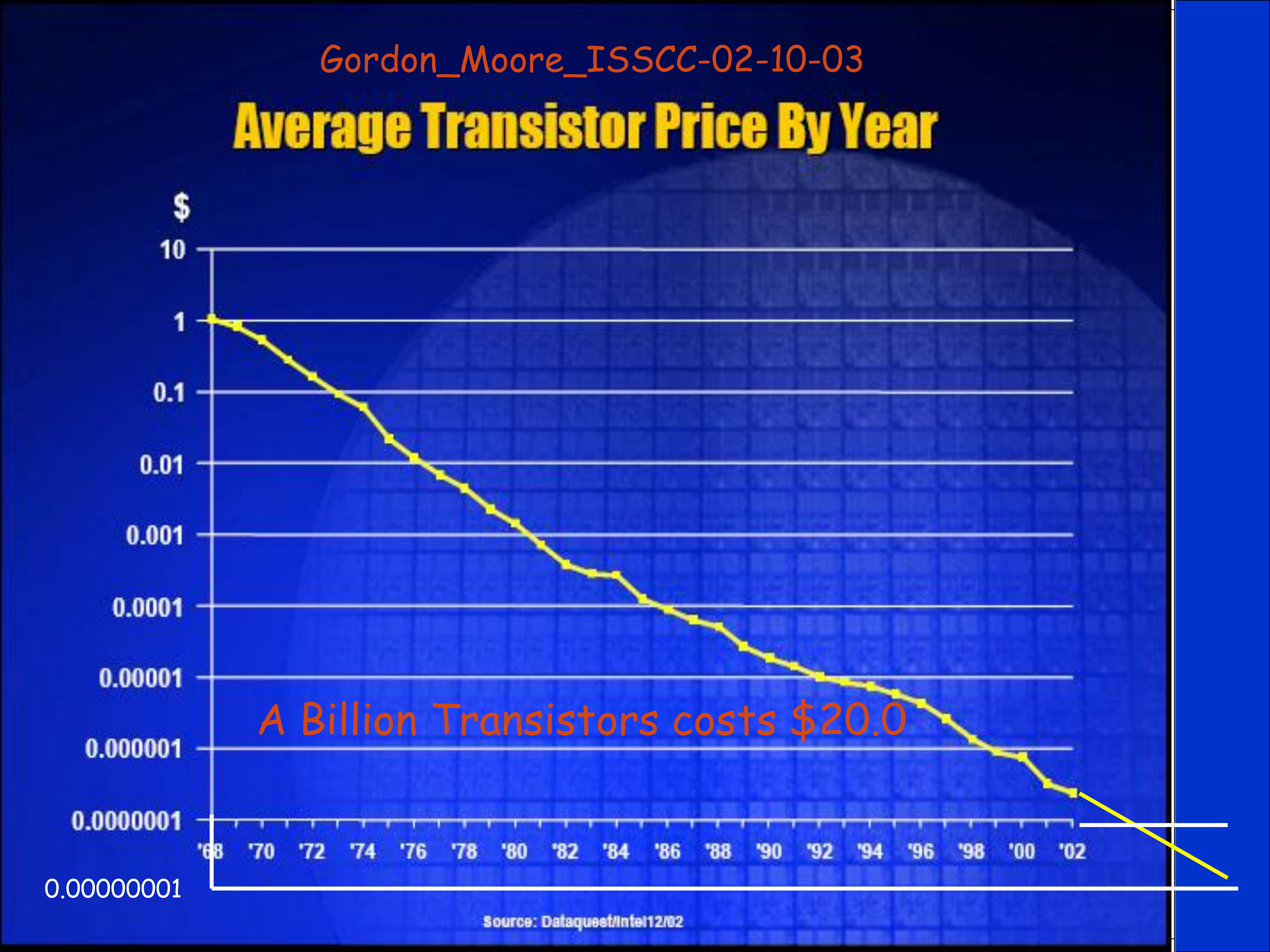
0.13-micron, Intel Pentium 4
300-mm silicon wafer.

Wow!

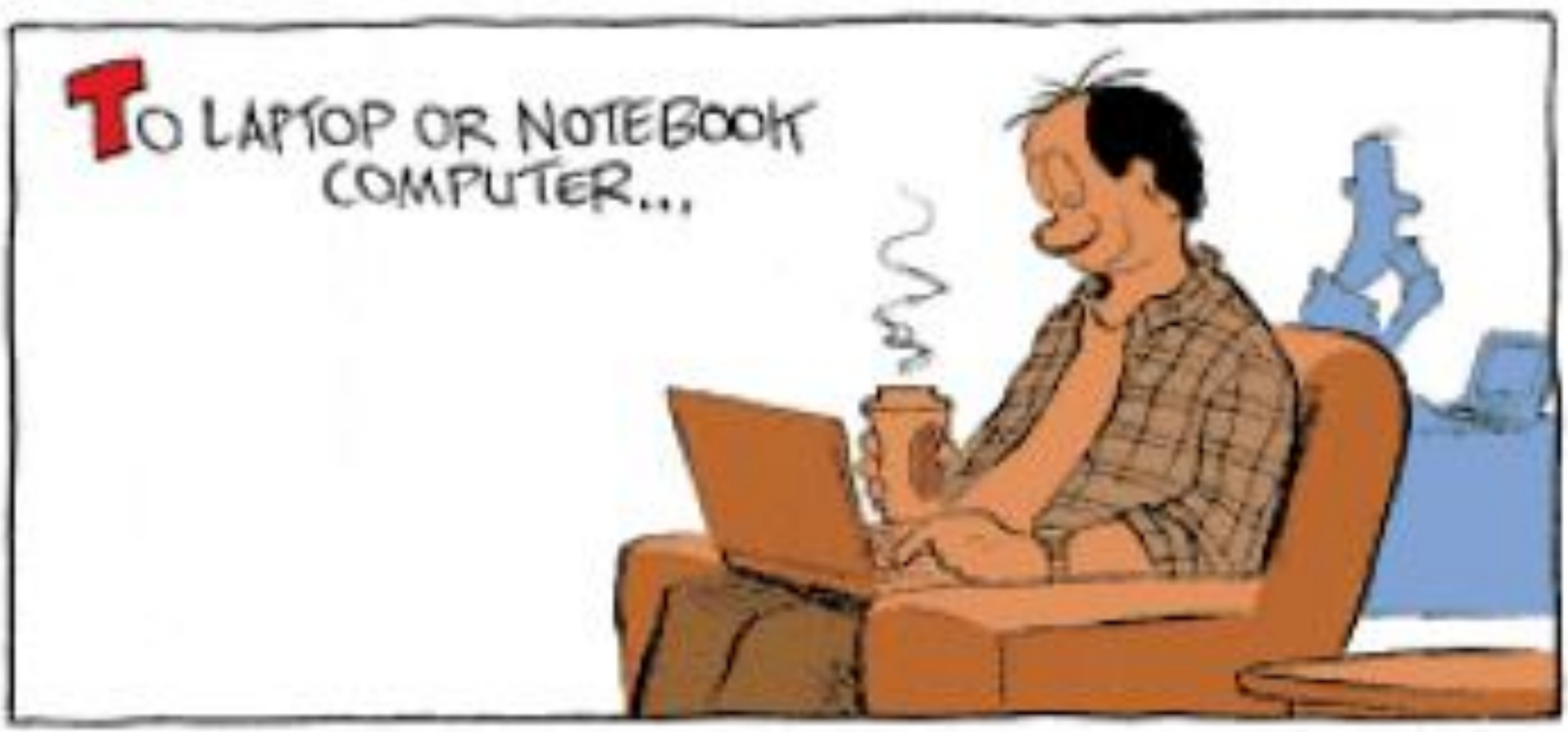
Long Grain Jasmine Rice

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


Gordon_Moore_ISSCC-02-10-03
Average Transistor Price By Year
$
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
0.0000001
0.00000001
'68
'70
'72
'74
'76
'78
'80
'82
'84
'86
'88
'90
'92
'94
'96
'98
'00
'02
A Billion Transistors costs $20.0
Source: Dataquest/Intel12/02

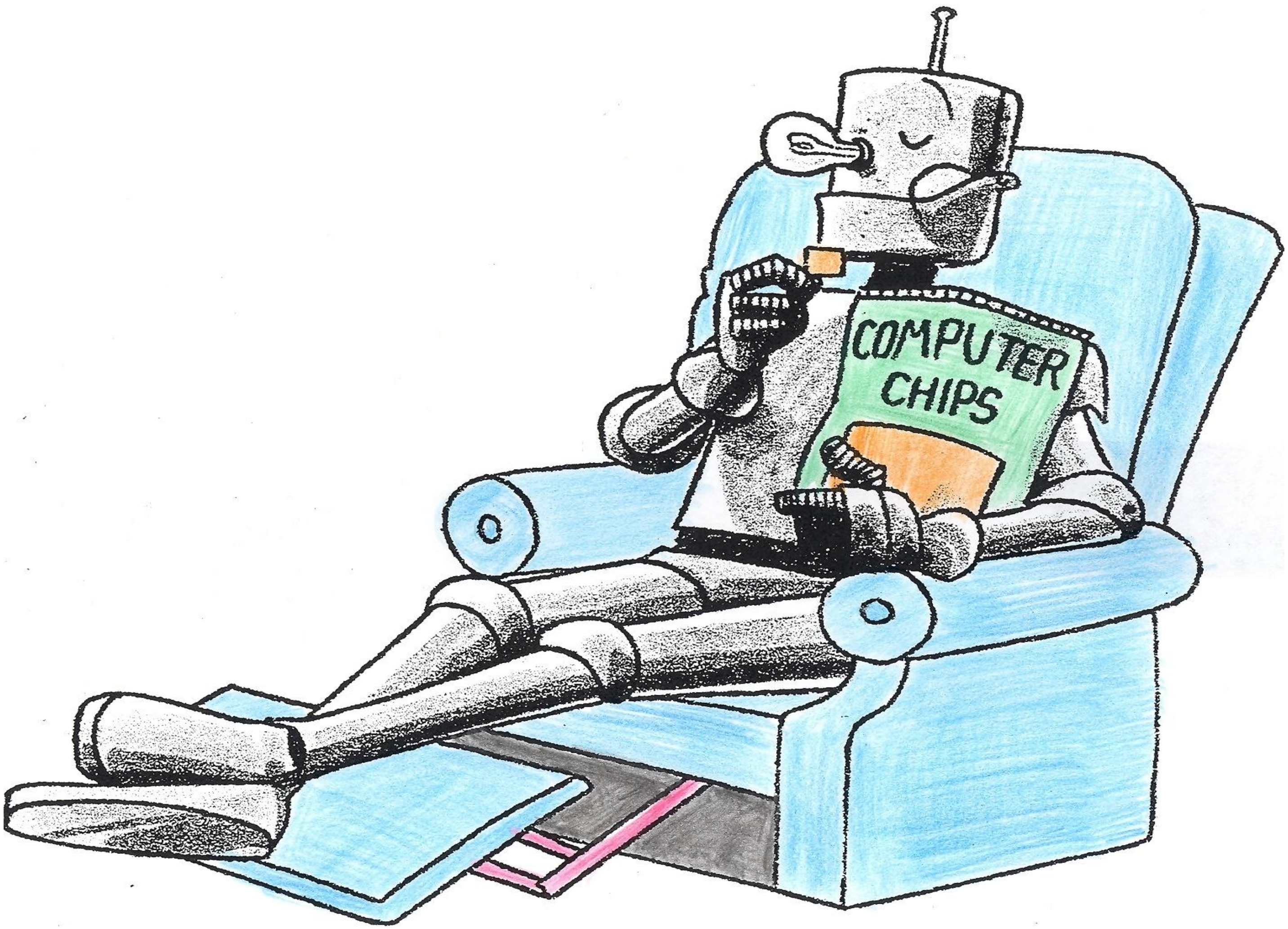

FROM DESKTOP COMPUTER...


TO LAPTOP OR NOTEBOOK COMPUTER...


TO HAND-
HELD
DEVICE.

Adam @ Home
Brian Basset

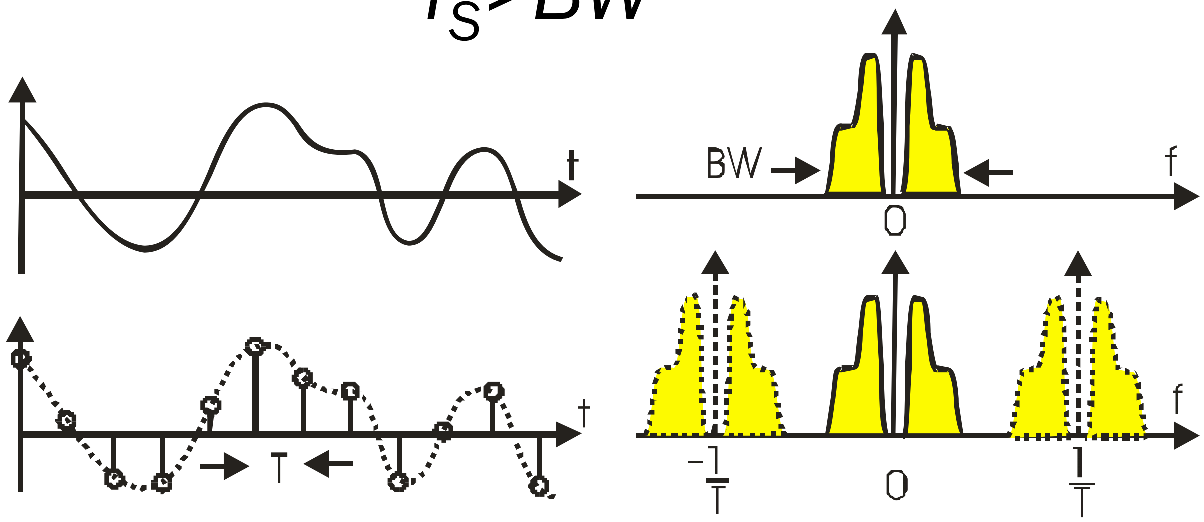
It’s all done with Computer Chips



Harry Nyquist, (1889-1960)

The Sampling Theorem

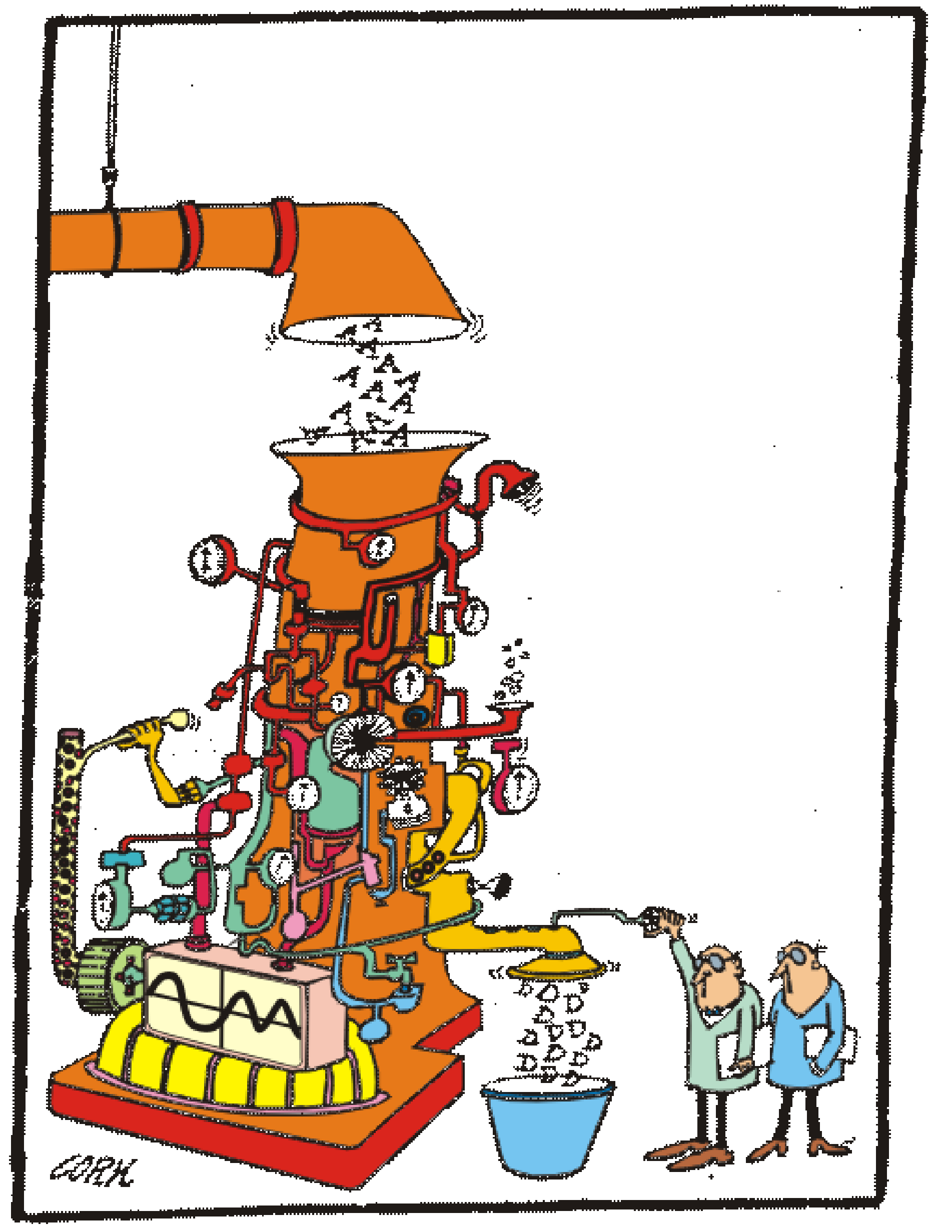
$$f_S > BW$$



Analog-to-Digital Converter

ADC

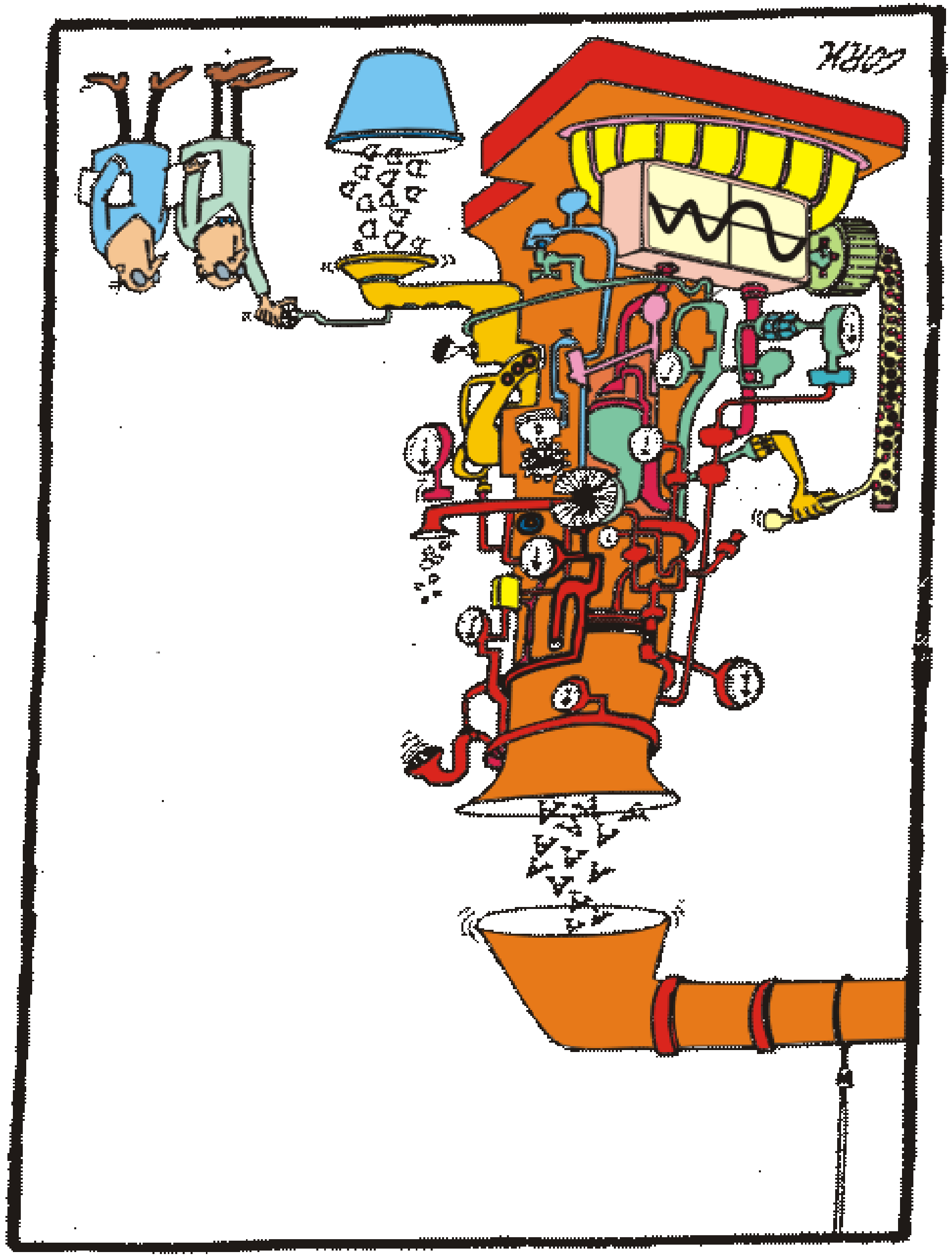
A-to-D



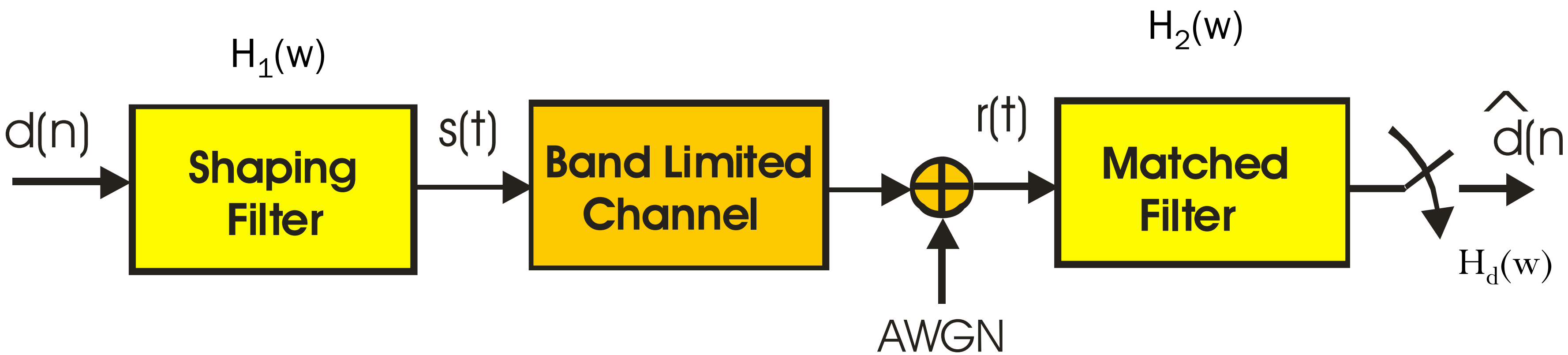
Digital-to-Analog Converter

DAC

D-to-A



Communication over Band Limited, AWGN Channel



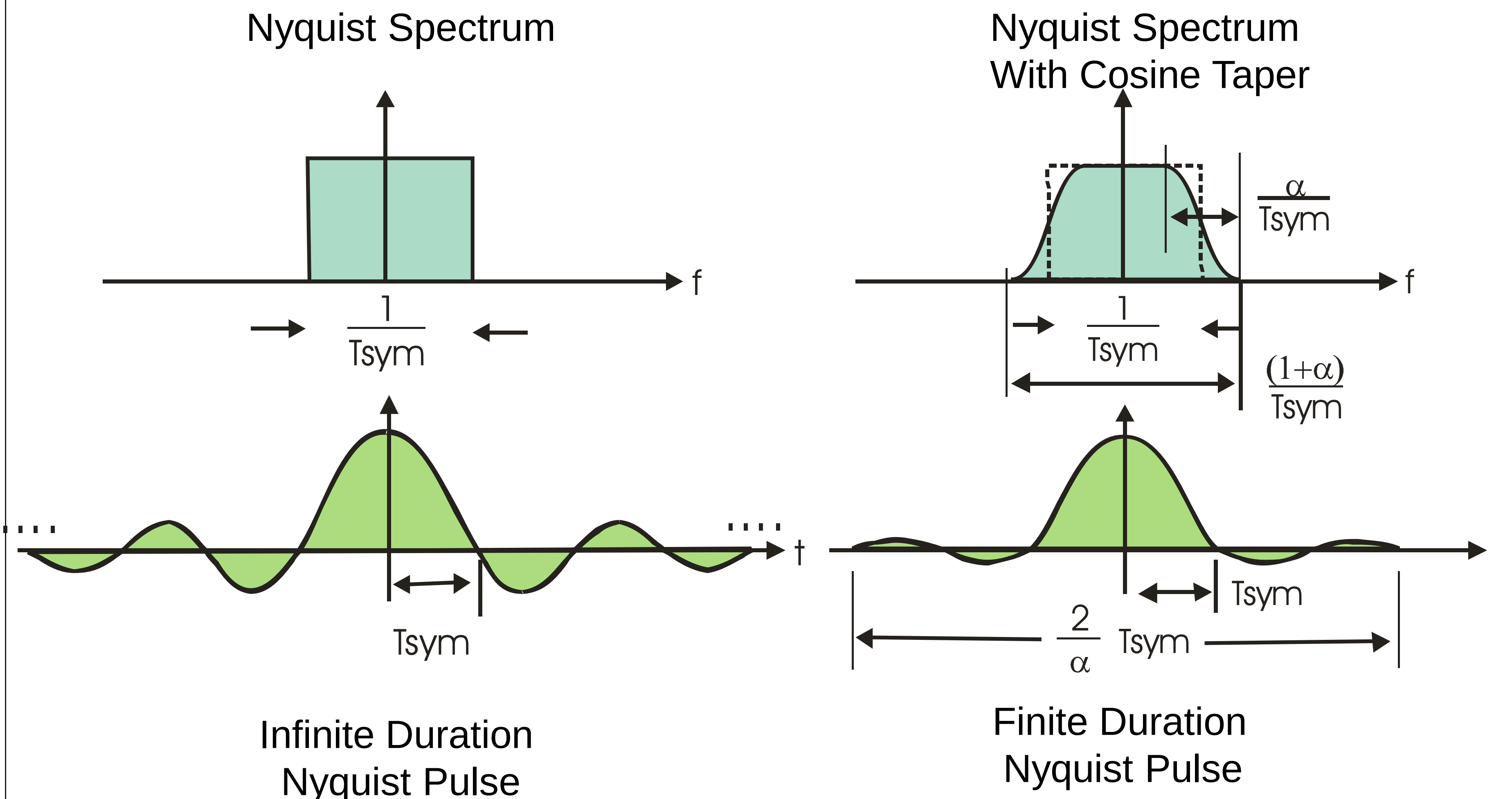
$$H_2(\omega) = H_1^*(\omega)\, e^{\,j\omega\tau}$$ (Maximize SNR)

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

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

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

Band Limited Channel
Zero ISI and Causal Response

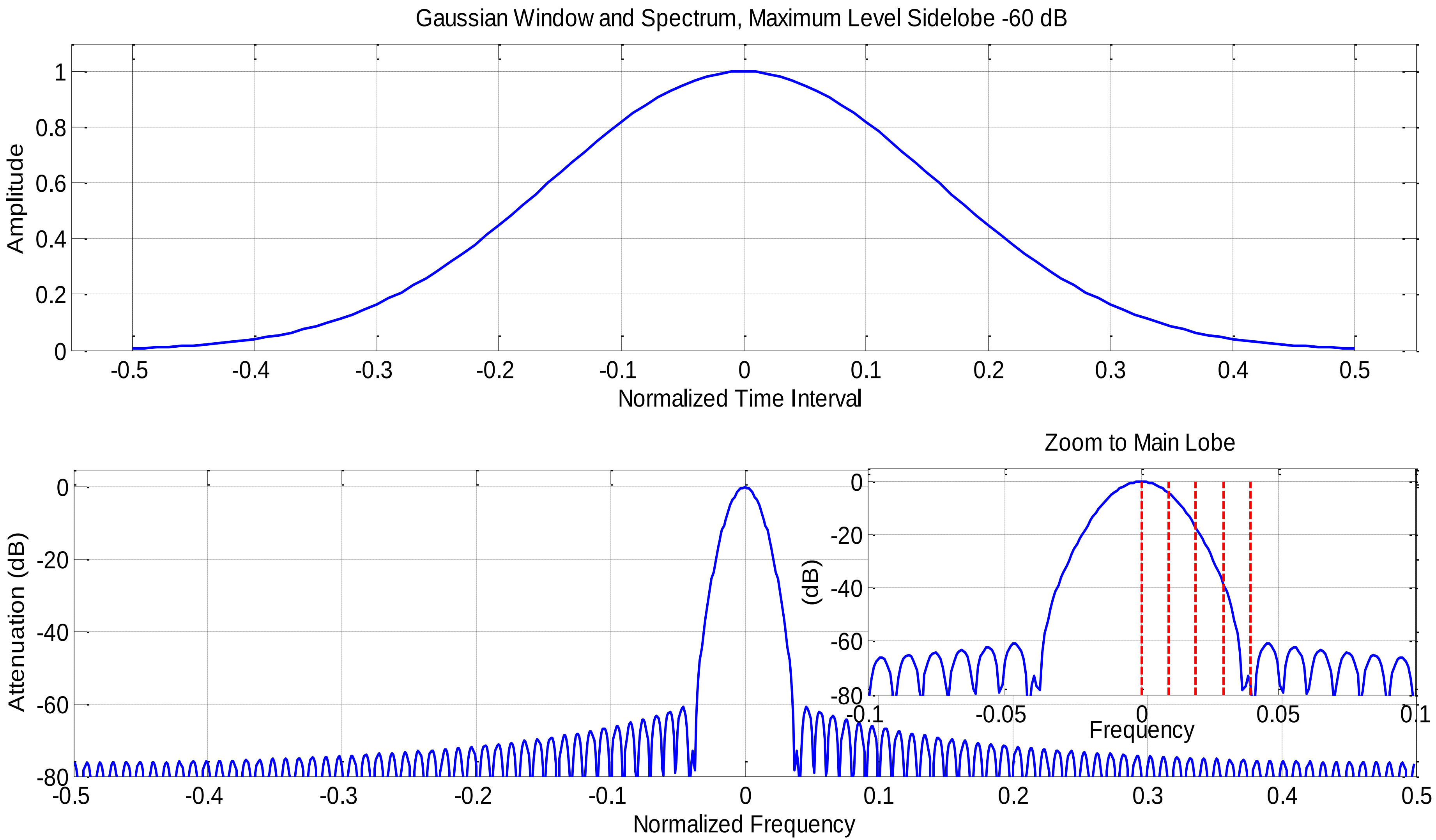


It's not what you don't know that gets you in trouble!

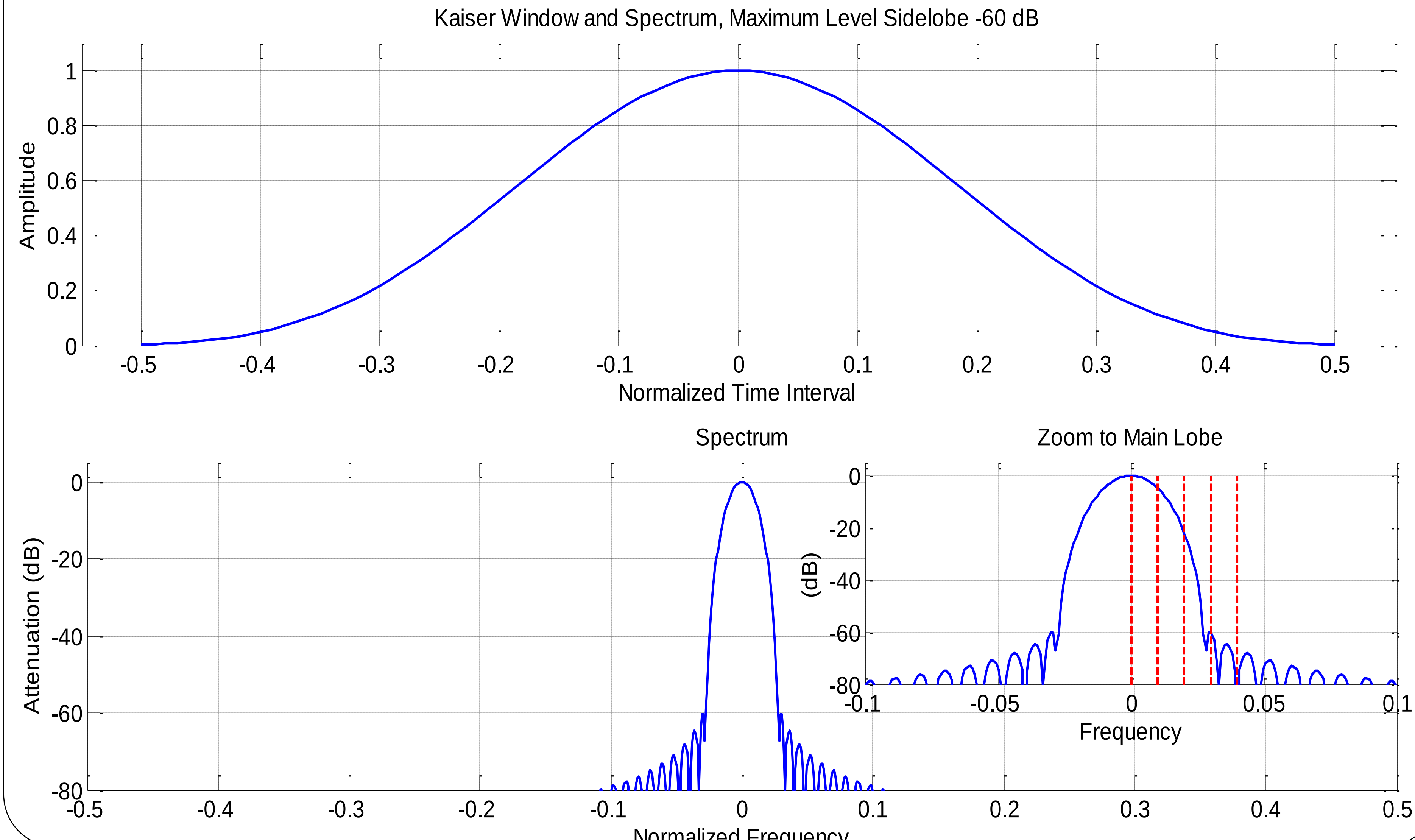
It's what you know for sure to be true that just ain't so!

Samuel Clemens

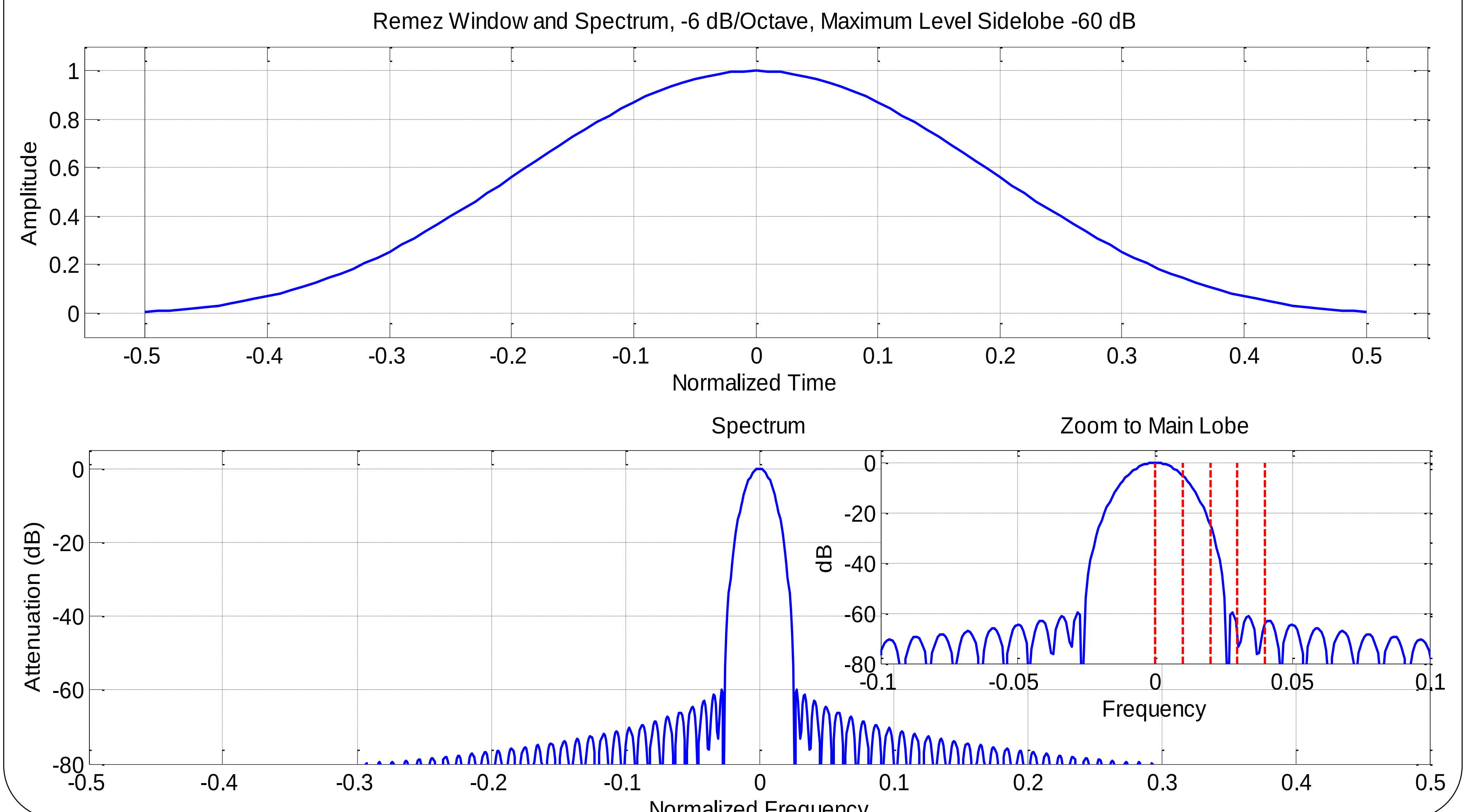
Spectral Resolution
Gaussian Window



Spectral Resolution
Kaiser-Bessel Window

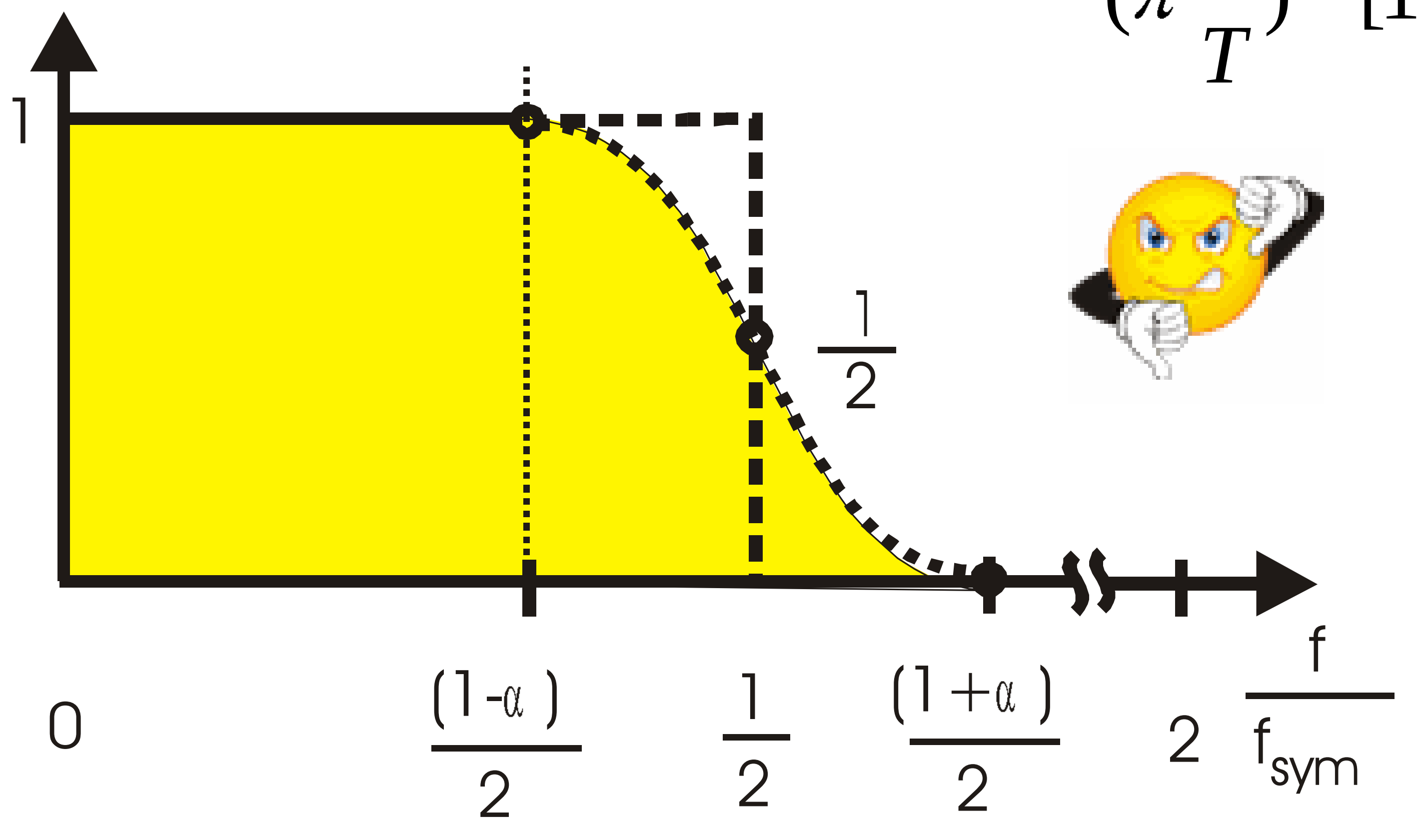


Spectral Resolution, Remez Minimum BW Window with -6-dB/Oct. Side Lobes

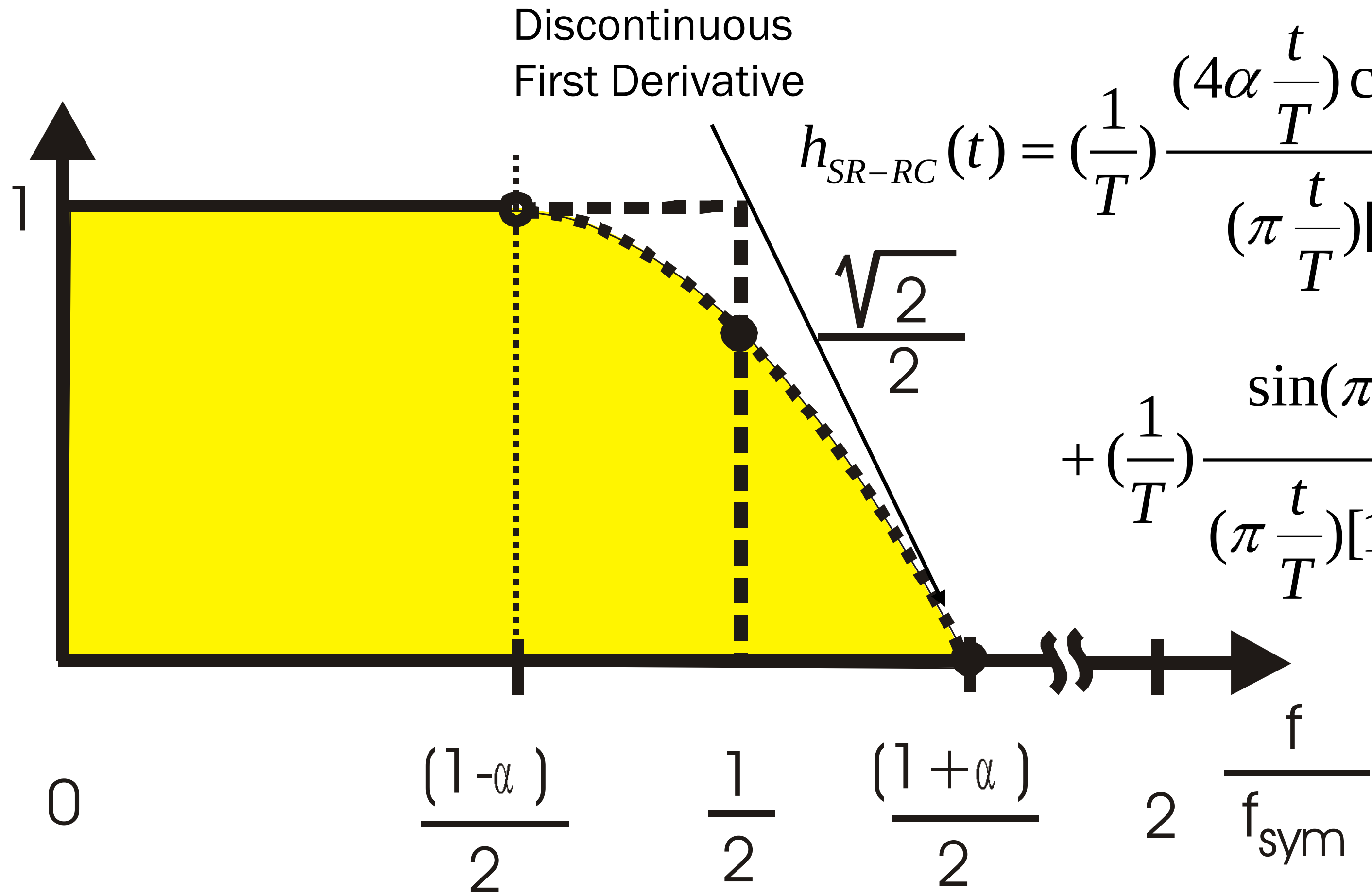


Cosine Tapered Nyquist Spectrum

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

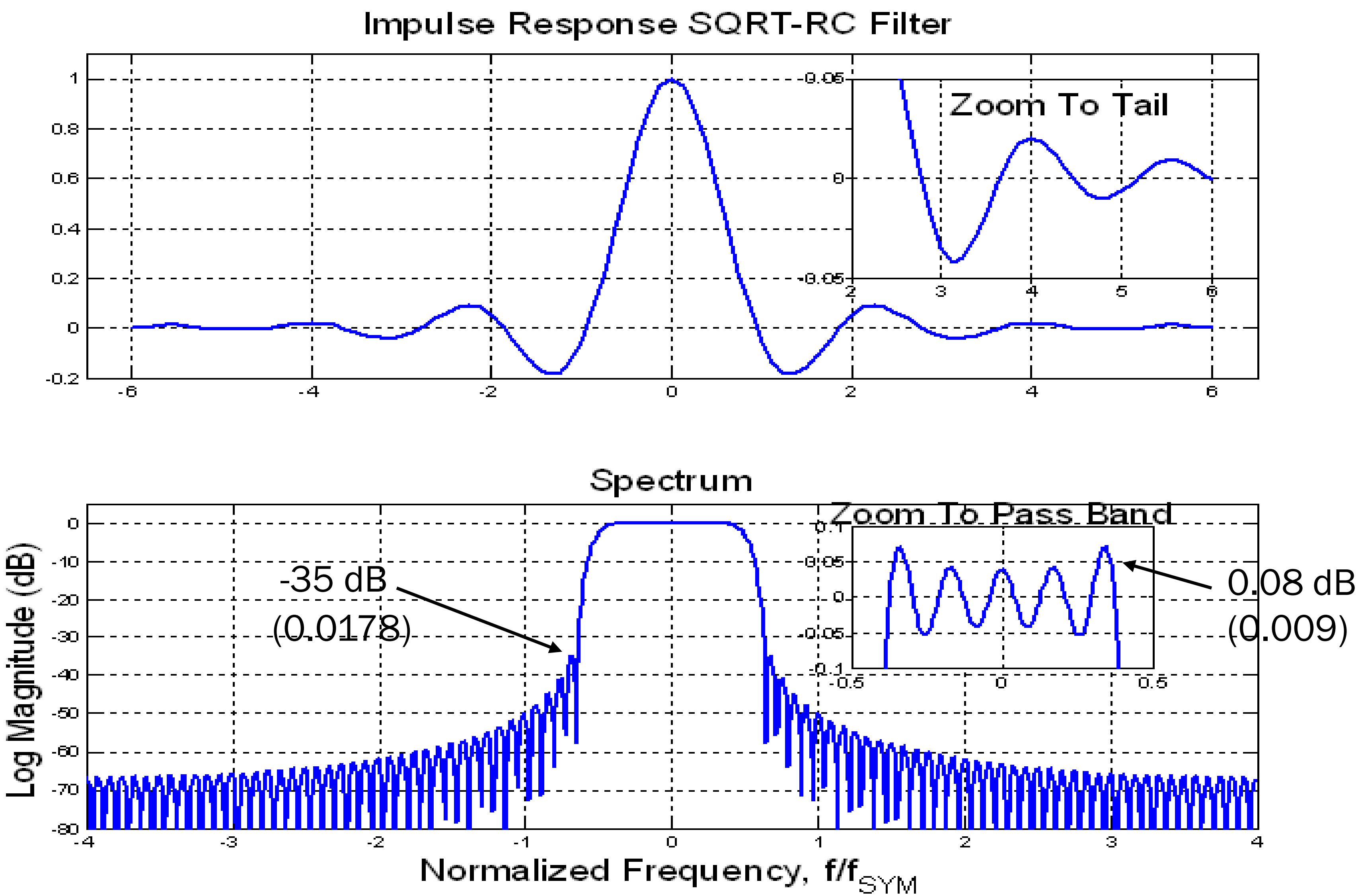


Square-Root
Cosine Tapered Nyquist Filter

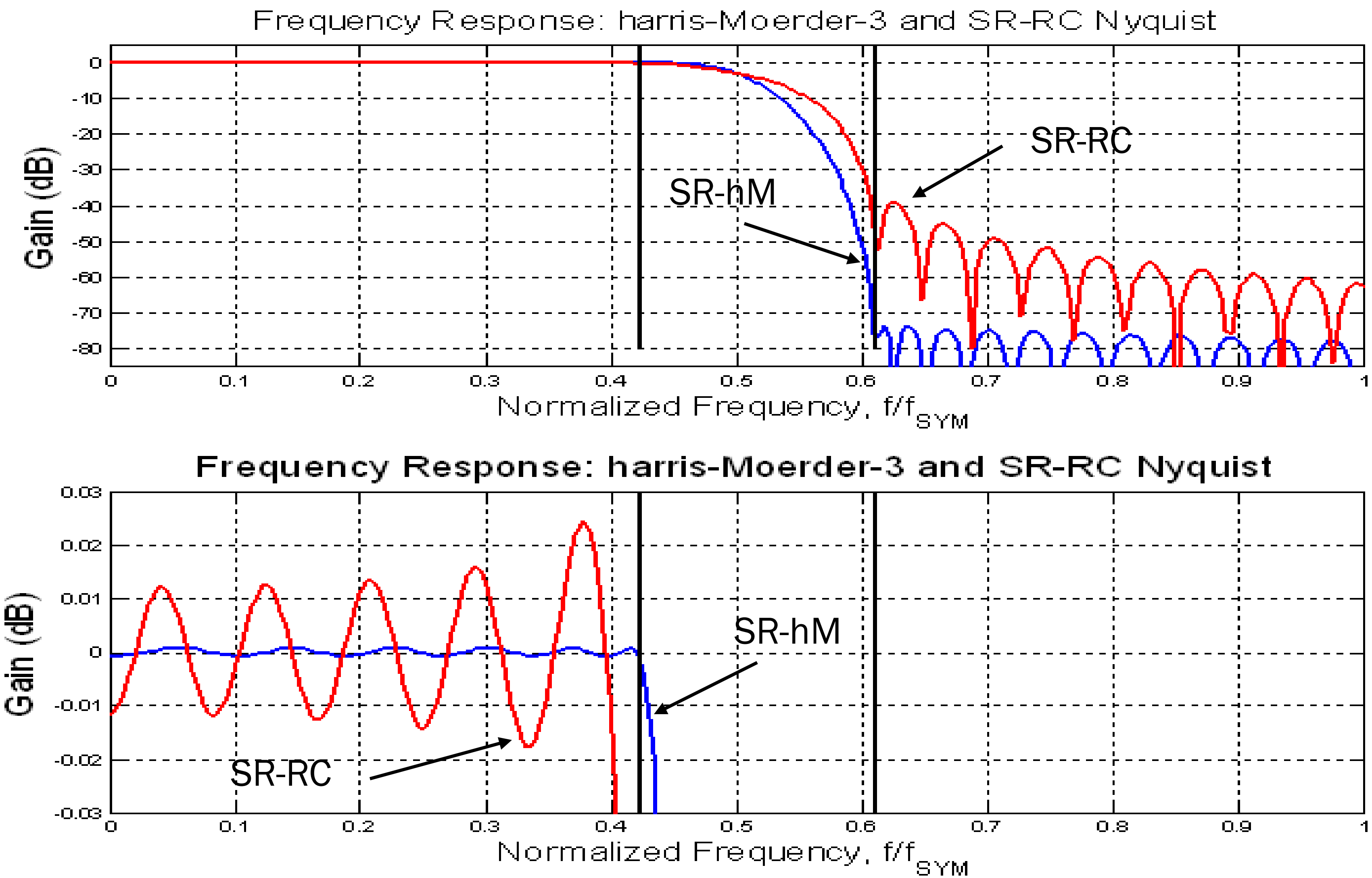


$$h_{SR-RC}(t) = \left(\frac{1}{T}\right)\frac{\left(4\alpha\frac{t}{T}\right)\cos\left(\pi(1+\alpha)\frac{t}{T}\right)}{\left(\pi\frac{t}{T}\right)\left[1-\left(4\alpha\frac{t}{T}\right)^{2}\right]} + \left(\frac{1}{T}\right)\frac{\sin\left(\pi(1-\alpha)\frac{t}{T}\right)}{\left(\pi\frac{t}{T}\right)\left[1-\left(4\alpha\frac{t}{T}\right)^{2}\right]}$$

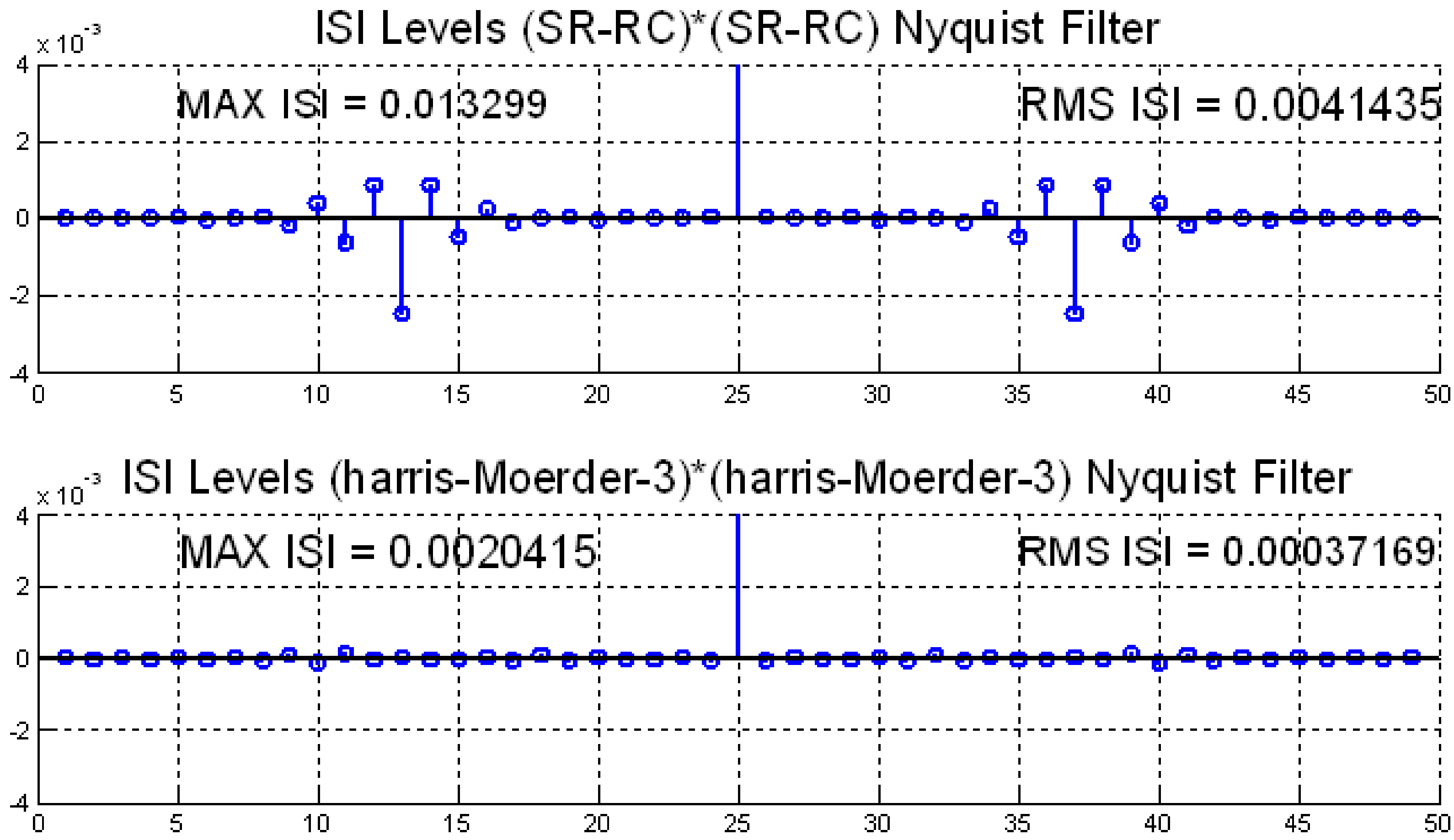
SQRT-RC Impulse Response Finite Duration, Rectangle Window



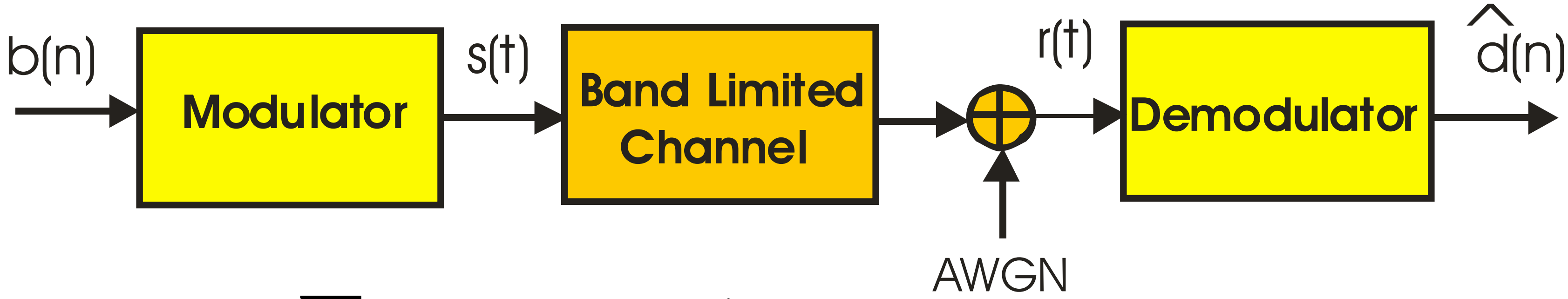
Spectra of SR-hM and SR-RC Nyquist Filter



ISI Levels: RC-RC and hM-hM



Transmitter and Receiver
Modulator and Demodulator



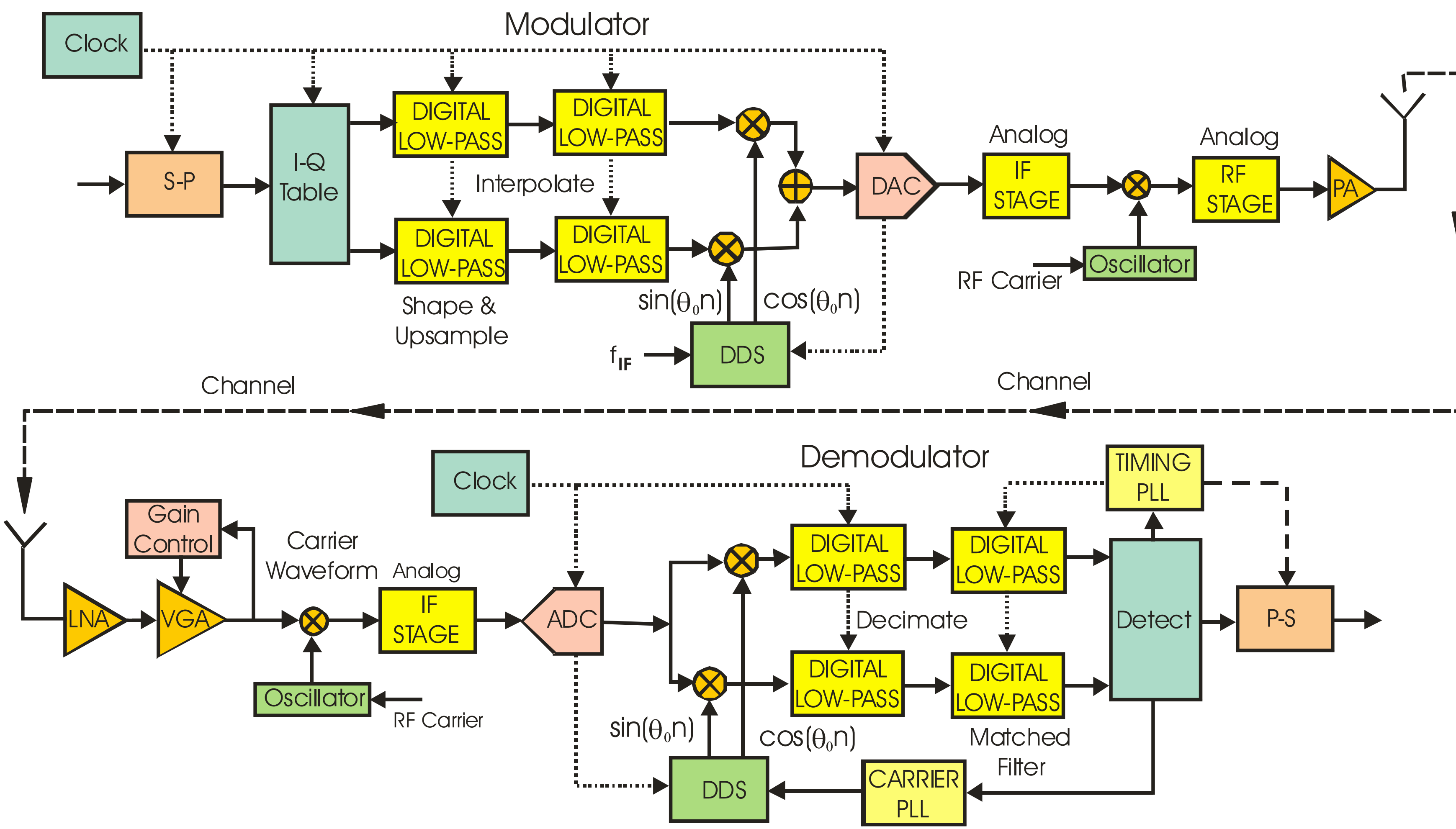
$$s(t) = \mathrm{Re}\{[\sum_k I_k g(t-kT)]e^{j\omega_c t}\}$$

$$= \mathrm{Re}\{R(t)e^{j\theta(t)}e^{j\omega_c t}\}$$

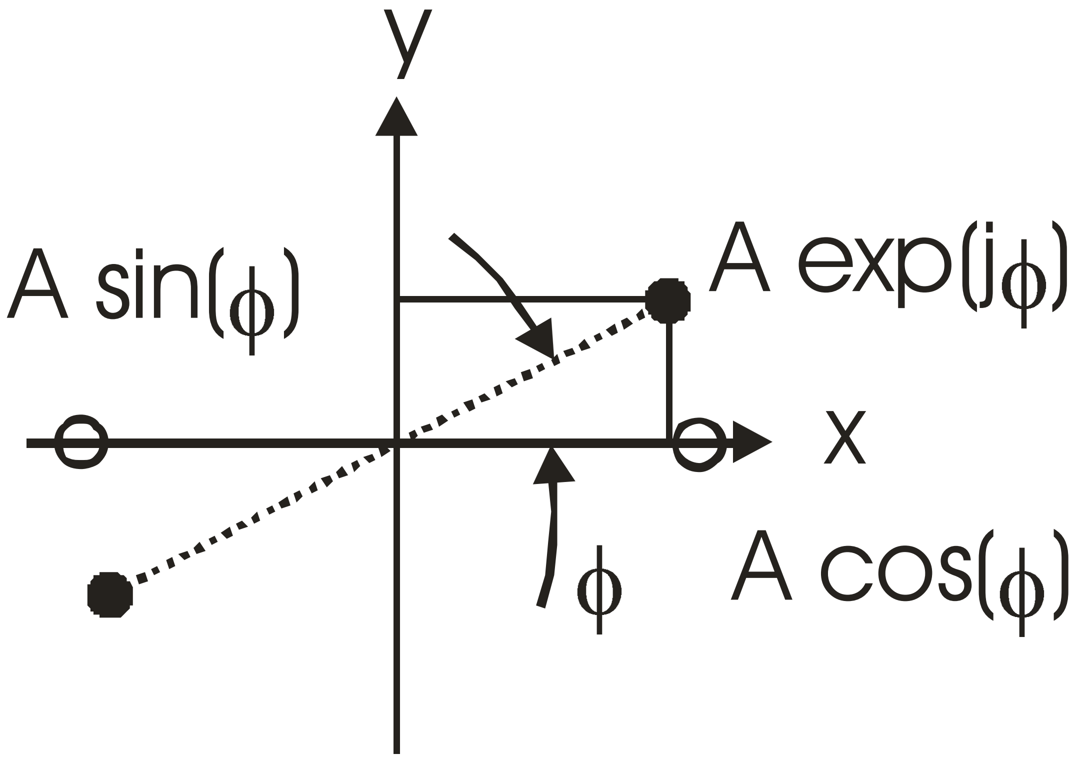
$$r(t) = \mathrm{Re}\{[A(t) * R(t-\tau)e^{j\theta(t-\tau)}]e^{j(\omega_c+\Delta\omega)(t-\tau)}\}$$

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

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



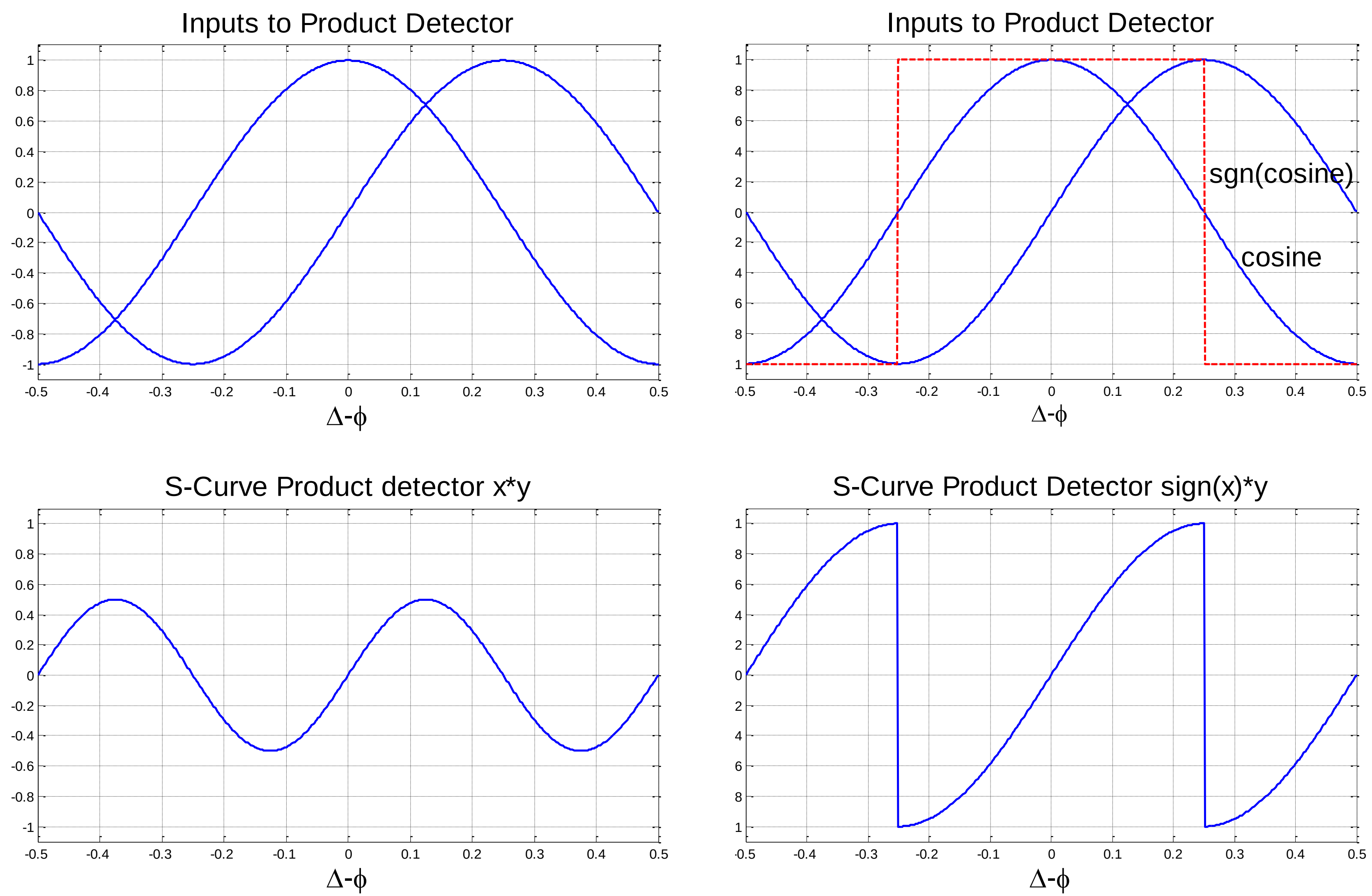
BPSK Phase Error



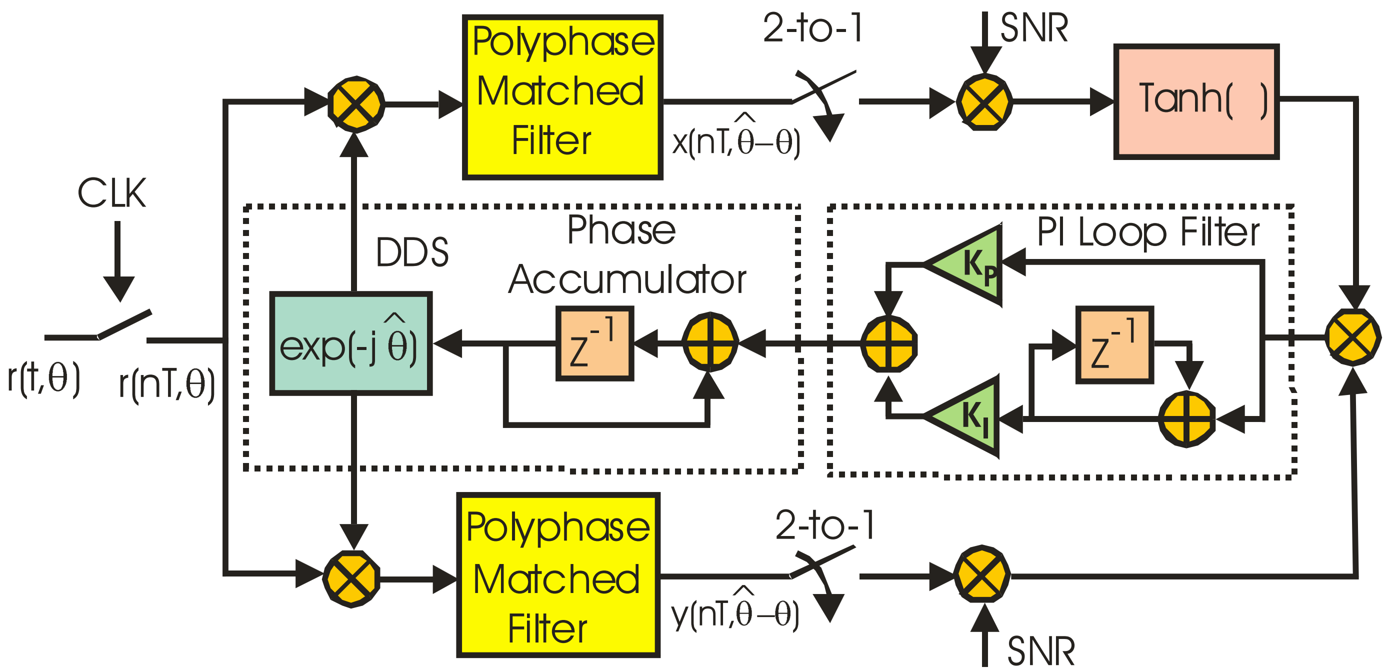
Consider x(n) y(n)

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

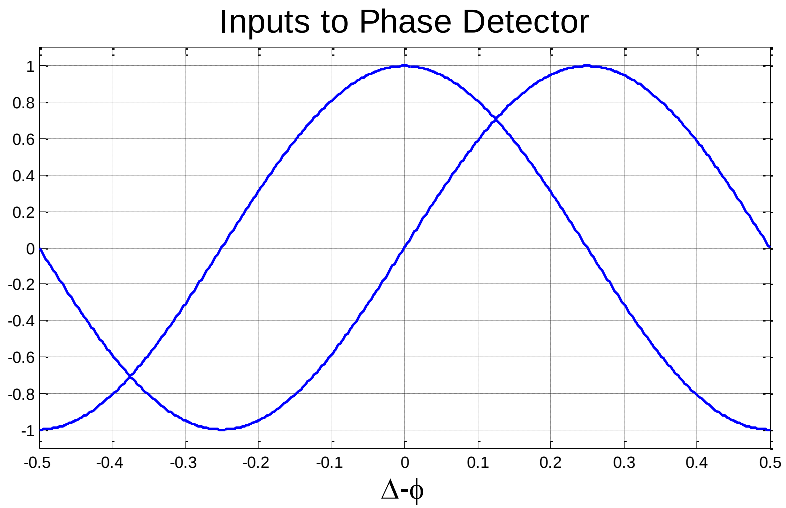
Phase Detectors for Modulated BPSK

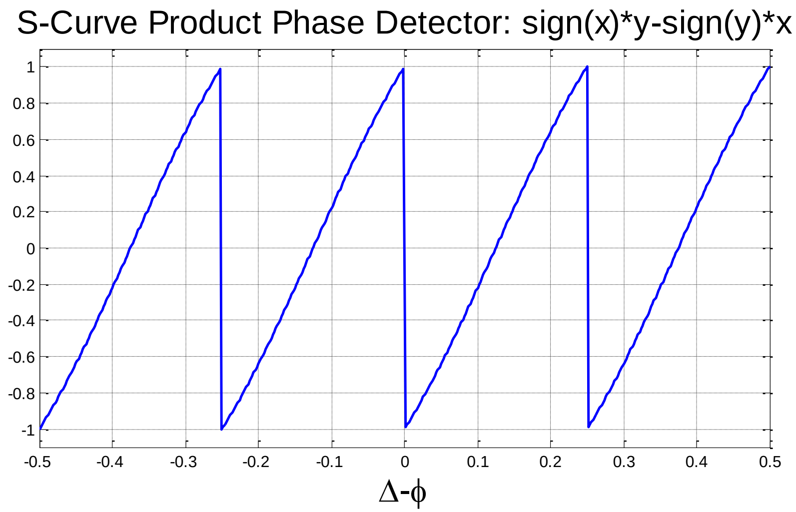


Second Tier Signal Processing Task, Carrier Recovery Phase Locked Loop

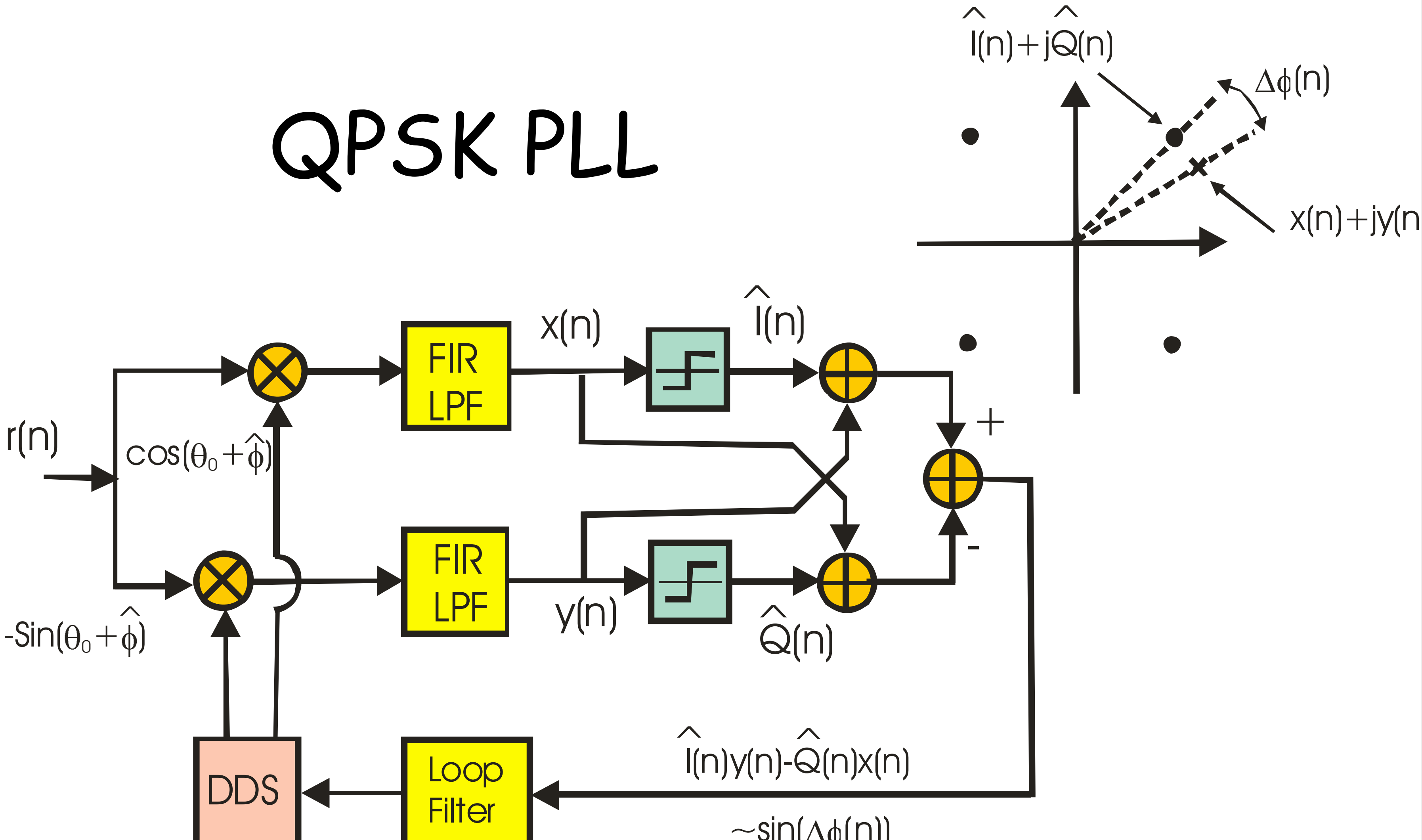


Phase Detectors for Modulated QPSK



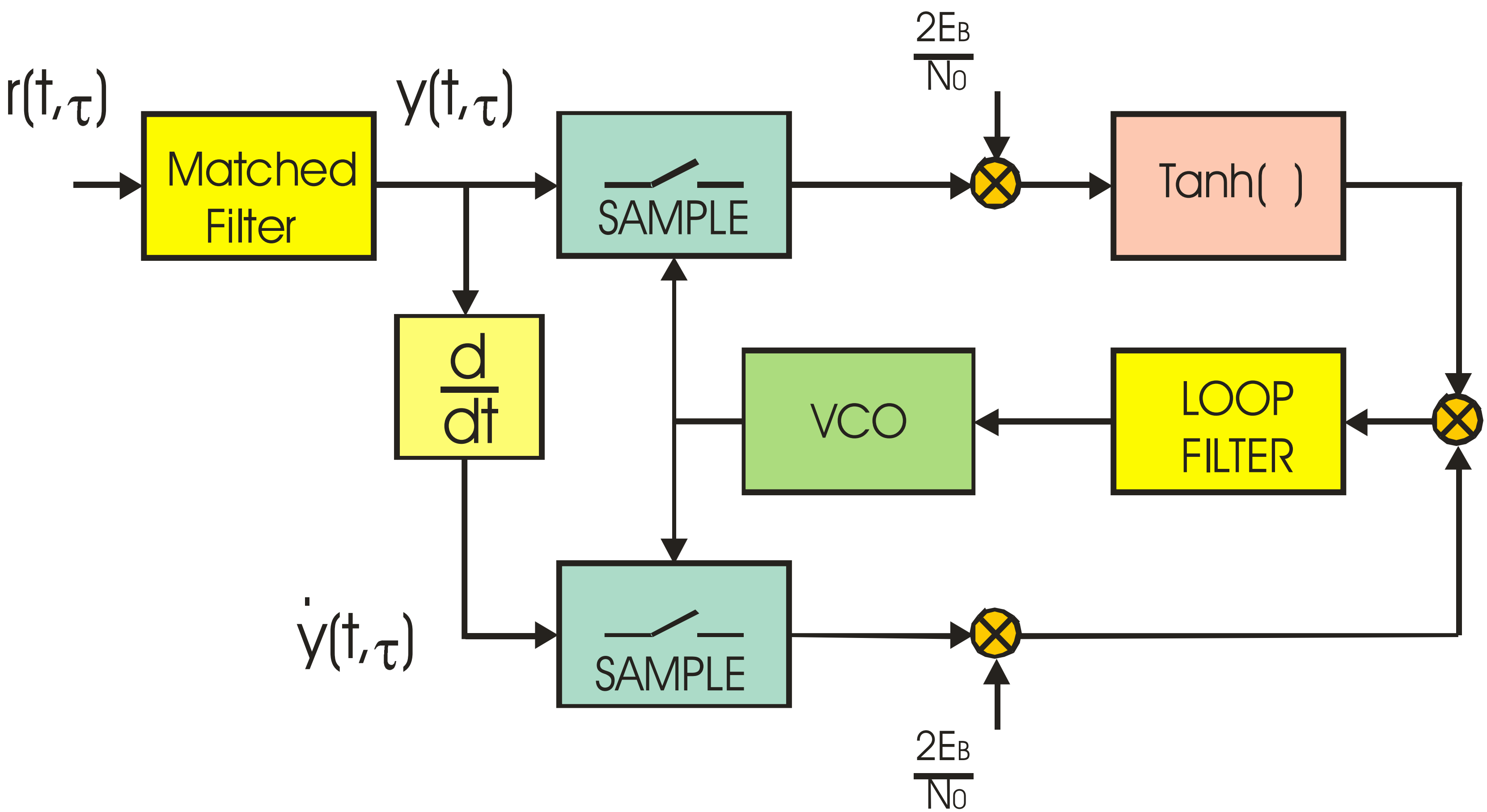


QPSK PLL

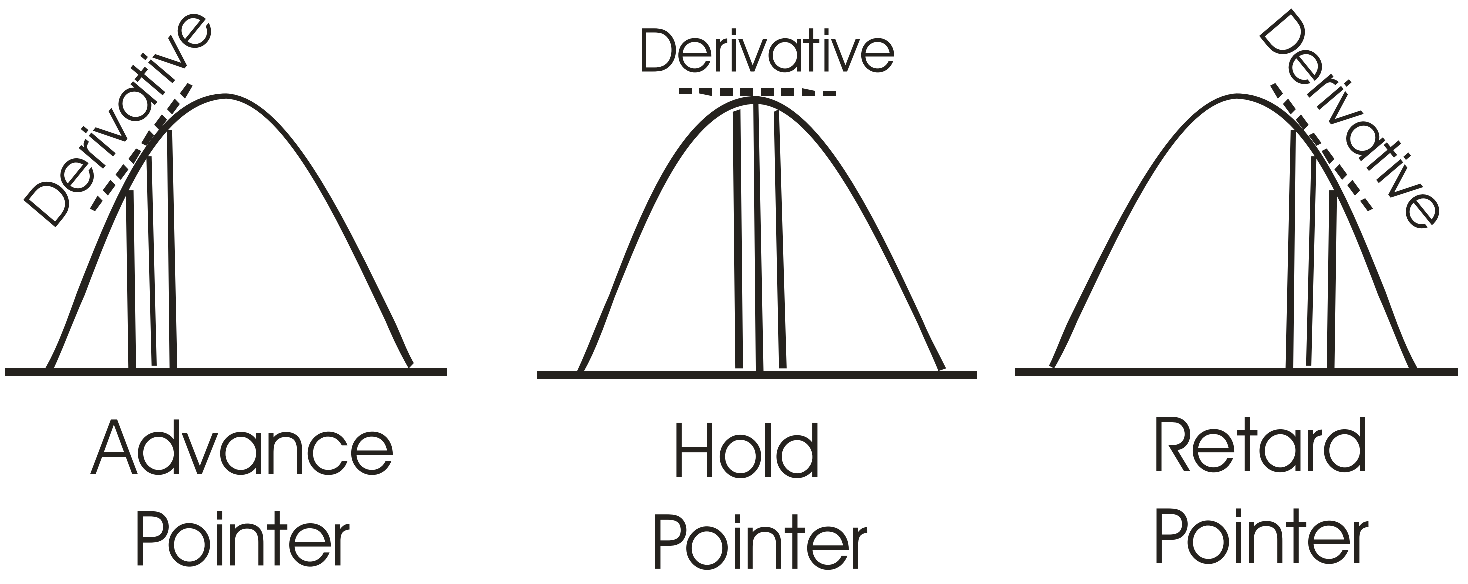


Direct Digital Synthesizer

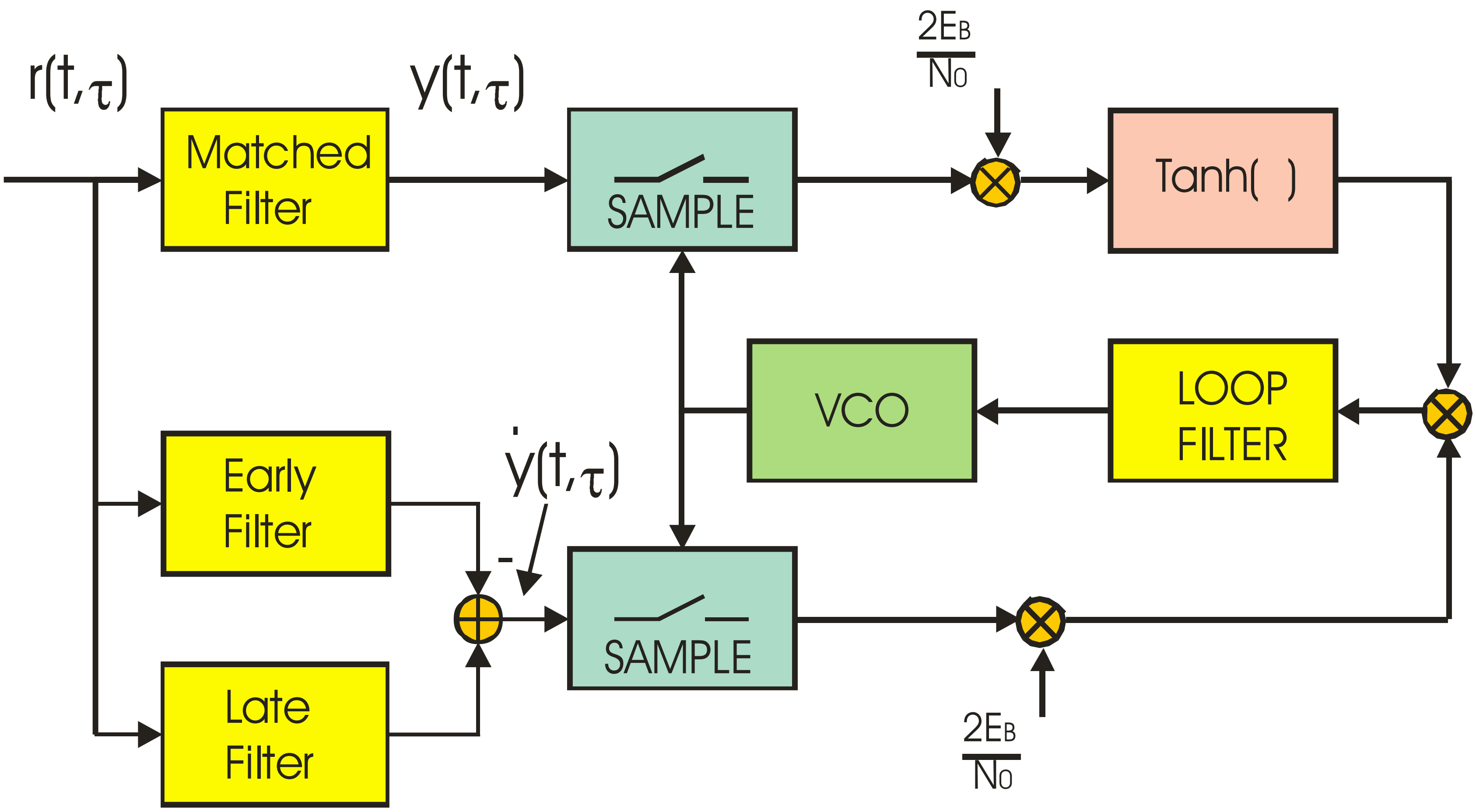
Maximum Likelihood Timing Recovery



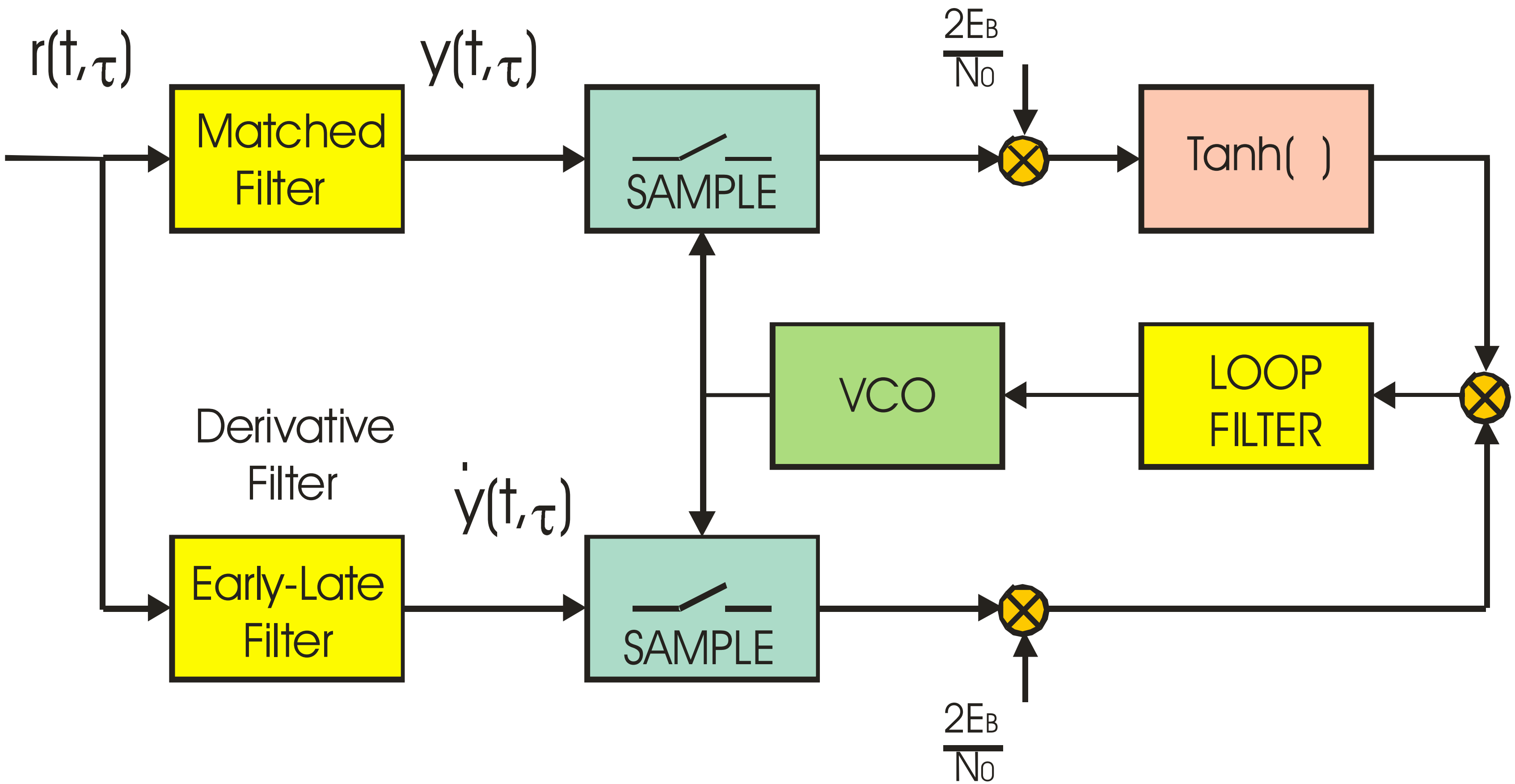
Derivative with Help of Nearby Neighbors (Early and Late)



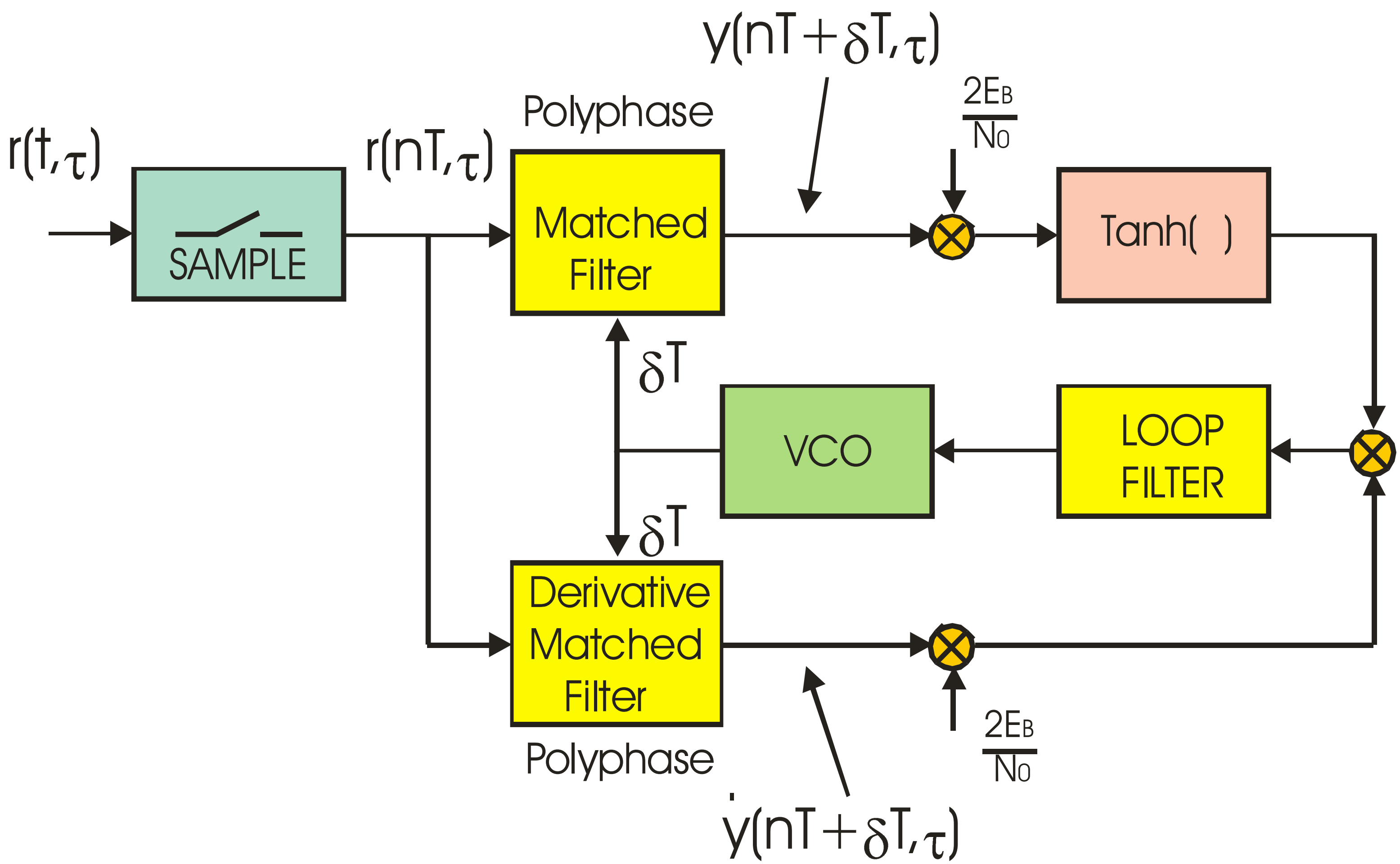
Early-Late Gate Derivative



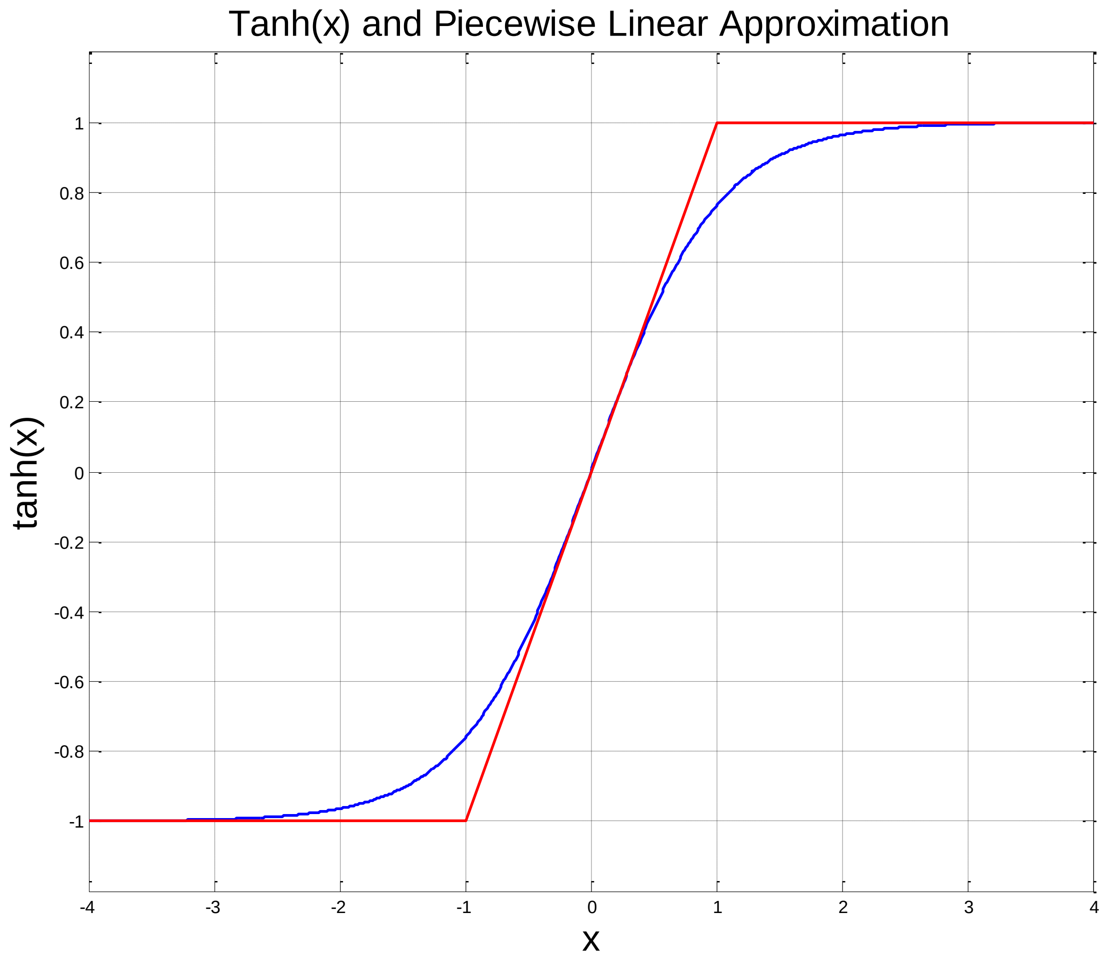
Combining Early and Late Gates in a One Derivative Filter



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



Approximating Tanh(x)



Sub Optimal Approximations

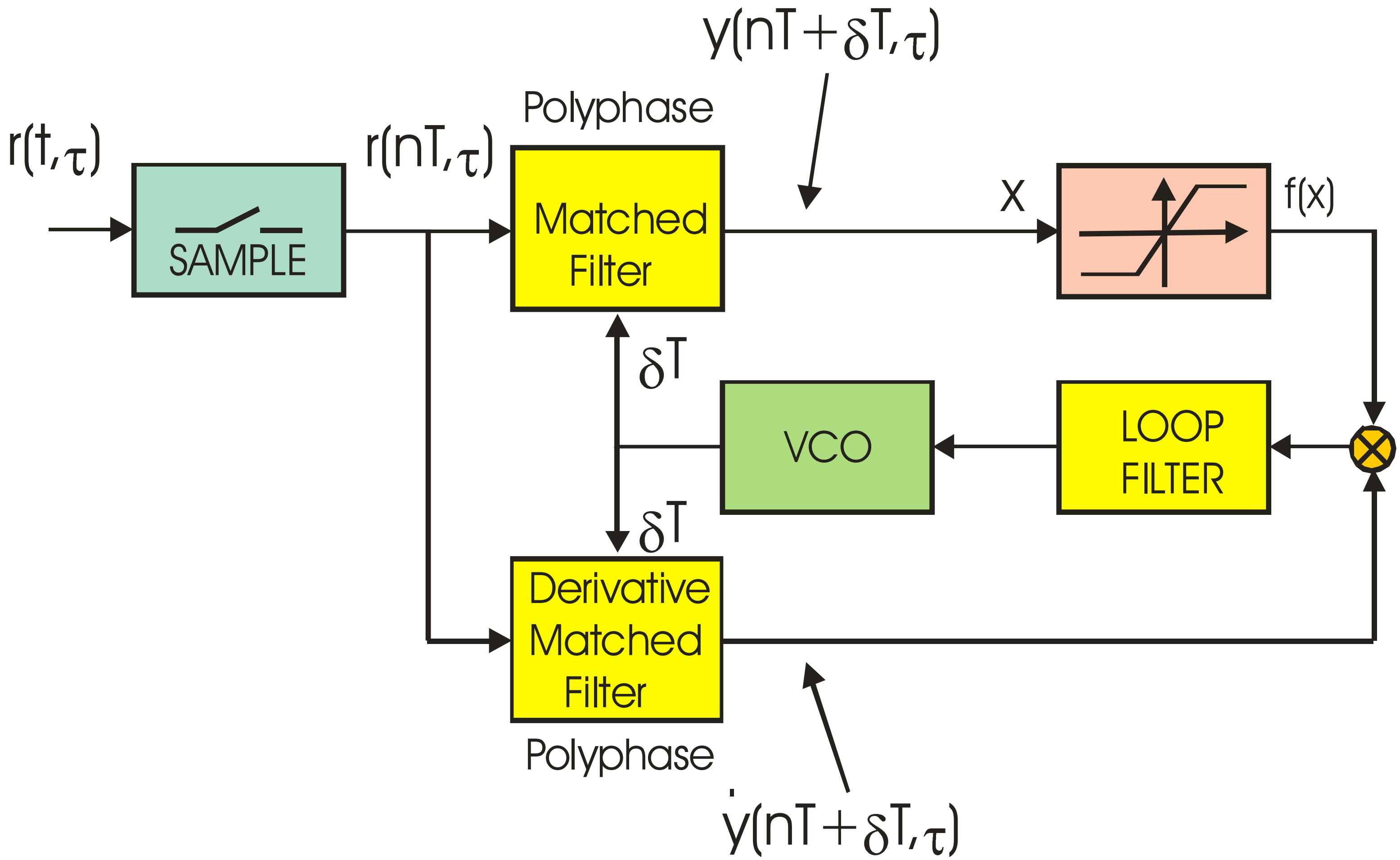
- Replace $2Eb/N_0$, SNR Gain with a Constant.
- Replace tanh(x) with Large SNR Approximation:

  $\tanh(x) \sim \mathrm{sign}(x)$
- Replace tanh(x) with Piecewise Approximation:

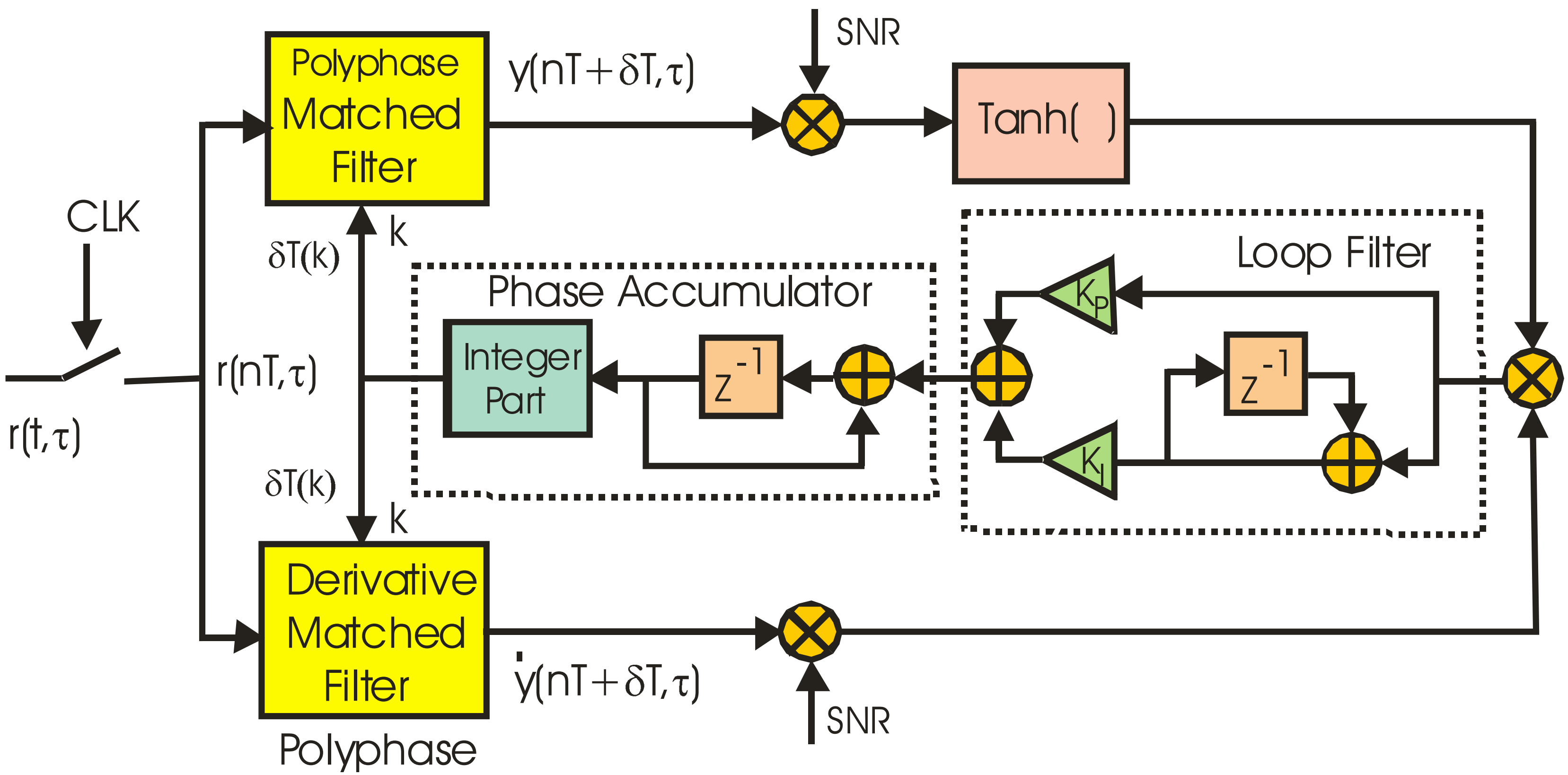
  $\tanh(x) \sim x \quad \text{for } |x| < 1$

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

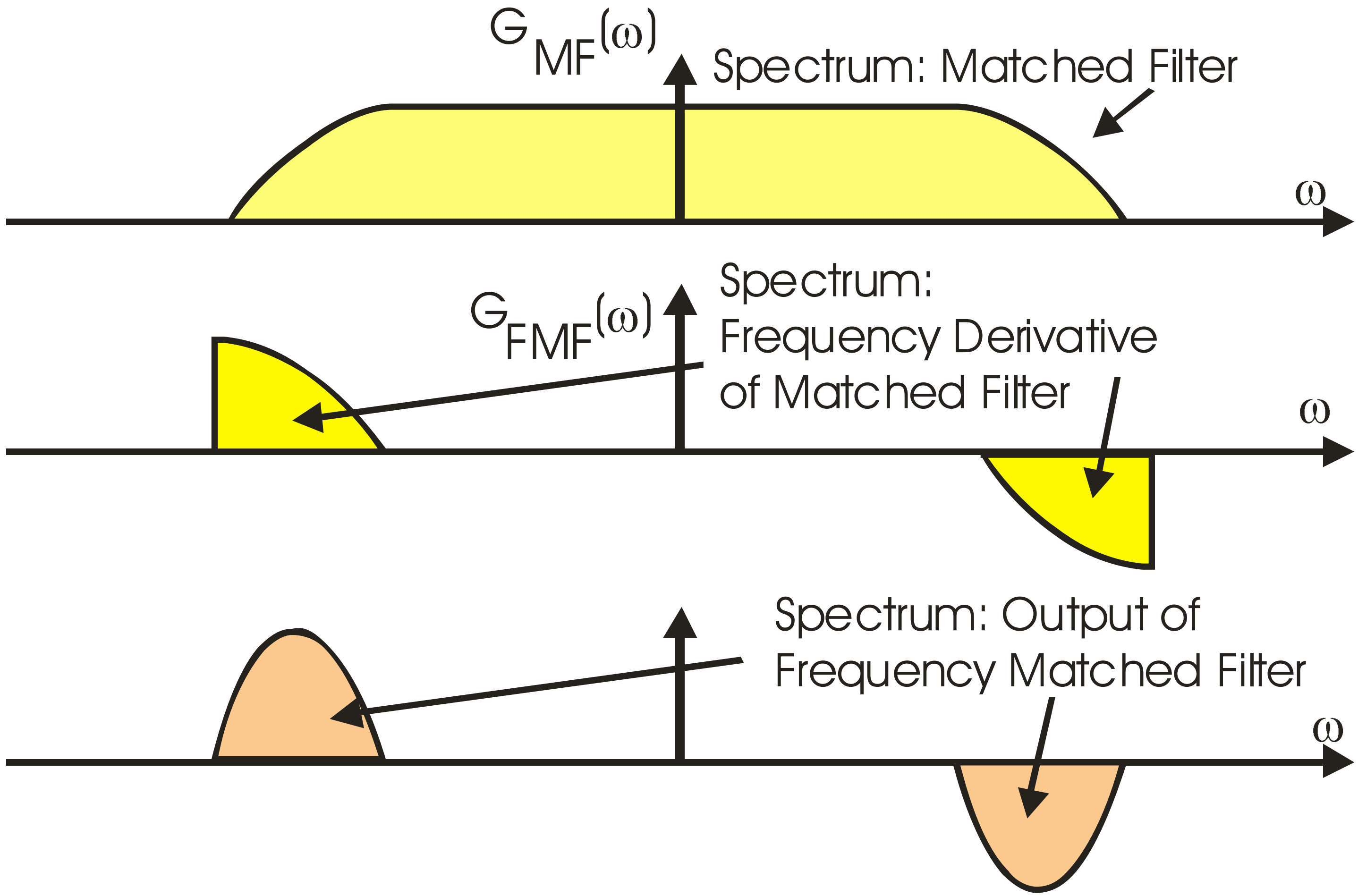
Sub Optimal Approximation



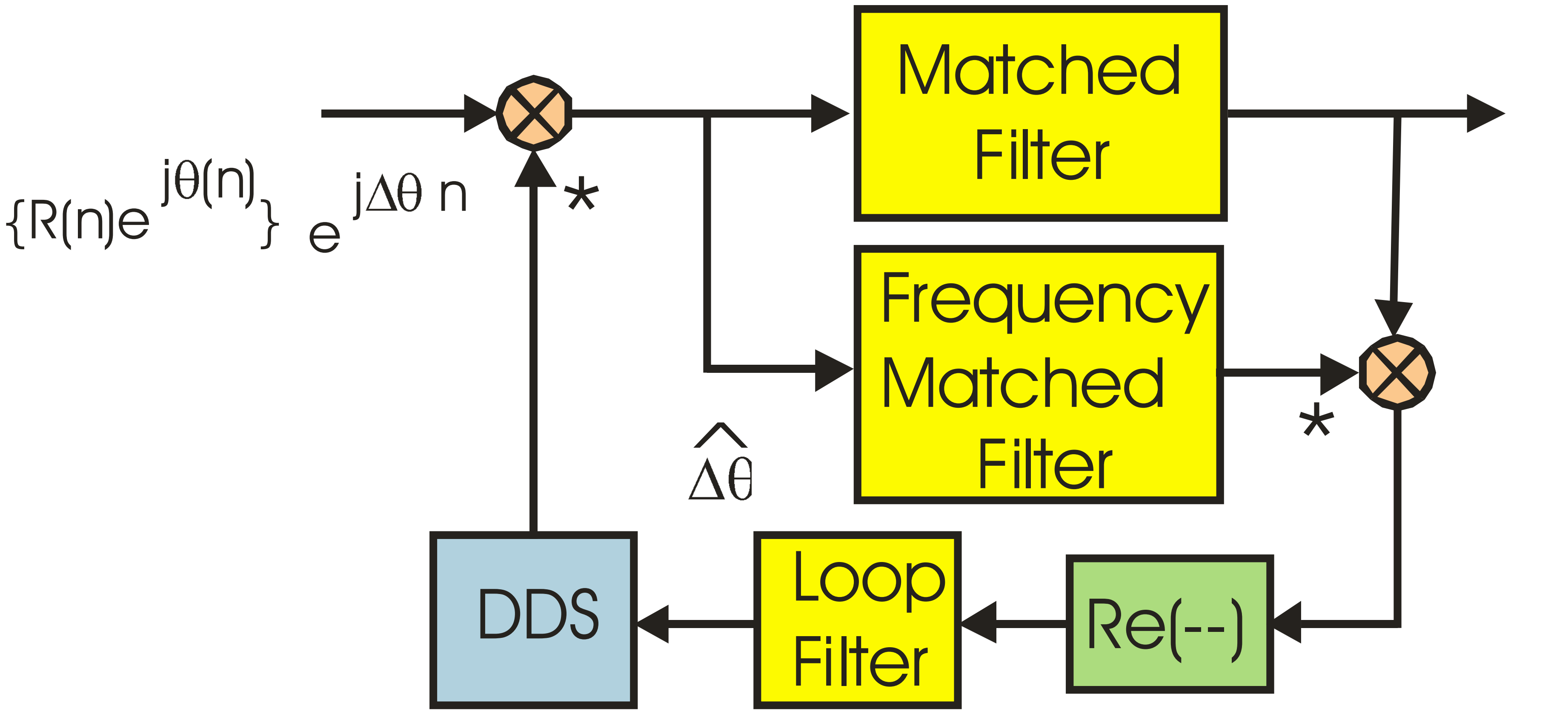
Second Tier Signal Processing Task, Timing Recovery Phase Locked Loop



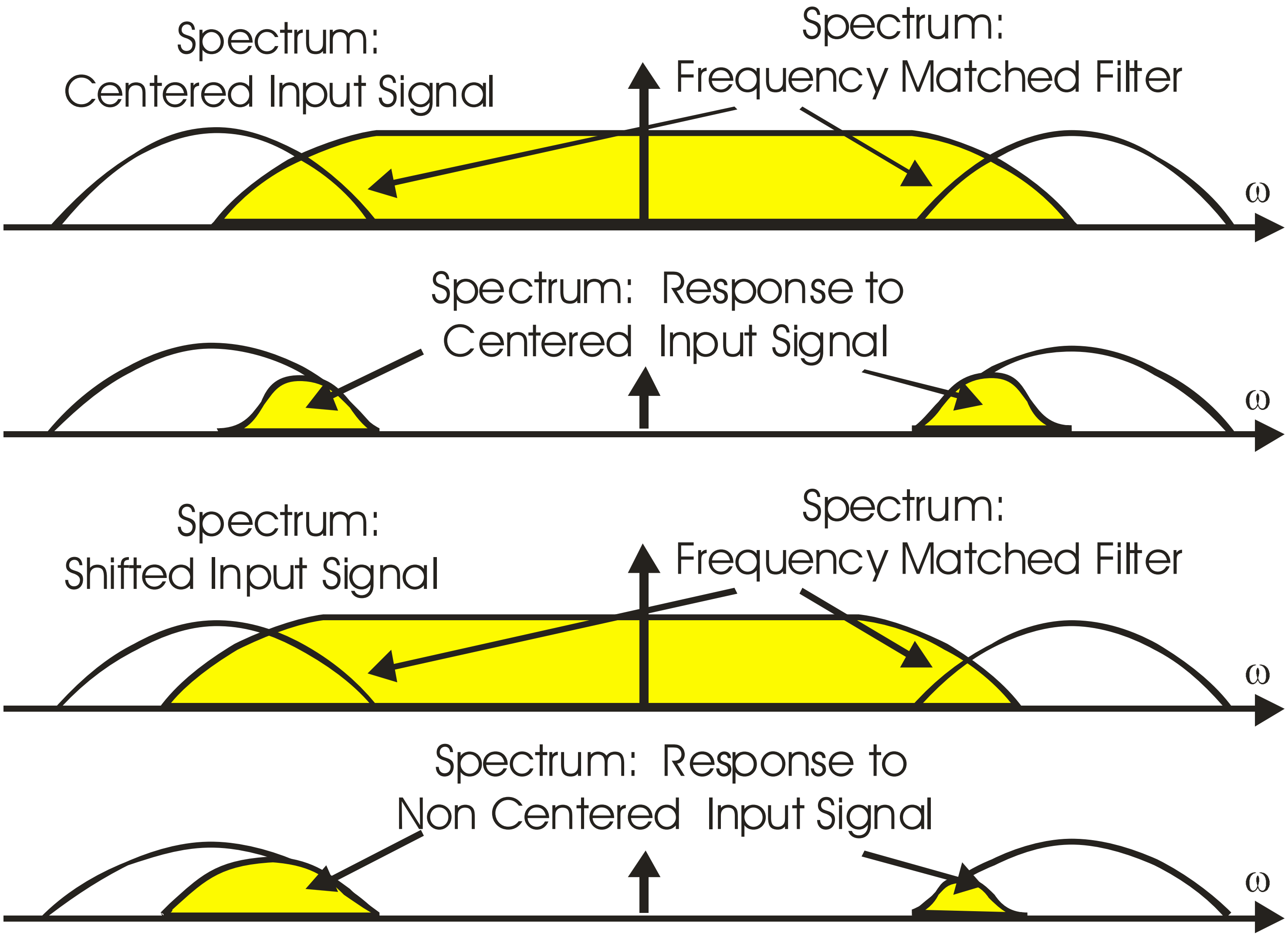
Band Edge Filter: BE(ω)=dH(ω)/dω



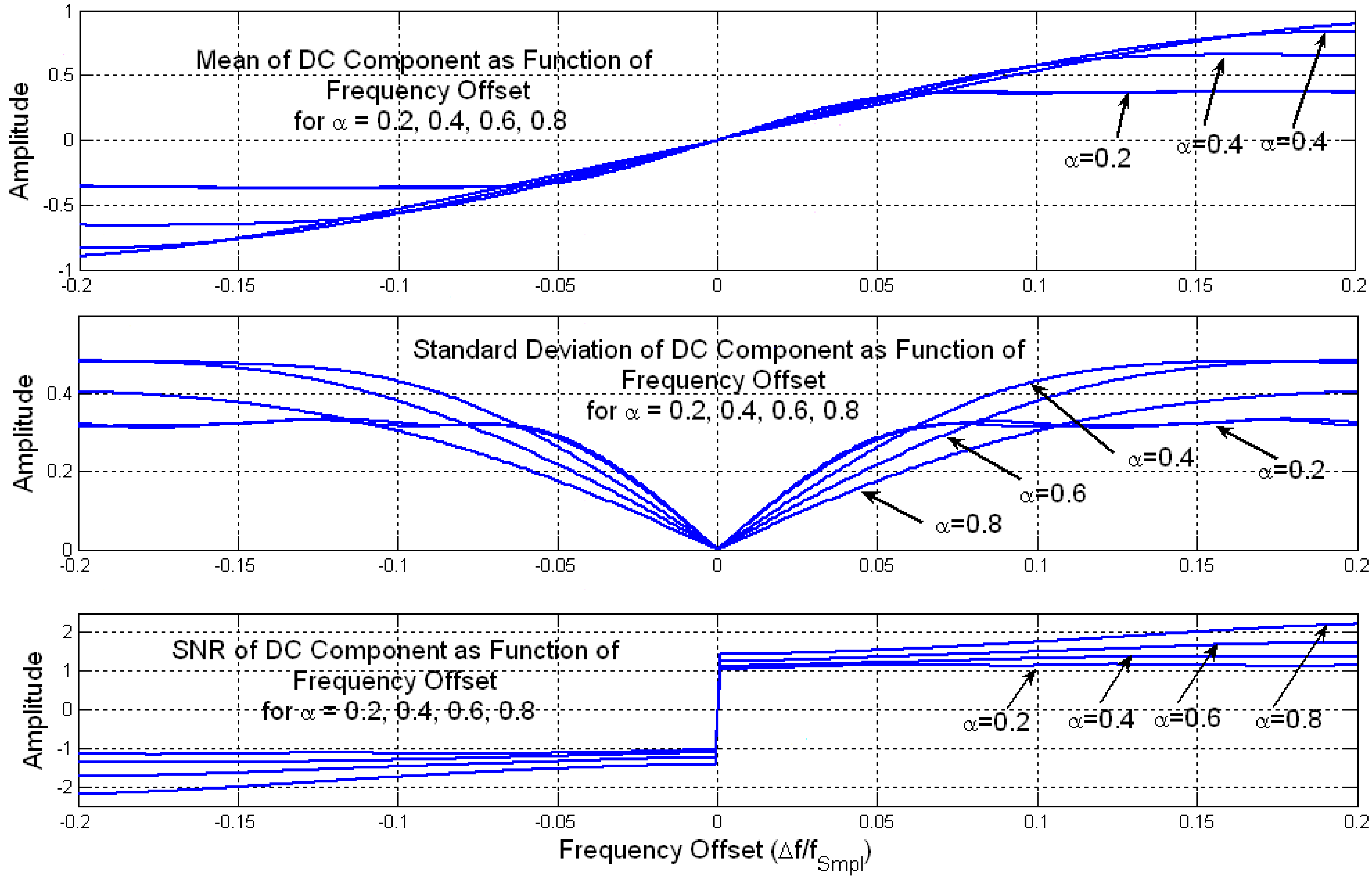
Band Edge Filter Based Frequency Locked Loop



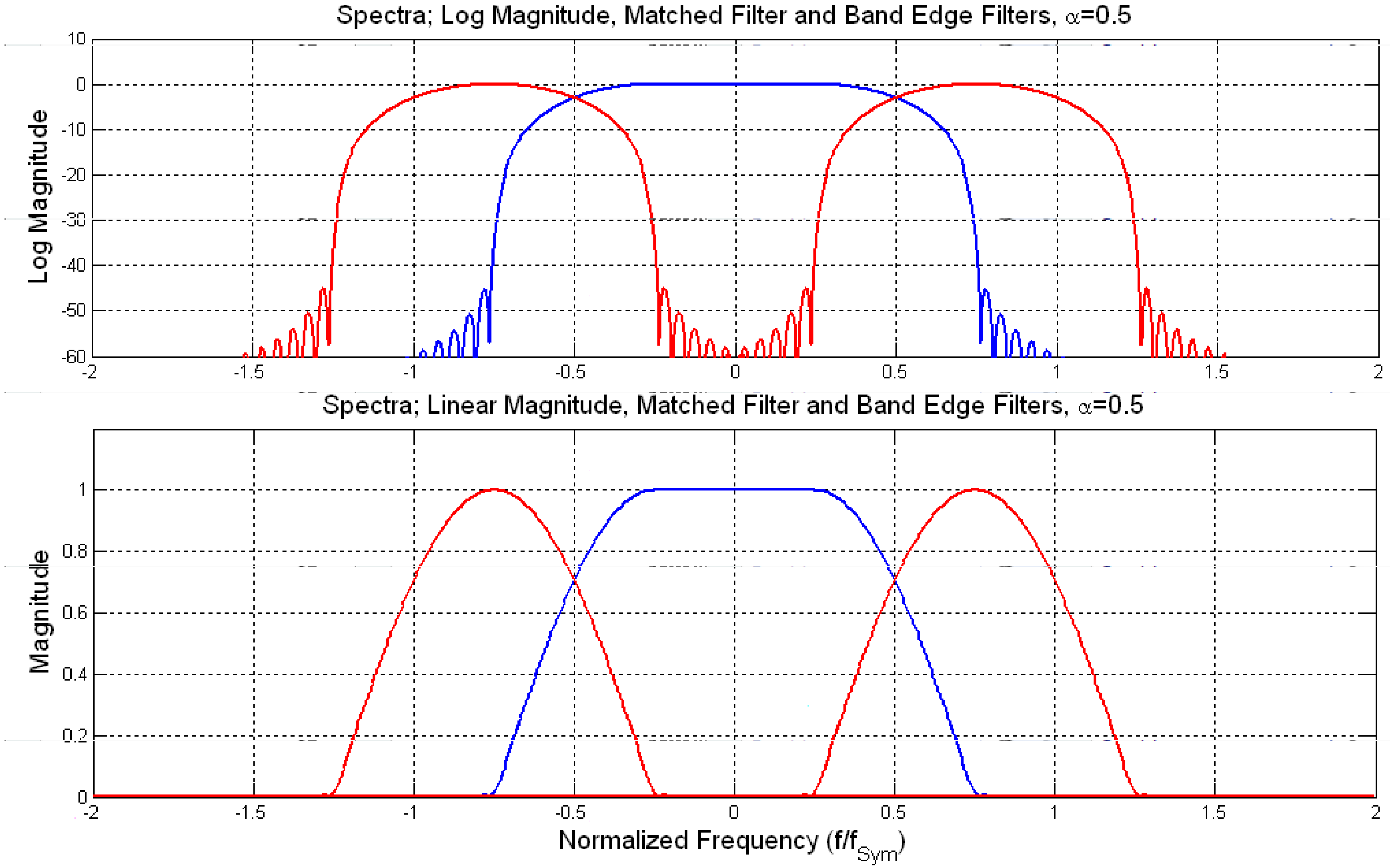
Energy Difference in Band Edges Sufficient Statistic to Frequency Lock



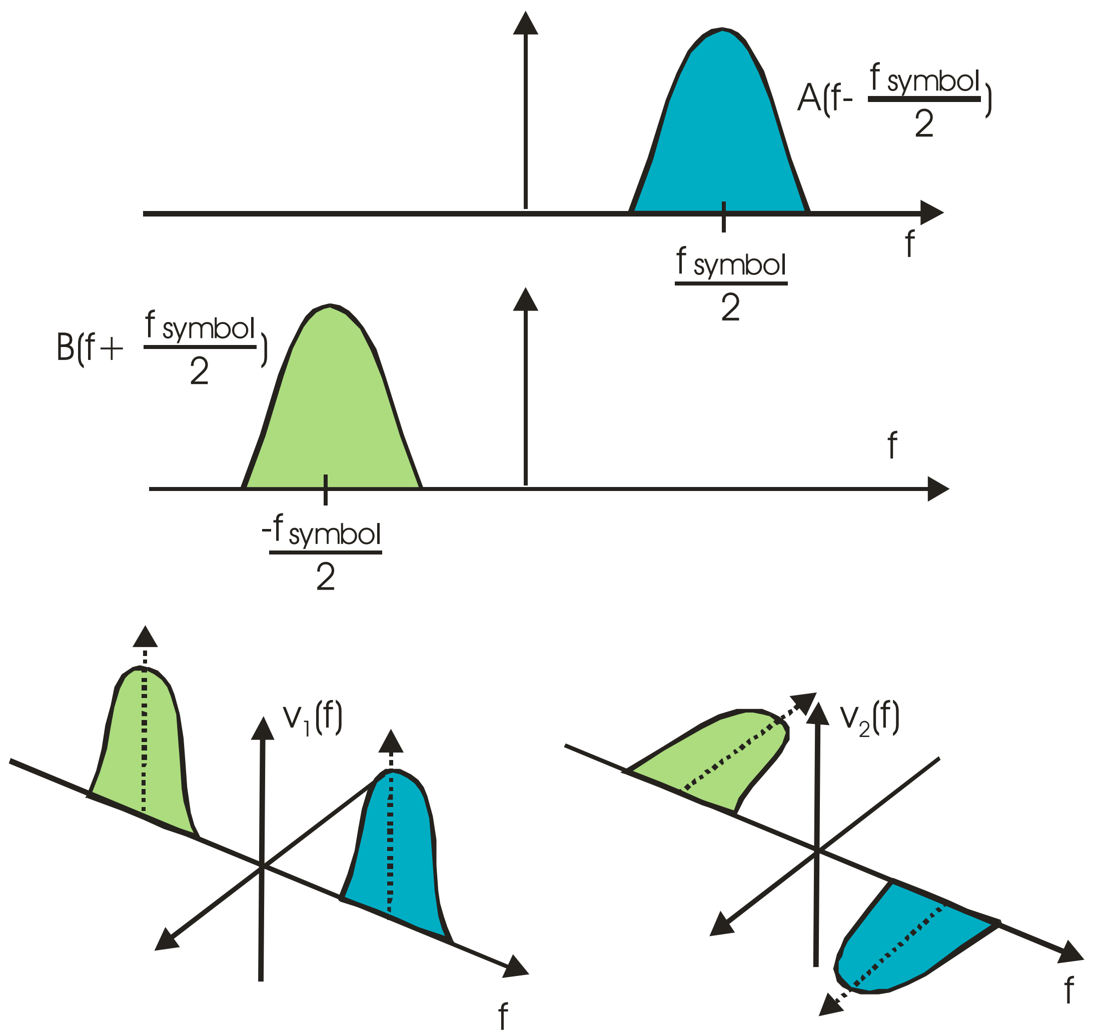
Mean and Variance of DC Term of Function of Frequency Offset



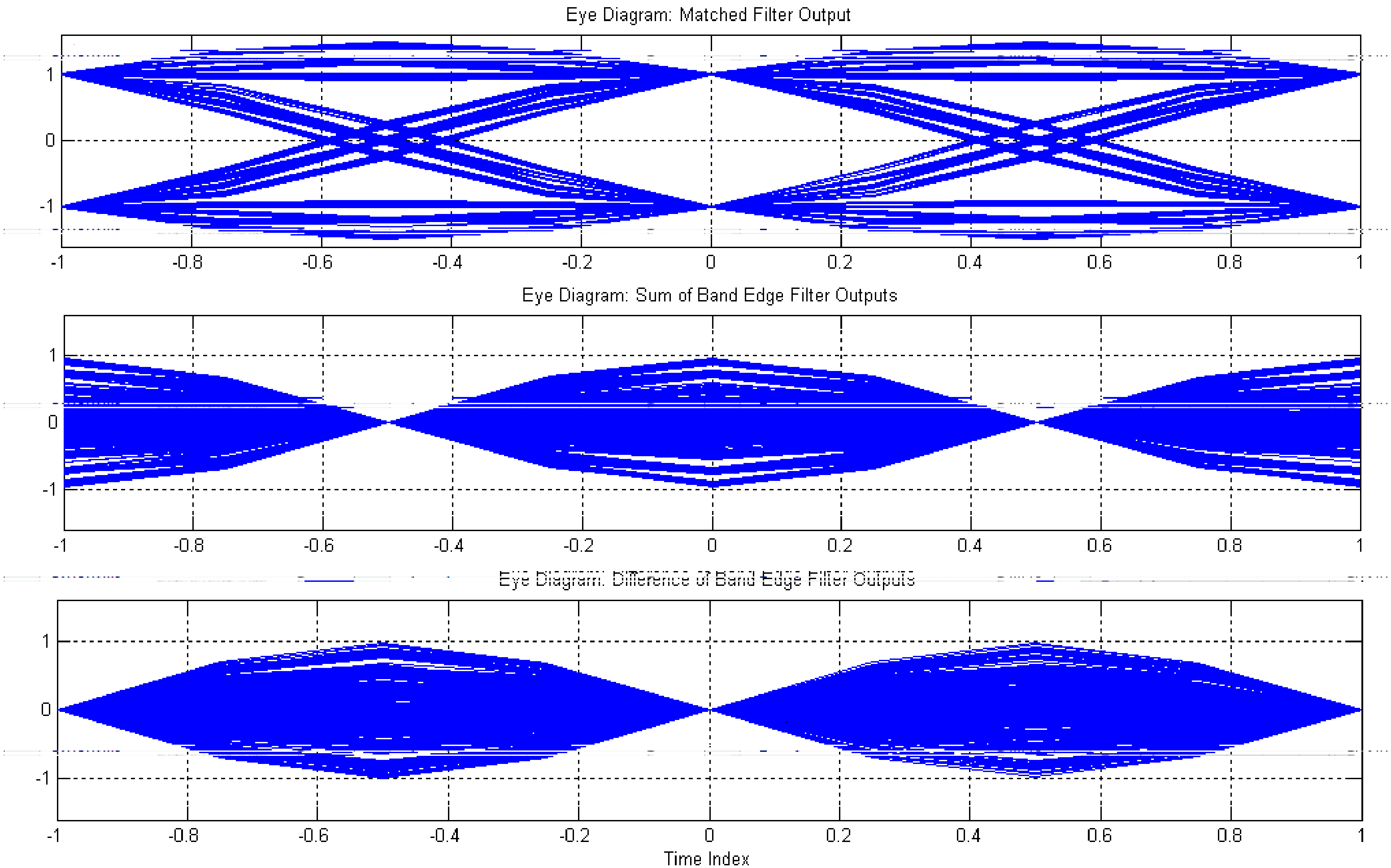
Spectra of Shaping and Band Edge Filters



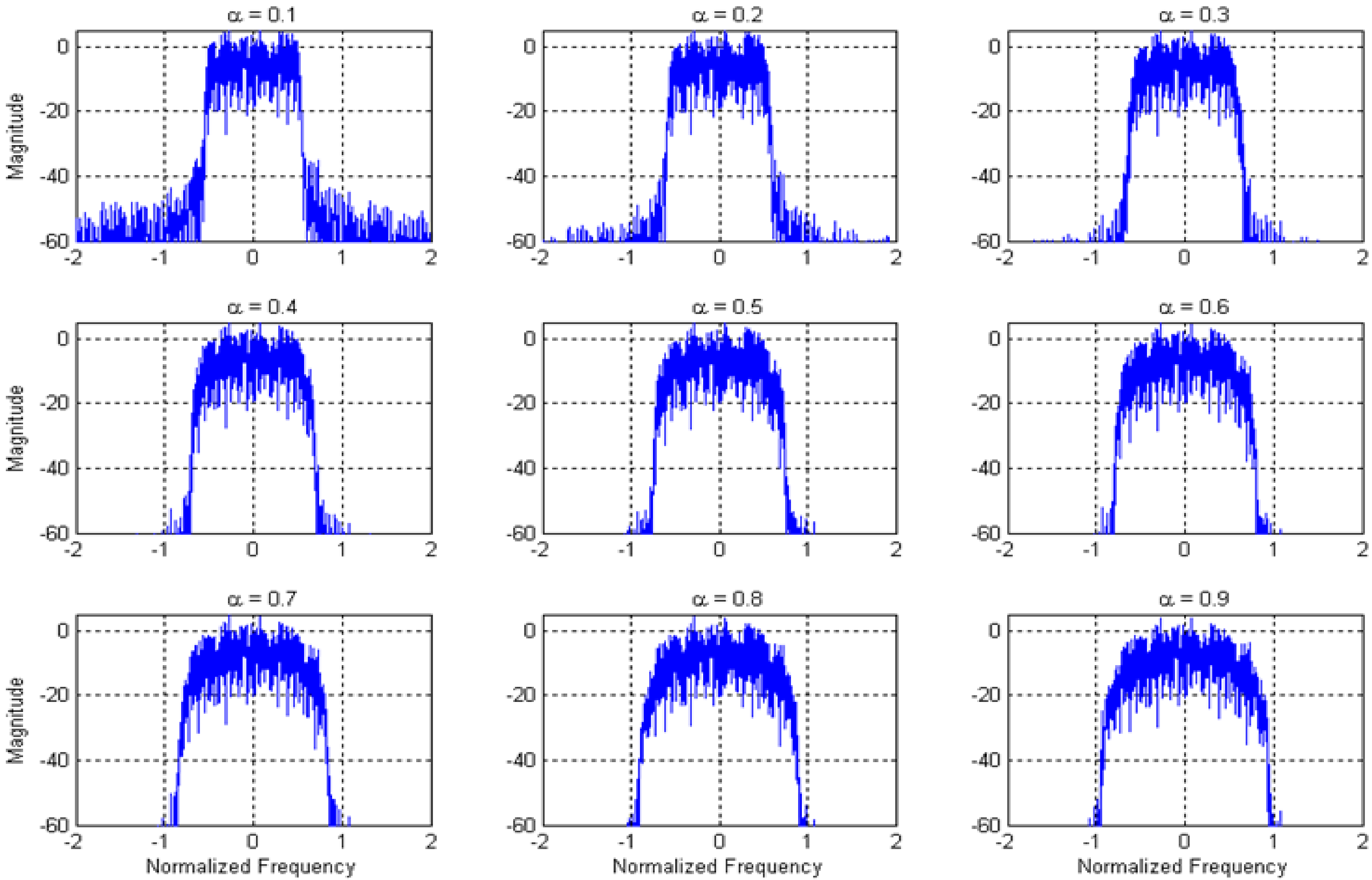
Spectra of Signals From Band Edges Combined to form Two New Signals



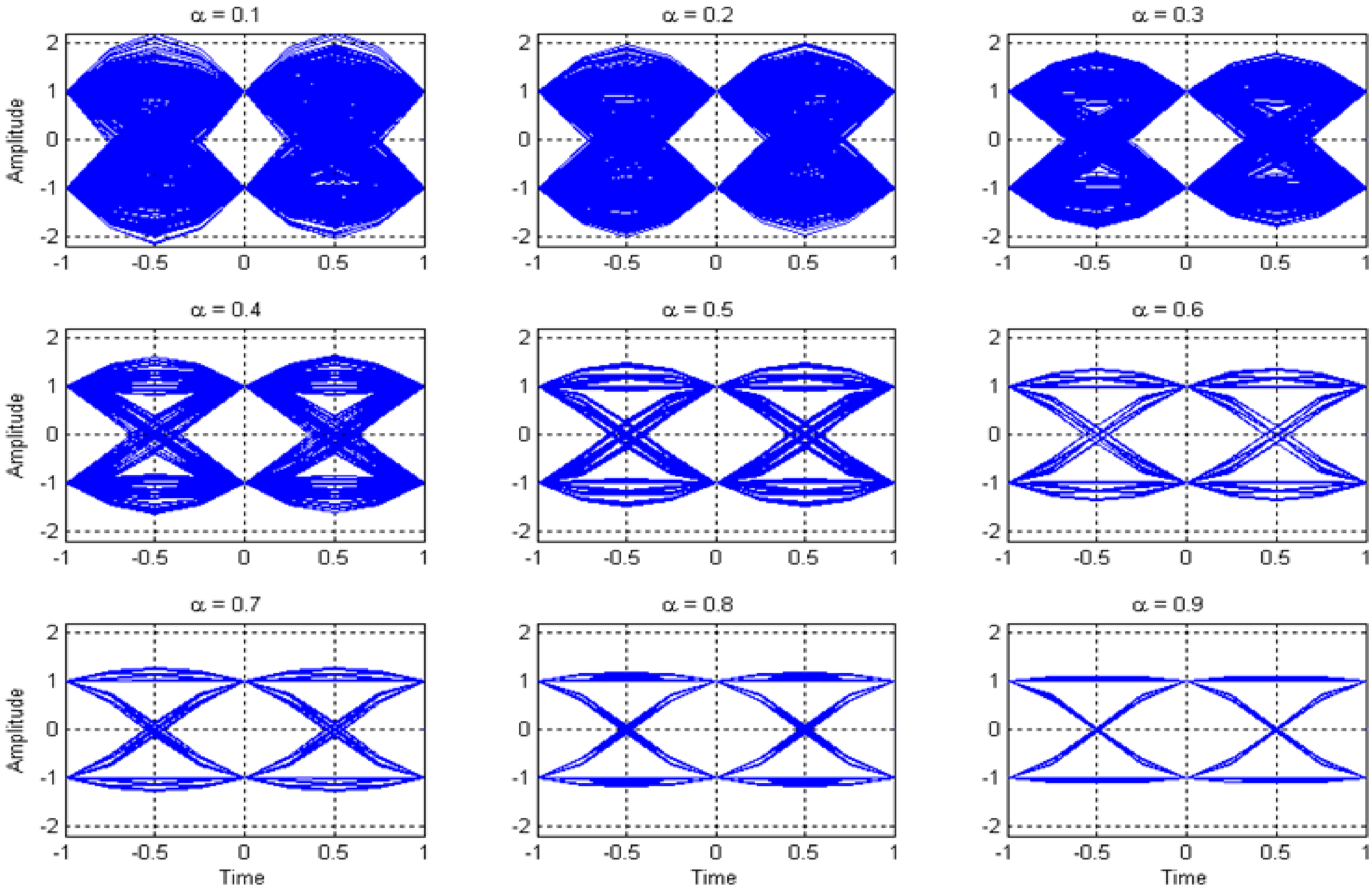
Eye Diagrams of Matched Filter and Sum and Difference Band-Edge Filters



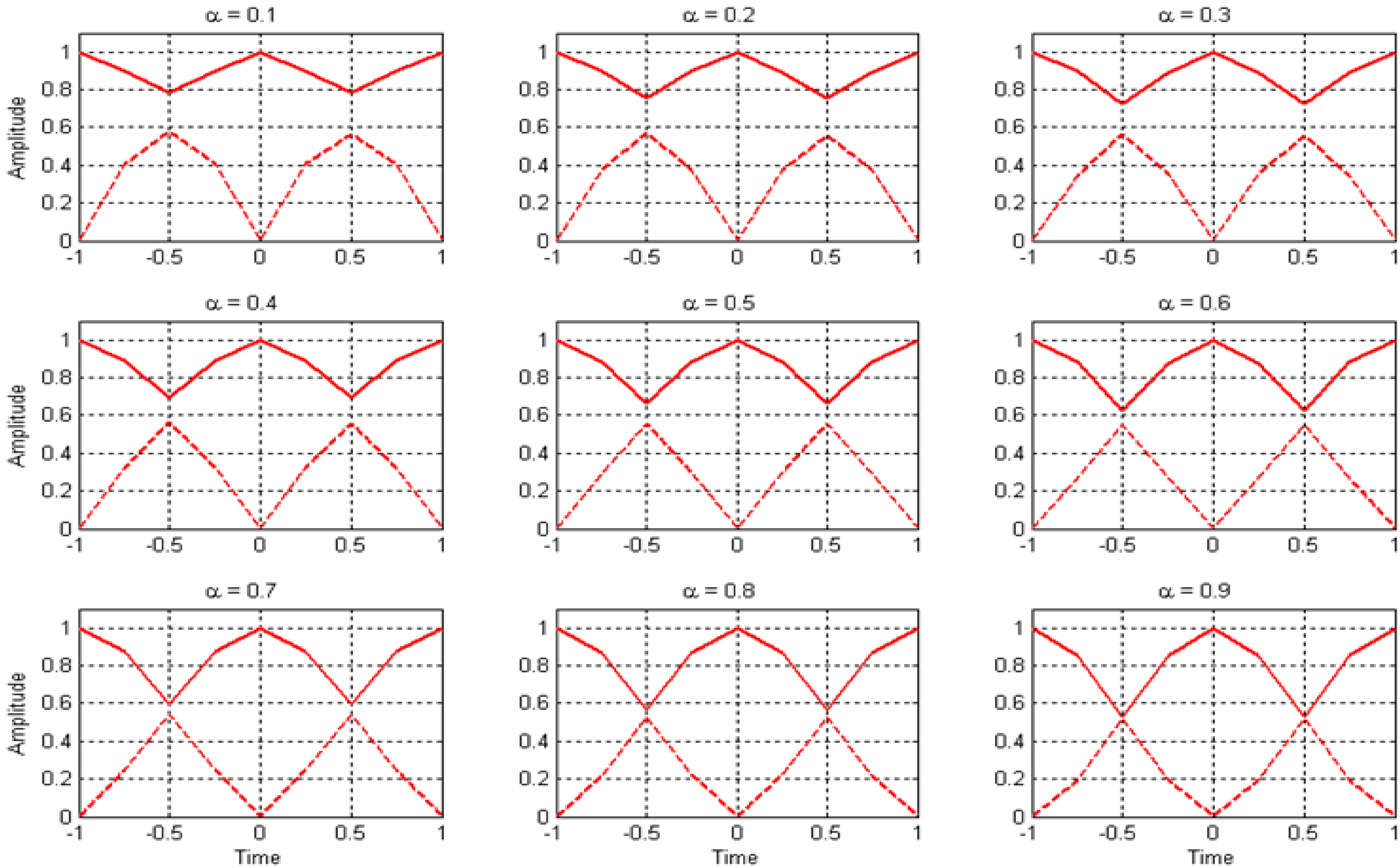
Spectra of SQRT Nyquist Shaped Modulation Signals over Range of Excess BW



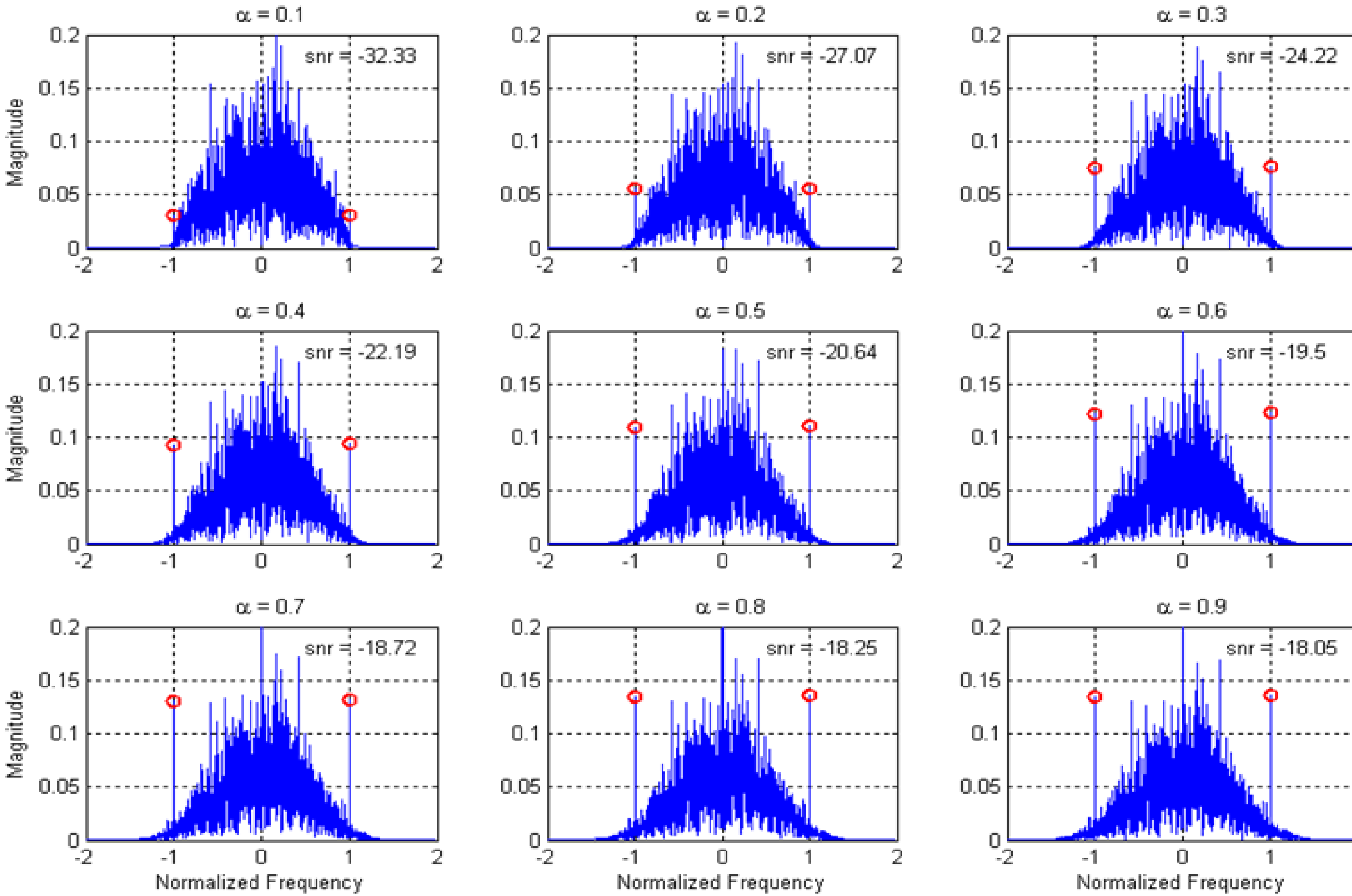
Eye Diagrams Matched Filter Output



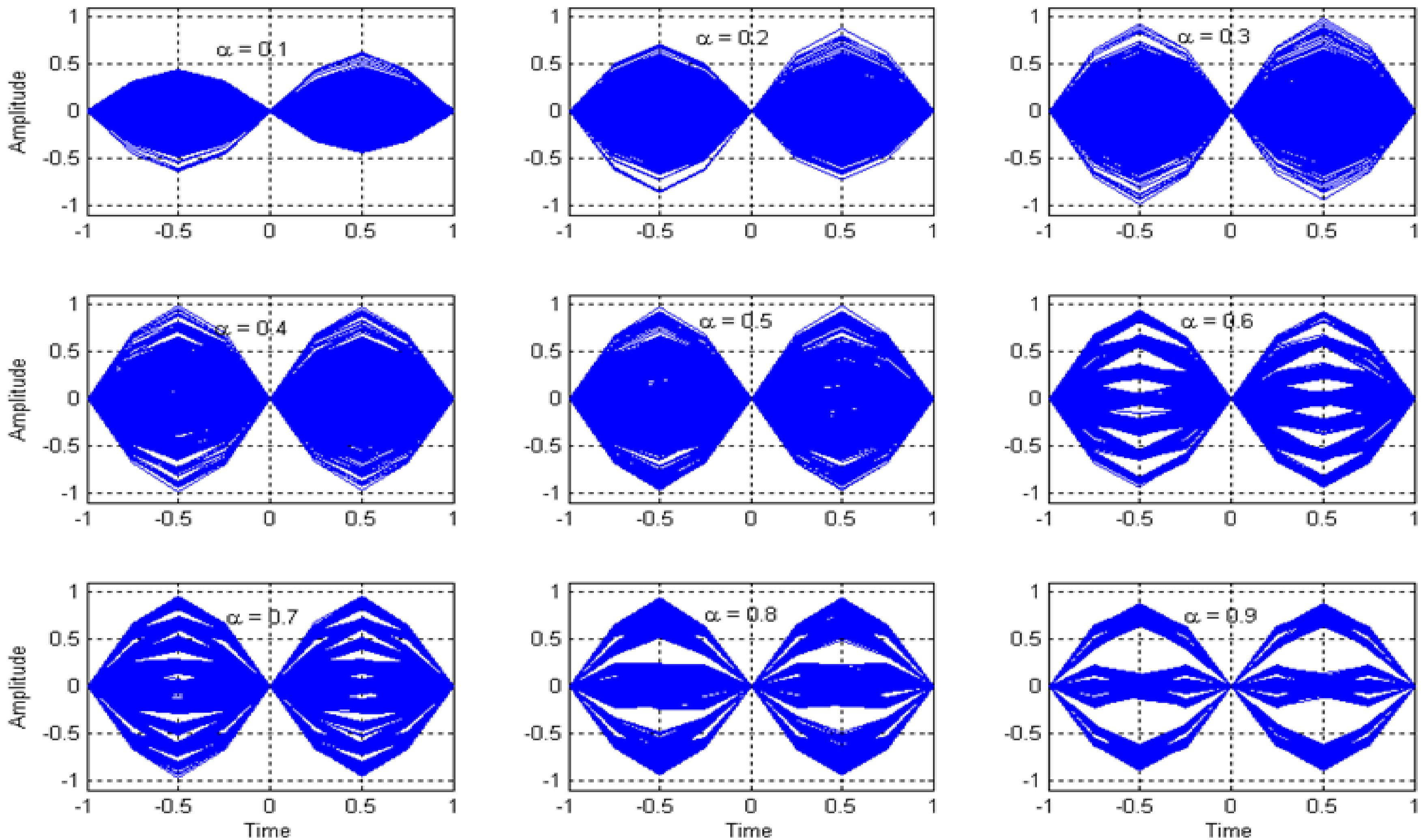
Cyclostationary Mean and Variance Eye Diagrams Magnitude Matched Filter



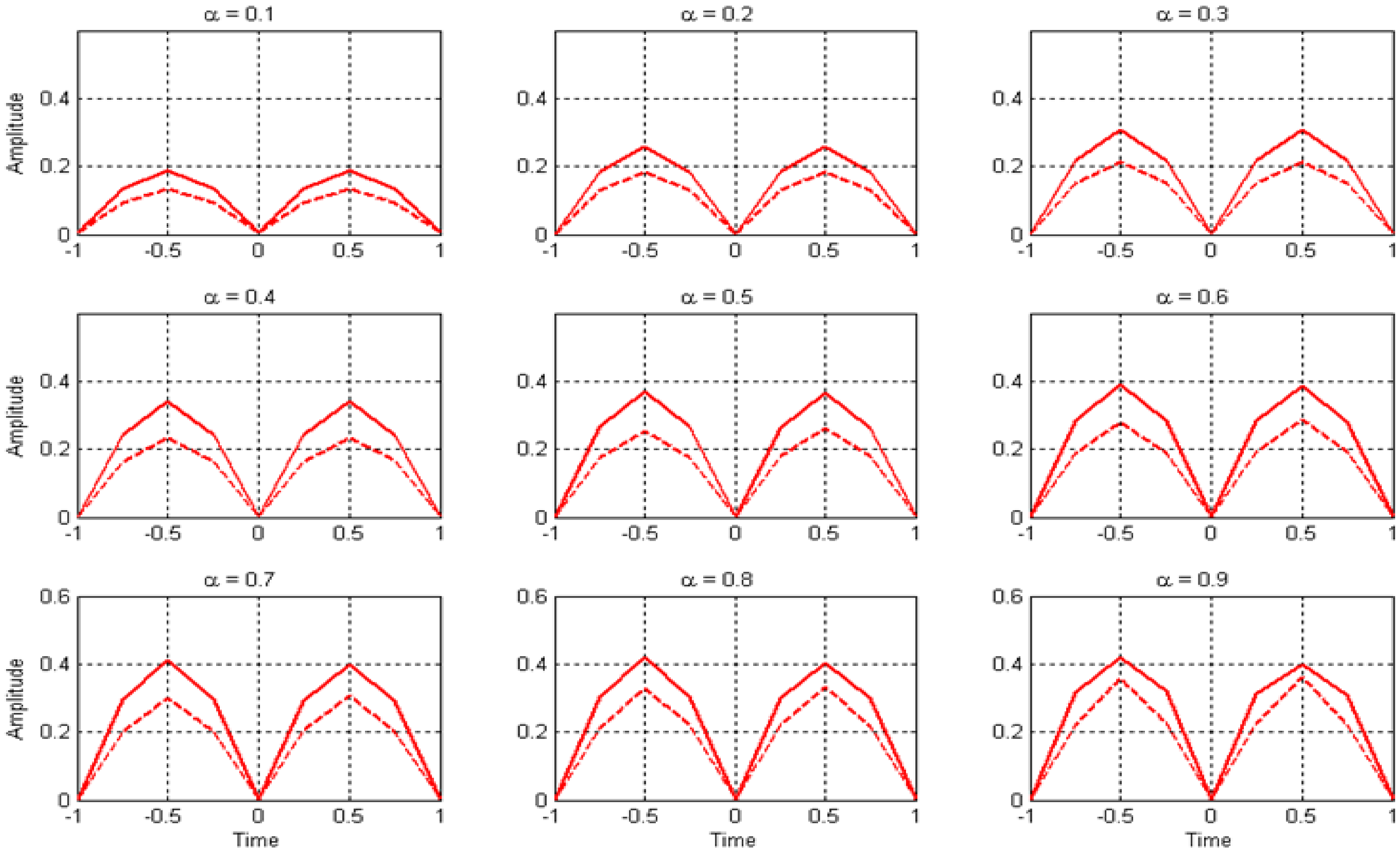
Spectral Lines from Excess BW: $MF(\omega) \times MF(\omega)^*$



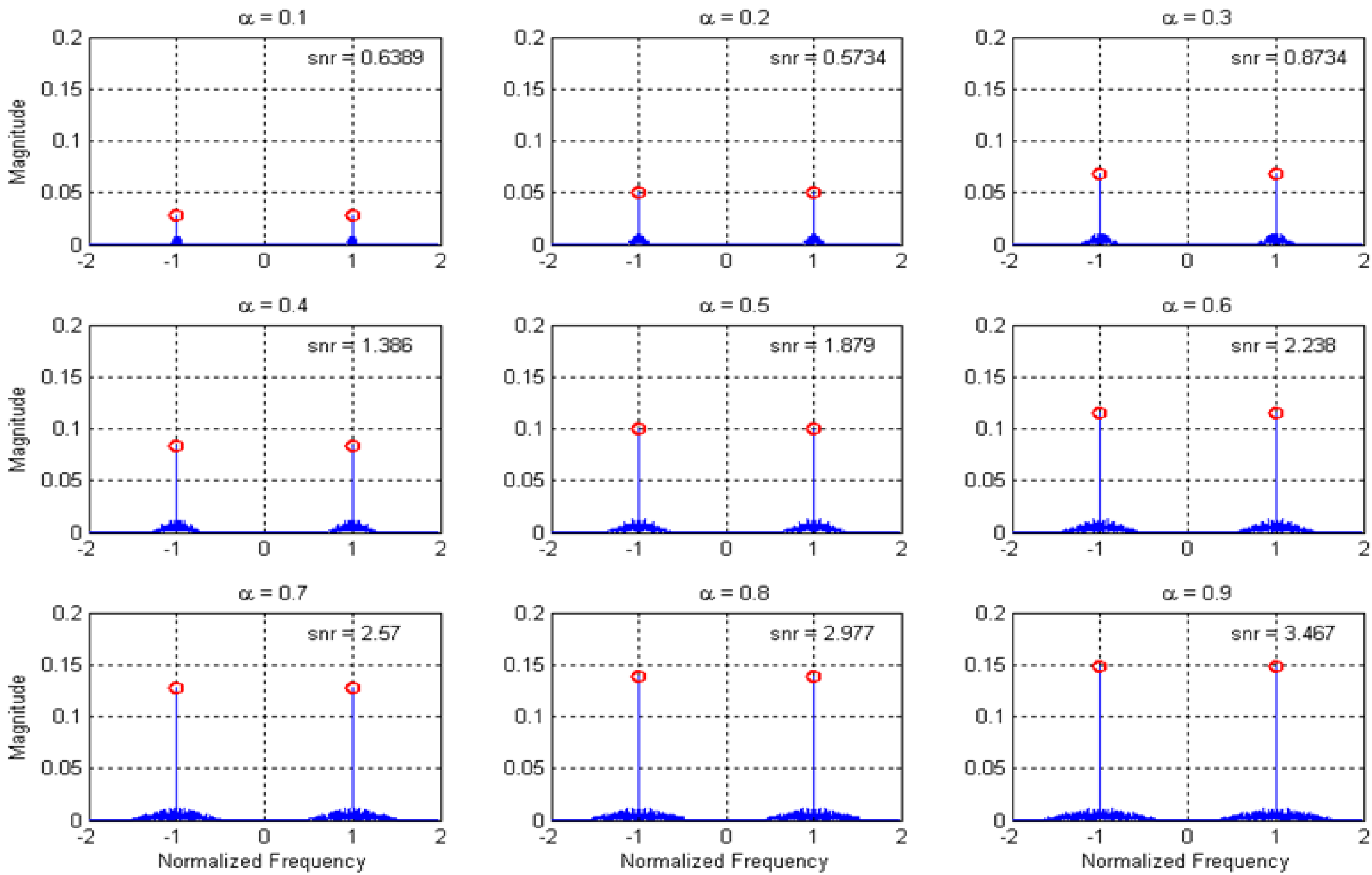
Eye Diagrams Band Edge Filter Output



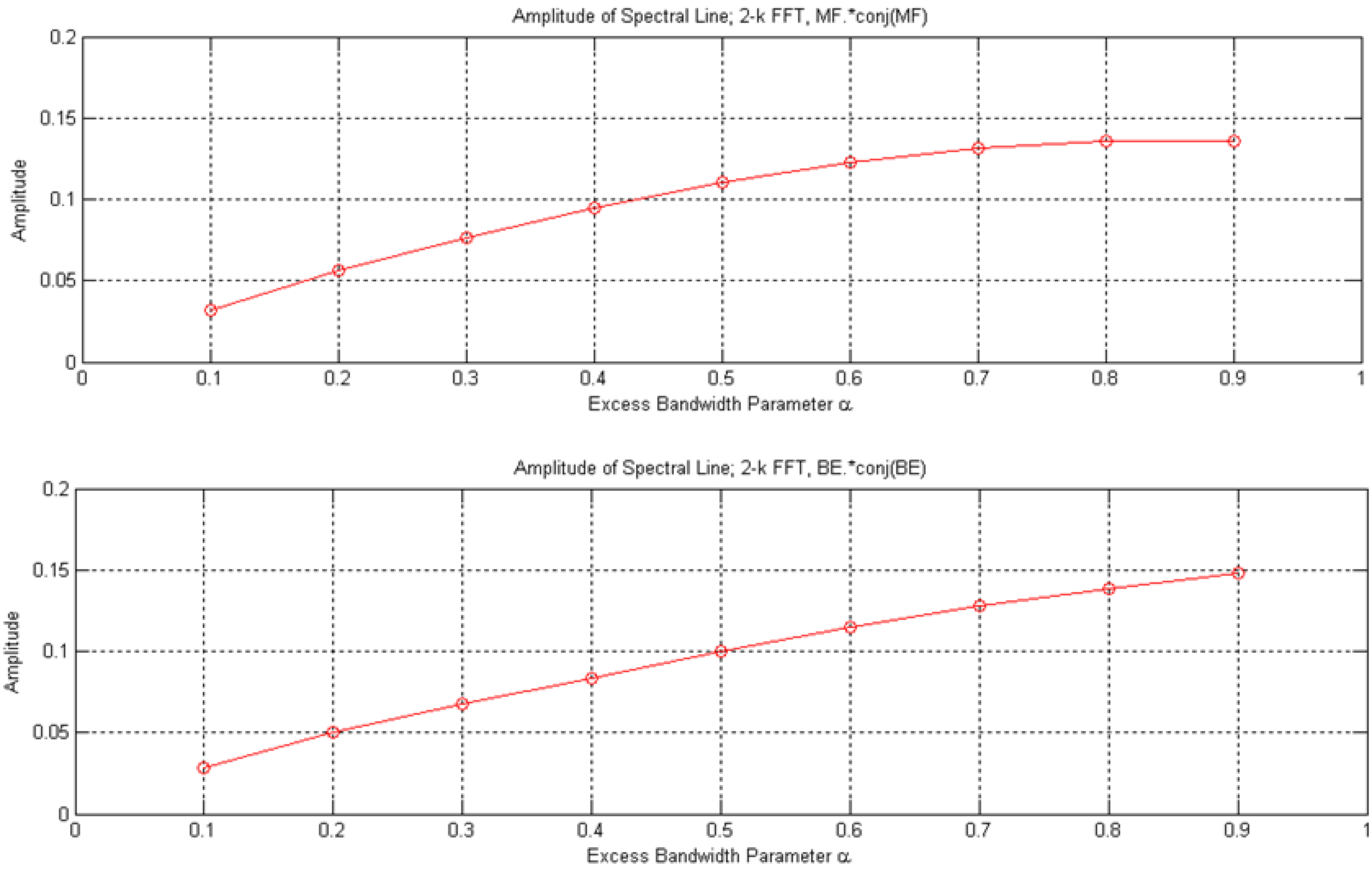
Cyclostationary Mean and Variance Eye Diagrams Magnitude Band Edge Filter



Spectra of BE(ω)xBE(ω)*



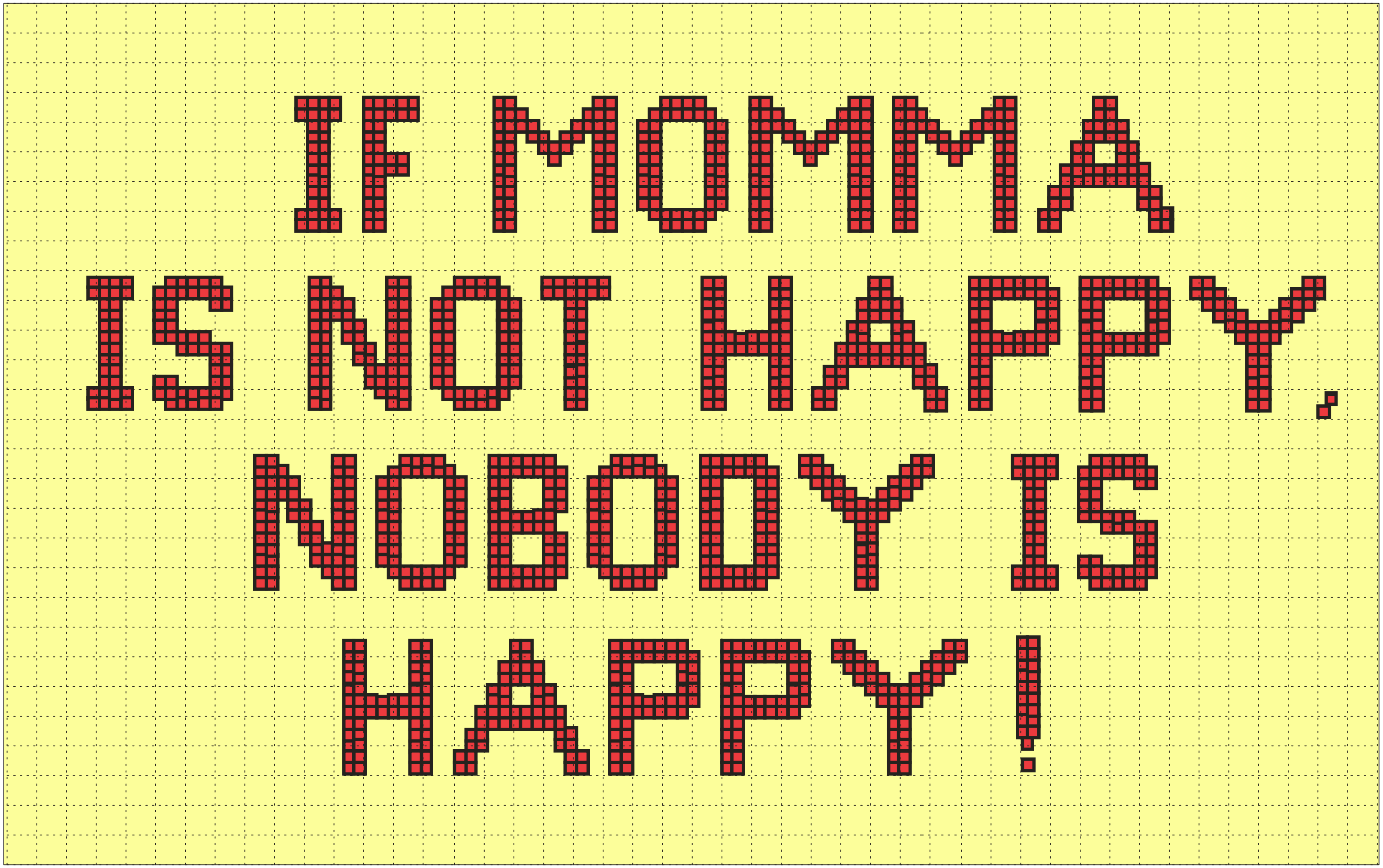
Amplitude of Spectral Timing Line from Excess Bandwidth



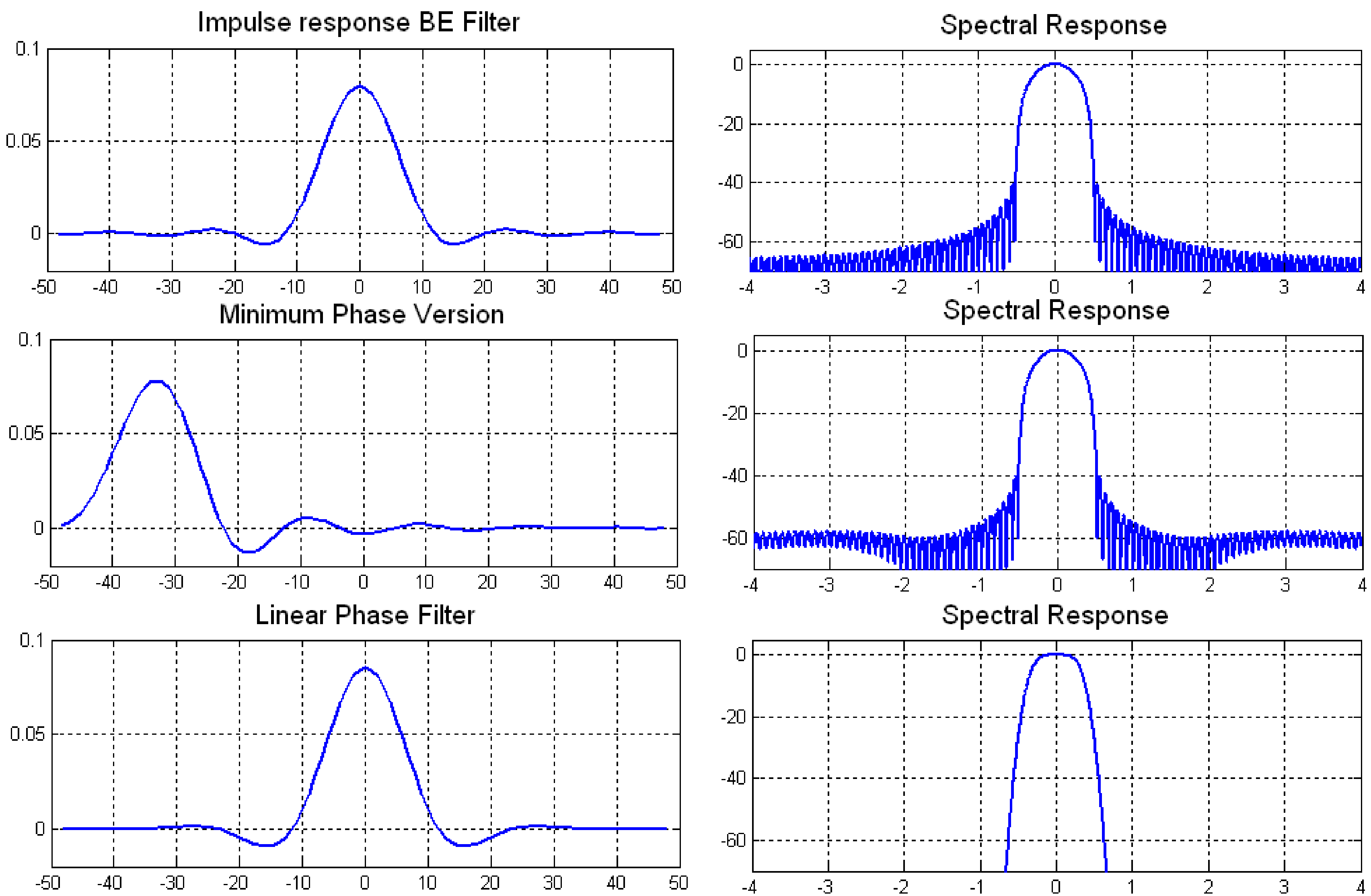
What Happens if there is no excess BW?

- 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!)

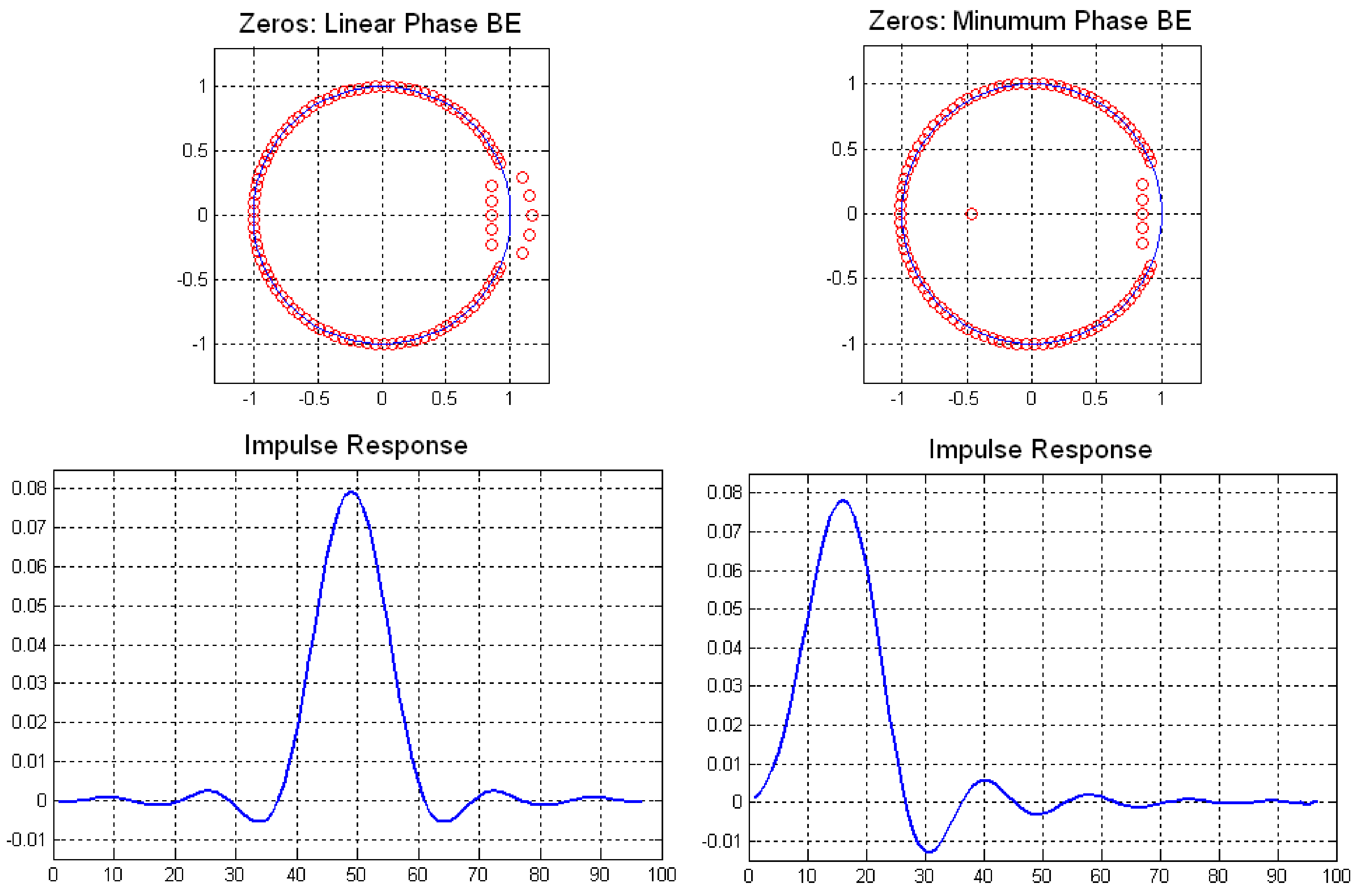
The Synchronizers' Needle Point



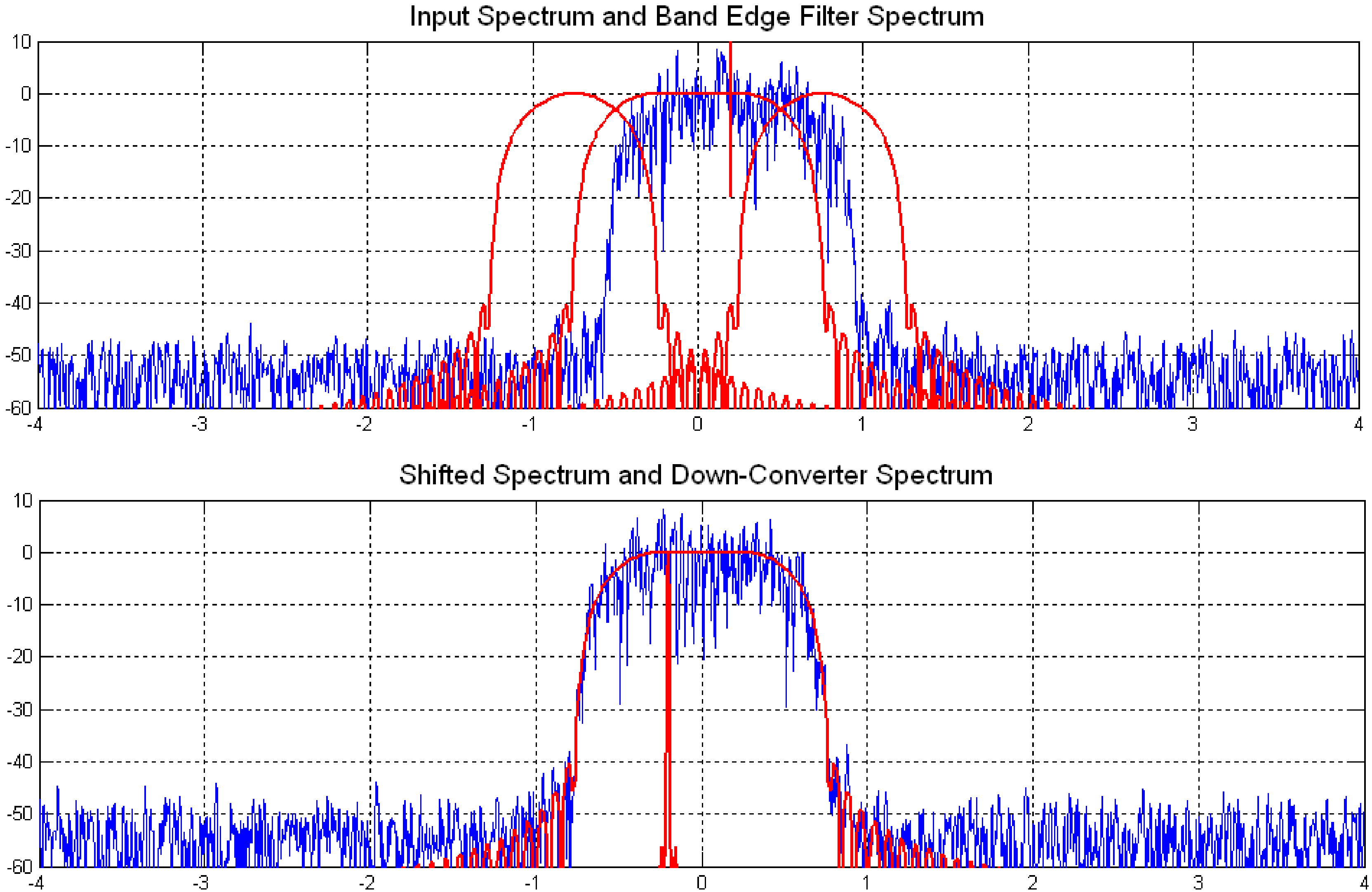
Band Edge Filters and Approximations



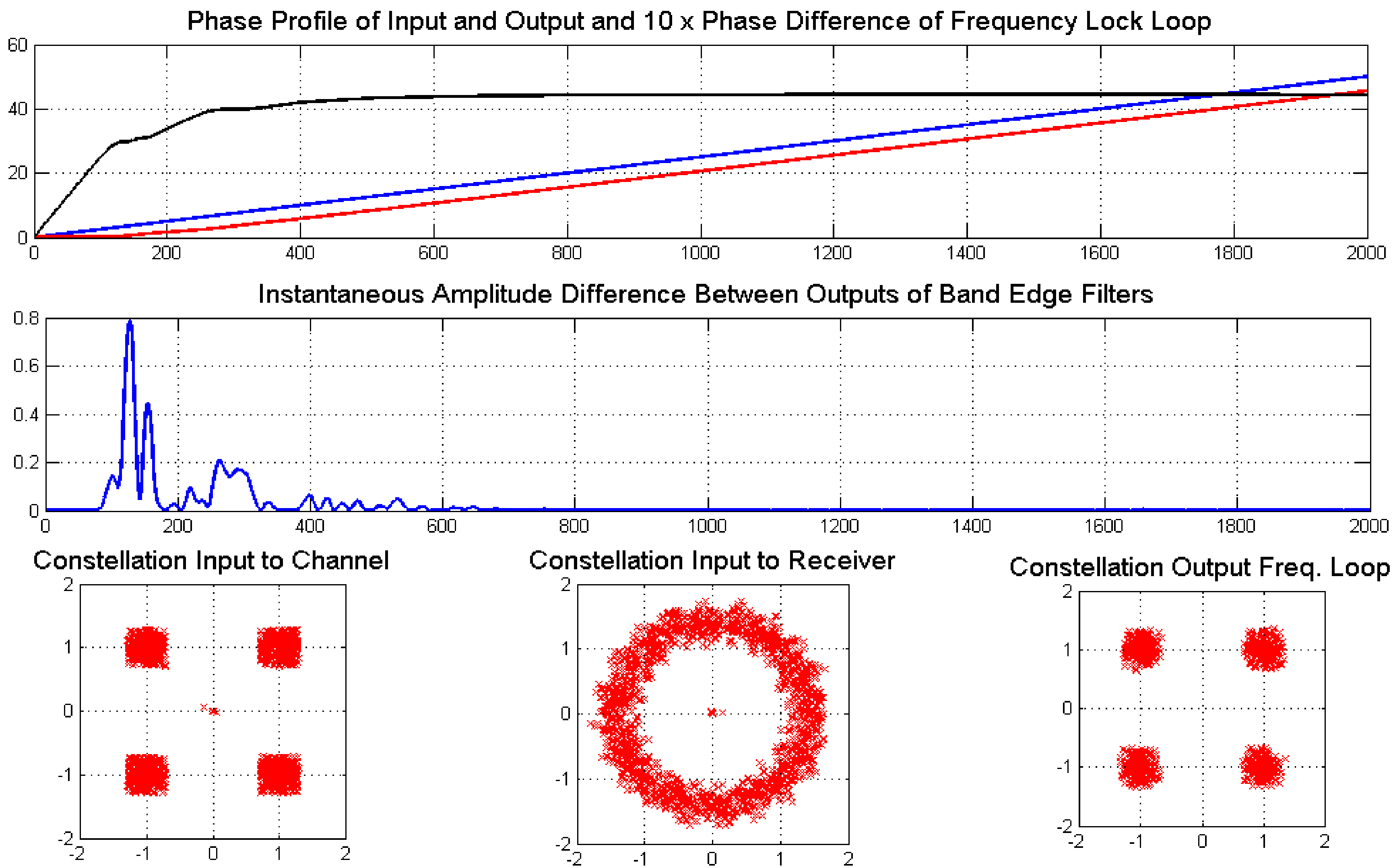
Linear and Minimum Phase BE Filters



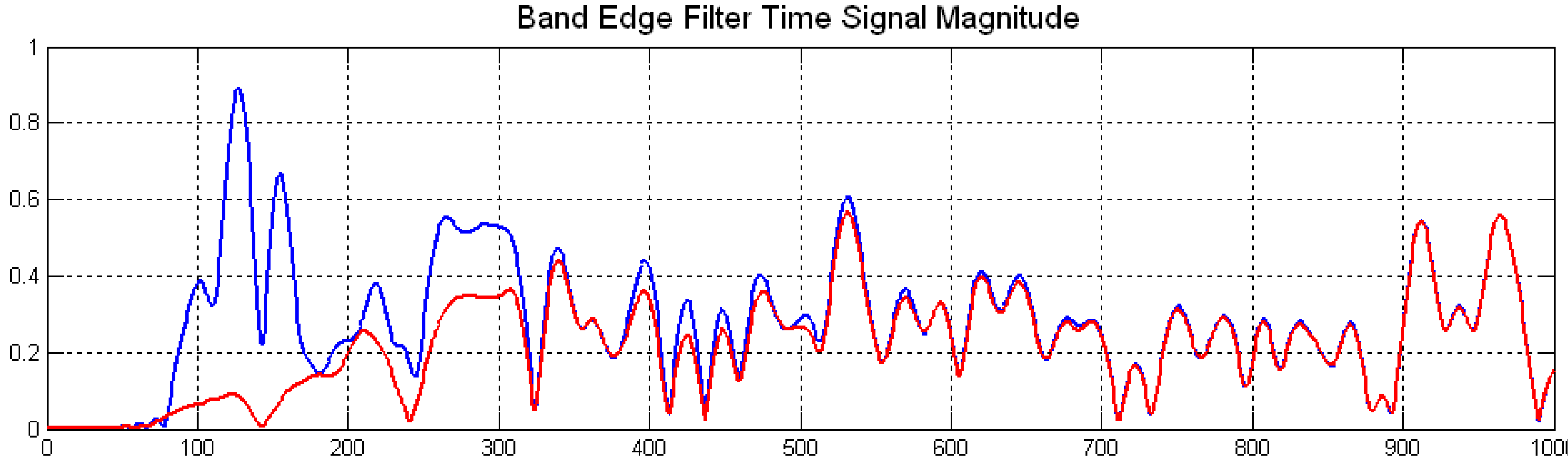
Frequency Offset Spectra and BE Filters in Frequency Lock Loop

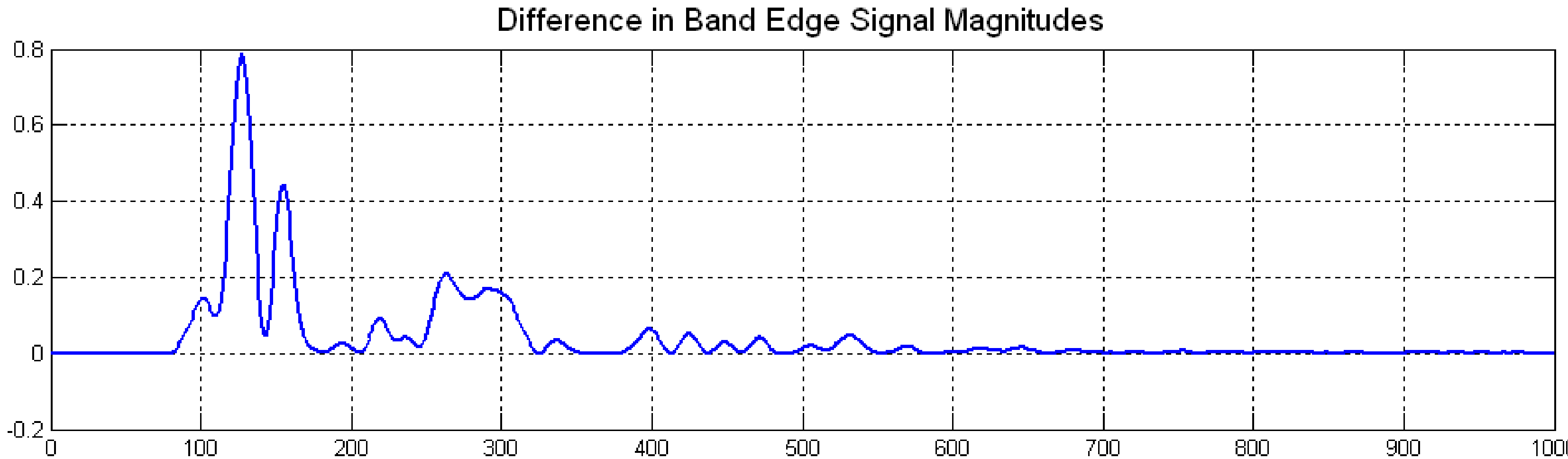


Phase Profiles of Freq Lock Loop

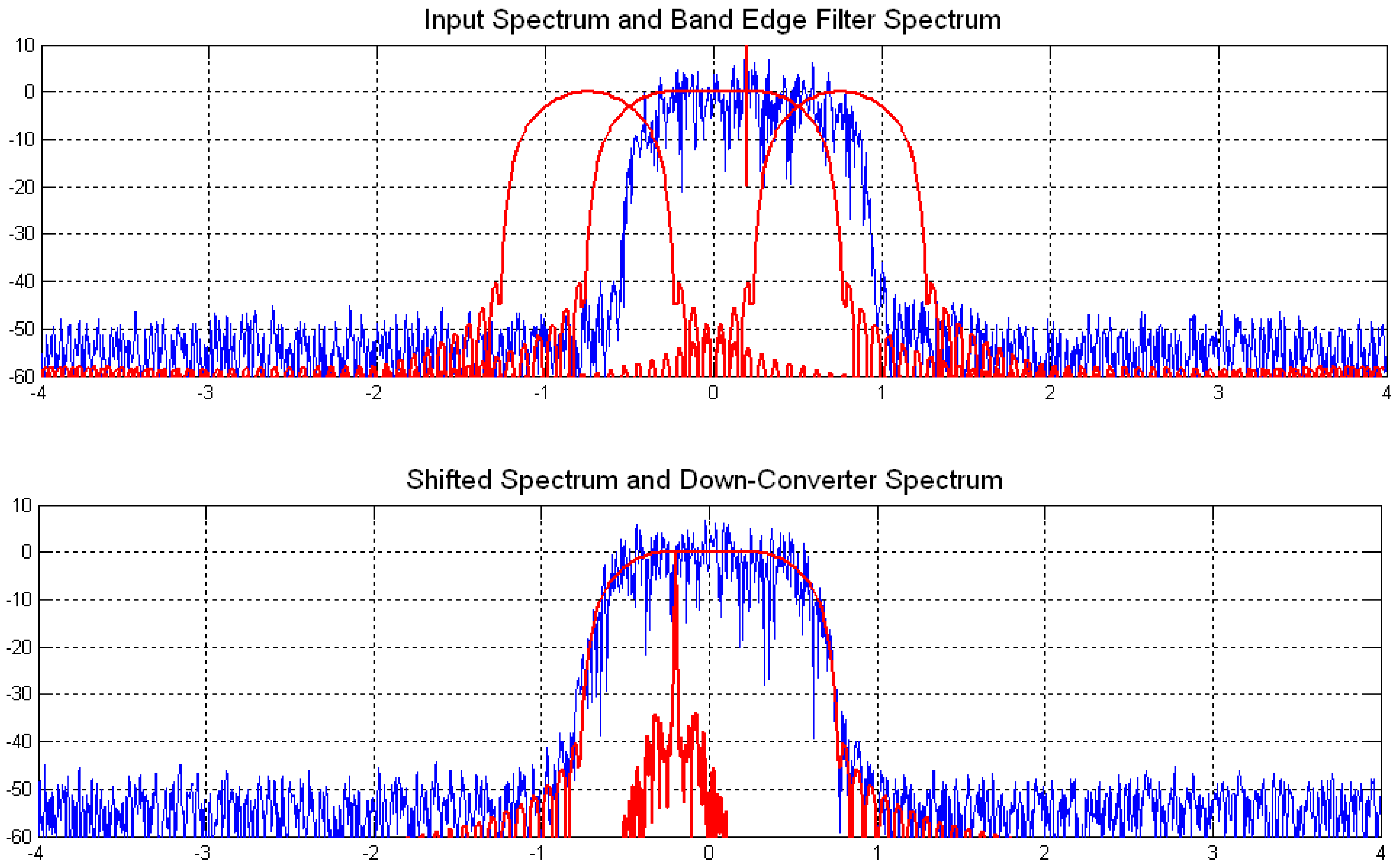


Time Series from BE Filters During Frequency Acquisition

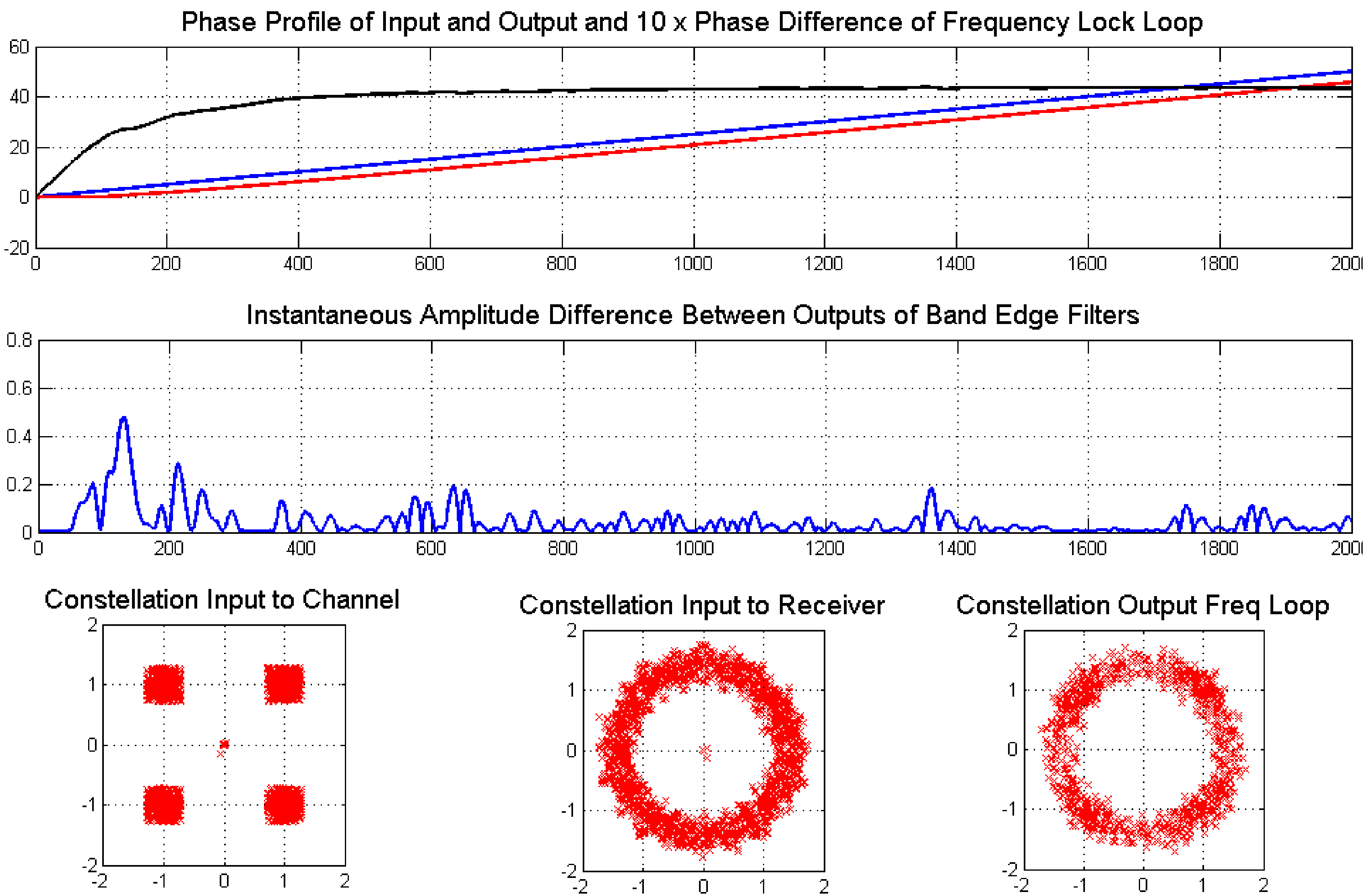




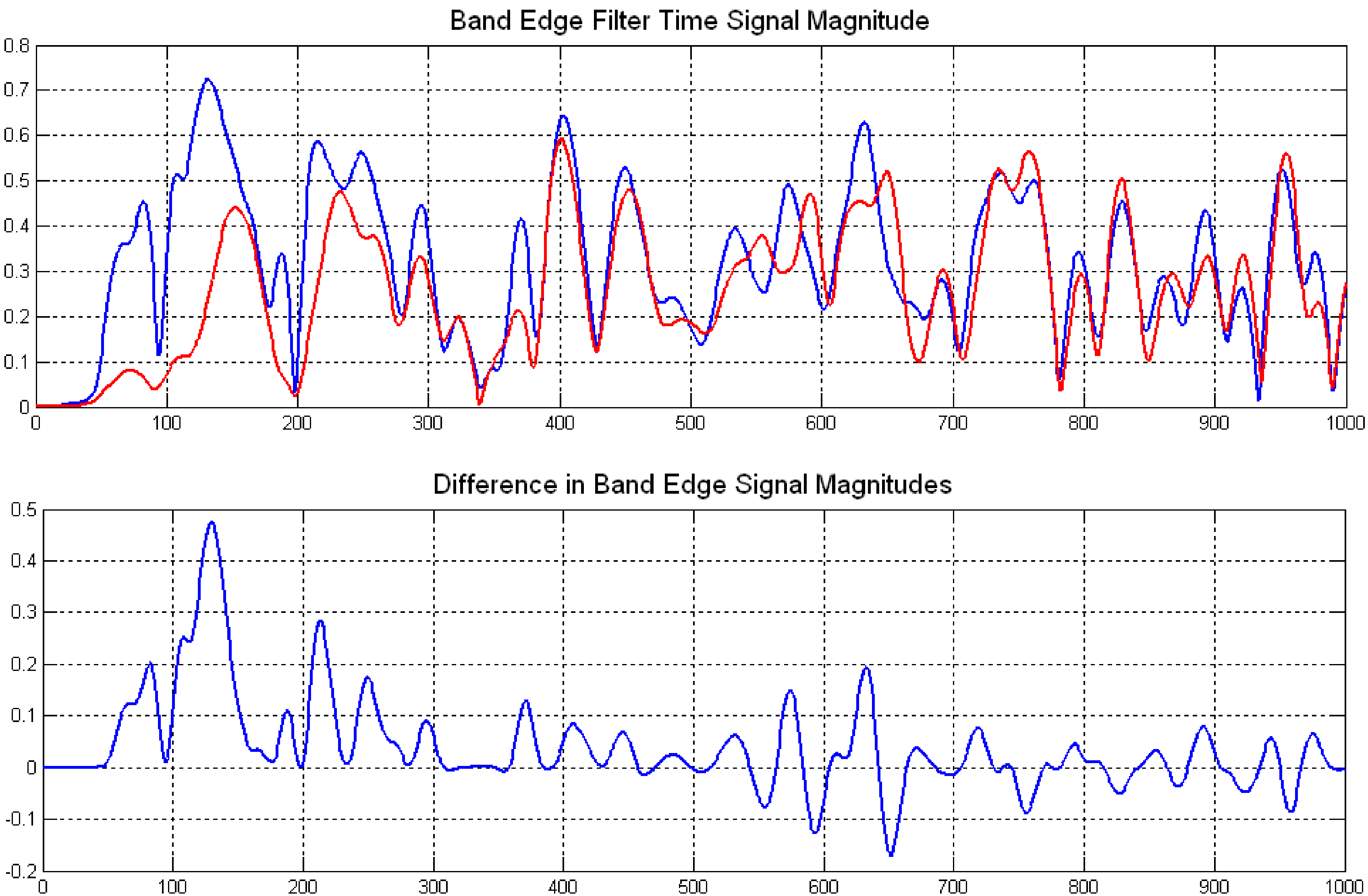
Frequency Offset Spectra and Minimum Phase BE Filters in Frequency Lock Loop



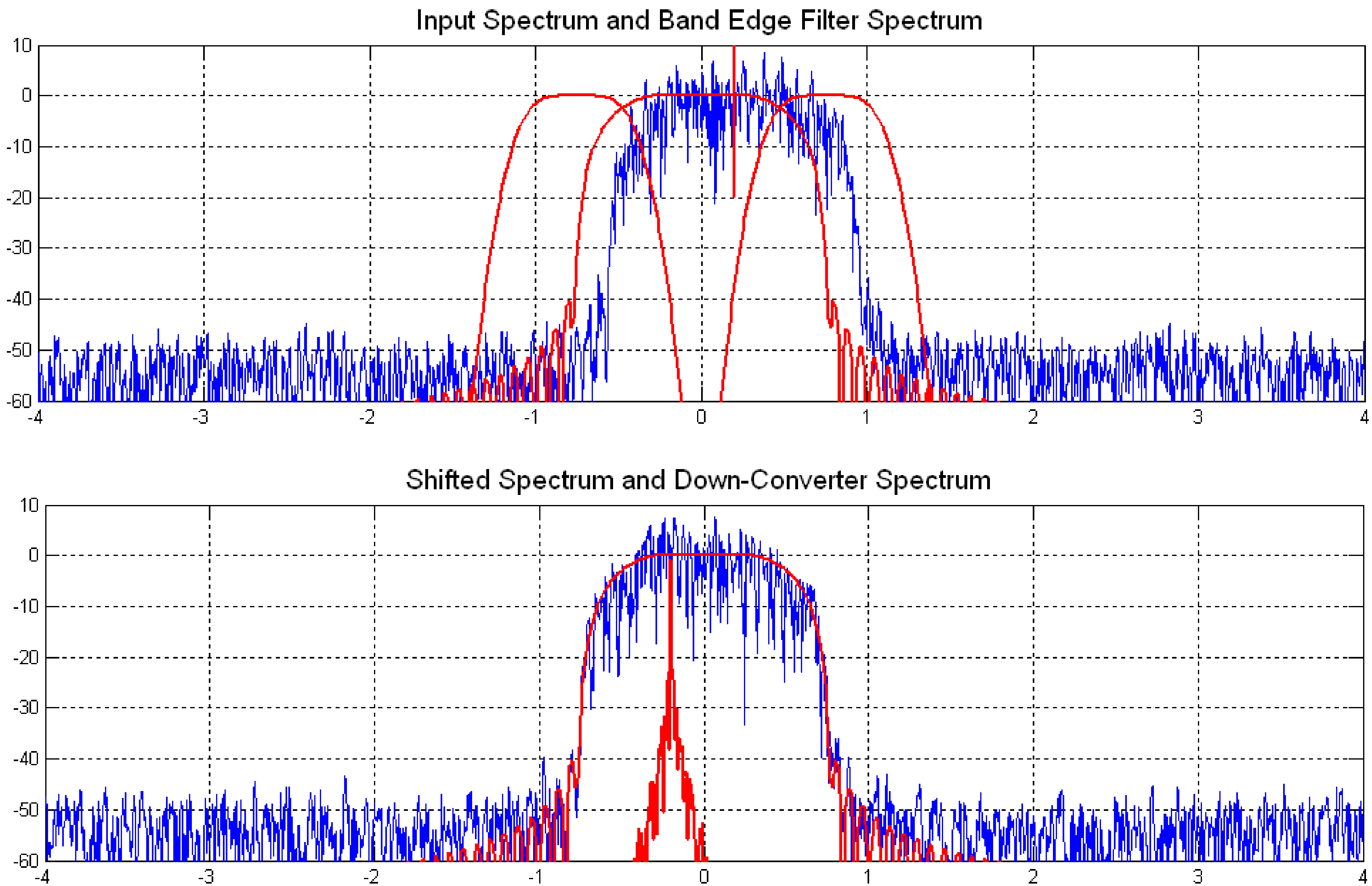
Phase Profiles of Freq Lock Loop



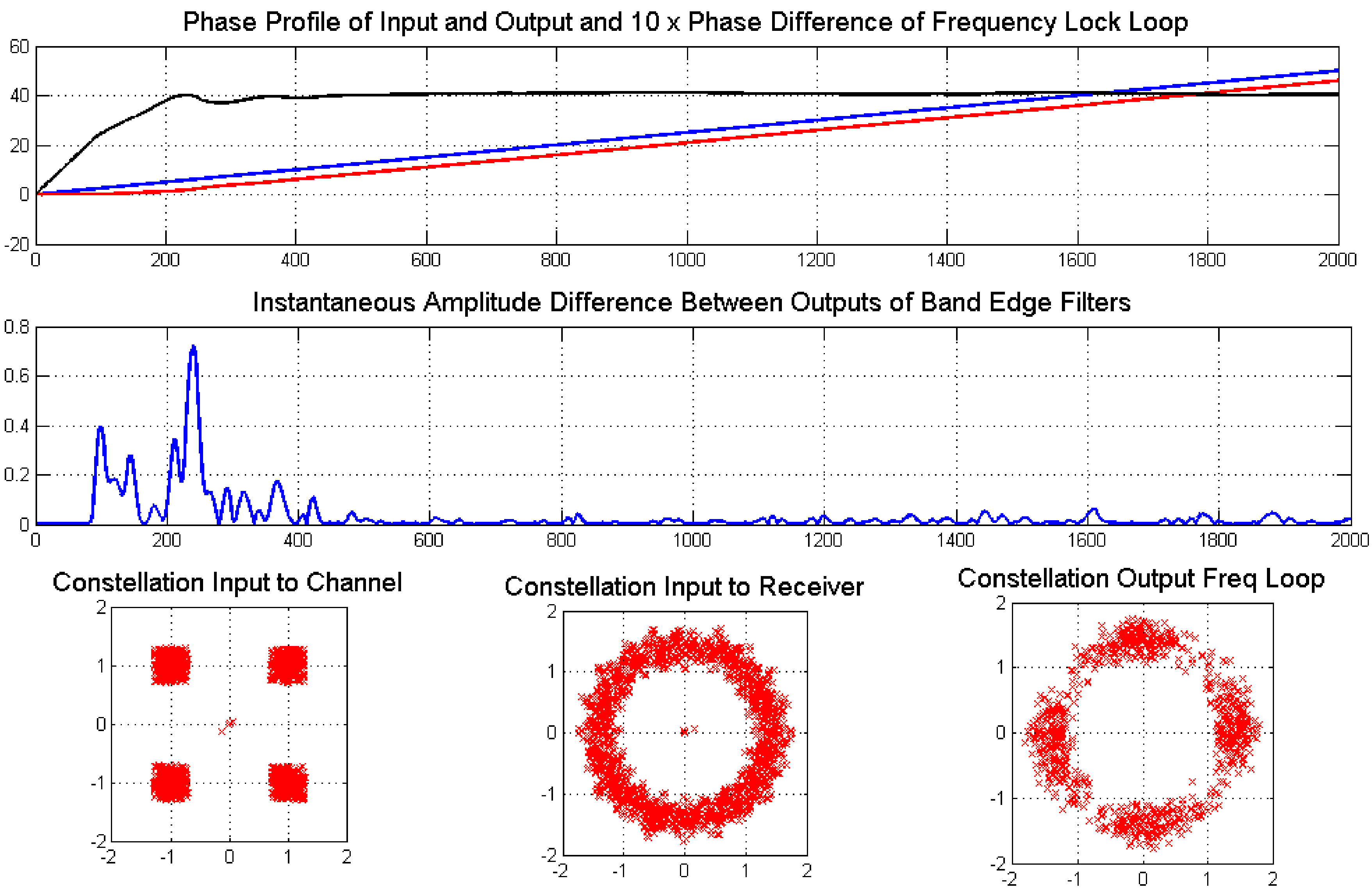
Time Series from BE Filters During Frequency Acquisition



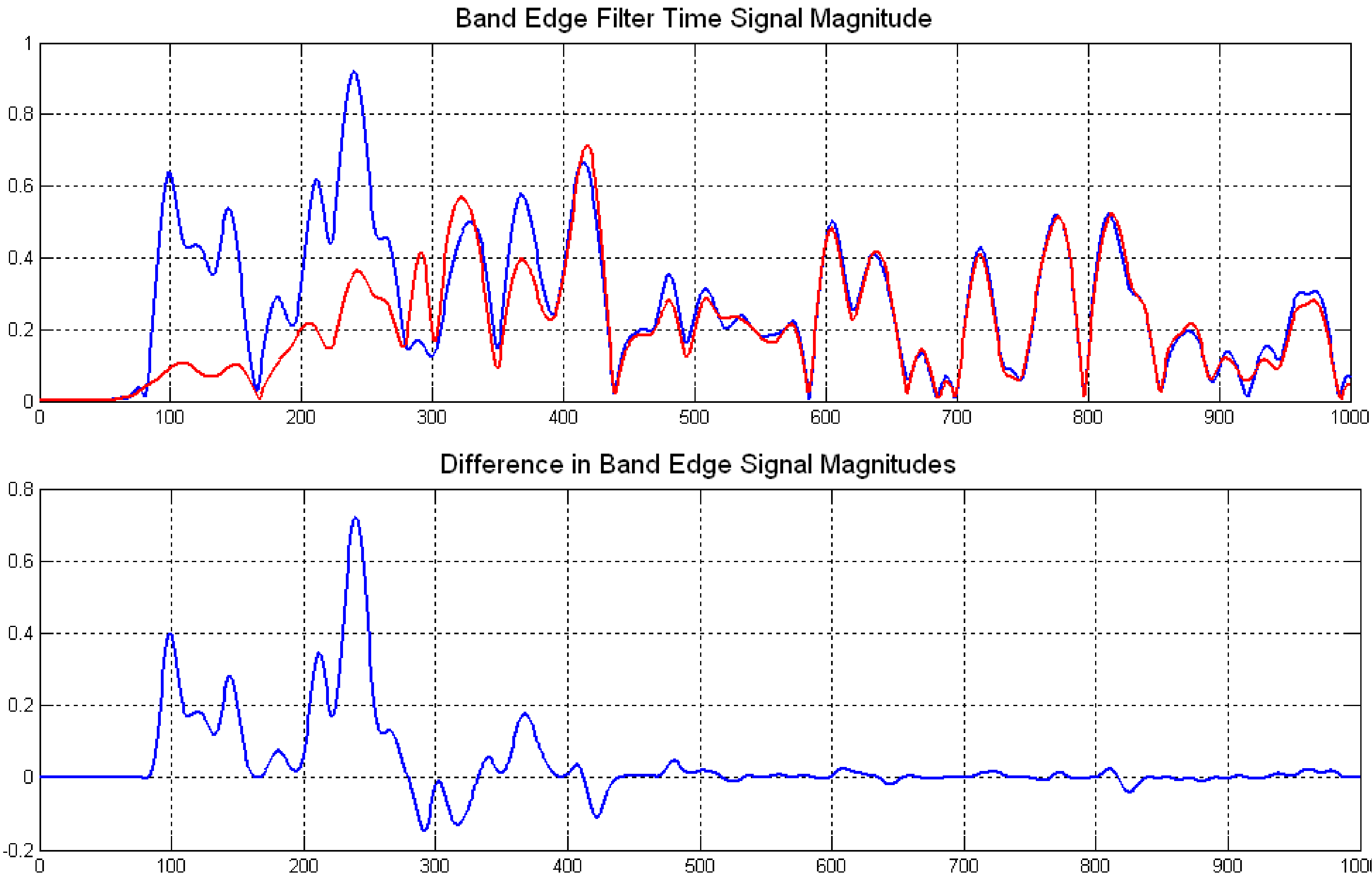
Frequency Offset Spectra and Linear Phase FIR Substitute for BE Filters in Frequency Lock Loop



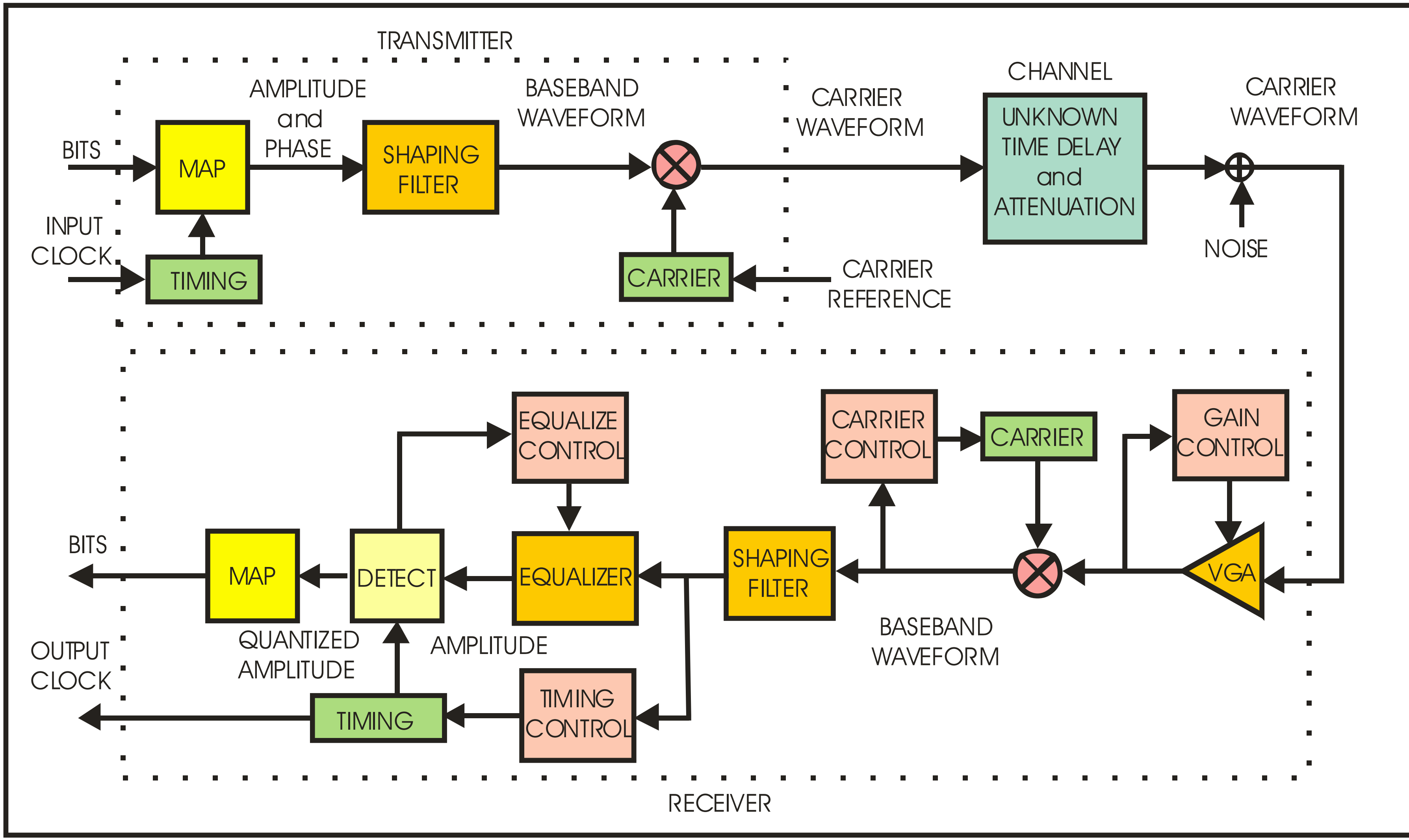
Phase Profiles of Freq Lock Loop



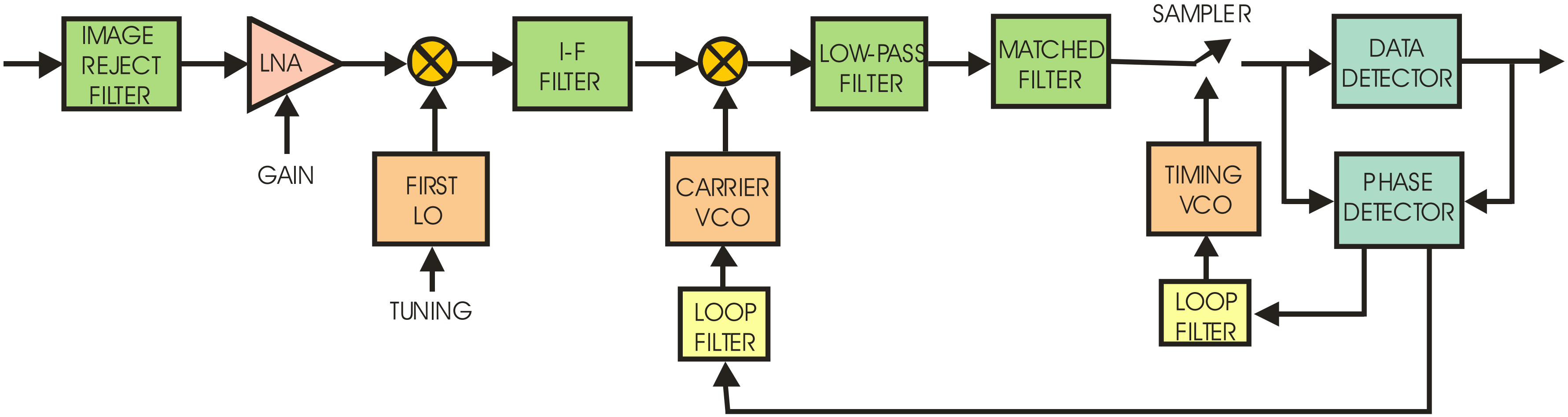
Time Series from BE Filters During Frequency Acquisition



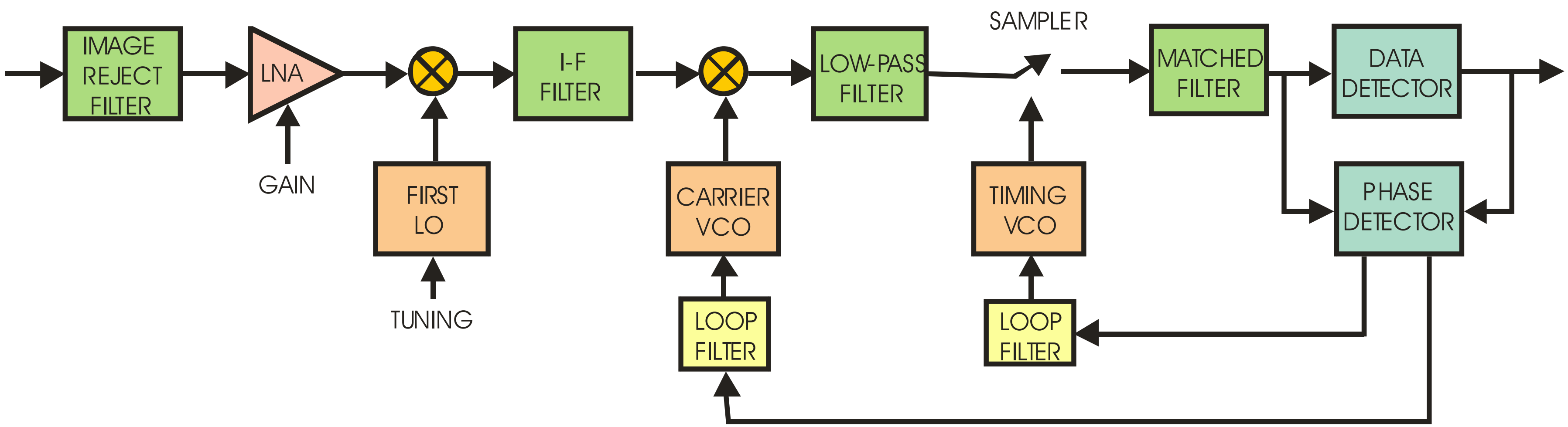
Asymmetric Processing



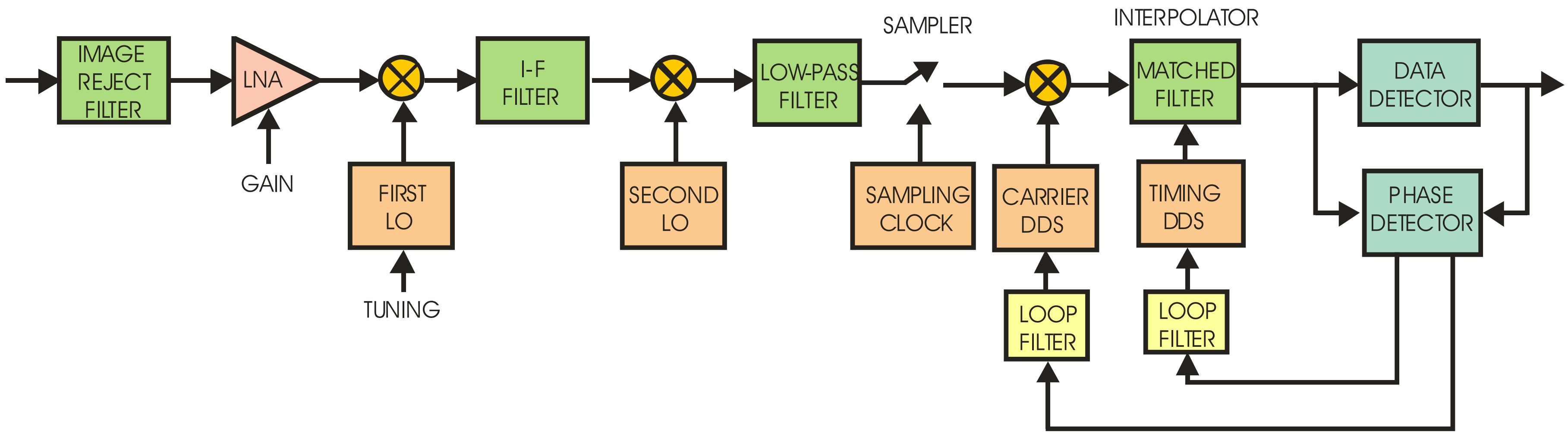
First Generation Receiver
Analog Signal Conditioning



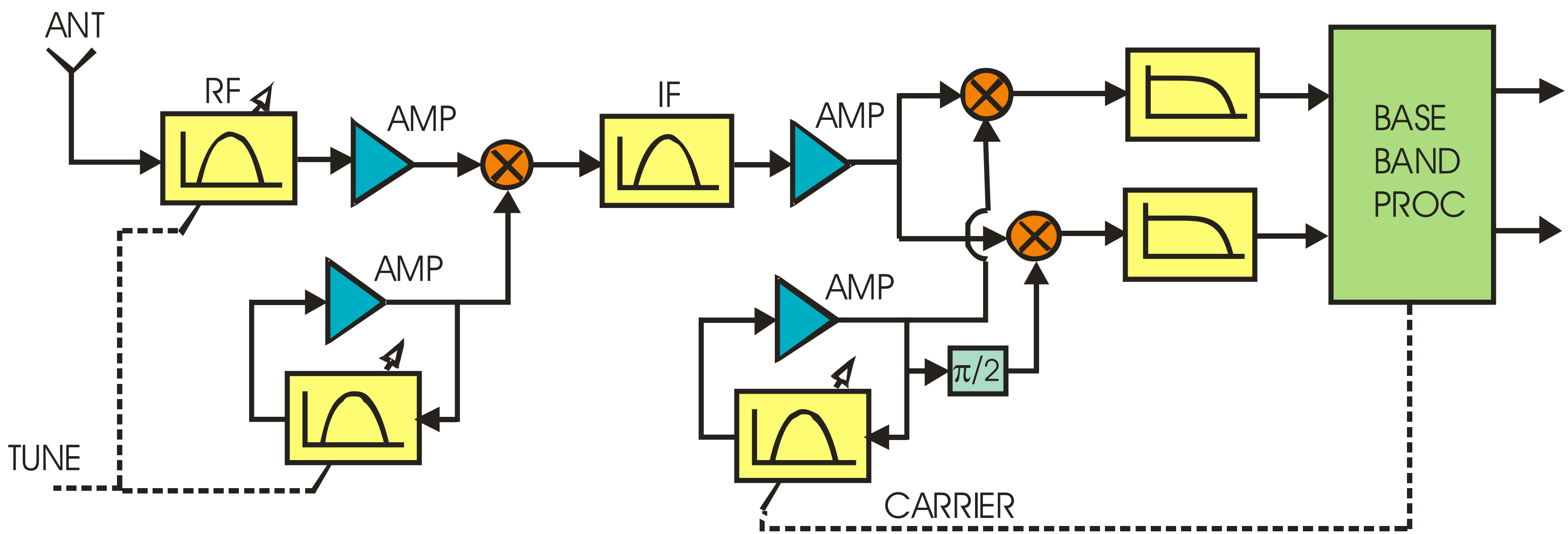
Second Generation Receiver DSP Based Signal Processing



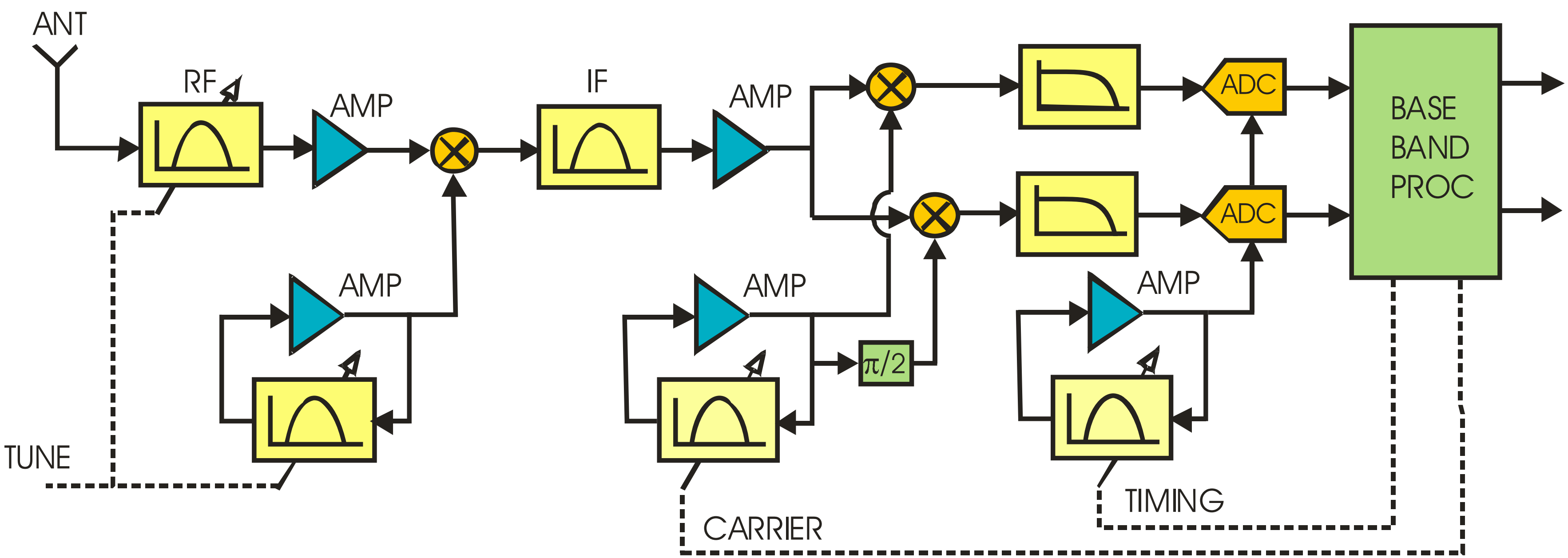
Third Generation Receiver DSP Based Signal Conditioning



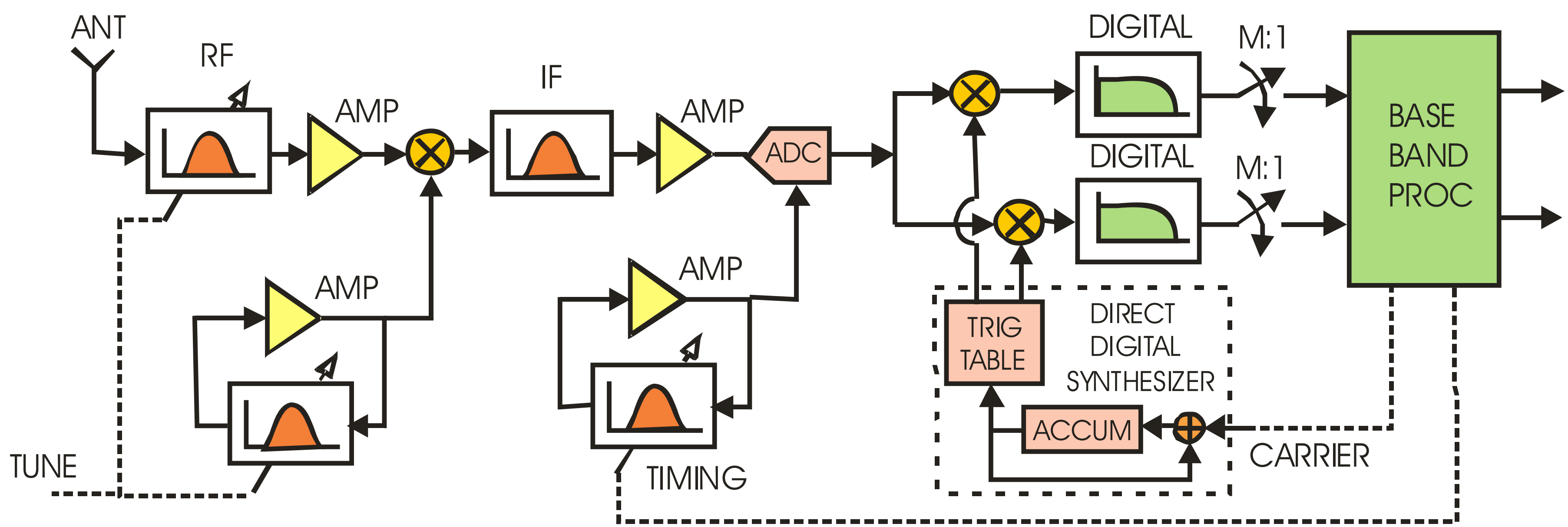
Build Your Own Carrier for Final Down Conversion



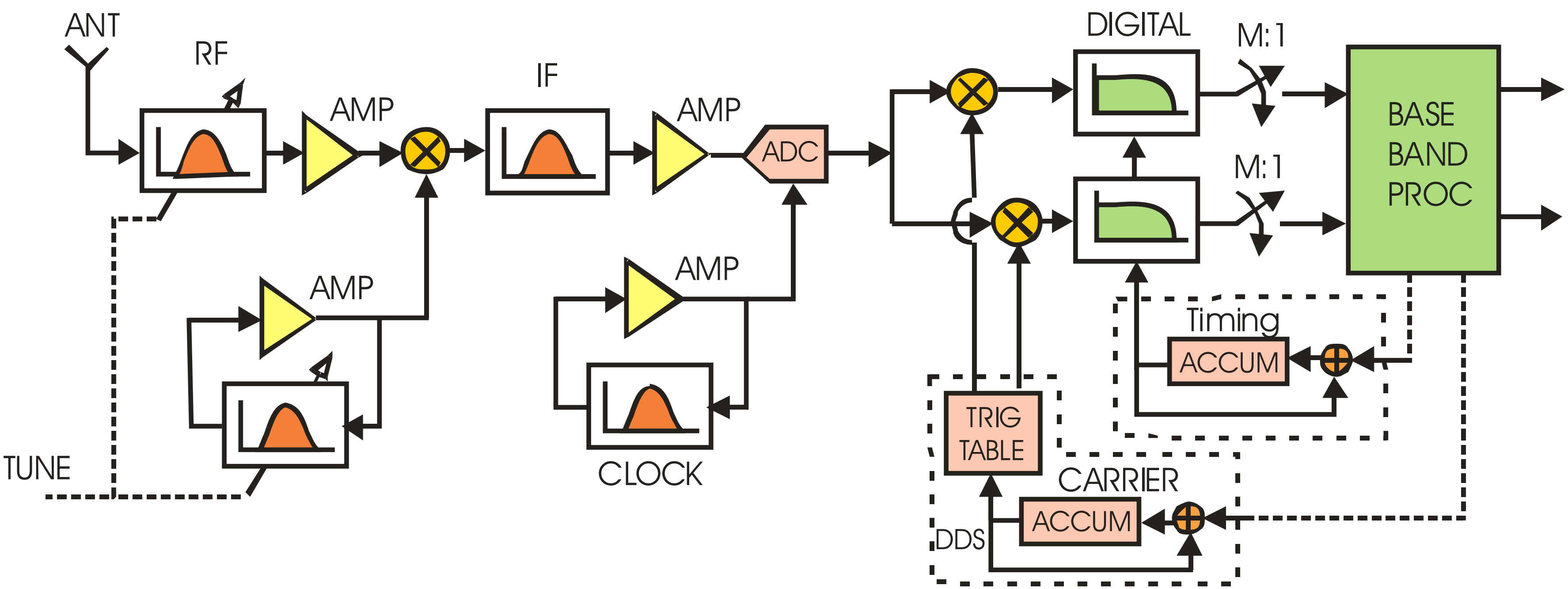
First Generation Digital Receiver



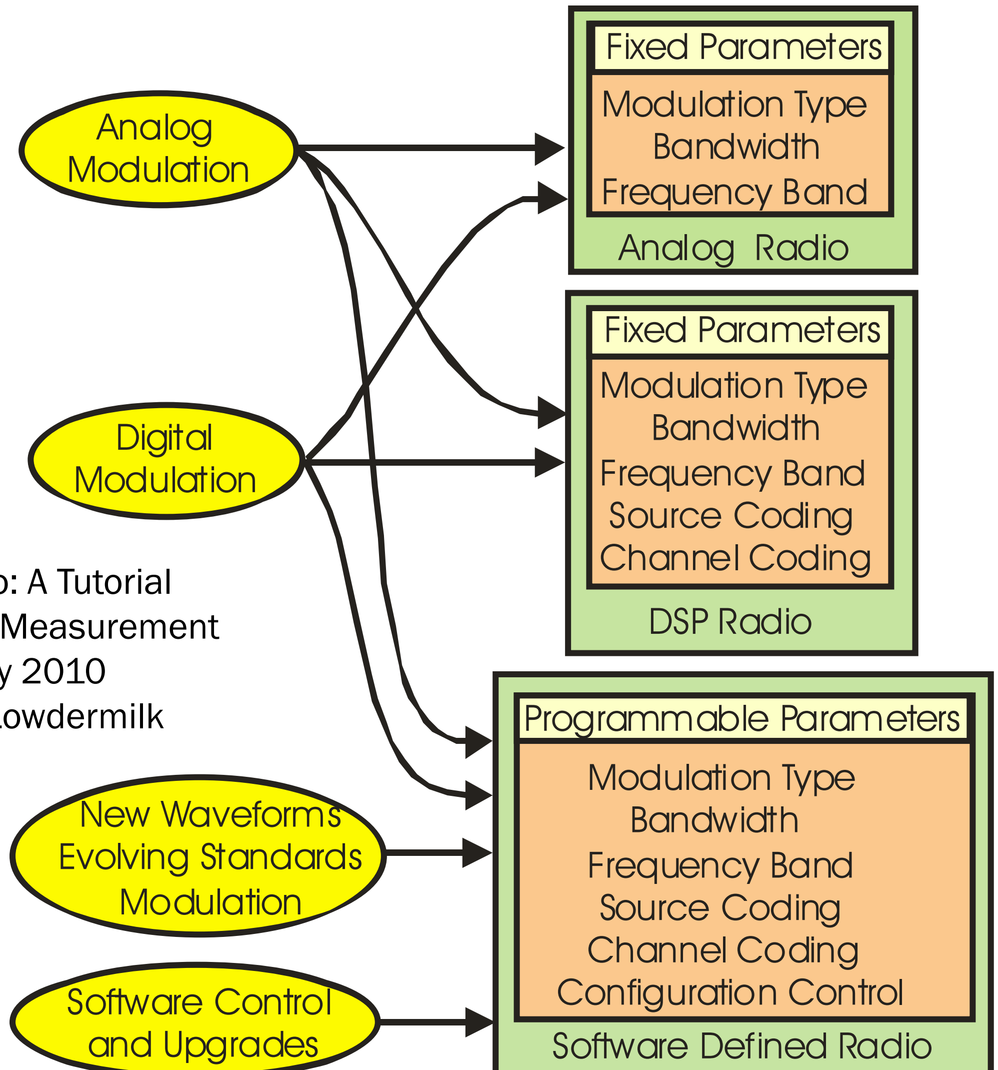
Second Generation Digital Receiver



Third Generation Digital Receiver

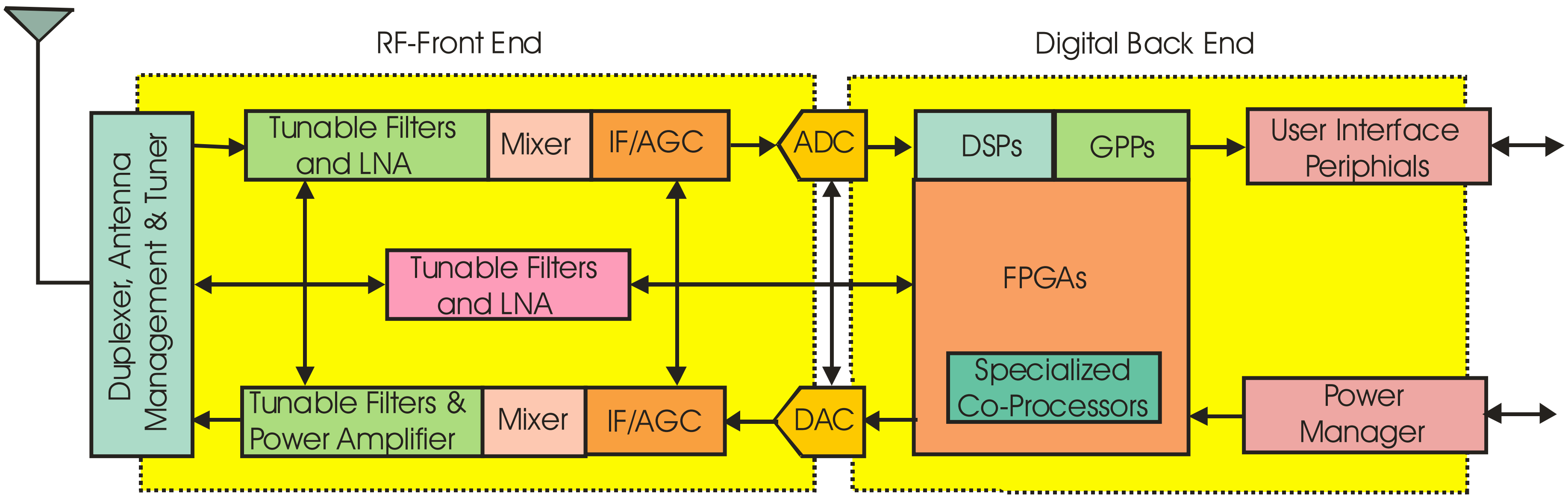


Signals and Underlying Structure of Analog Radio, DSP Radio, and Software Defined Radio

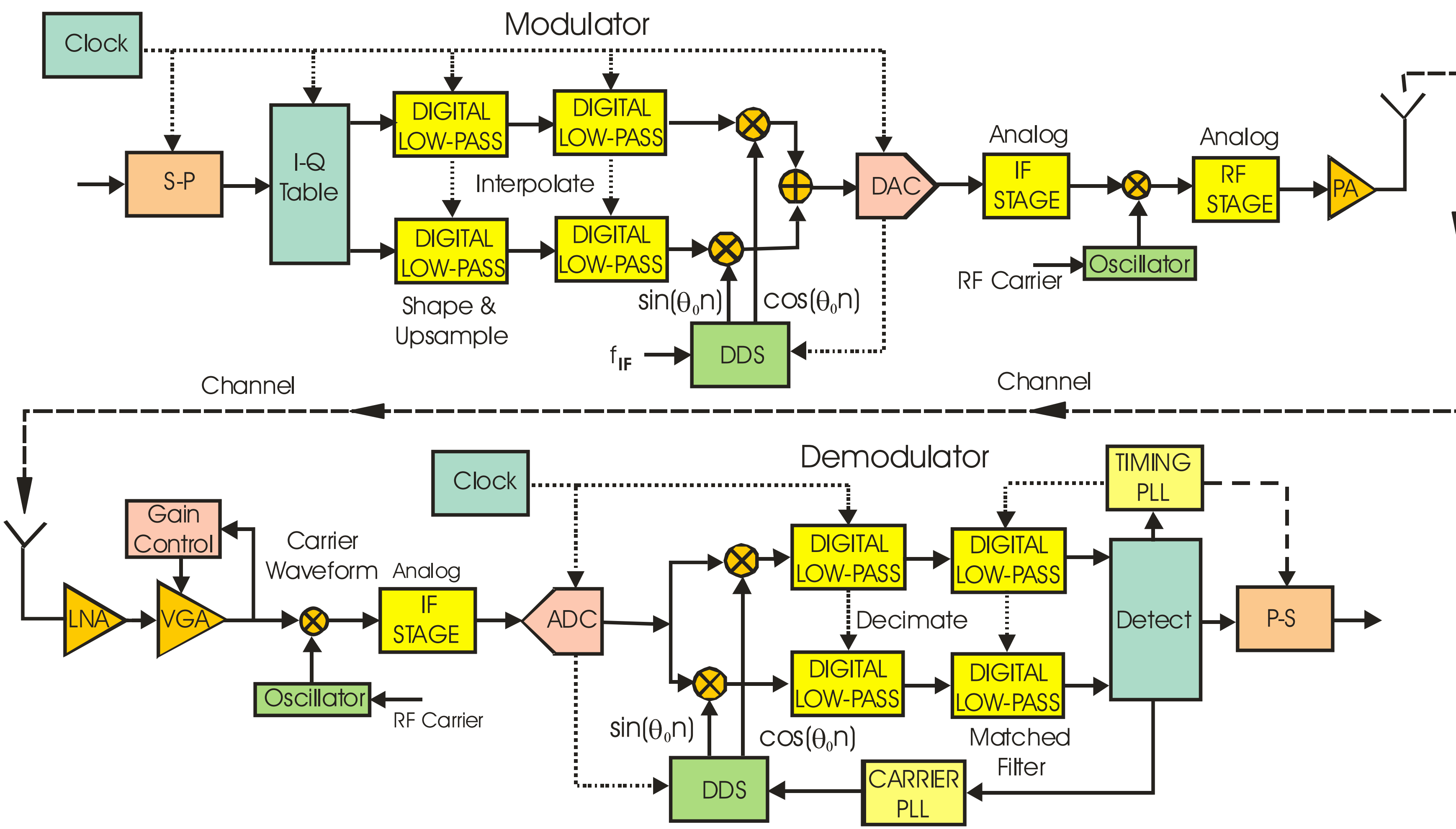


Software Defined Radio: A Tutorial
IEEE Instrumentation and Measurement
Magazine, February 2010
fred harris and Wade Lowdermilk

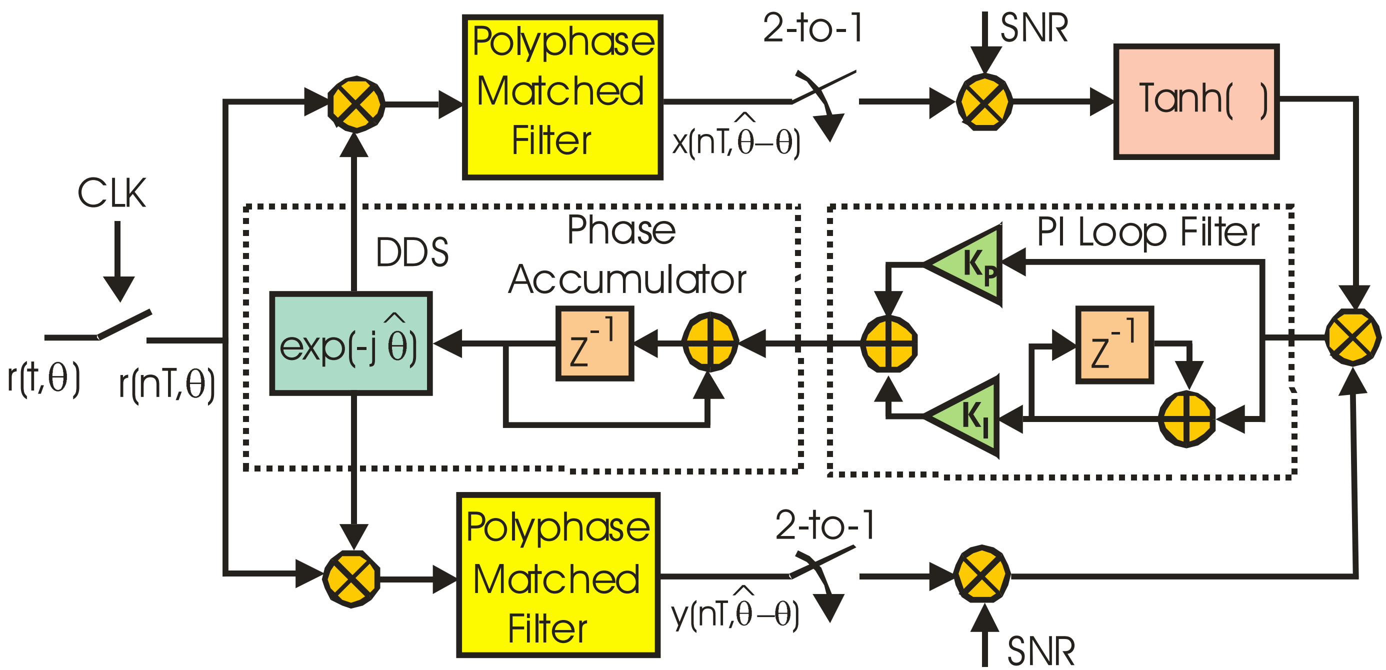
High Level Block Diagram of Software Defined Radio. Radio is segmented into RF Processing Front End Block, Baseband Waveform Digital Signal Processing Back End Block, and Interface to Data Processing Higher Level User Application and Interface Blocks.



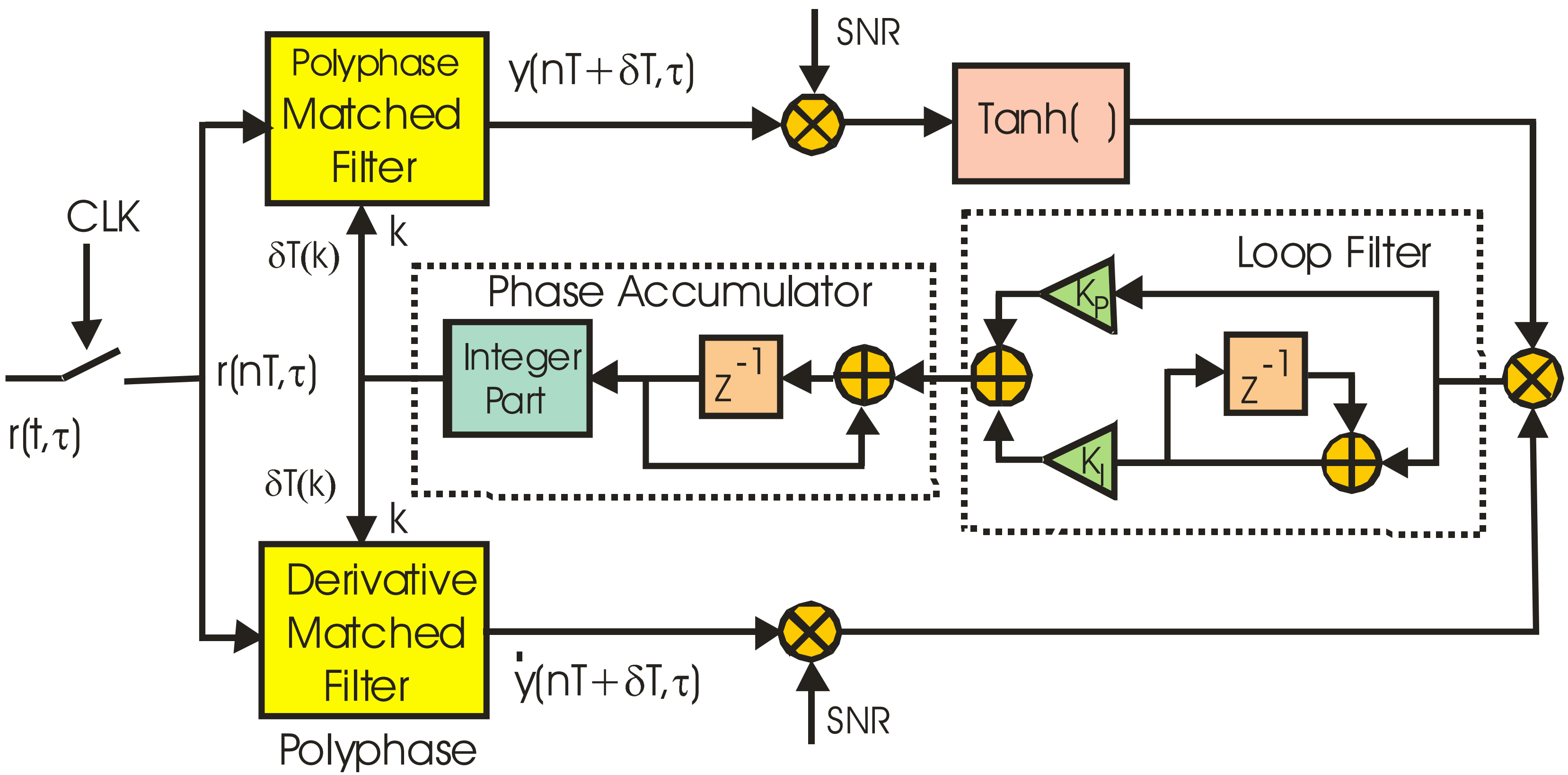
First Tier, Primary Signal Processing Tasks in a Typical Transmitter and Receiver



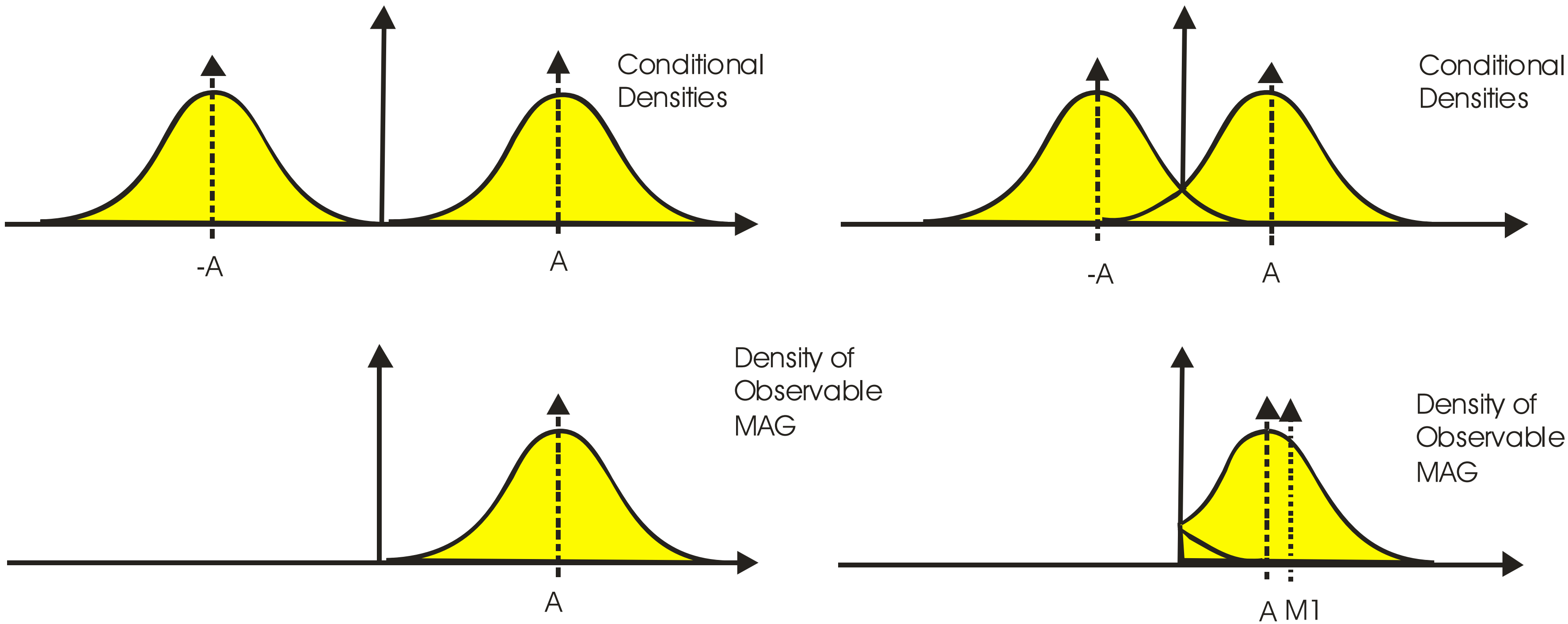
Second Tier Signal Processing Task, Carrier Recovery Phase Locked Loop



Second Tier Signal Processing Task, Timing Recovery Phase Locked Loop

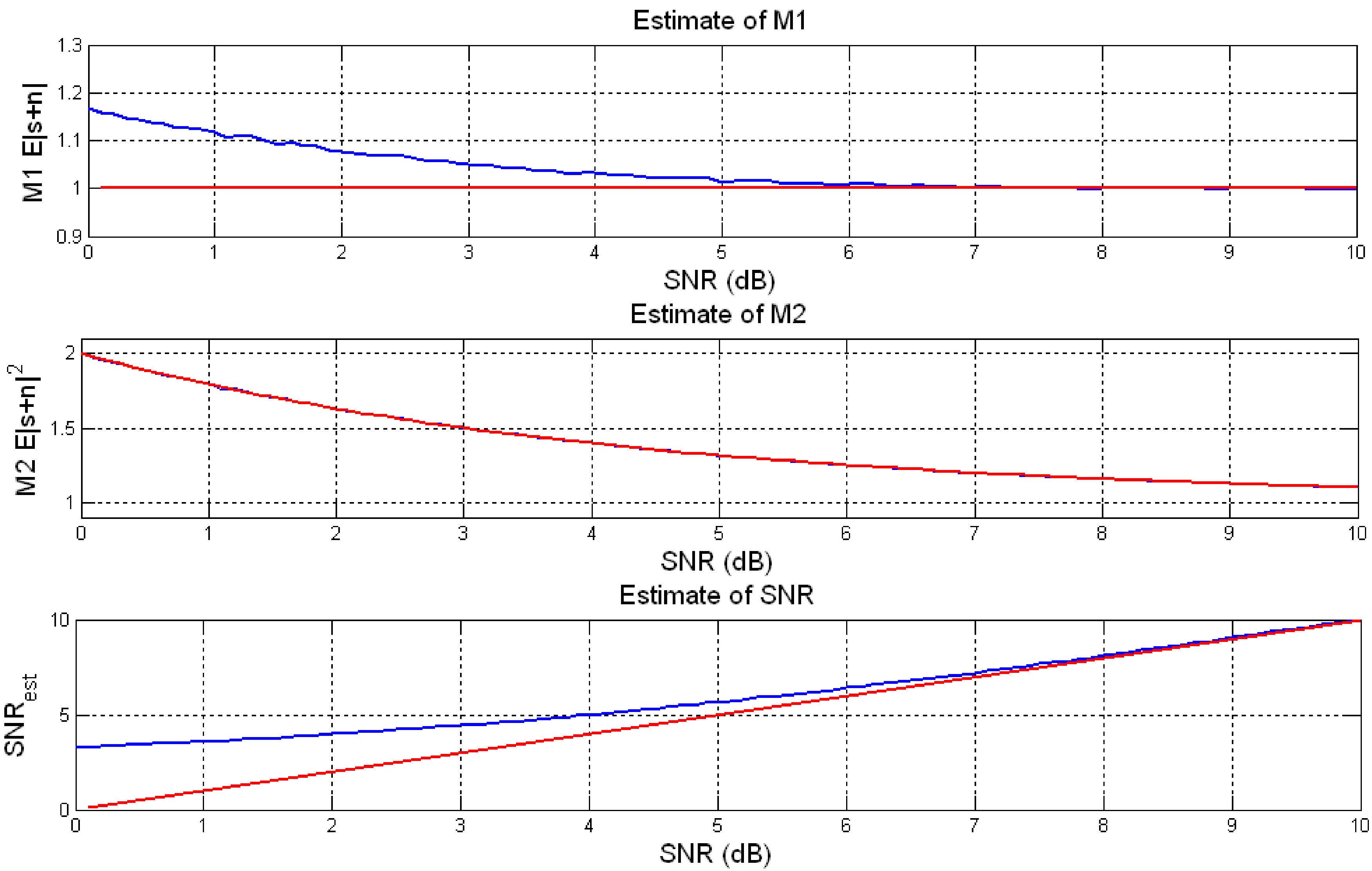


Estimate Signal Mean and Variance at High SNR and Low SNR

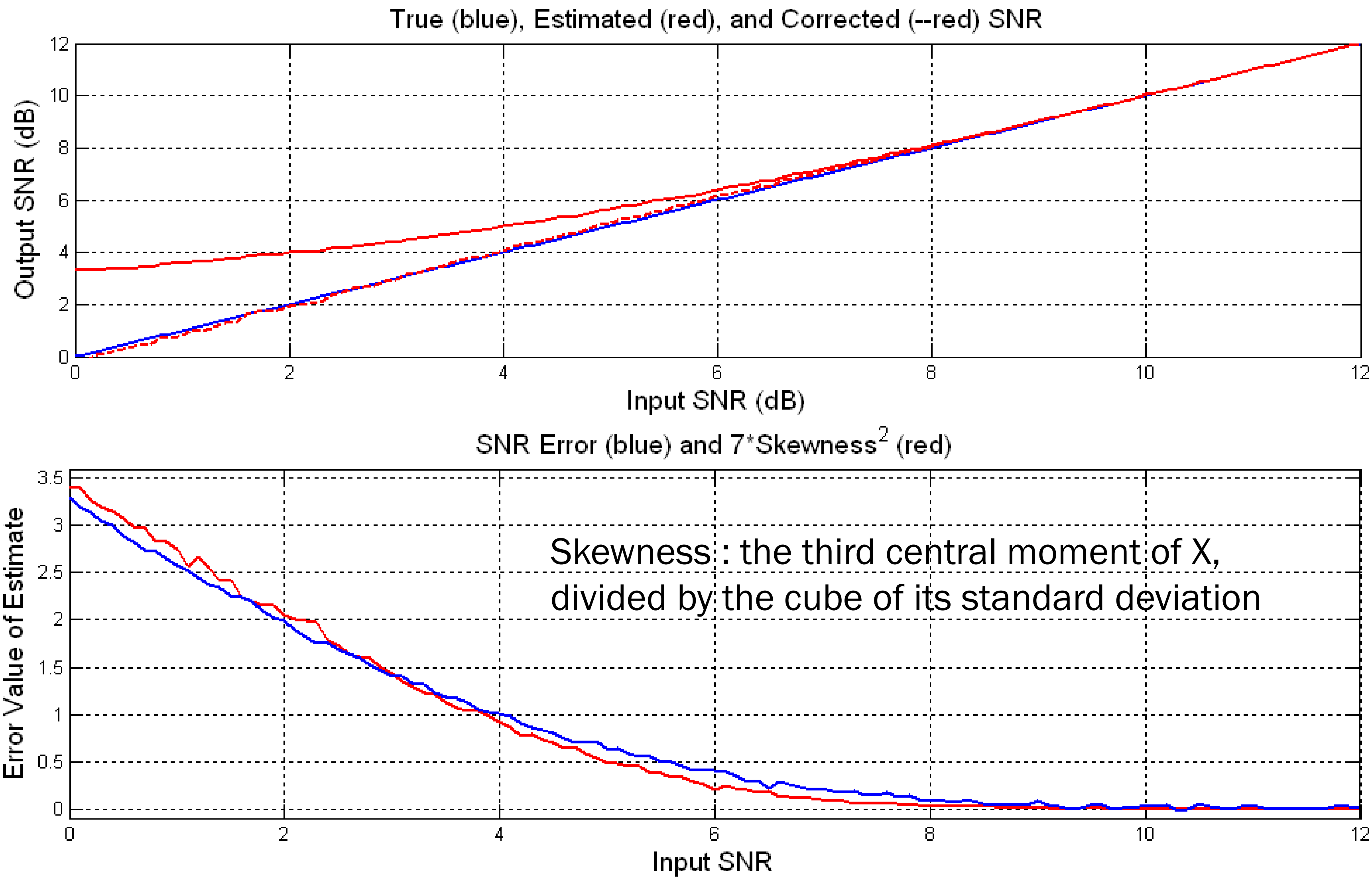


Estimate of Mean is too High
Estimate of variance is too Low

Estimates of Moments and SNR as Function of SNR

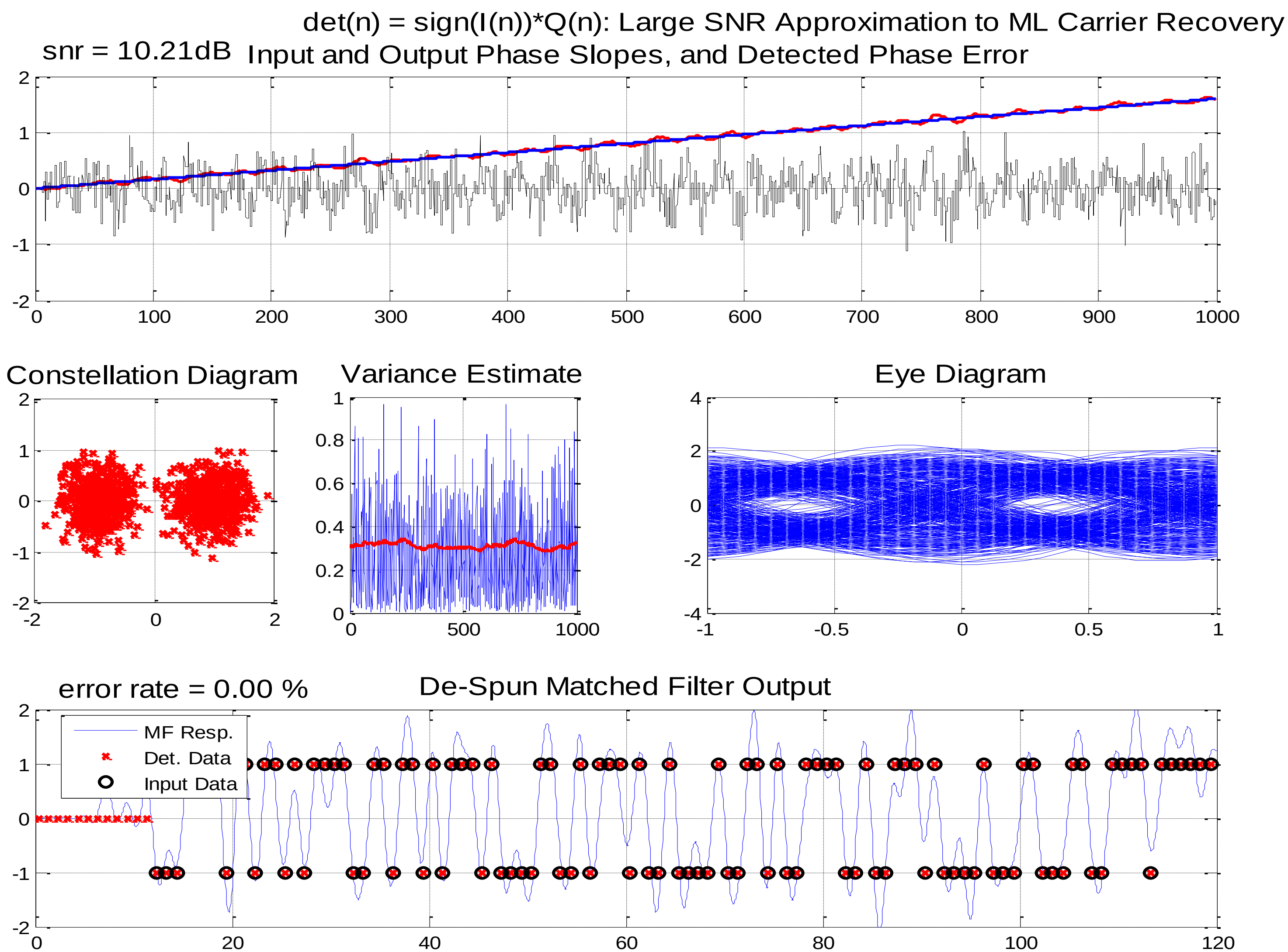


Skewness: A Measure of Estimated SNR Error

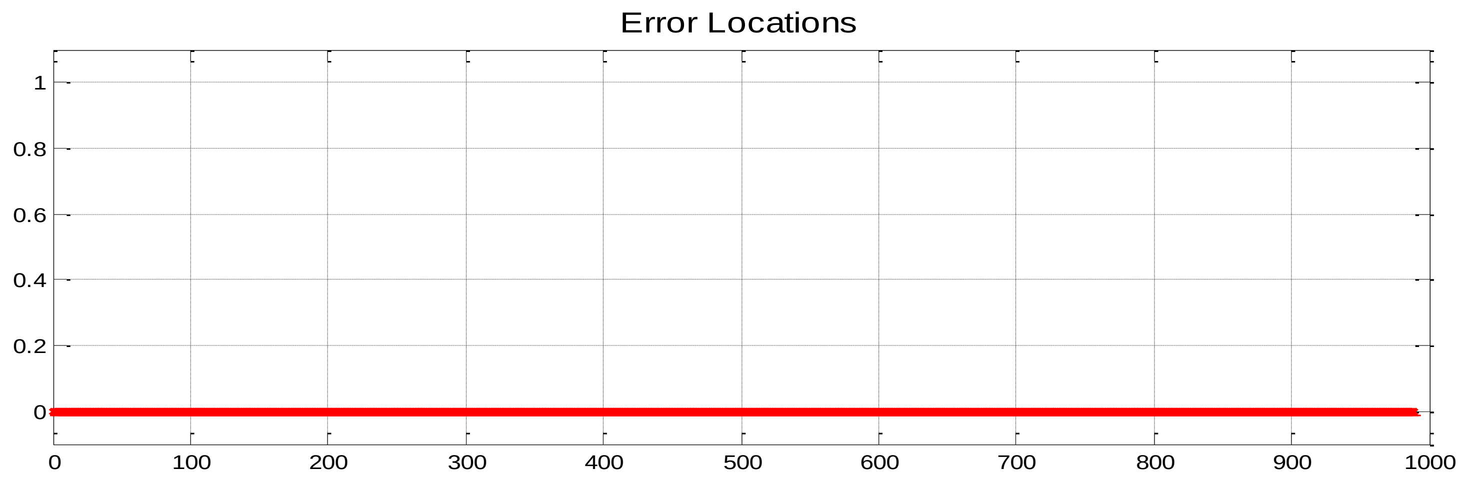


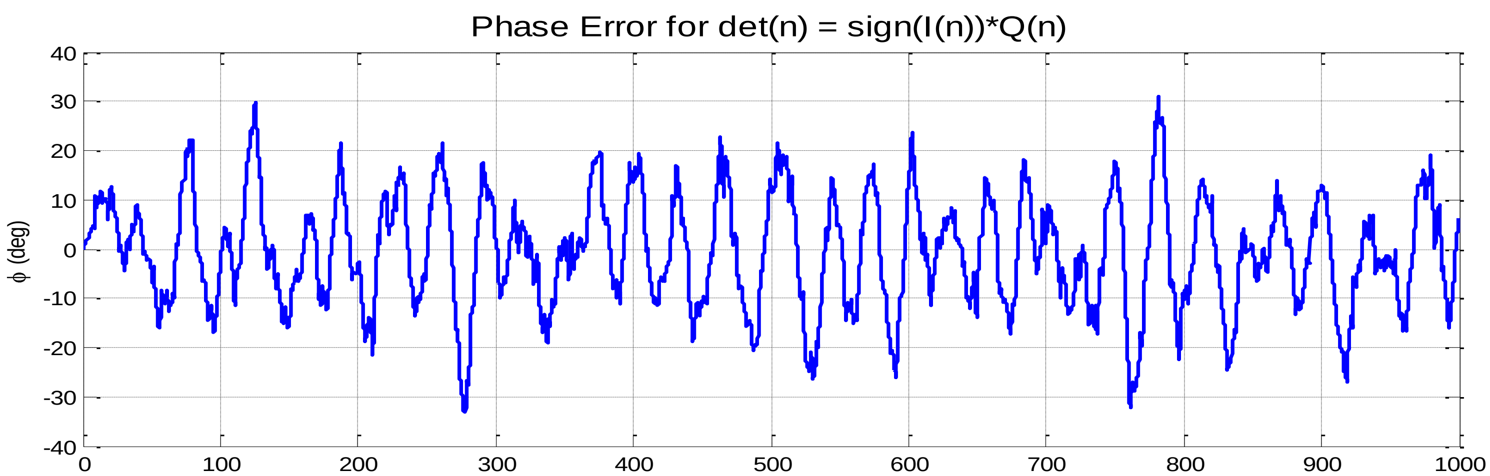
Skewness : the third central moment of X, divided by the cube of its standard deviation

BPSK Large SNR Approximation to ML

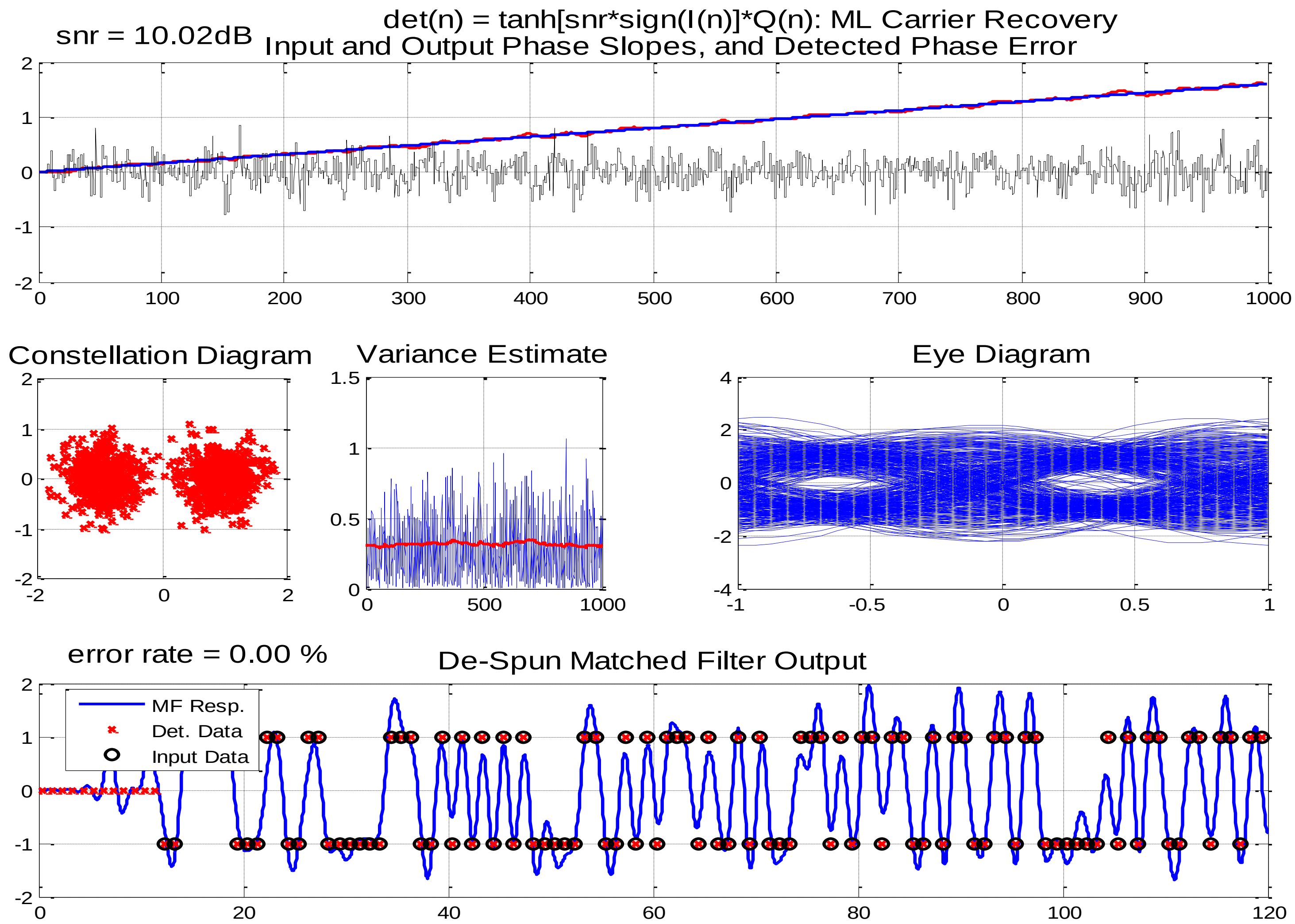


BPSK Large SNR Approximation to ML

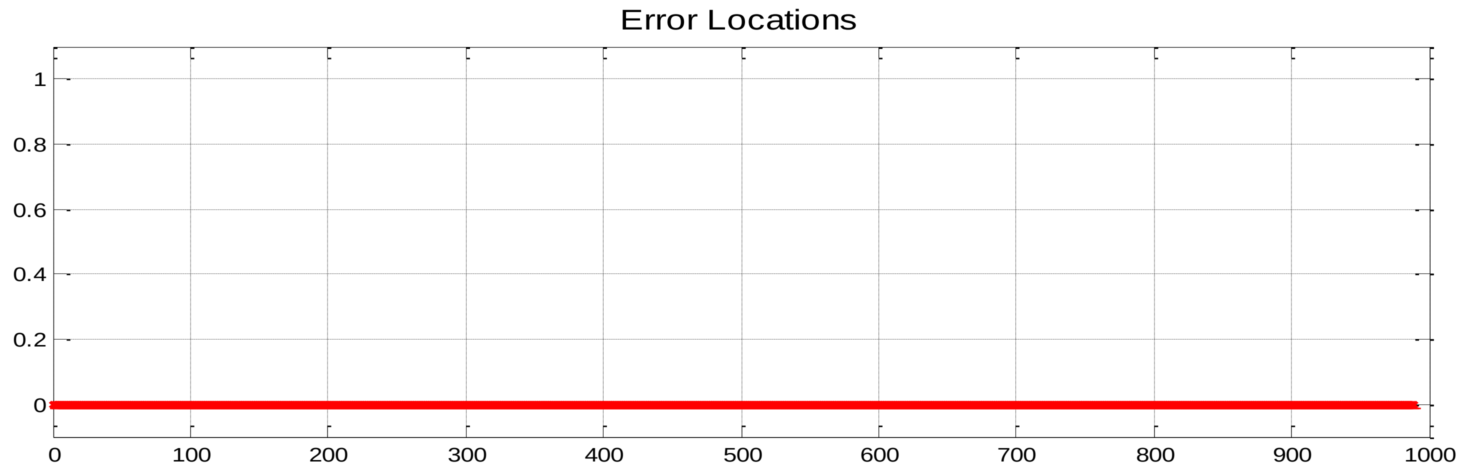


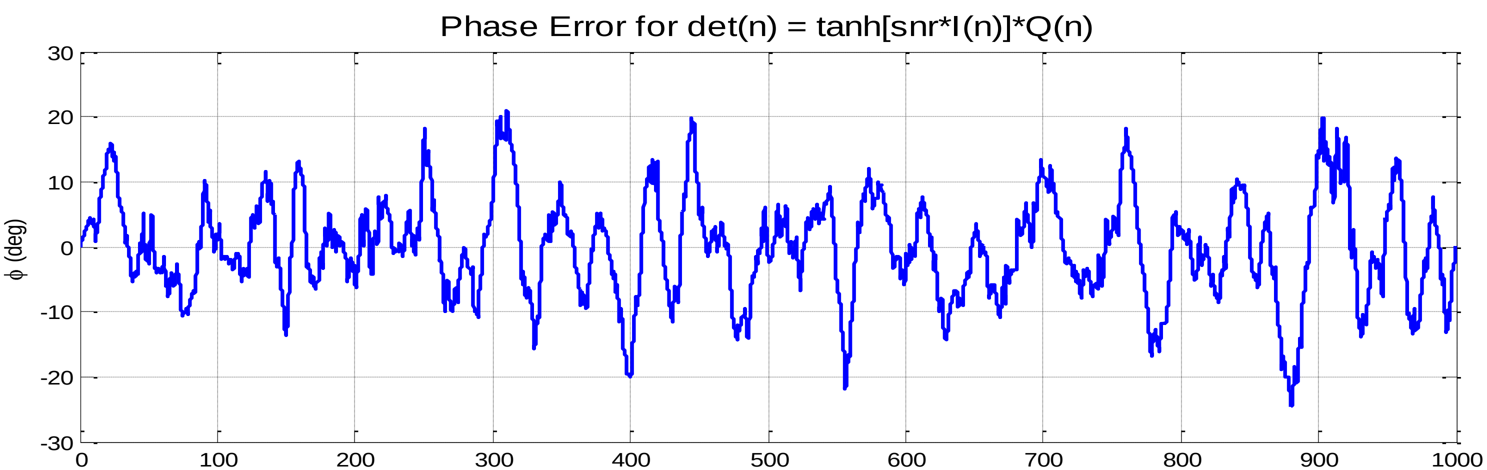


BPSK ML Carrier Recovery Loop

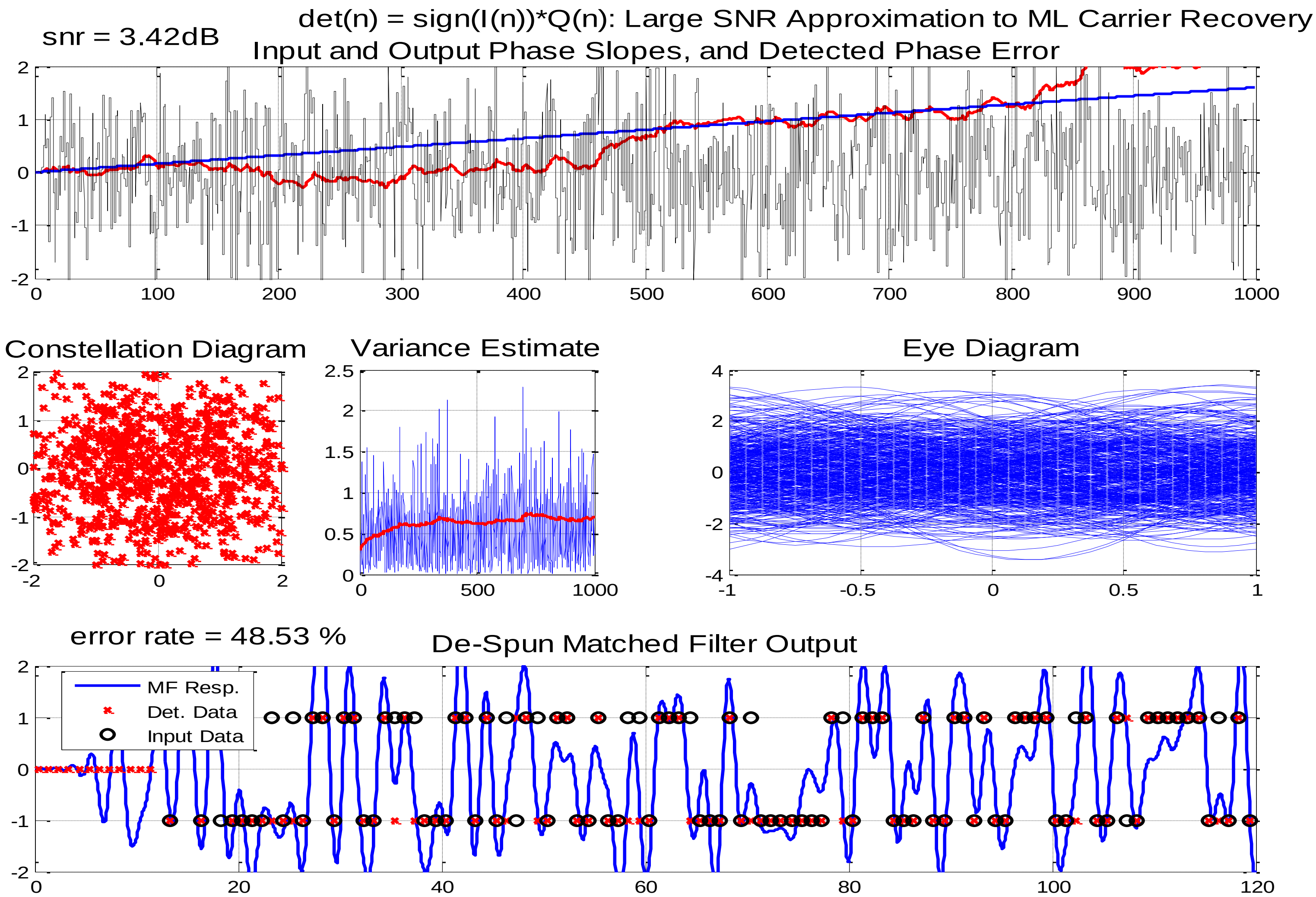


BPSK ML Carrier Recovery Loop

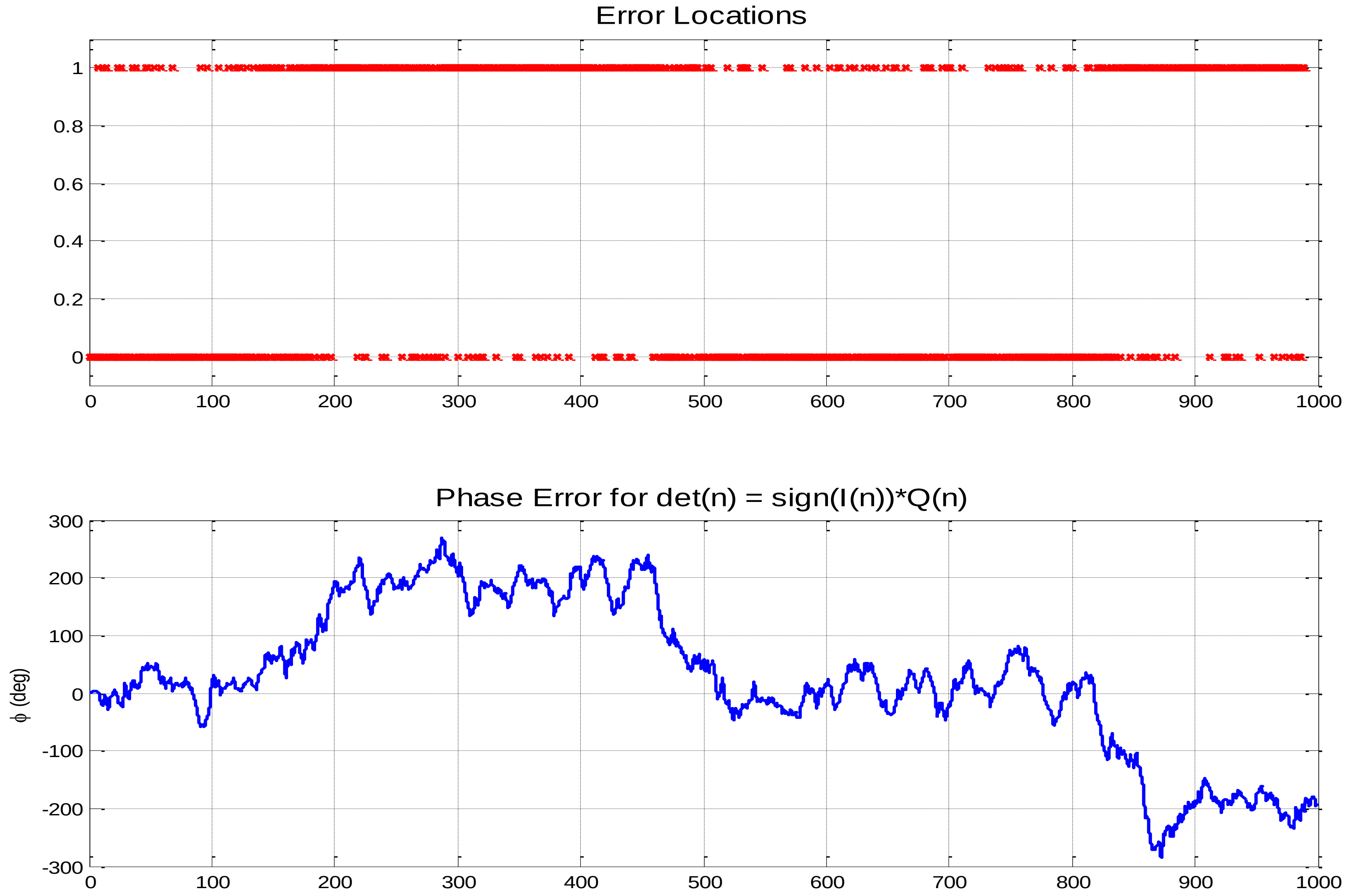




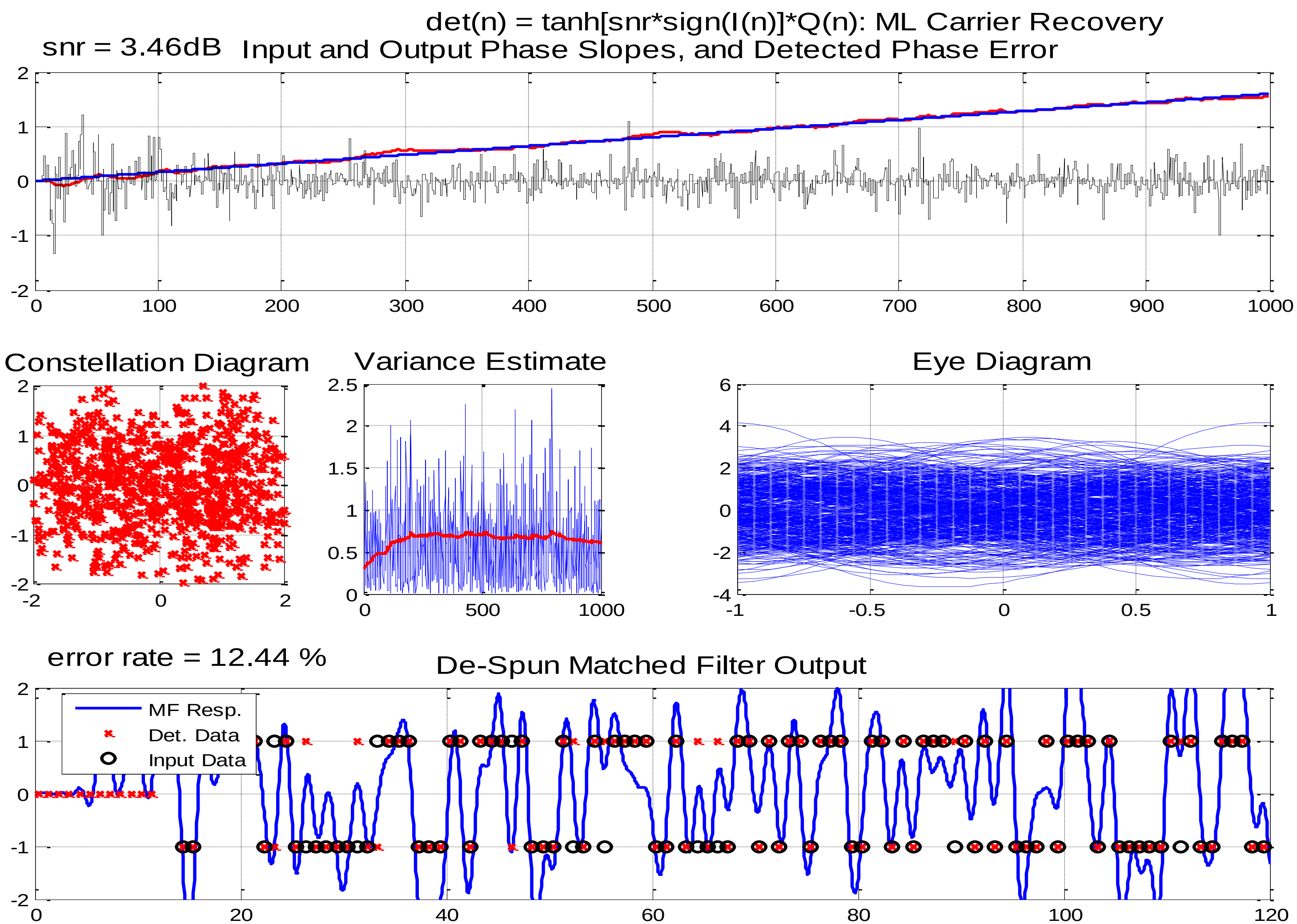
BPSK Large SNR Approximation to ML



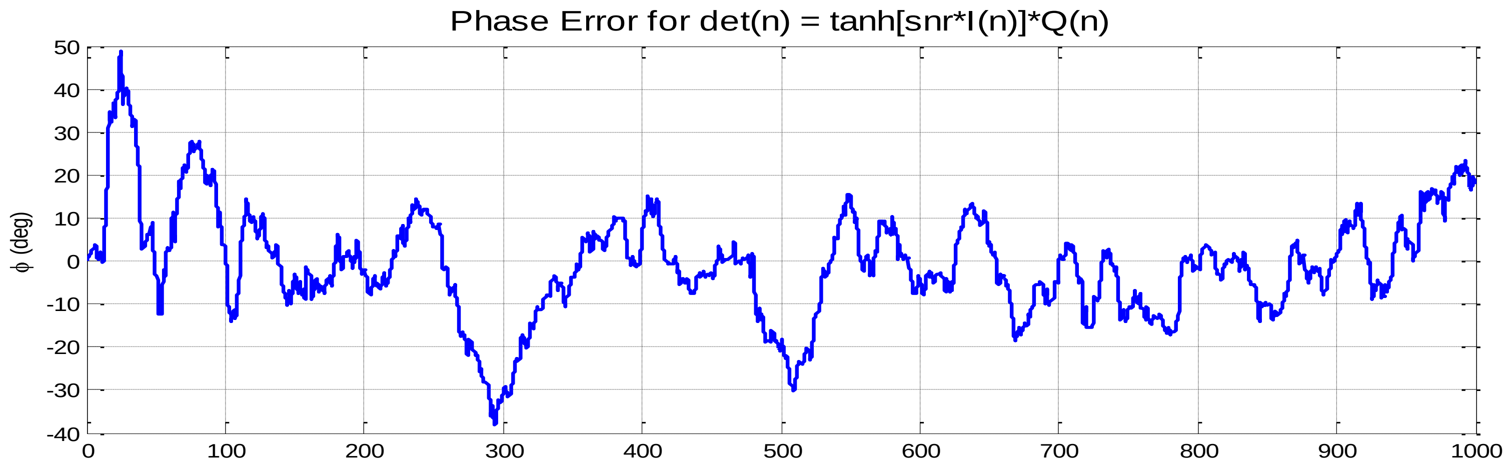
BPSK Large SNR Approximation to ML



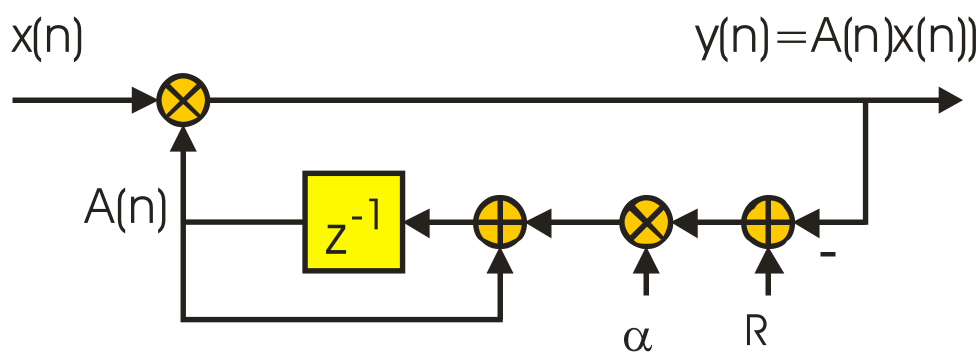
BPSK ML Carrier Recovery Loop



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 = constant

then

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

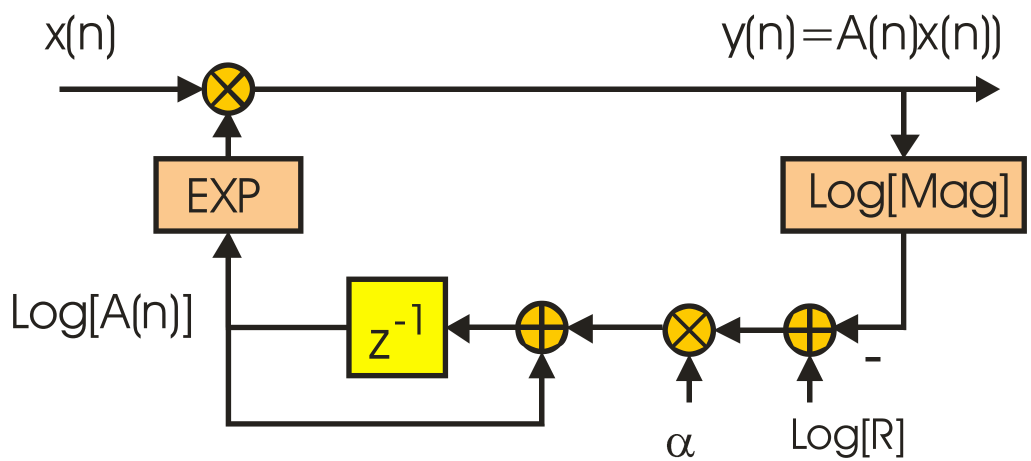
note that α c < 2.0.

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

The time constant is 1/α c samples.

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

Automatic Gain Control (2)



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

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

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

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

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

then

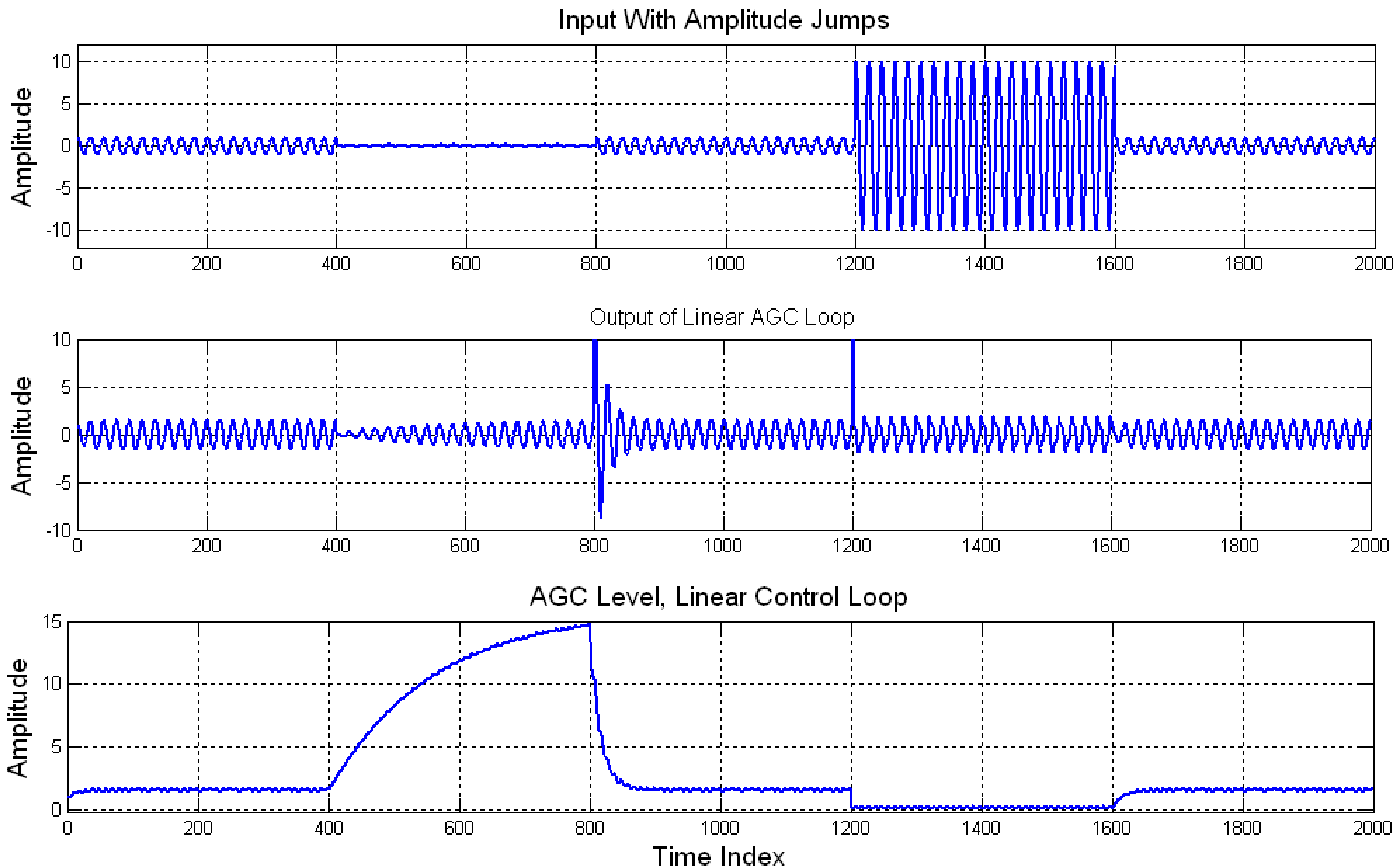
$$Log[A(n+1)] = Log[A(n)][1-\alpha] - \alpha\ Log[c/R]$$

note that $\alpha < 2.0$.

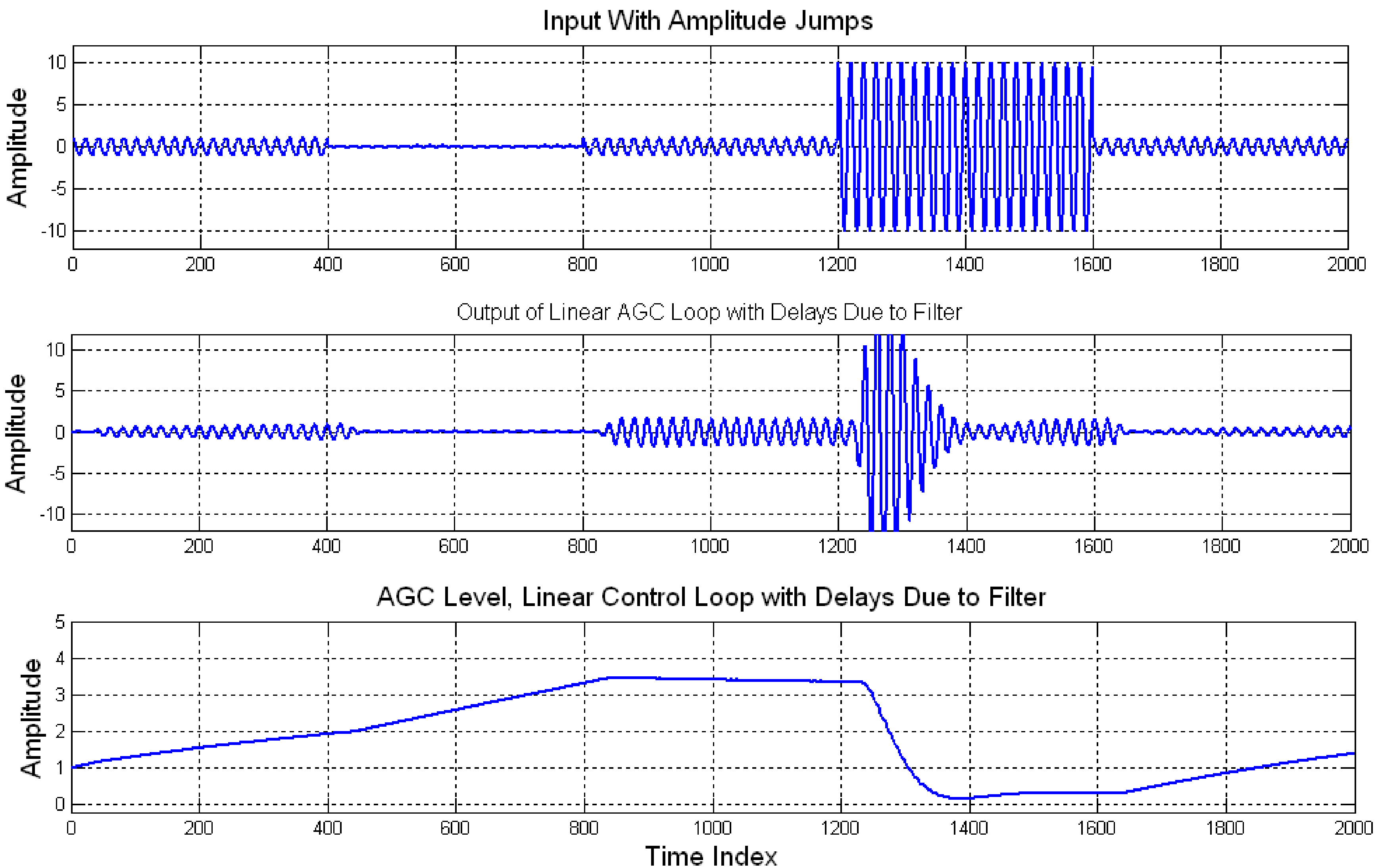
Steady state of this system is 1/c so that the steady state gain $A(\infty)$ is R/c and the steady state output $y(\infty)$ is c R/c or R.

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

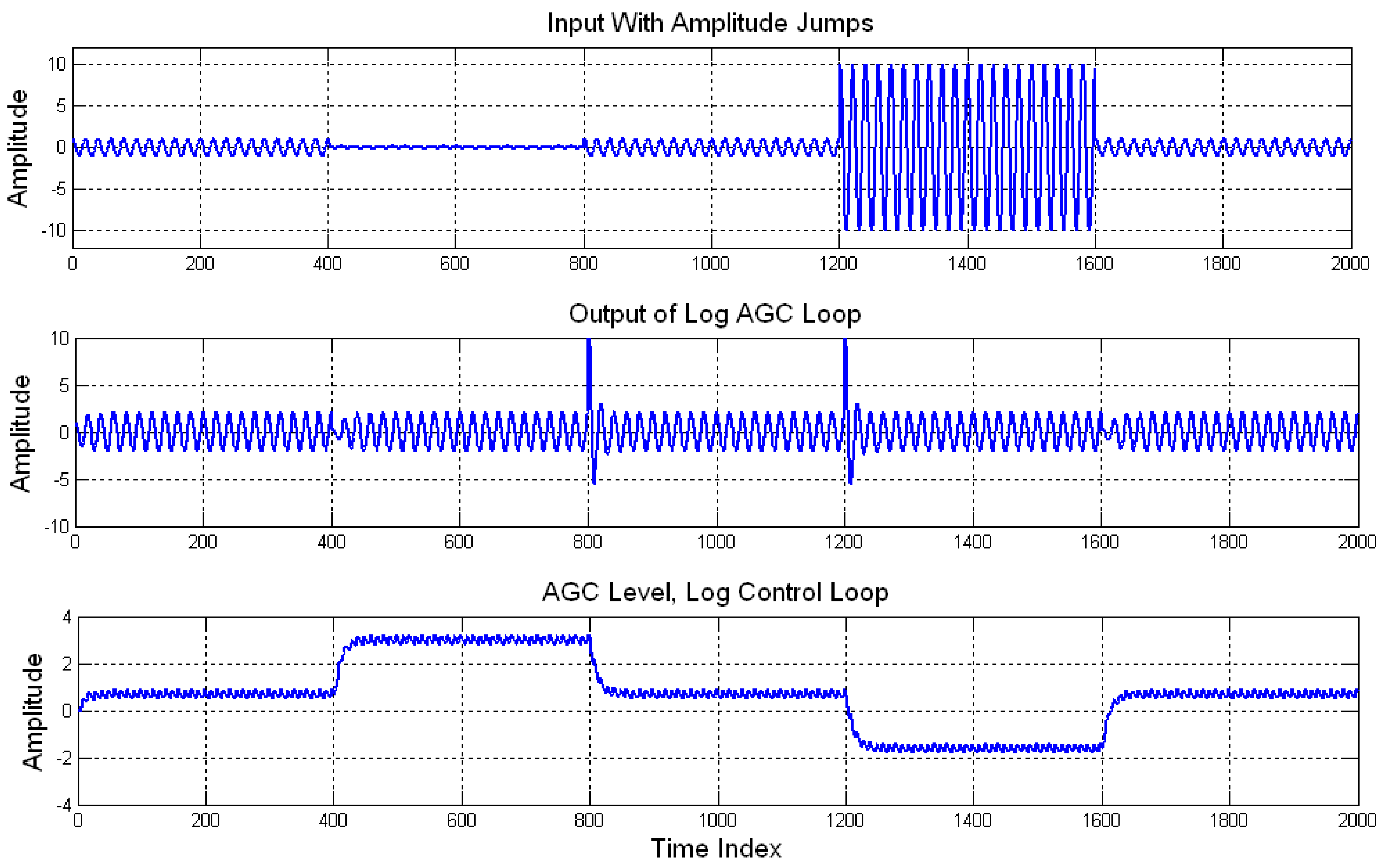
Linear Loop AGC Responses



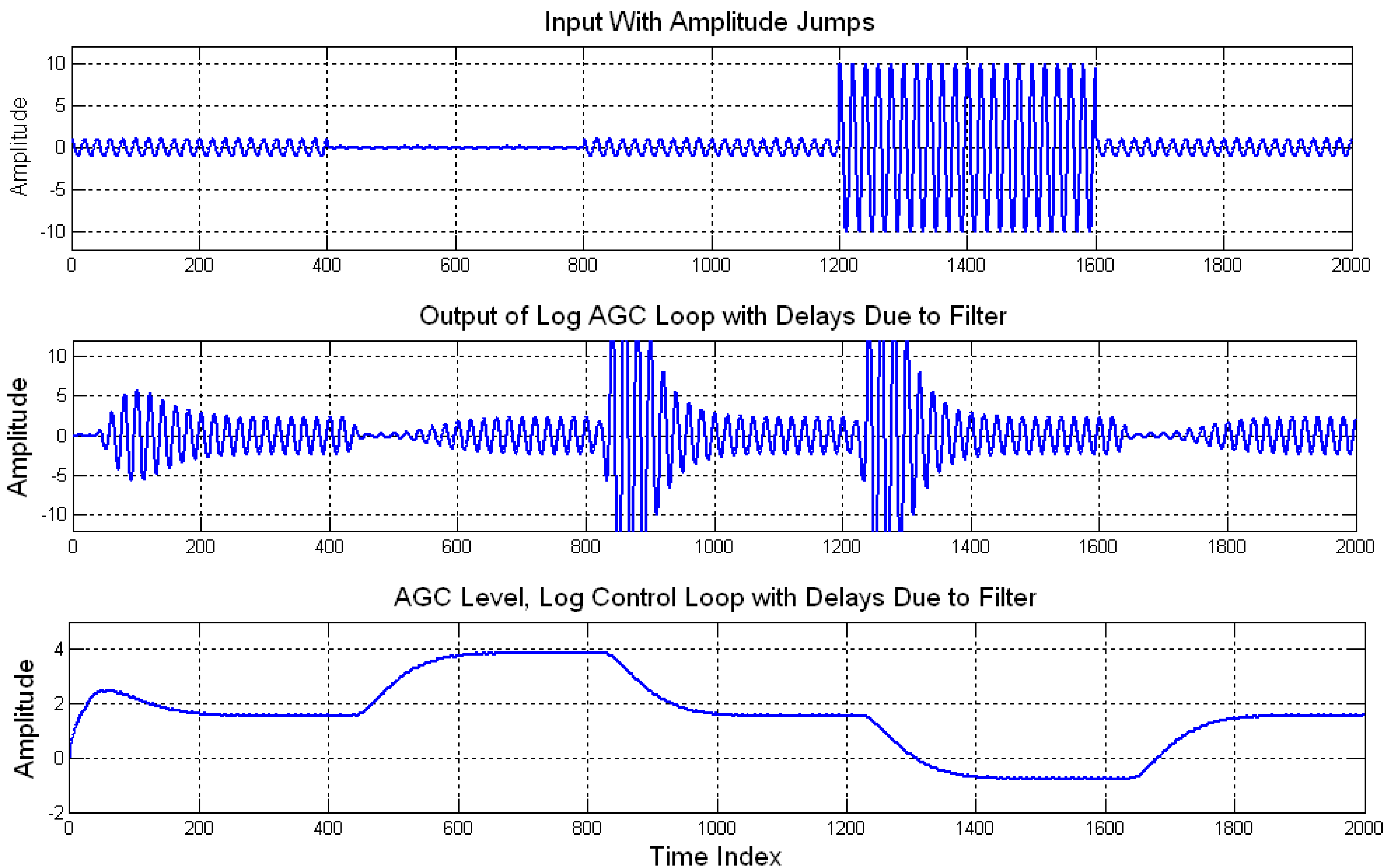
Linear Loop AGC Responses: with Filter Delays



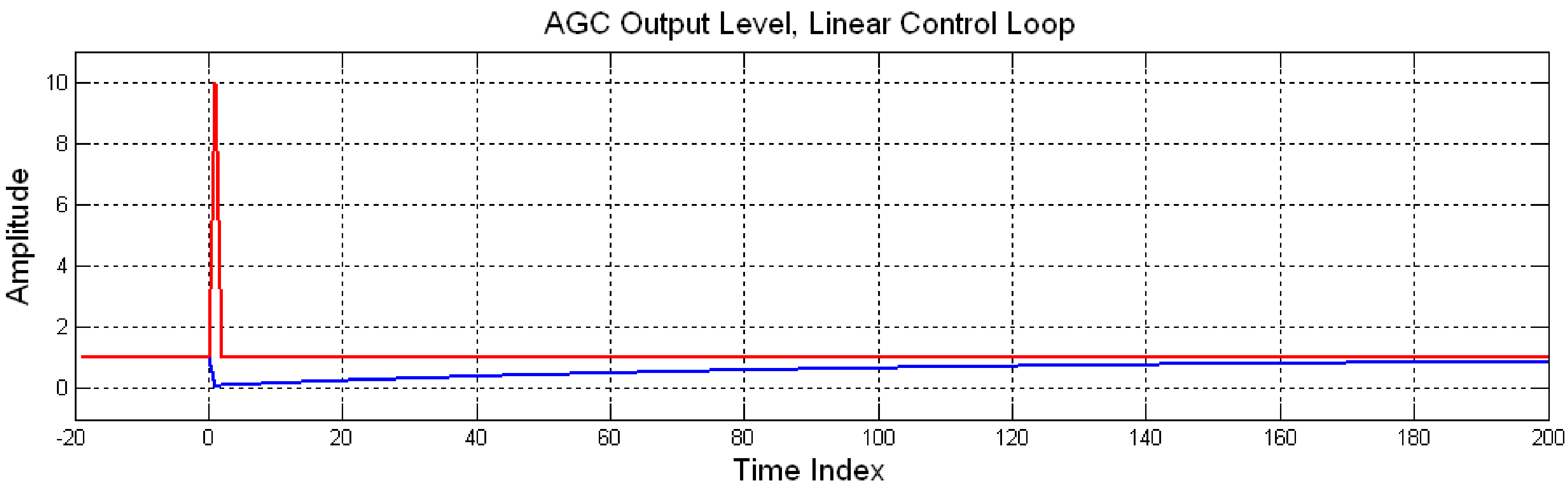
Log Loop AGC Responses

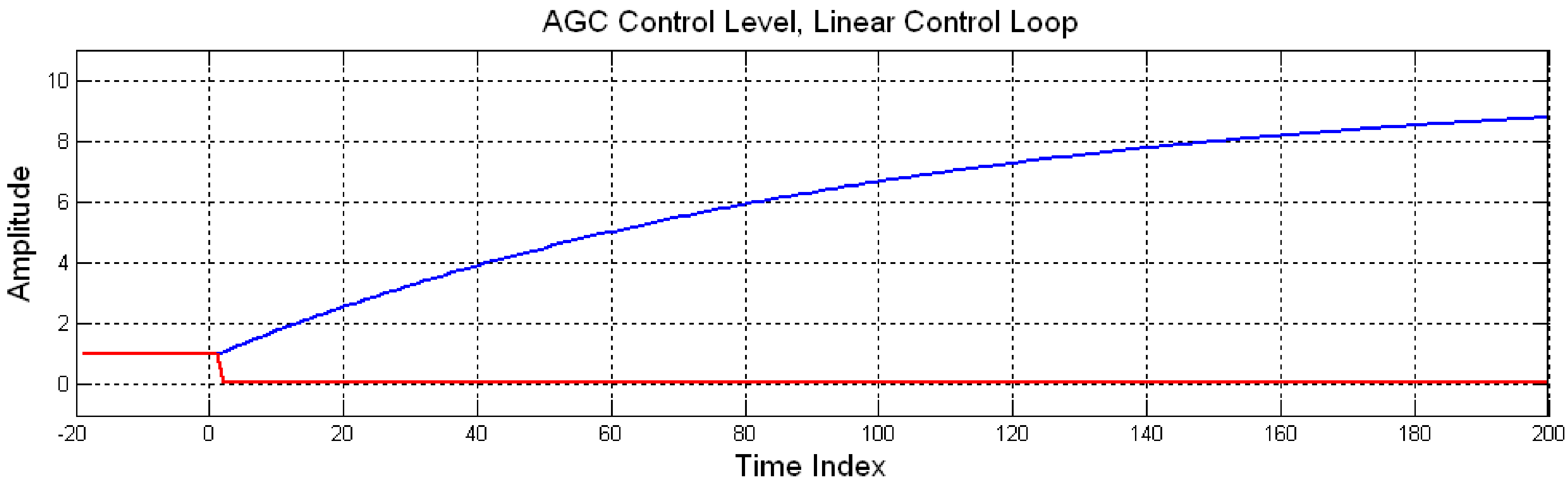


Log Loop AGC Responses: with Filter Delays

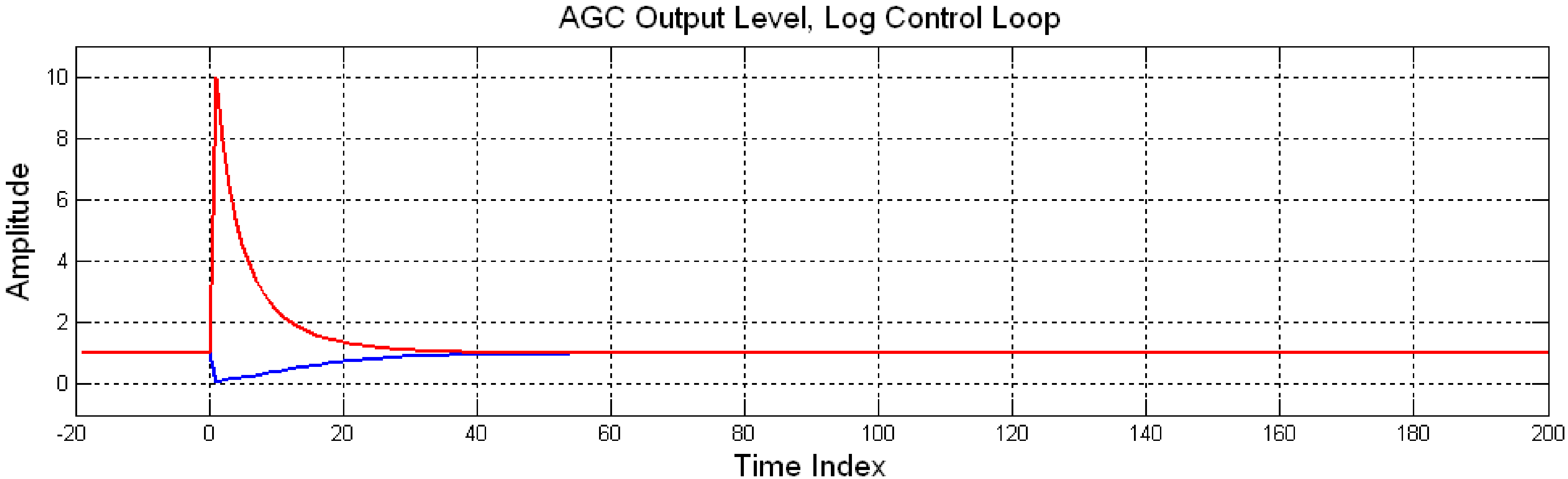


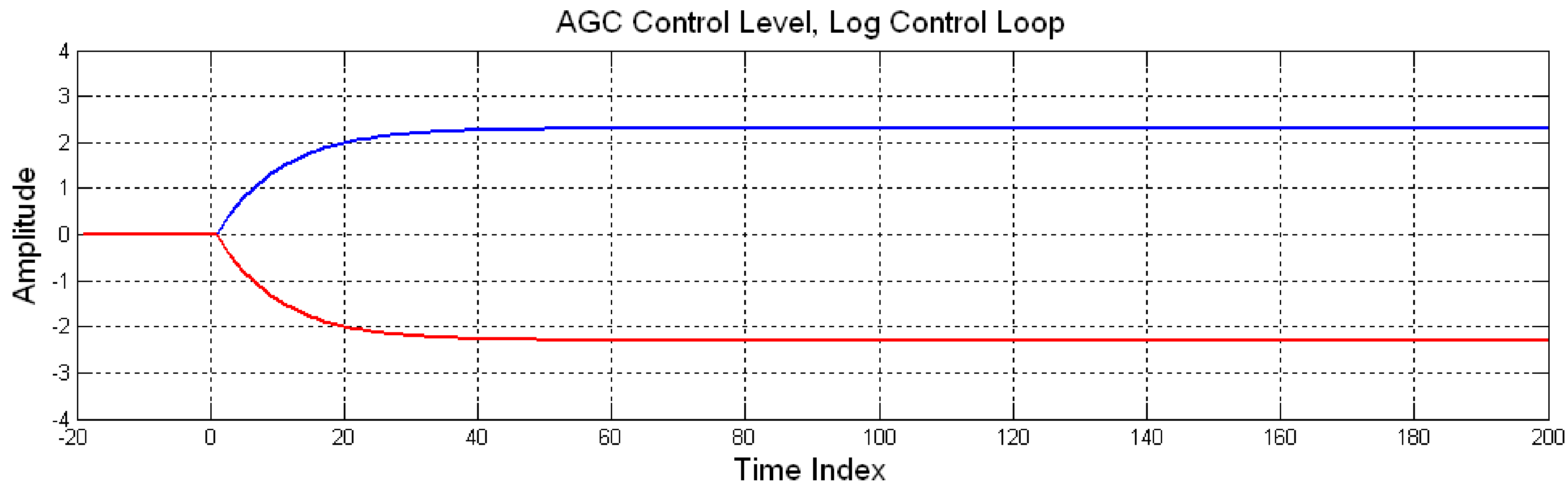
Linear Loop AGC Output and Control Levels



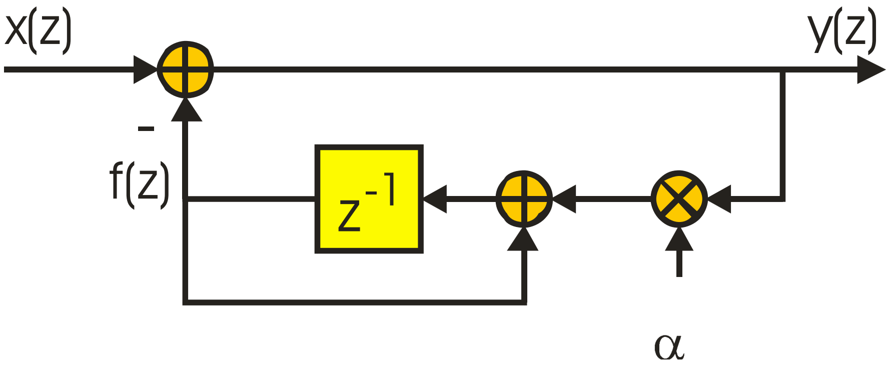


Log Loop AGC Output and Control Levels

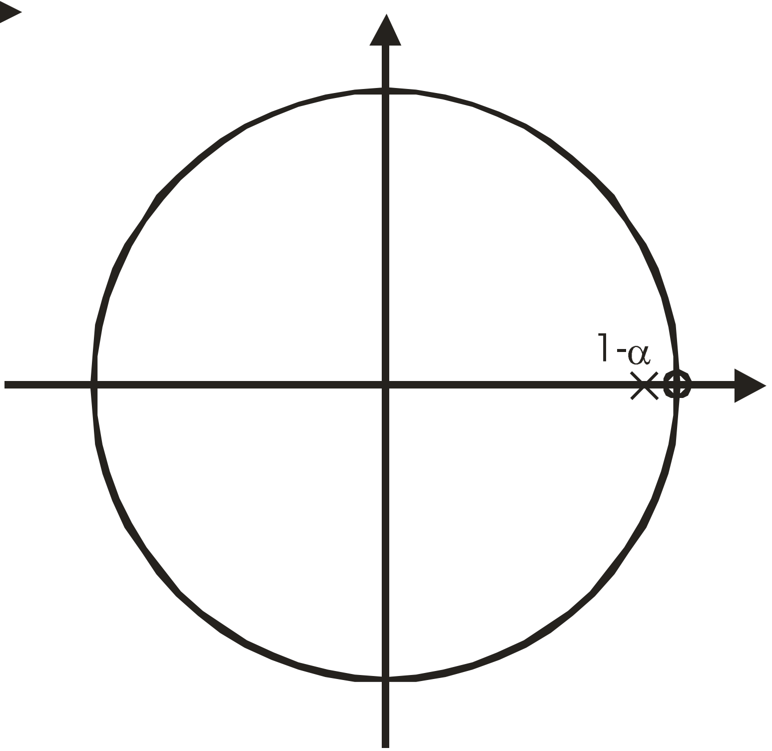




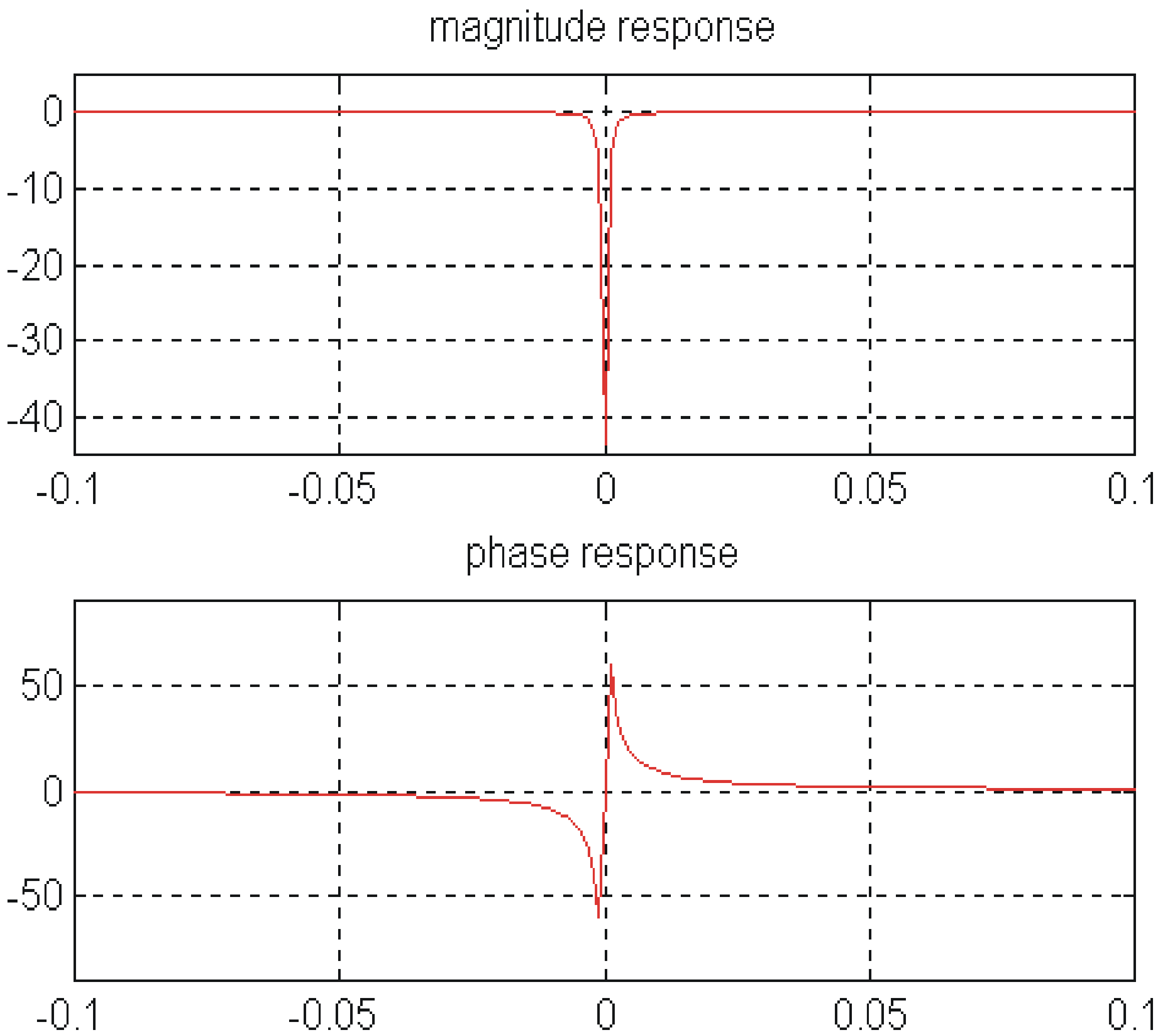
DC Canceller,
DC Notch Filter



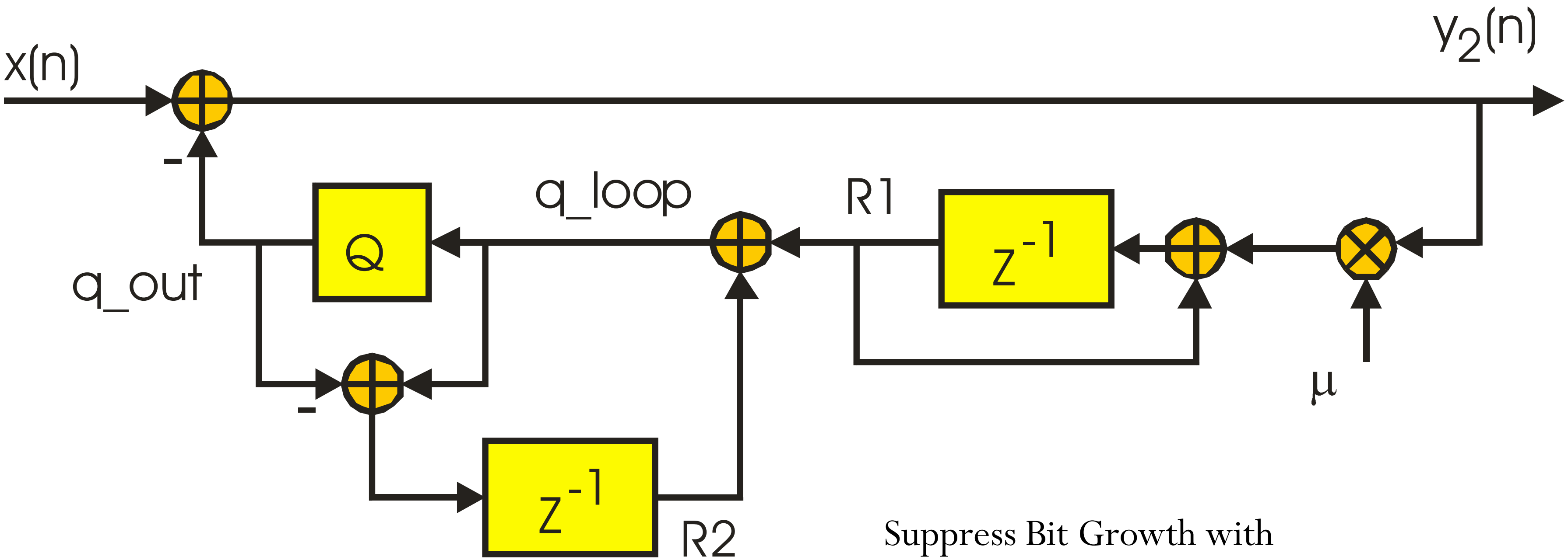
$$H(Z) = \frac{Z-1}{Z-(1-\alpha)}$$



Spectral Response

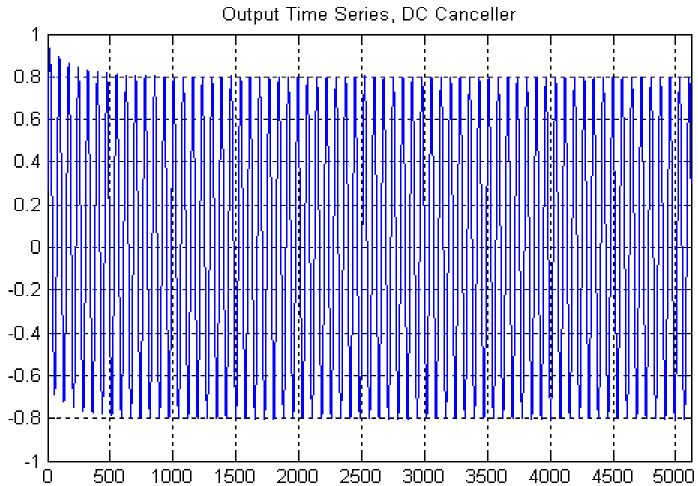


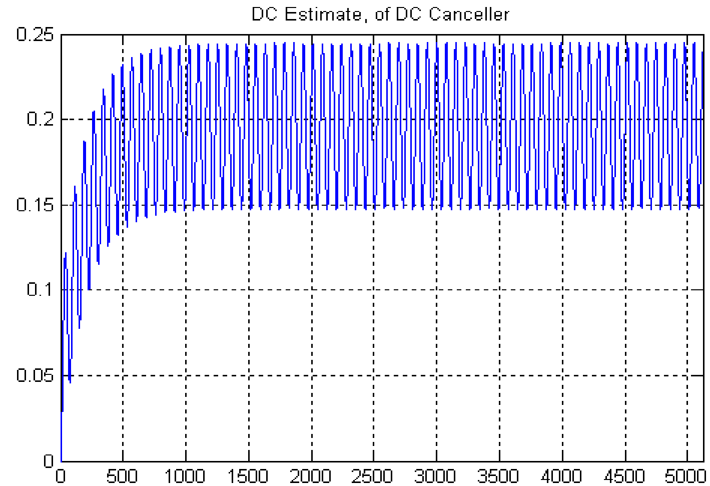
DC Canceller with Embedded Sigma-Delta Converter

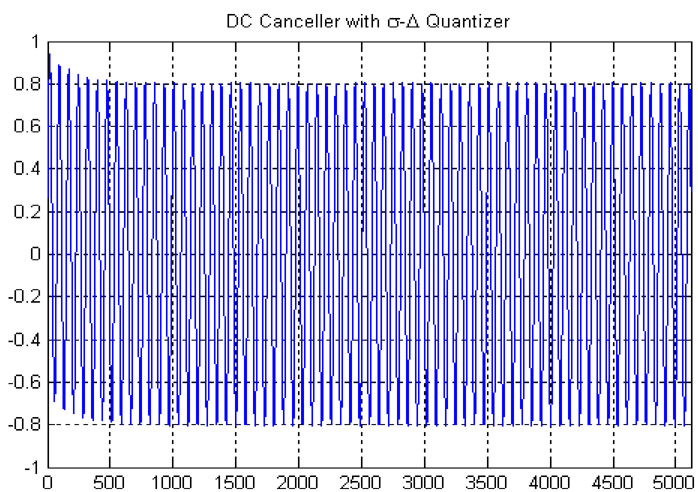


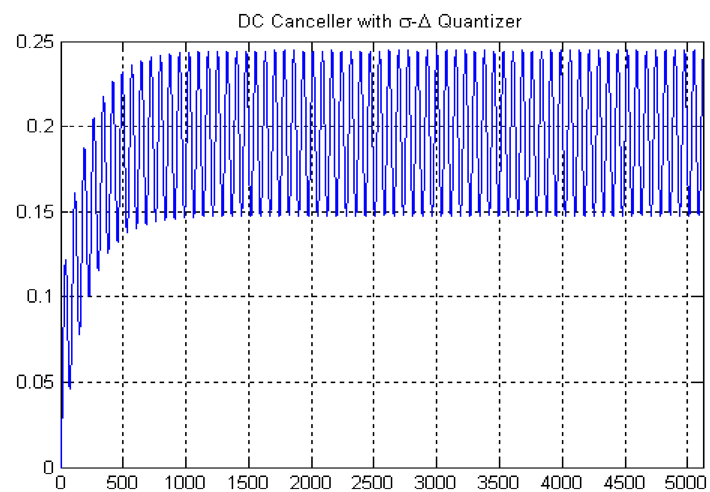
Suppress Bit Growth with
Sigma-Delta Converter in
Feedback Path

DC Canceller Time Series

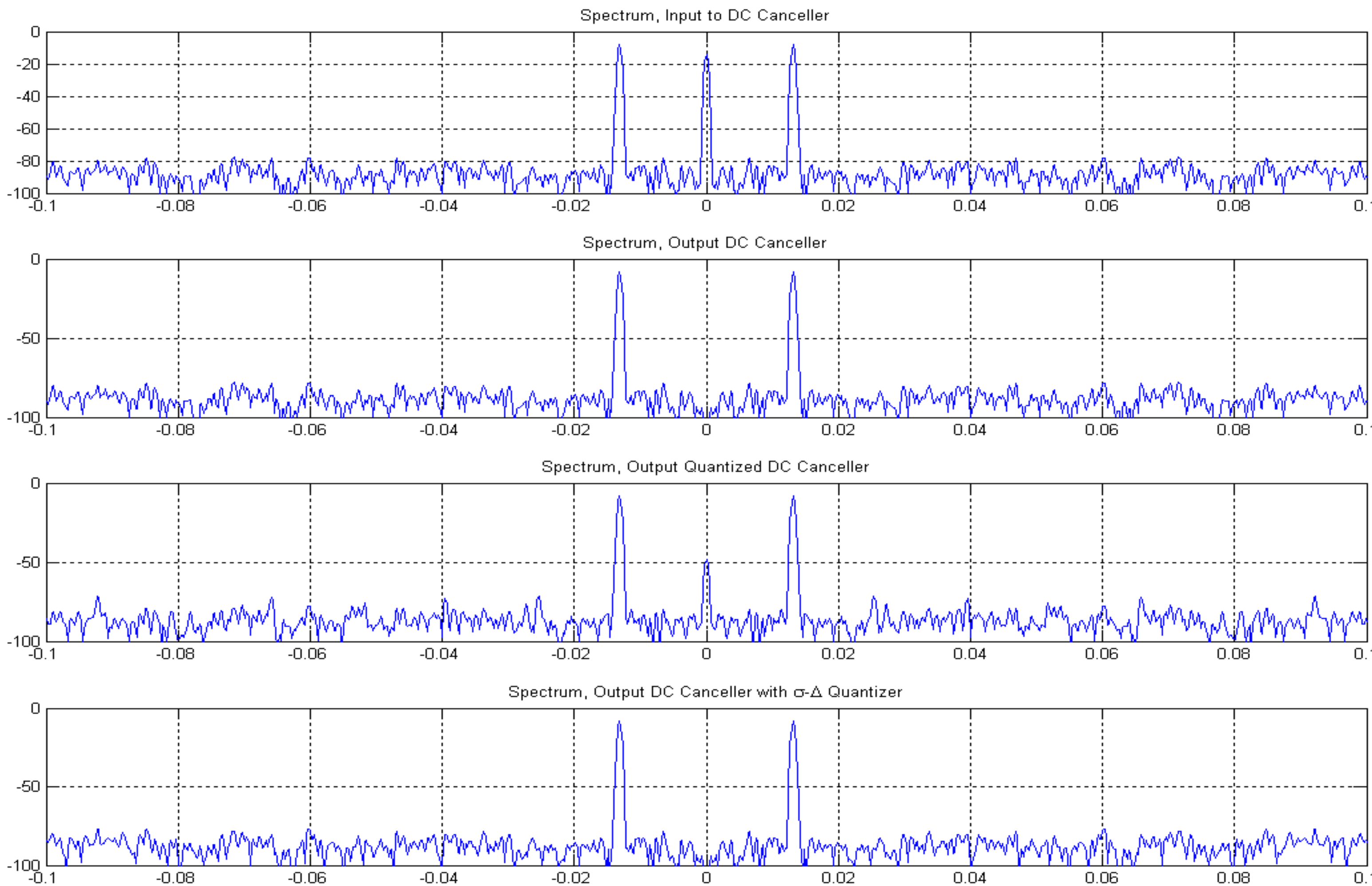




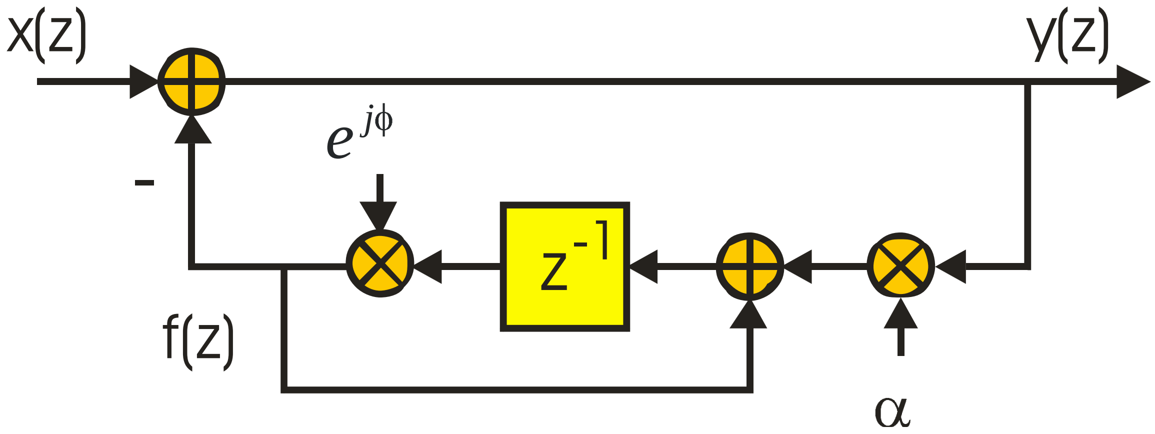


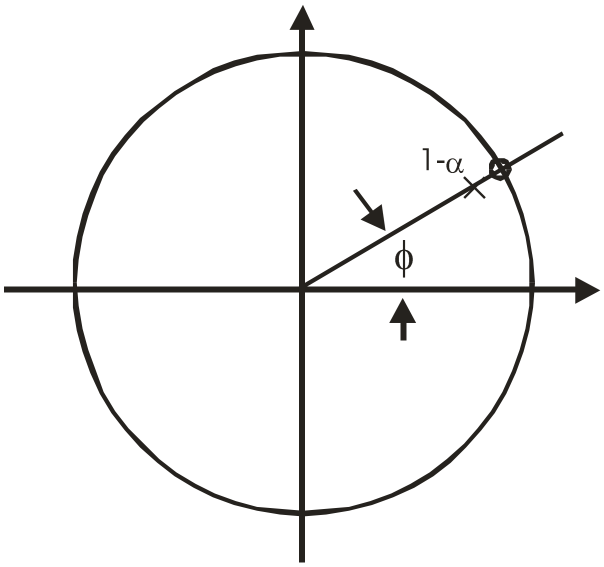


Spectra
Input and Output of Canceller



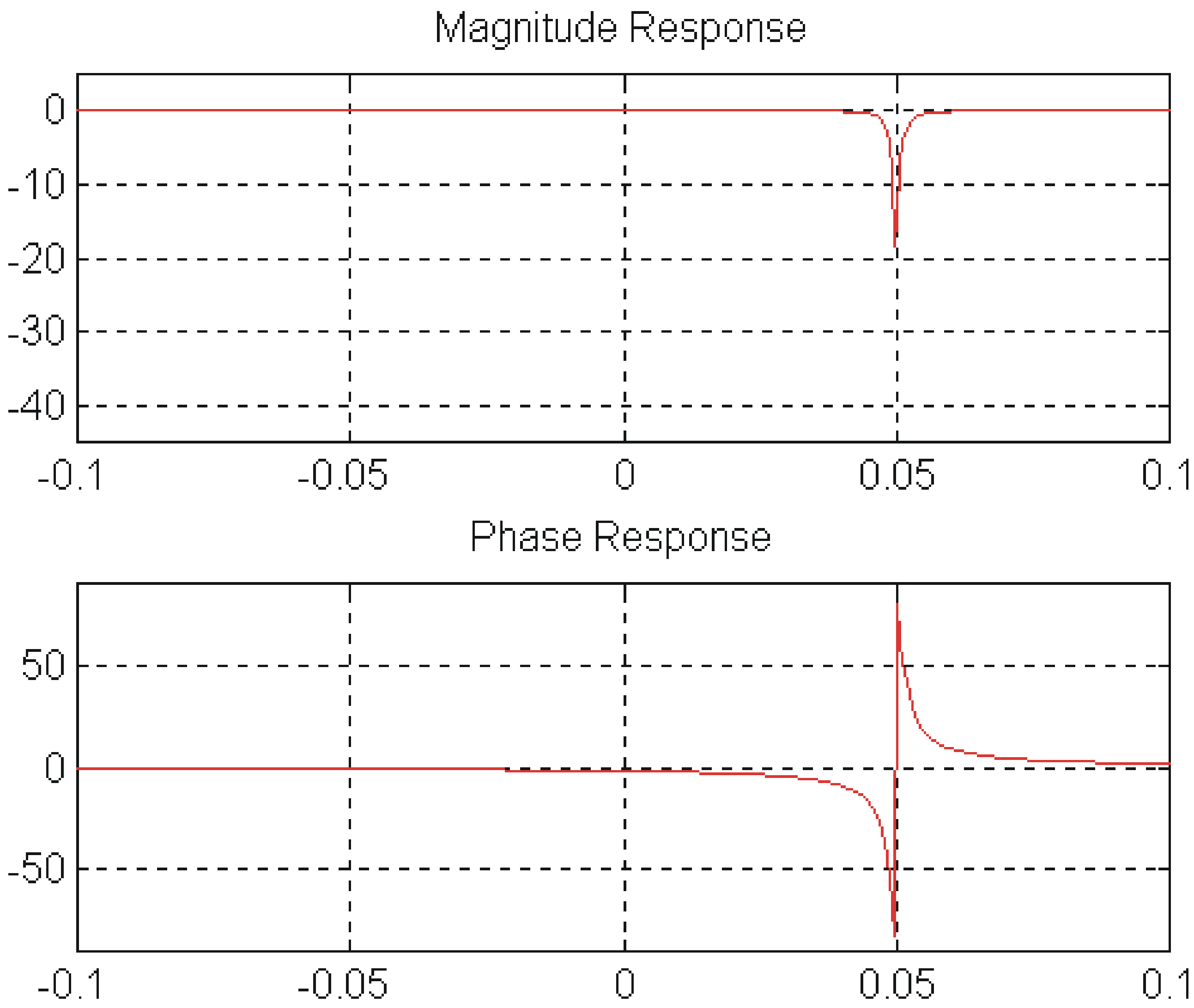
Tunable Notch,
Spin the Delay Line



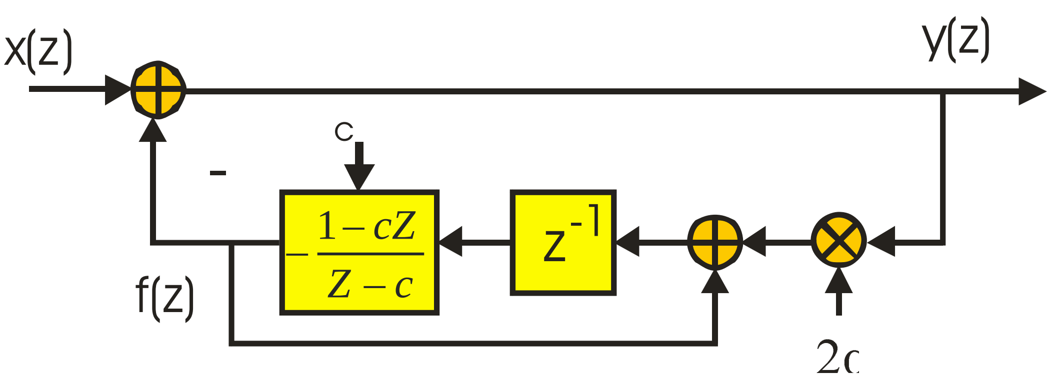


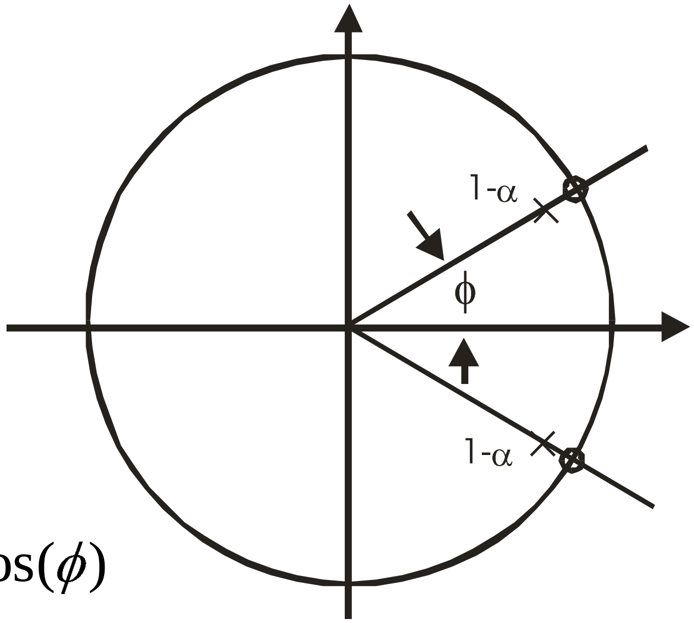
$$H(Z) = \frac{Z - e^{j\phi}}{Z - (1-\alpha)e^{j\phi}}$$

Spectral Response



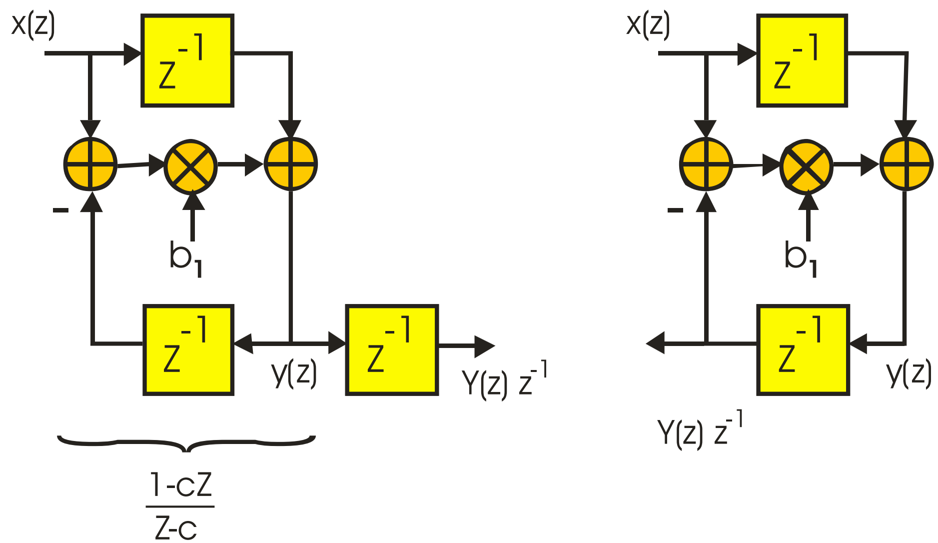
Tuning With LP-to-BP Transformation

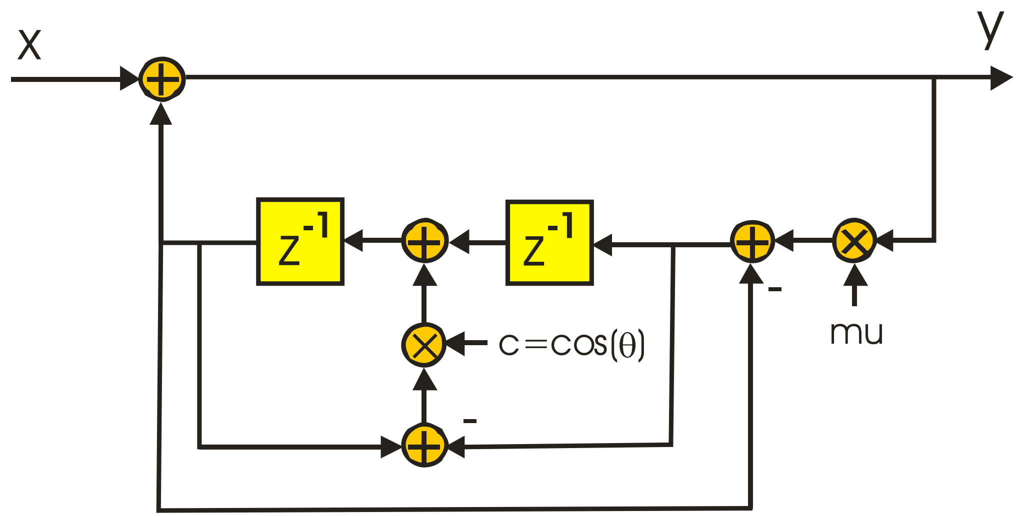




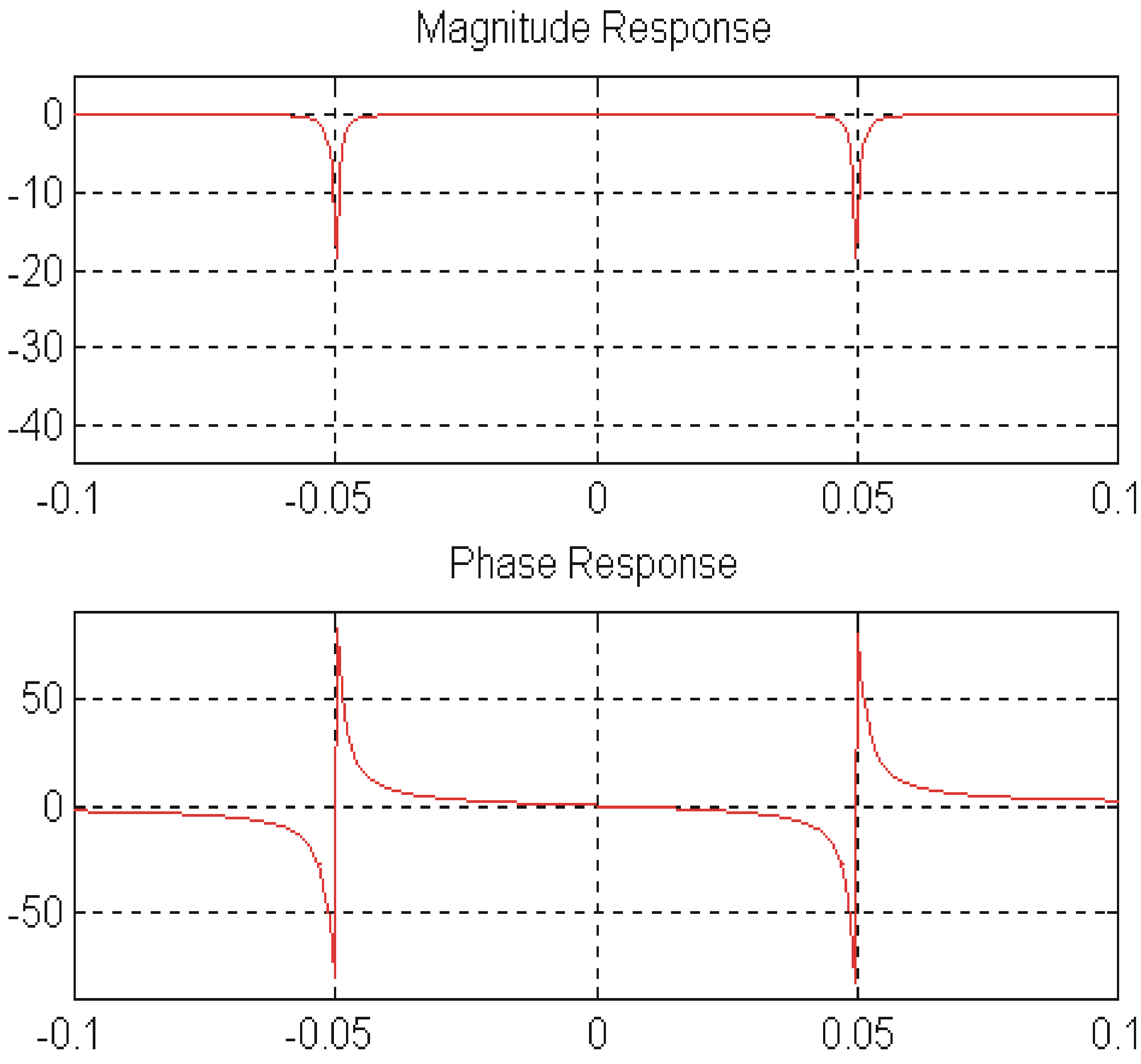
$$H(Z)=\frac{Z^{2}-2cZ+1}{Z^{2}-2c(1-\alpha)Z+(1-2\alpha)}:c=\cos(\phi)$$

Implementing LP-to-BP Transformation

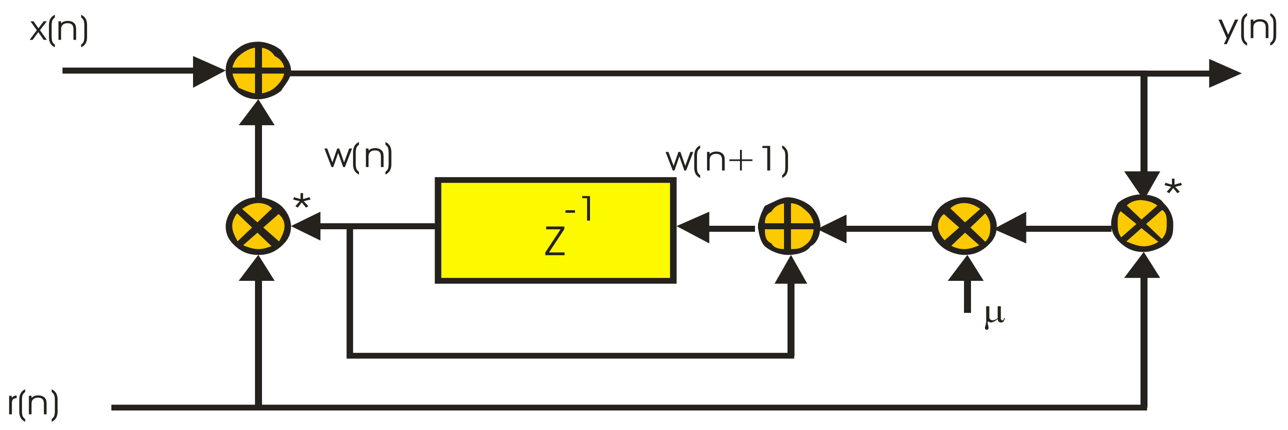


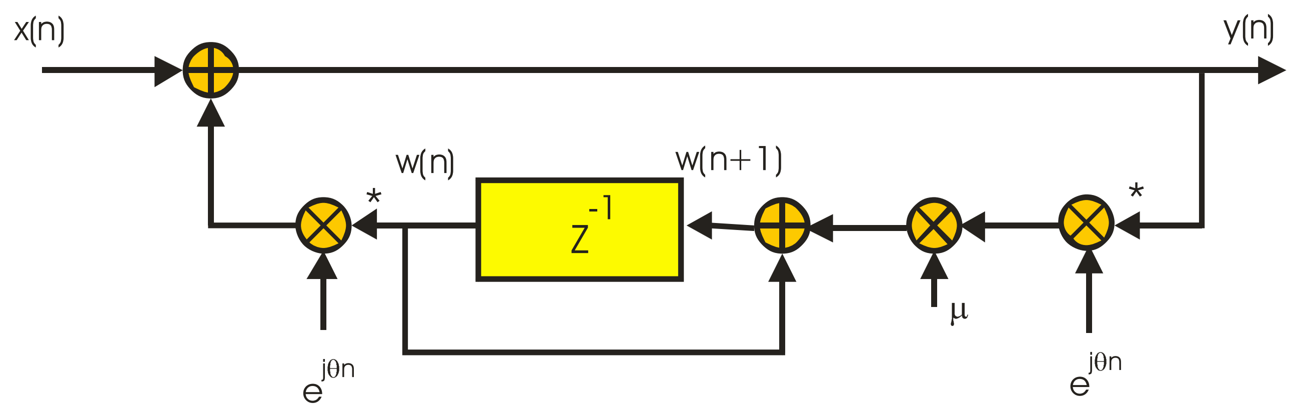


Spectral Response

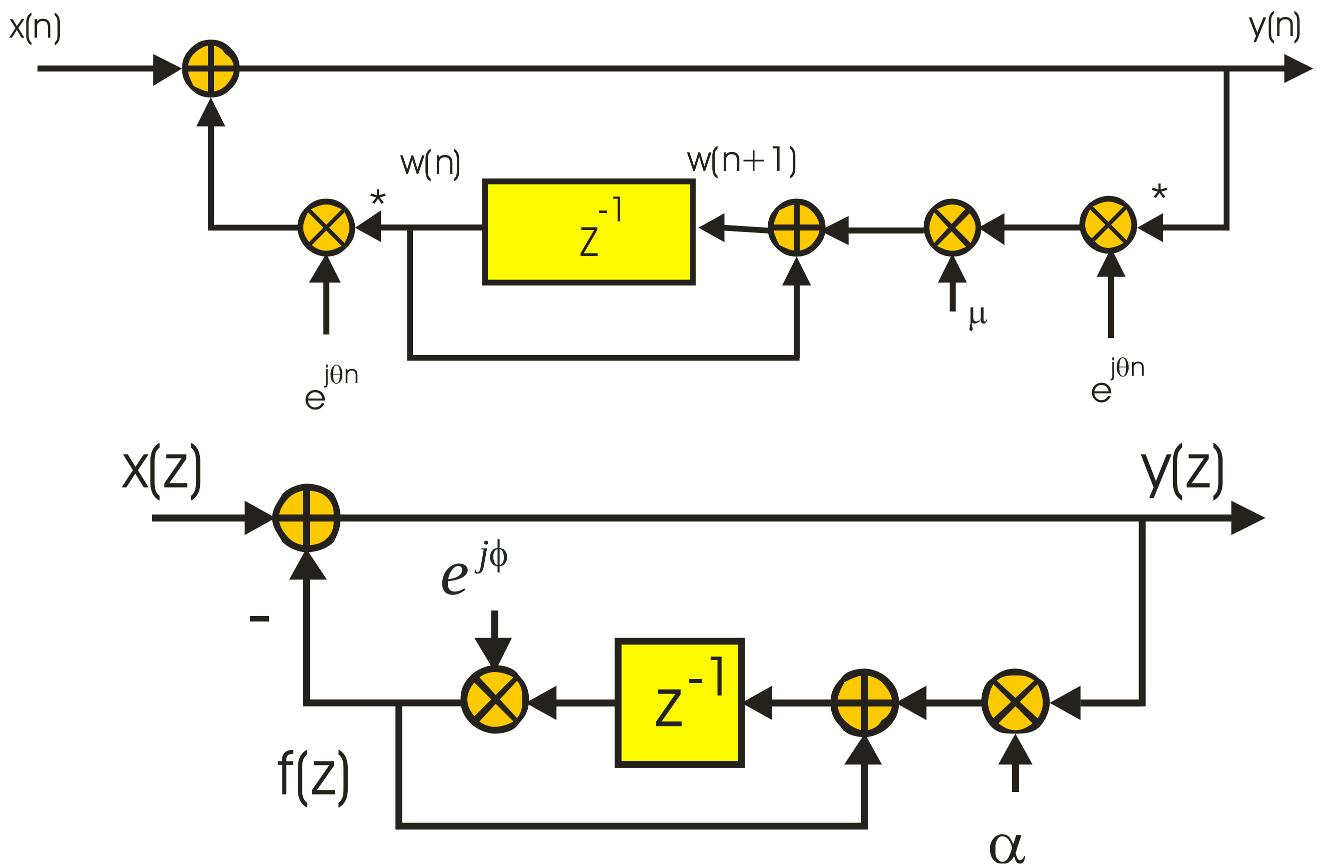


Self Tuning:
Reference Canceling

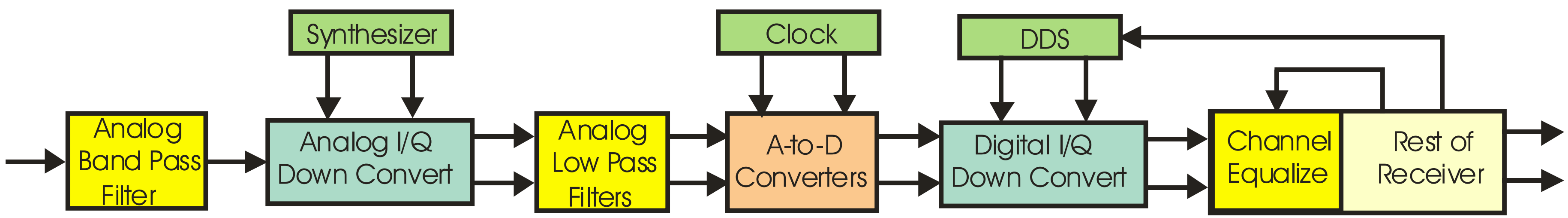




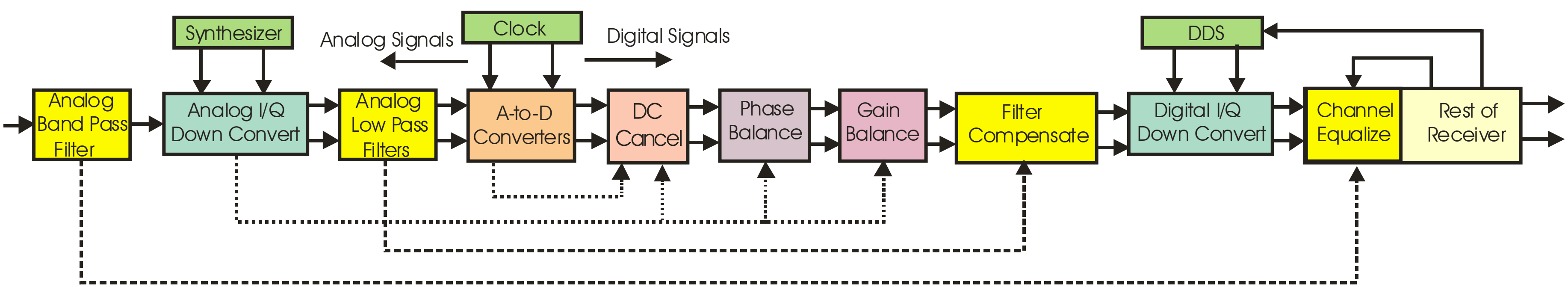
Filters have Same Transfer Function



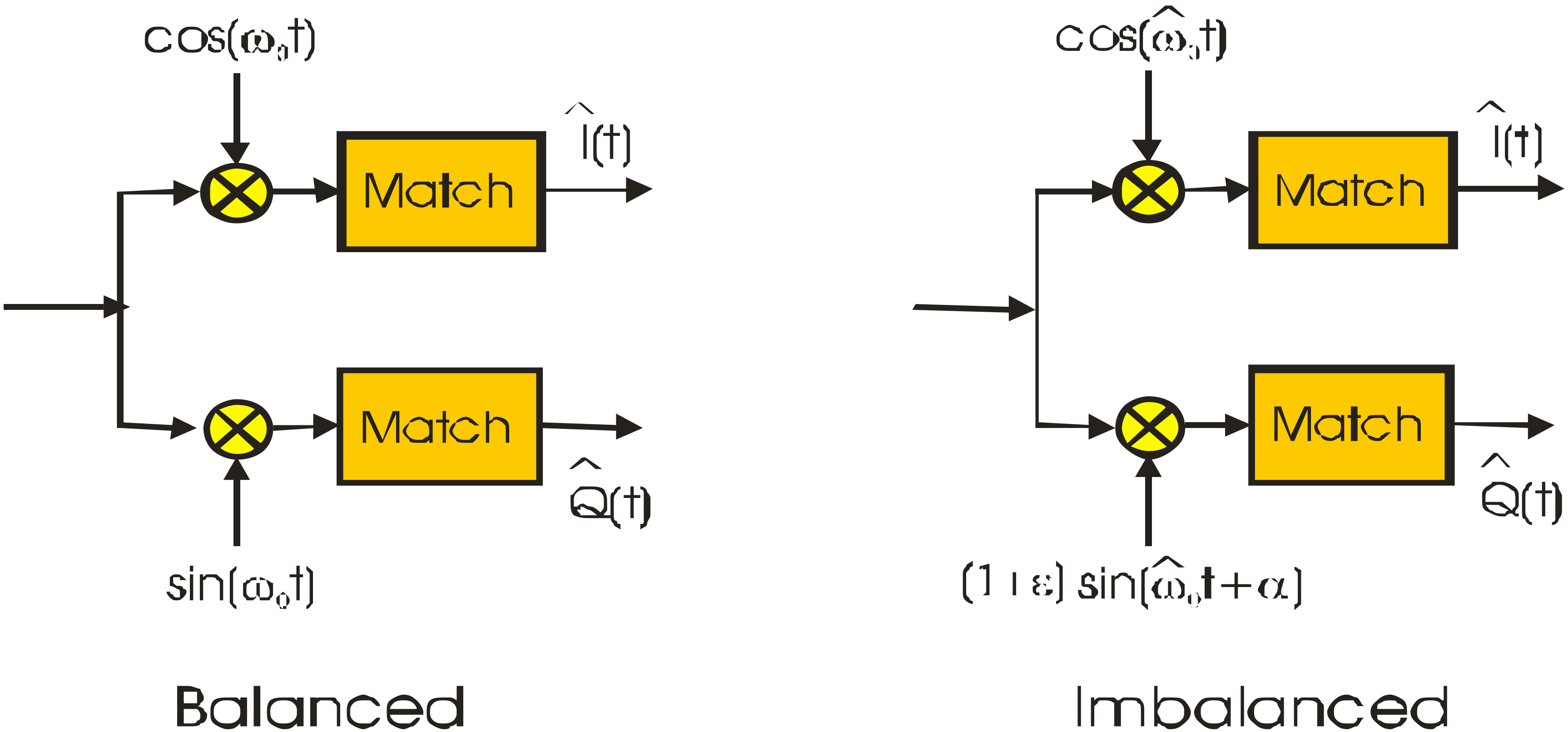
Block Diagram of Receiver with Ideal Signal Processing Blocks



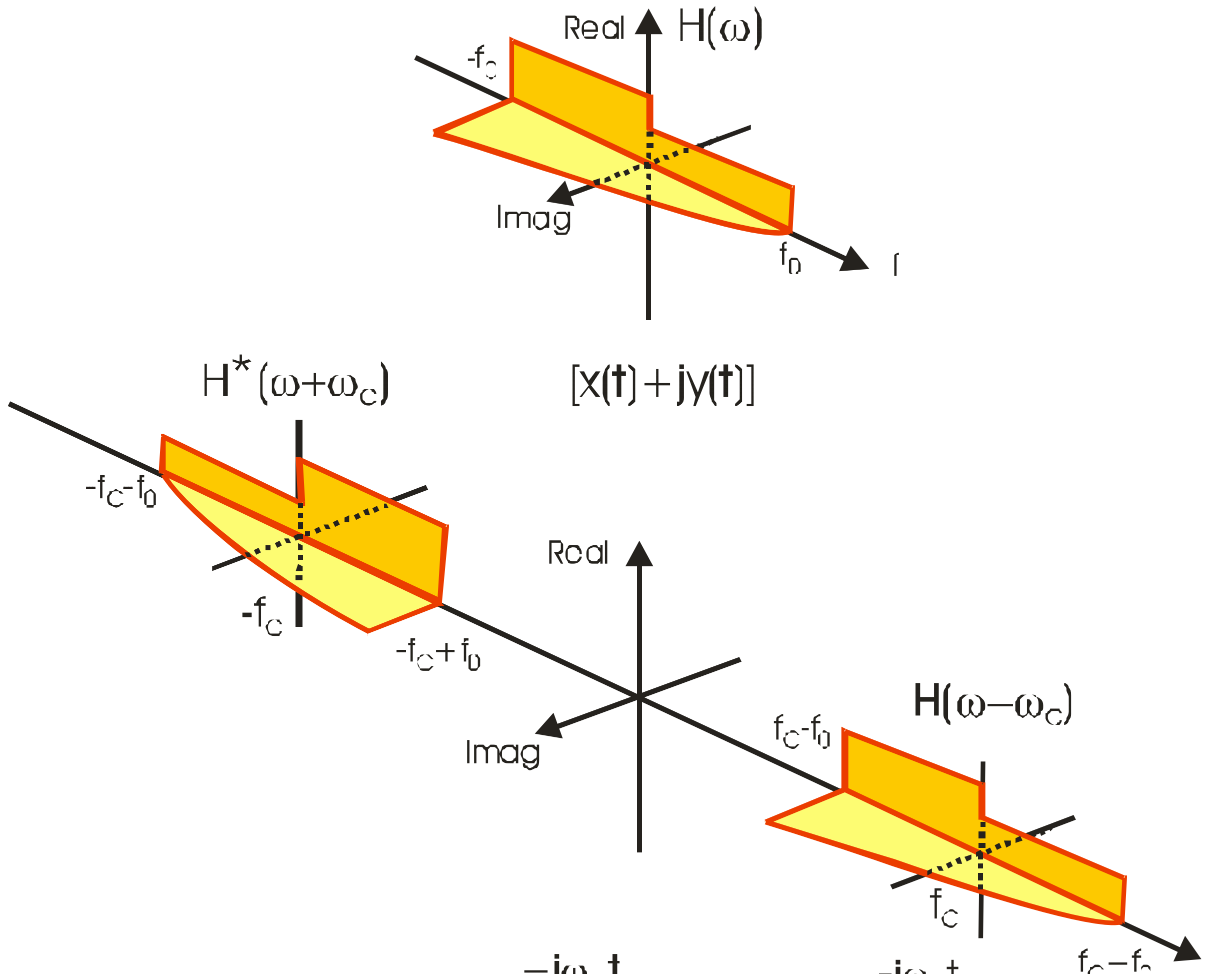
Block Diagram of Receiver with Non-Ideal Signal Processing Blocks and Associated Compensating Blocks



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



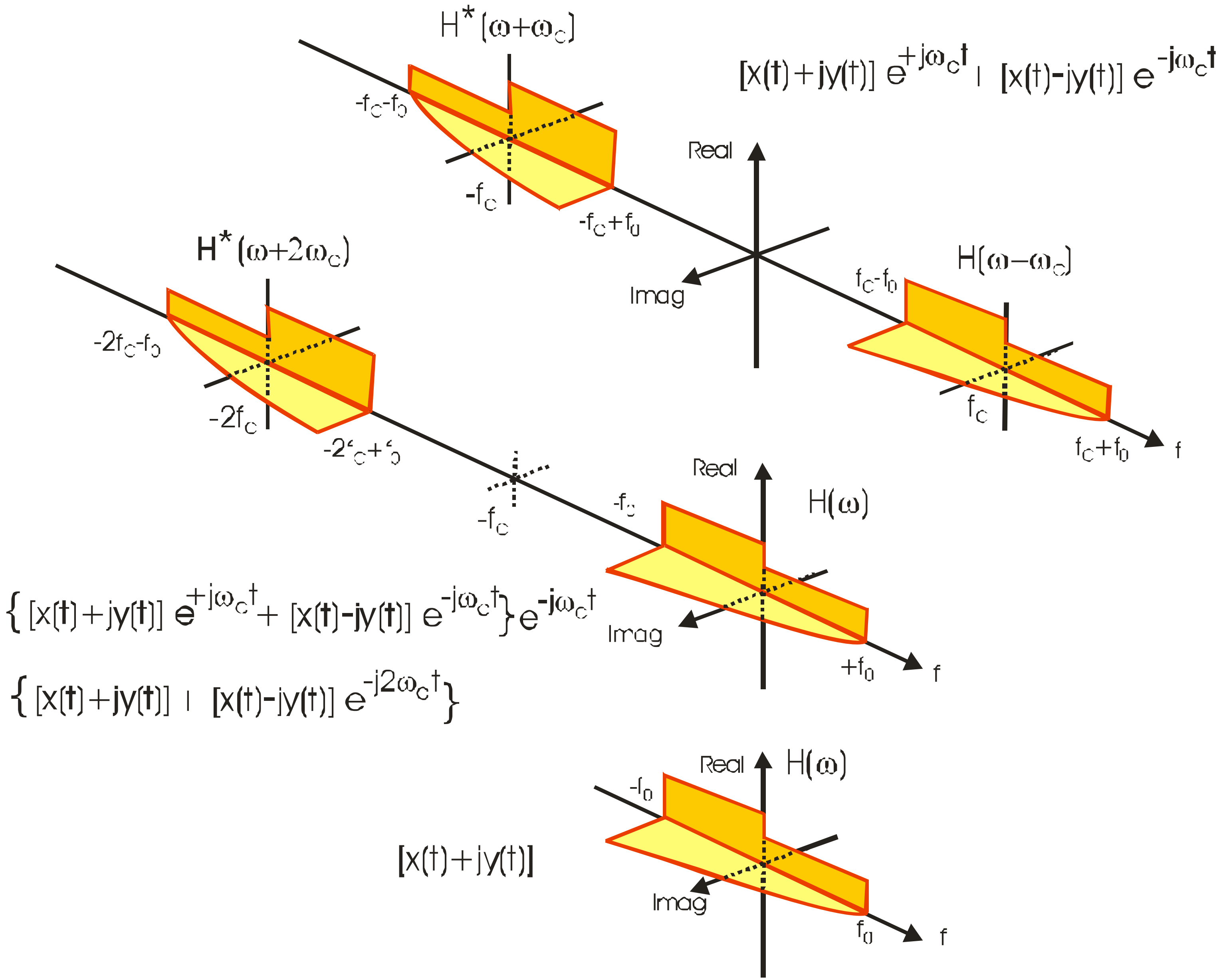
Complex Baseband & Real Band-Centered



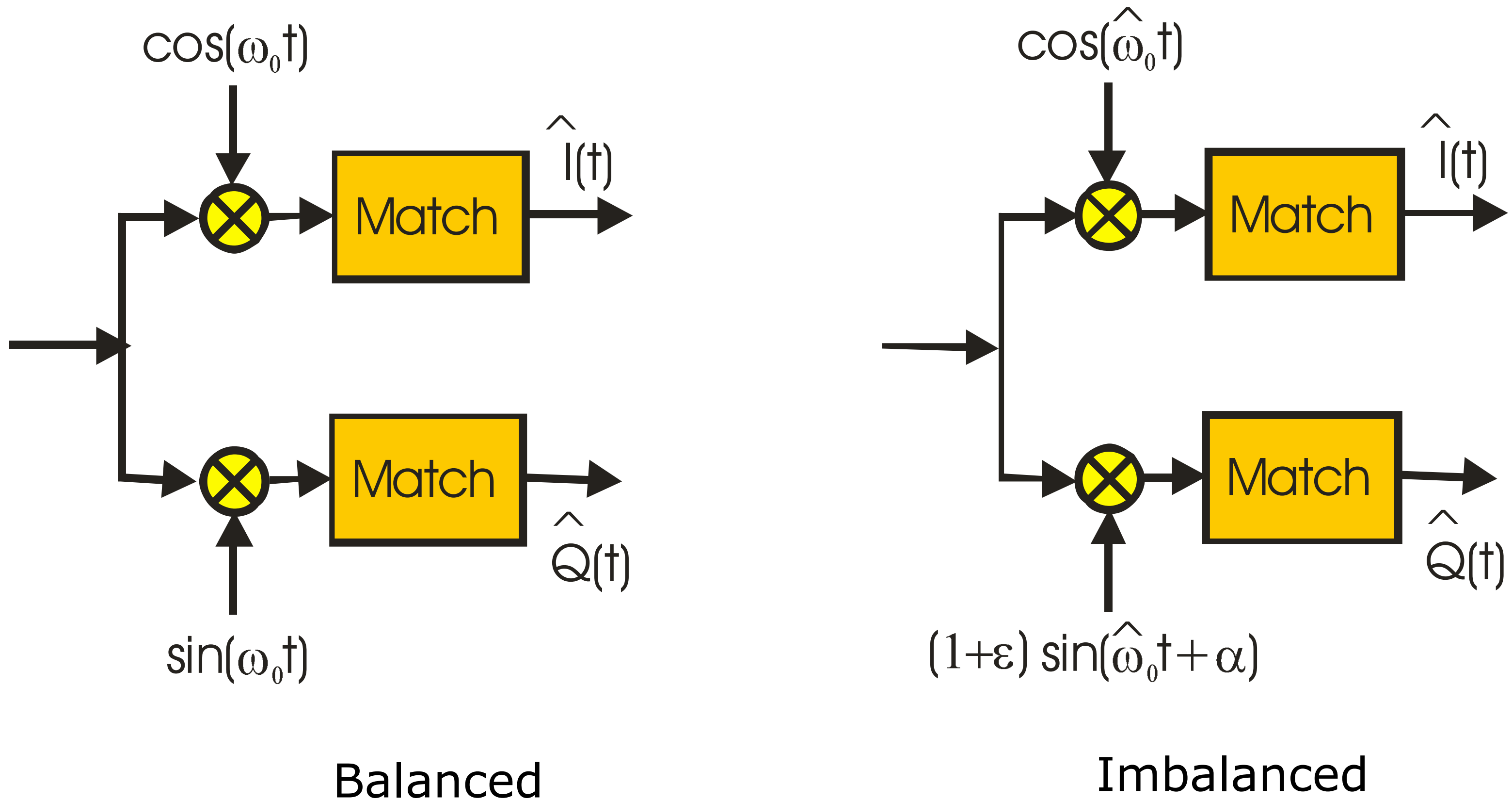
$$[x(t)+jy(t)]\, e^{-j\omega_c t} + [x(t)-jy(t)]\, e^{-j\omega_c t}$$

$$x(t)\cos(\omega_c t) - y(t)\sin(\omega_c t)$$

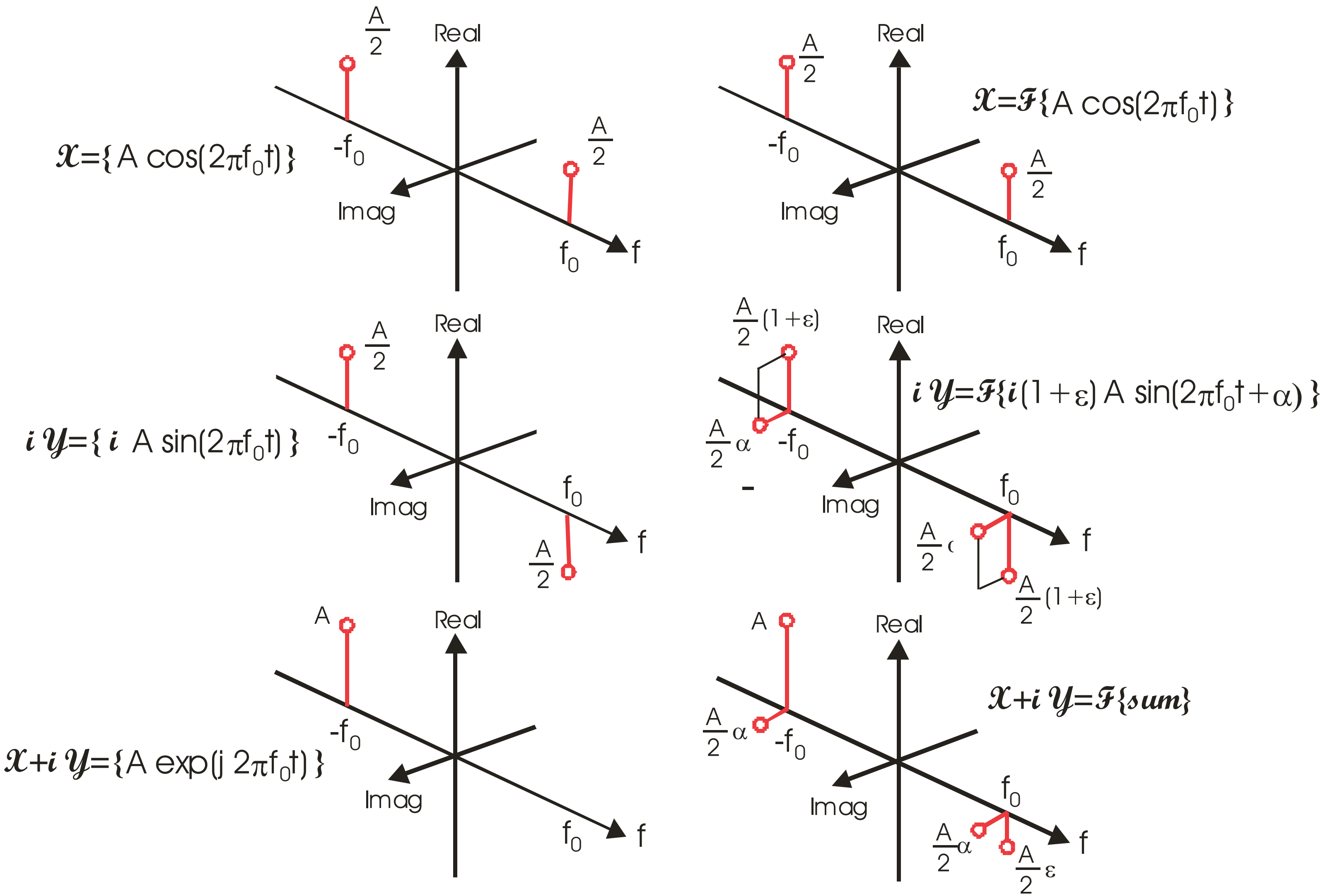
Complex Down Conversion



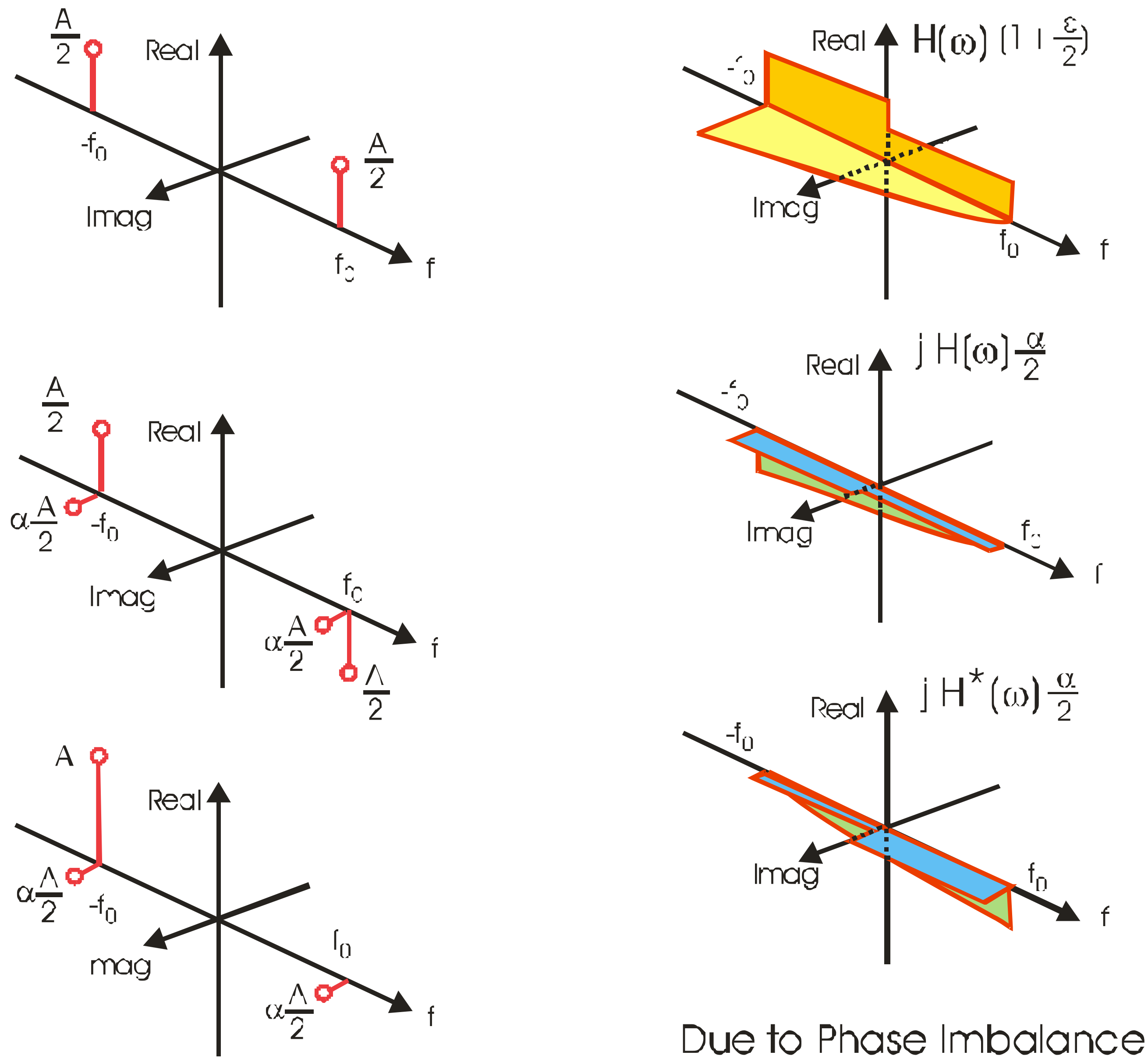
I-Q Gain and Phase Imbalance



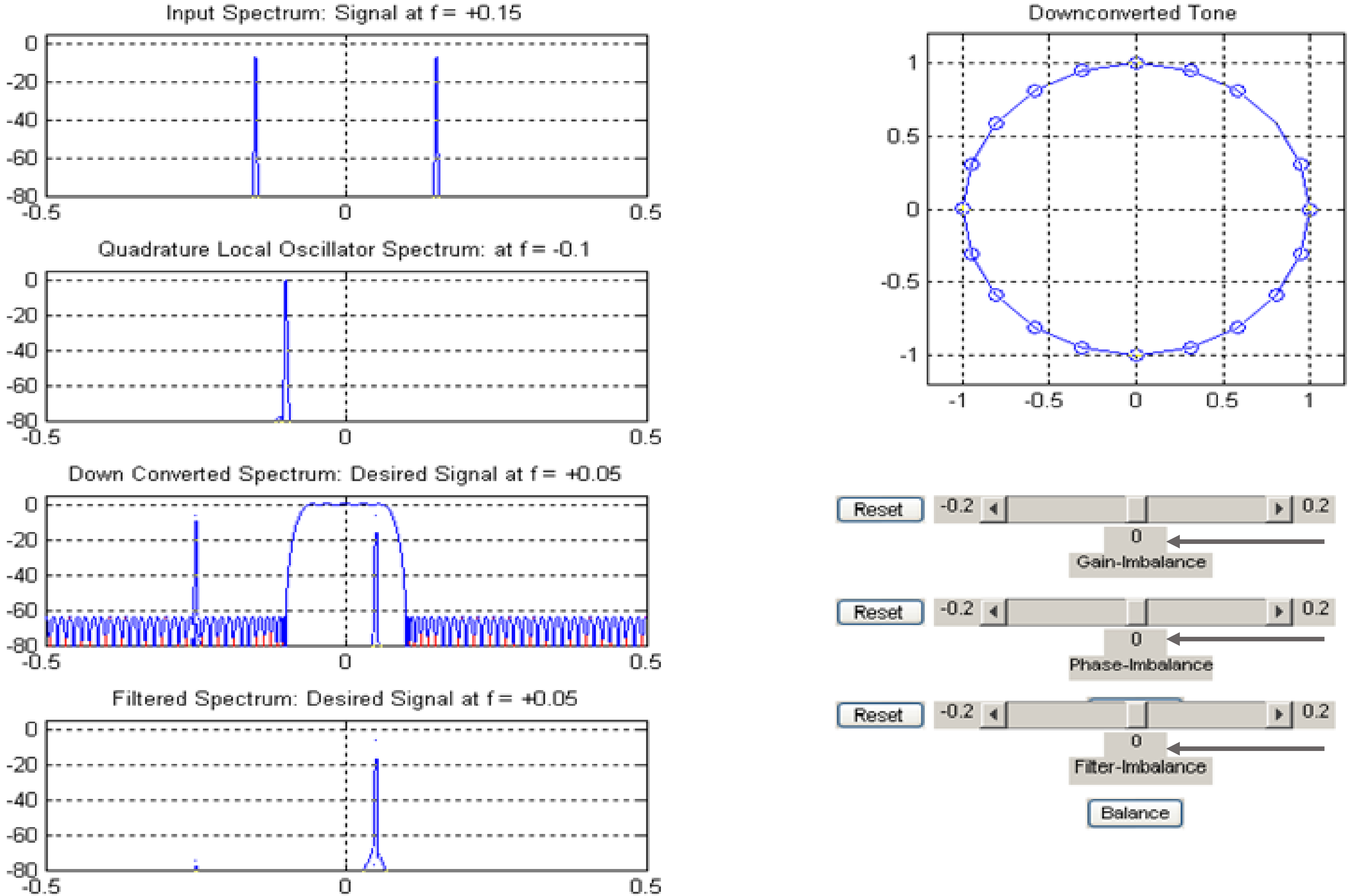
I-Q Imbalance: Image Spectral Terms



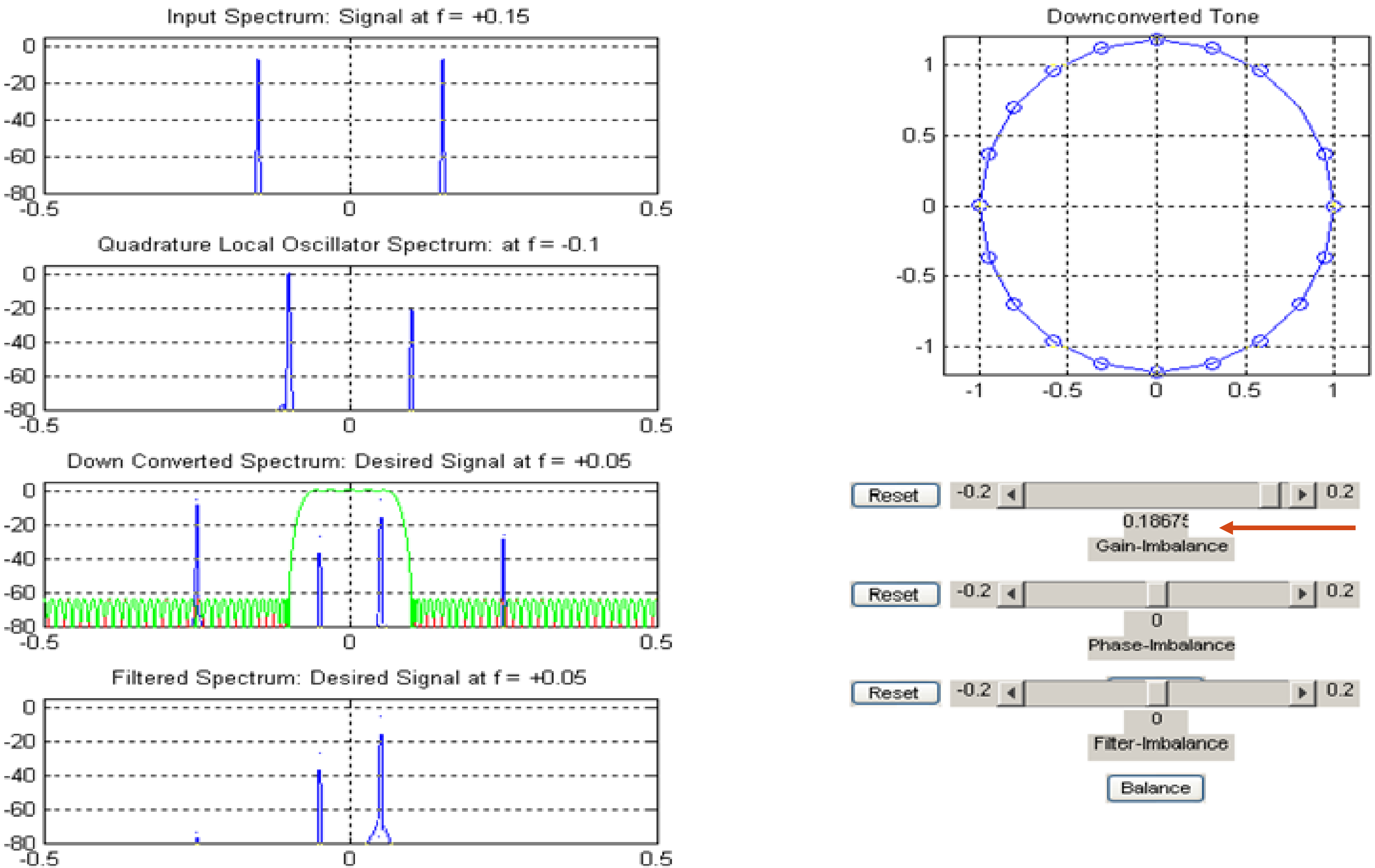
Effect of I-Q Imbalance



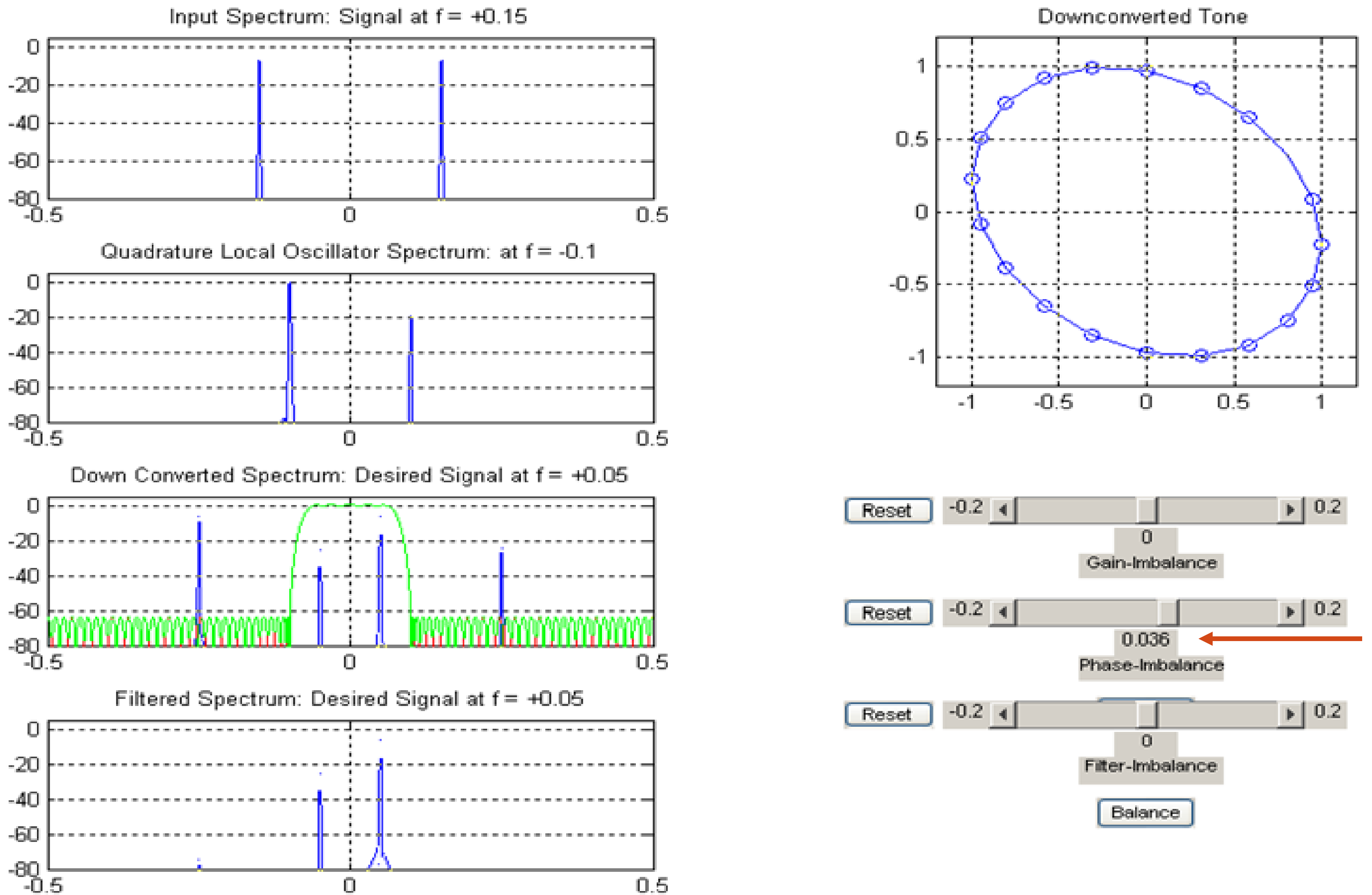
Balanced Mixers



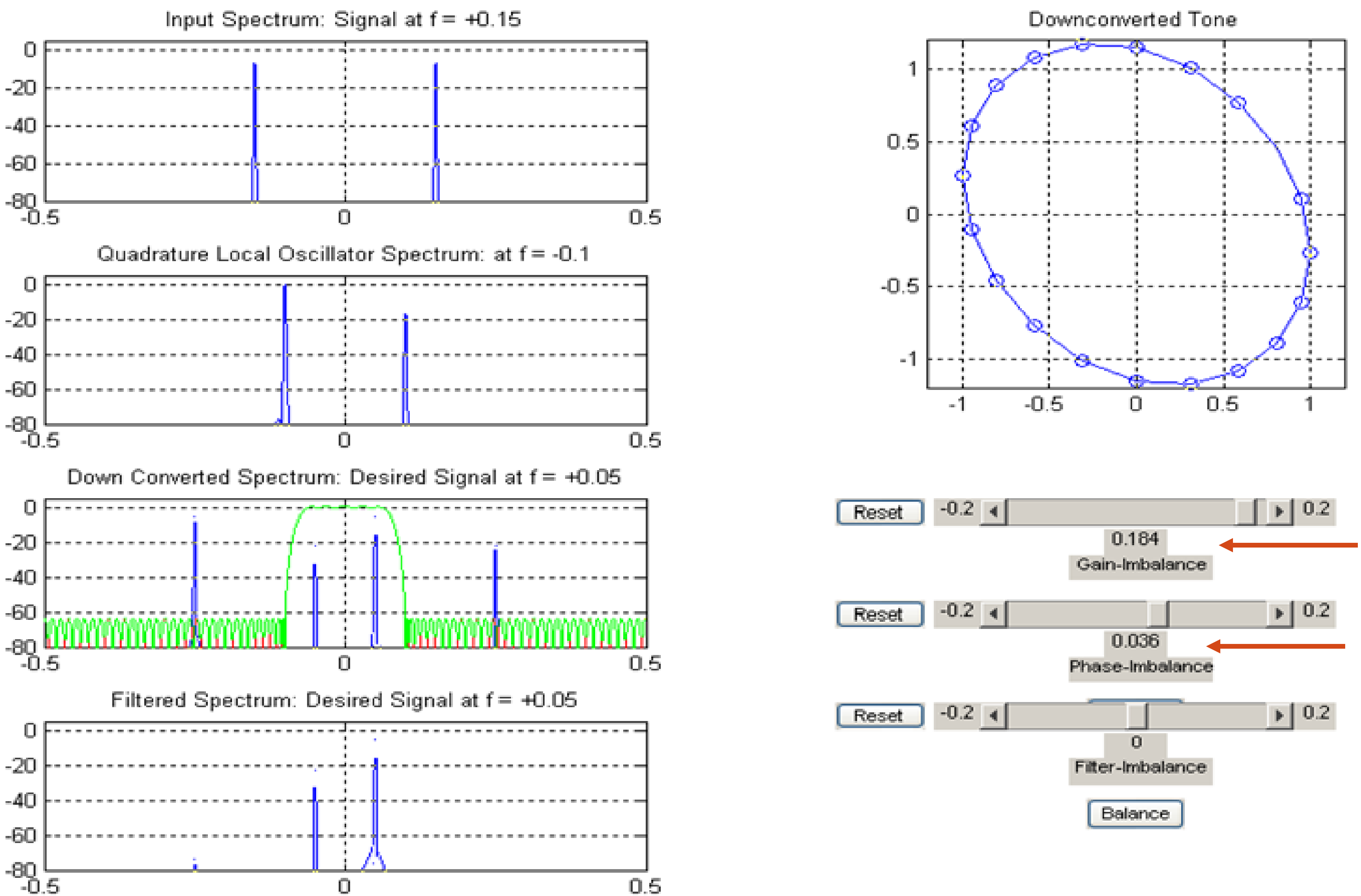
Gain Imbalance



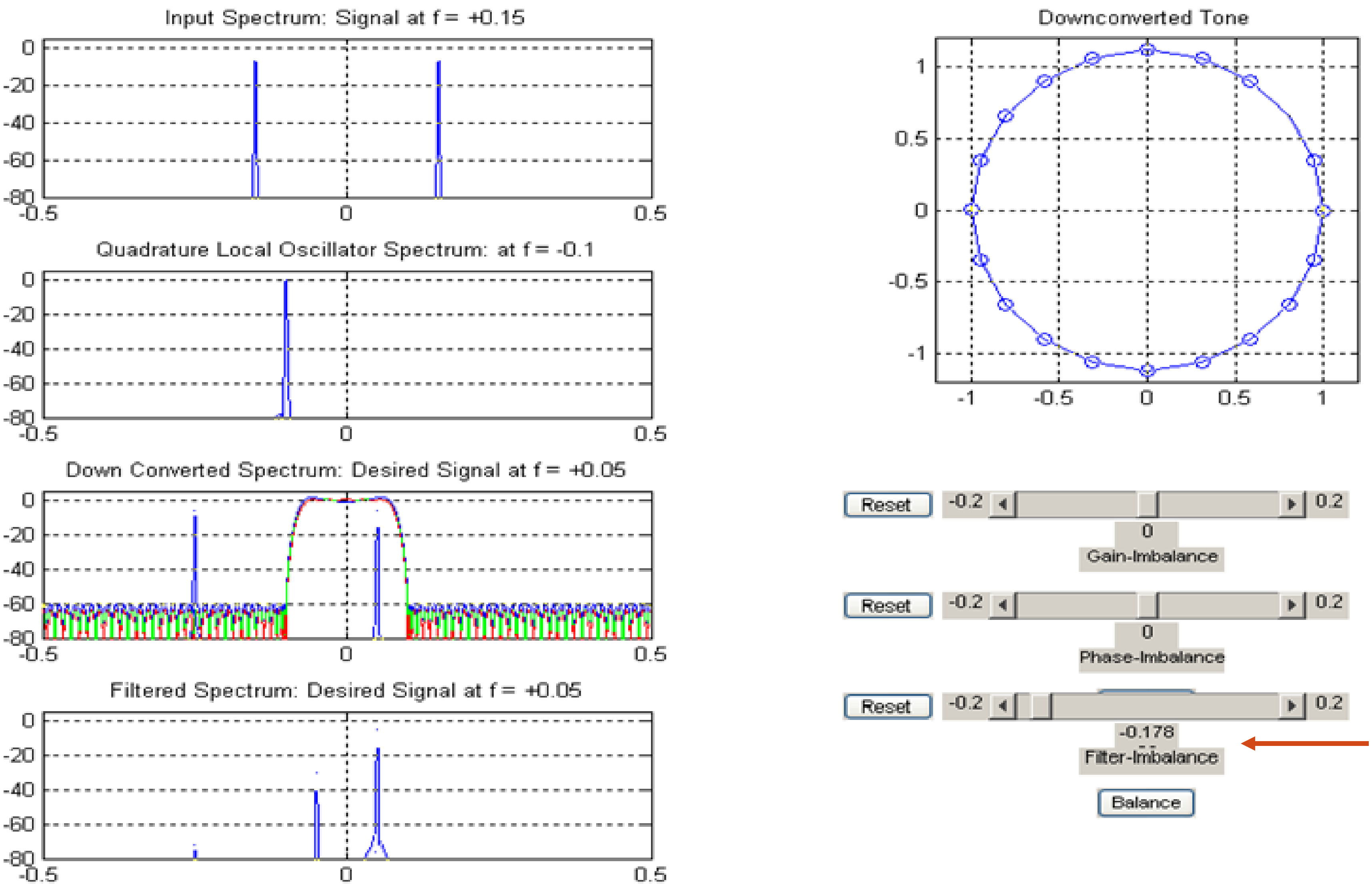
Phase Imbalance



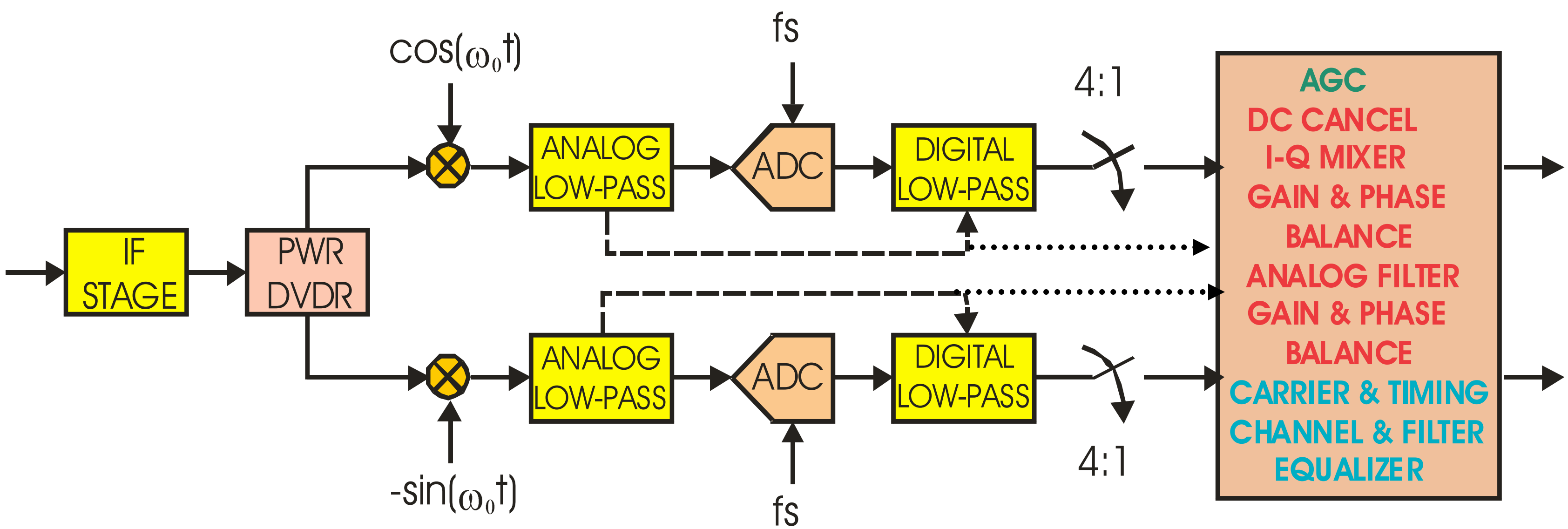
Gain and Phase Imbalance



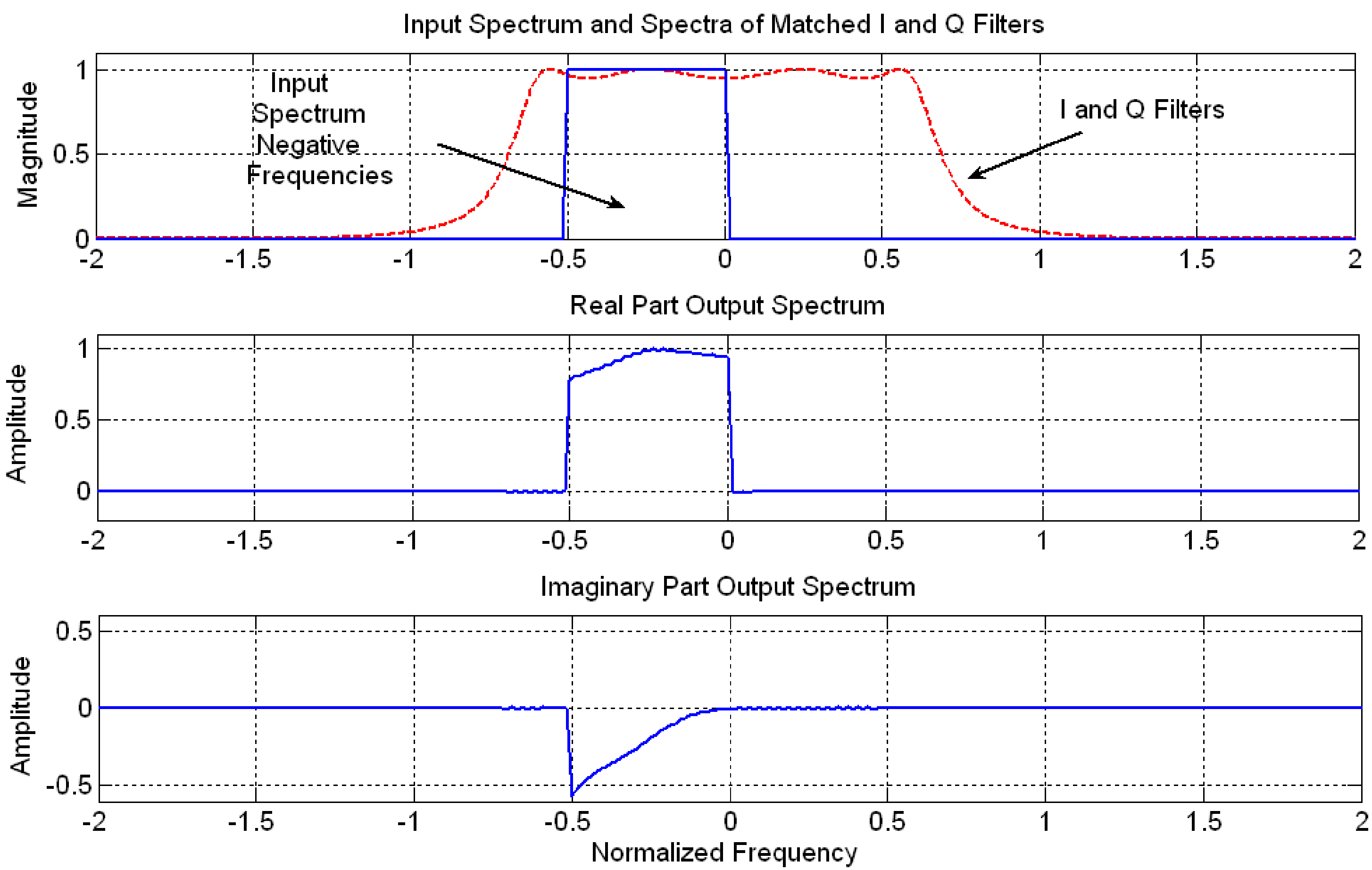
Filter Imbalance



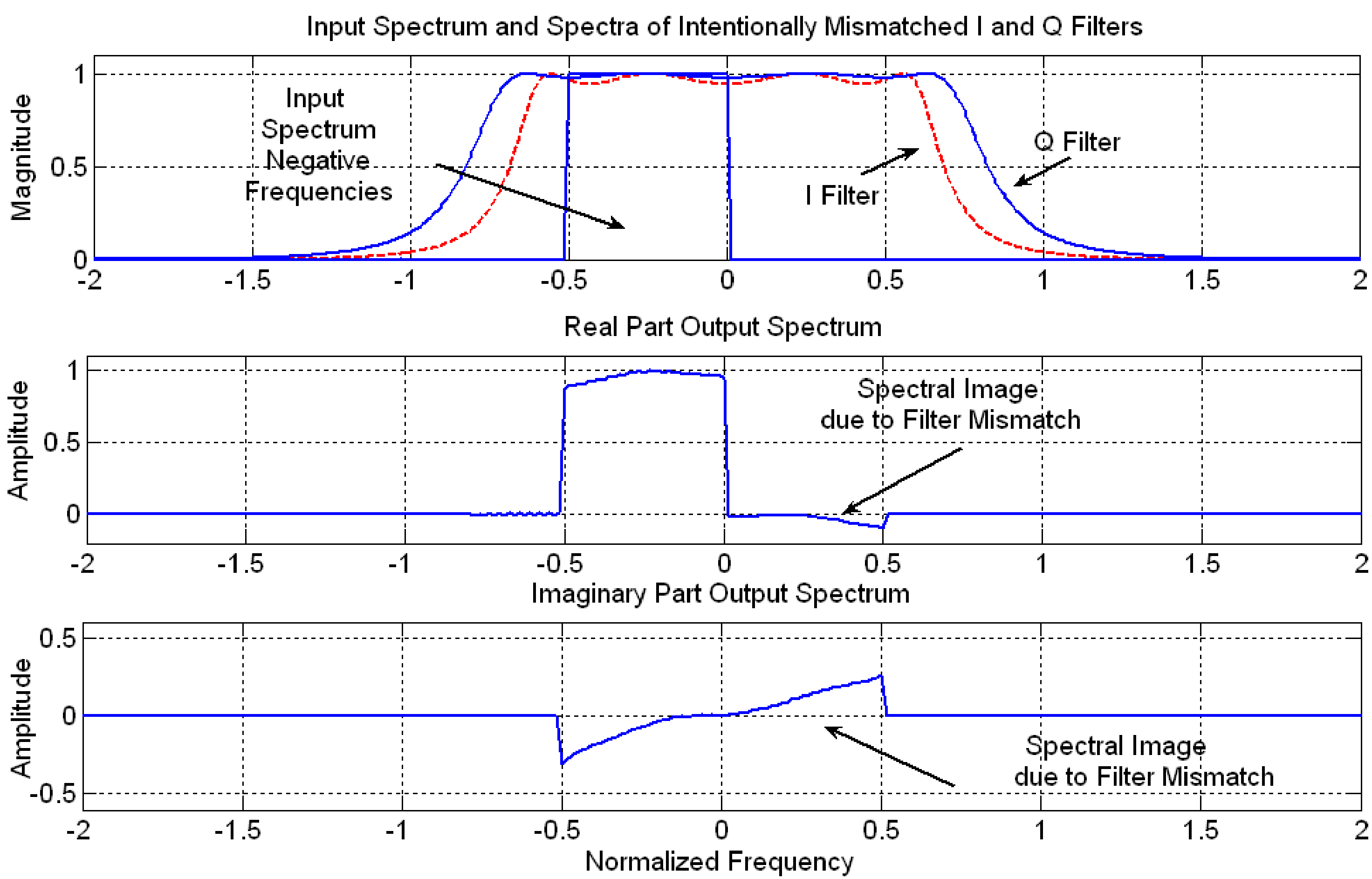
Gain and Phase Of Mismatched Analog Low-Pass Filter



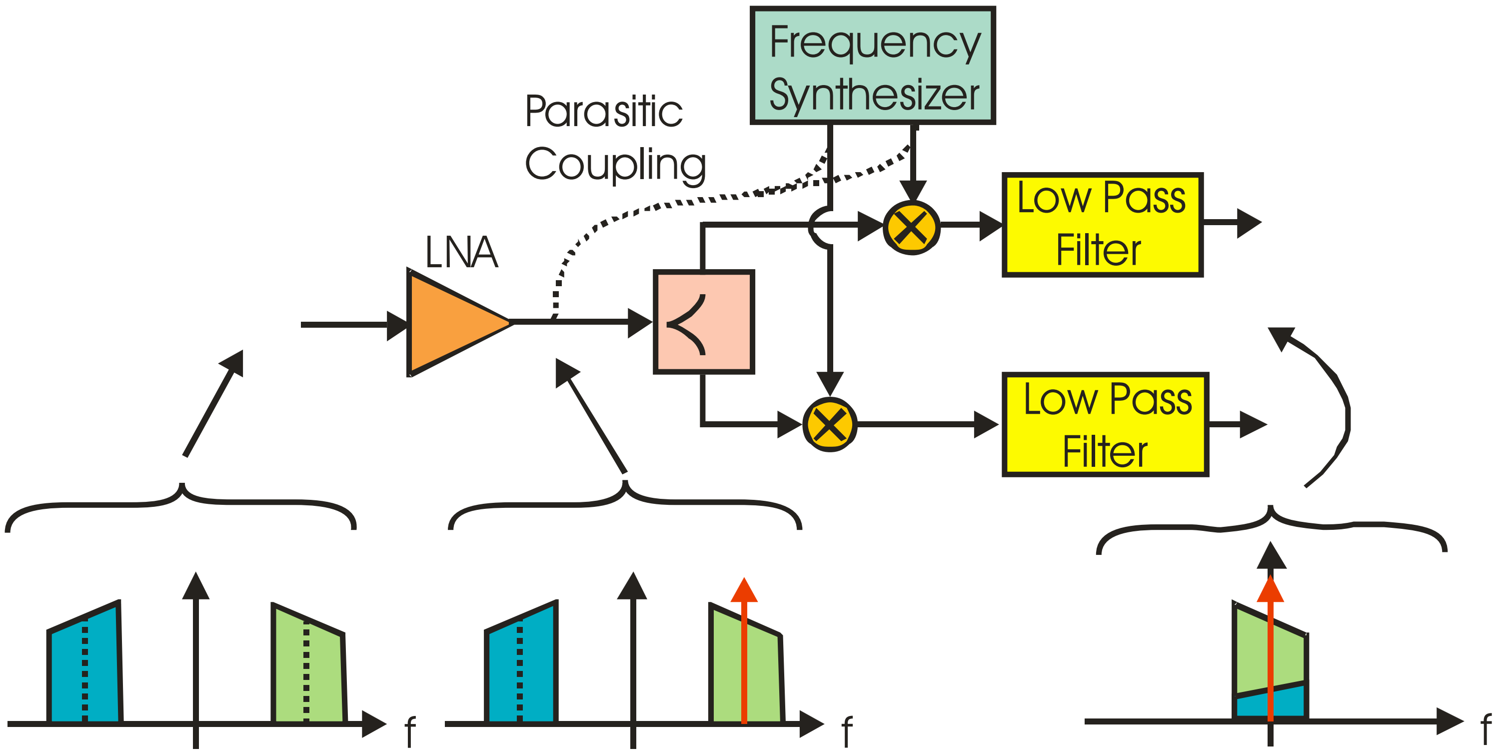
Gain and Phase Contributions of I-Q Matched Low Pass Filters



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

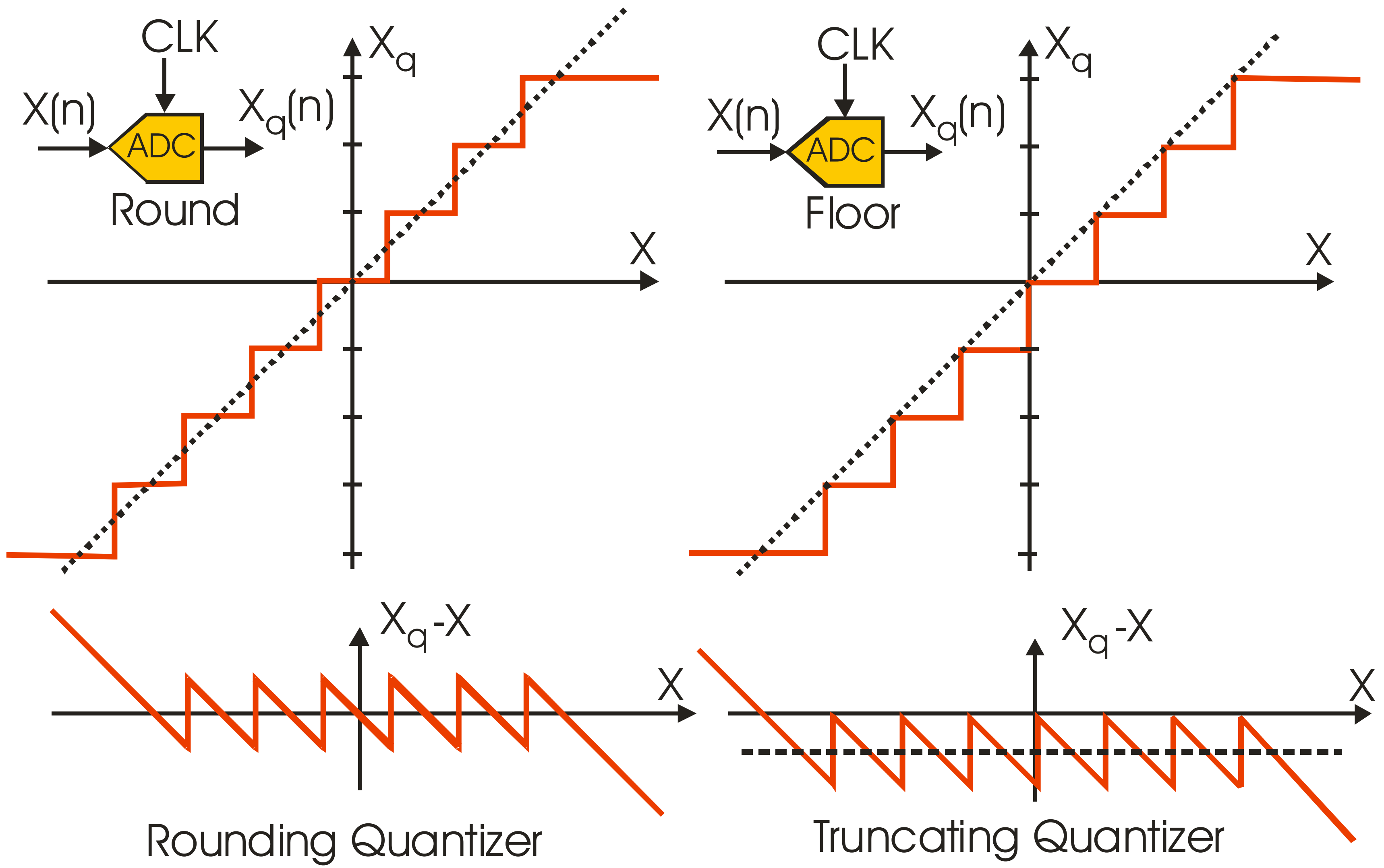


I-Q Imbalance and Self Mixing

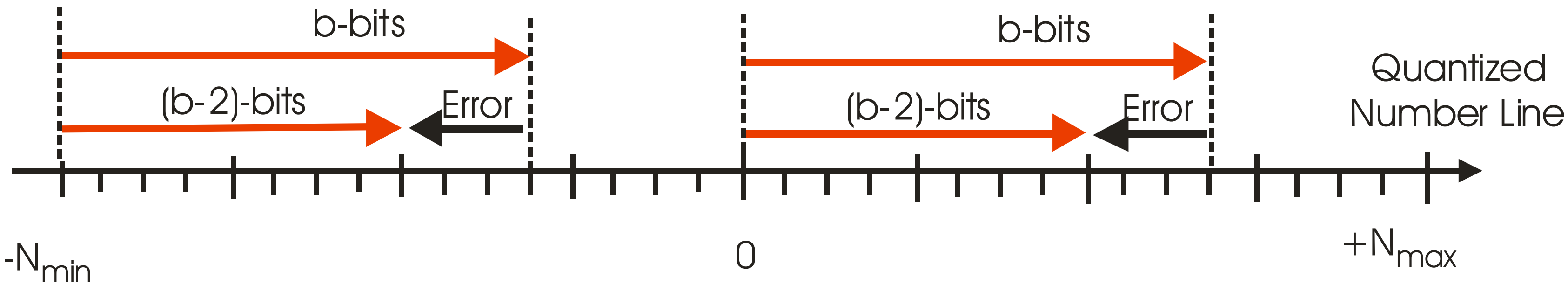


DC Offset: Self Mixing
Desired Component: Mixing
Spectral Image: I-Q Imbalance

Truncating Quantizers: DC Bias



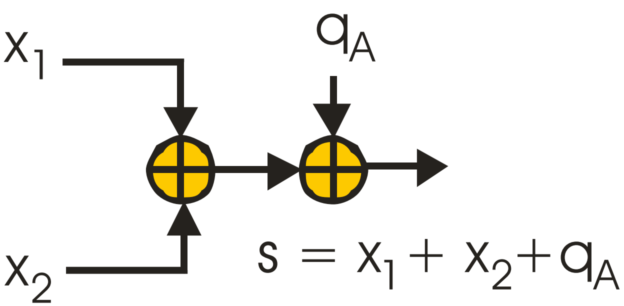
2's Complement Arithmetic; DC Bias



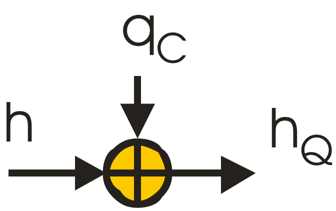
Negative numbers:
Measure displacement from reference.
Reference = -Nmin

Positive numbers:
Measure displacement from reference.
Reference = 0

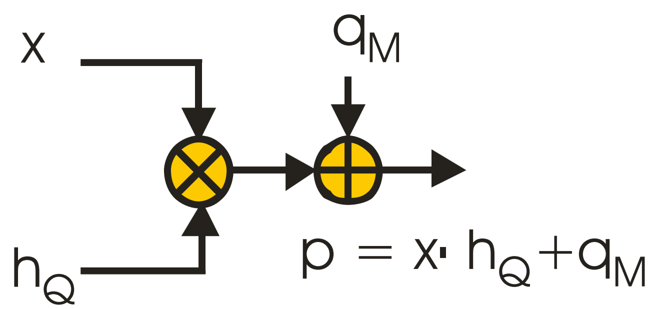
Errors Due to finite Arithmetic



Quantize Addition

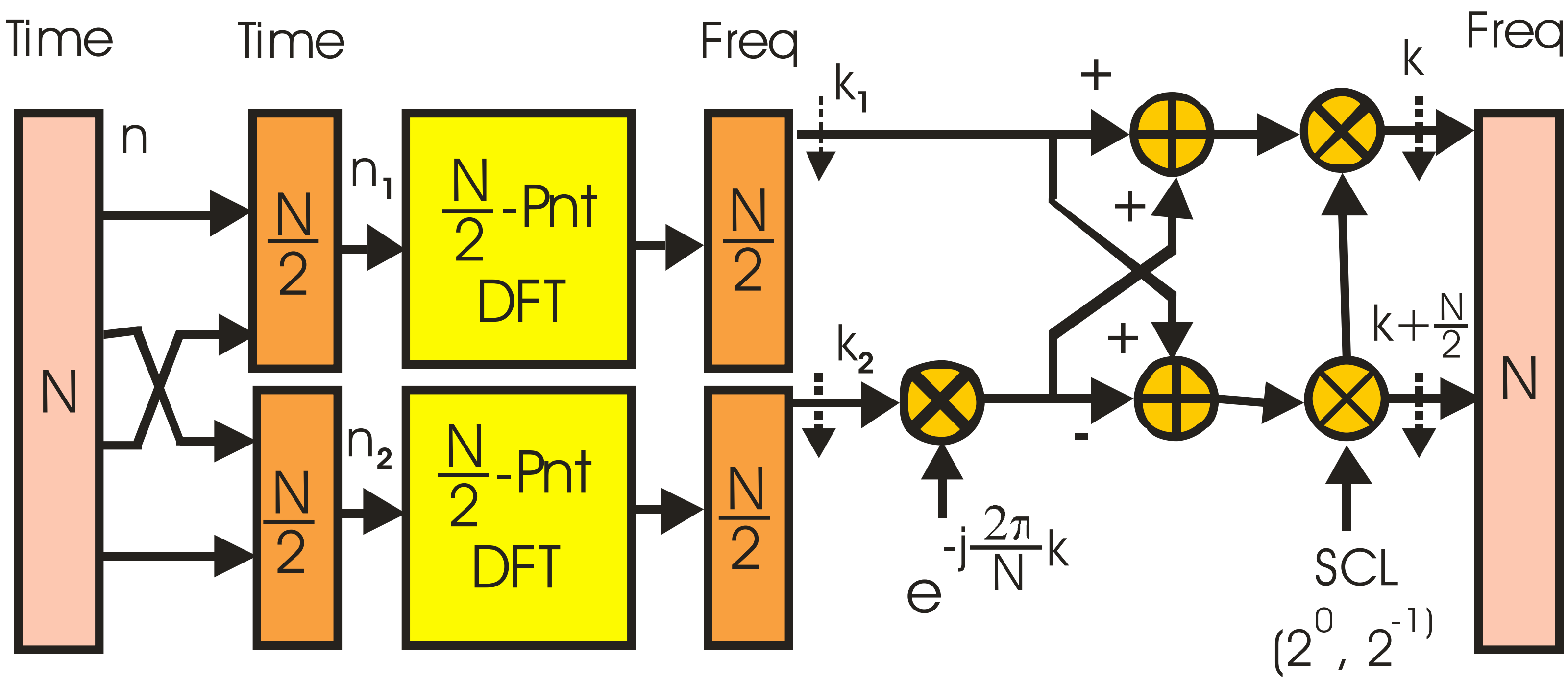


Quantize Coefficient

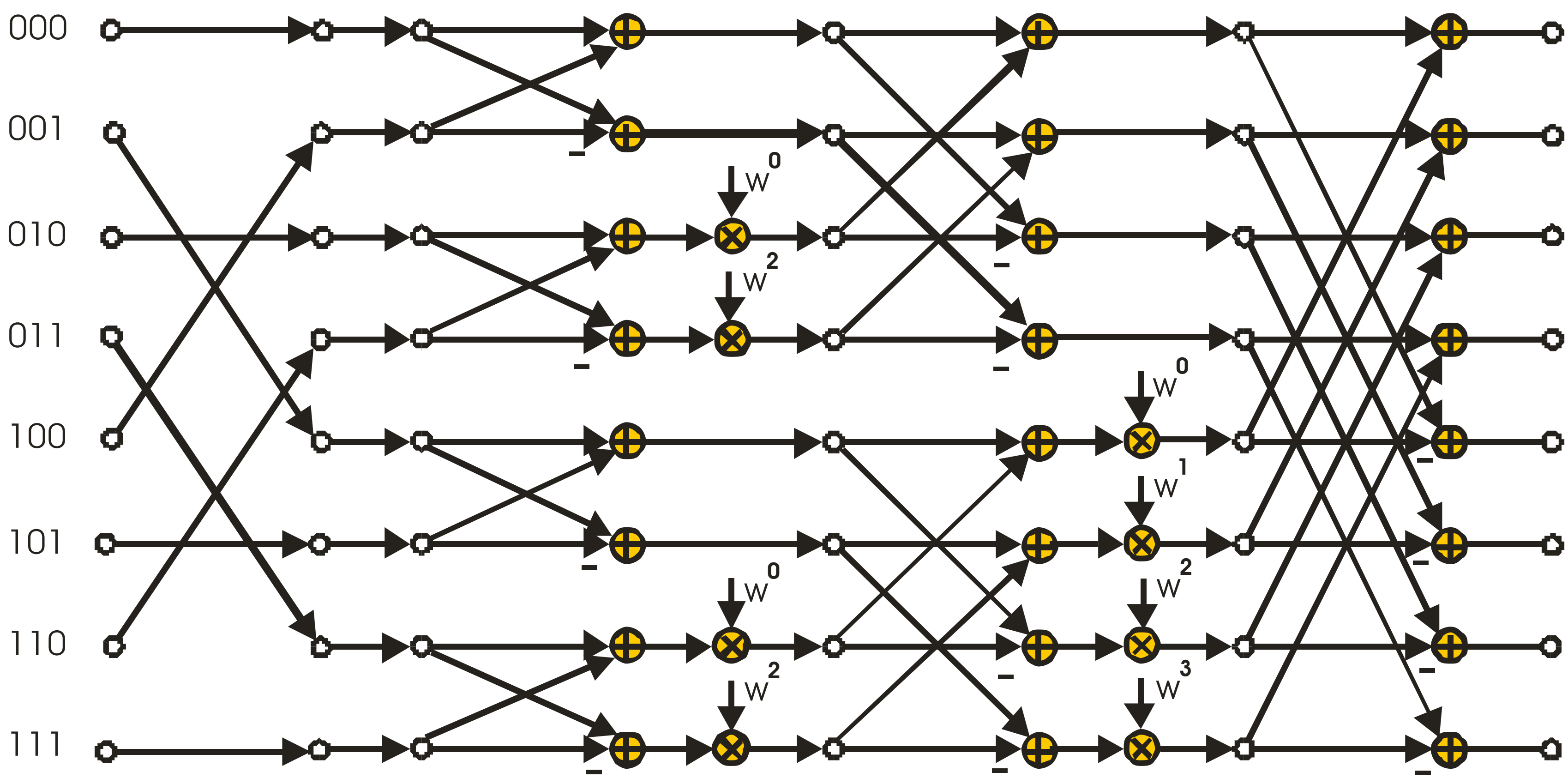


Quantize Multiplication

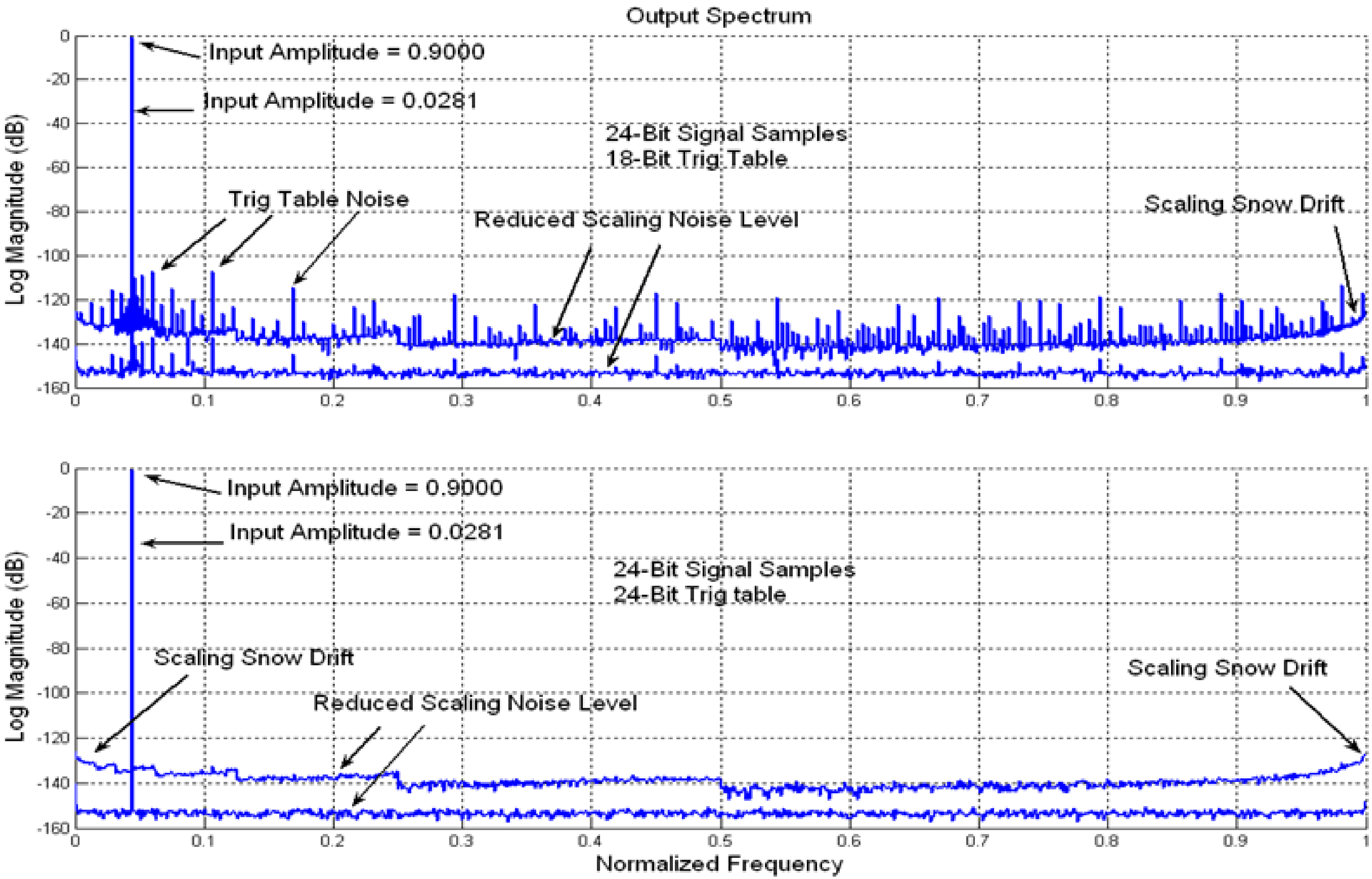
Finite Arithmetic in Radix-2 FFT Algorithm



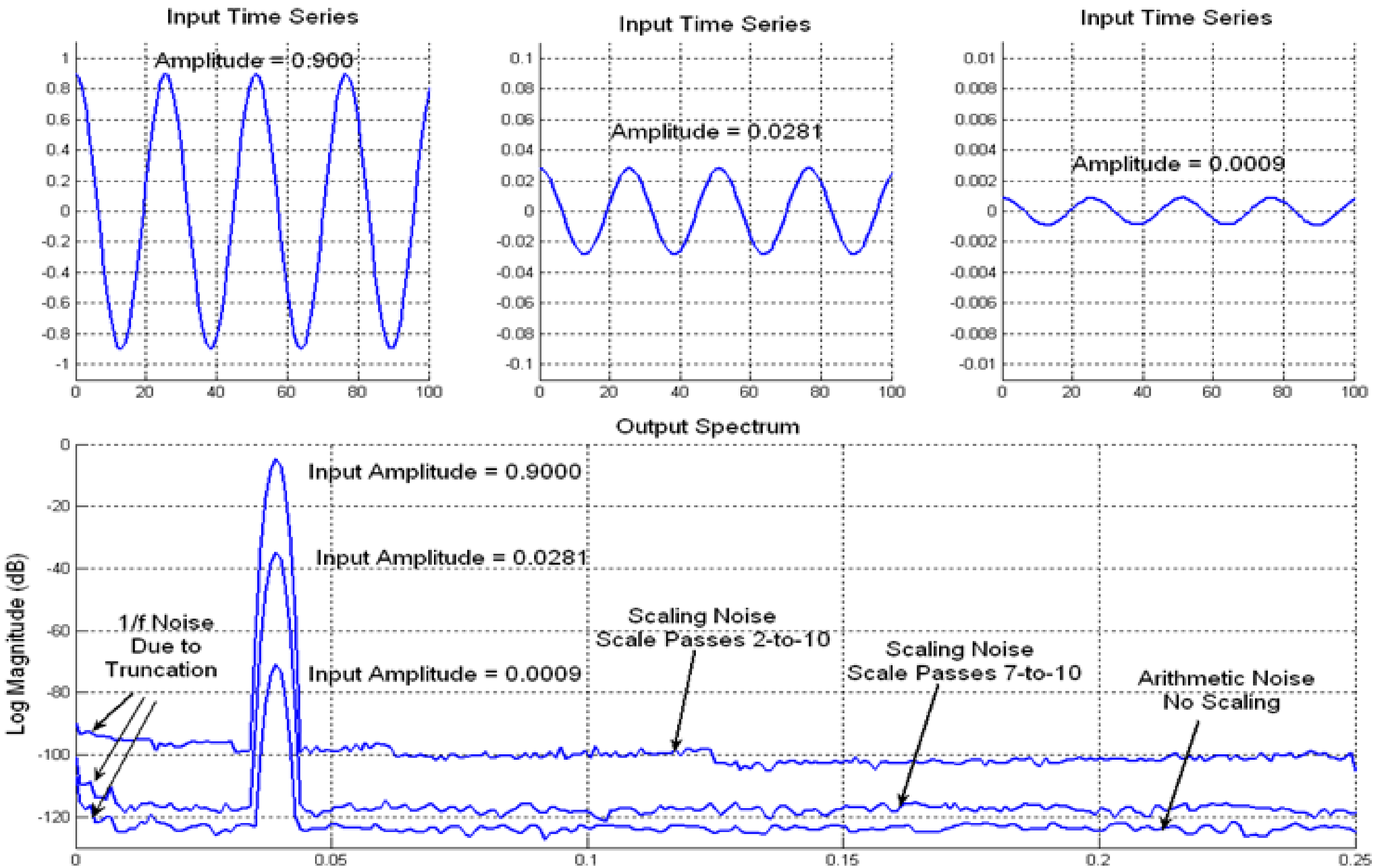
Radix-2 FFT Signal Flow Diagram



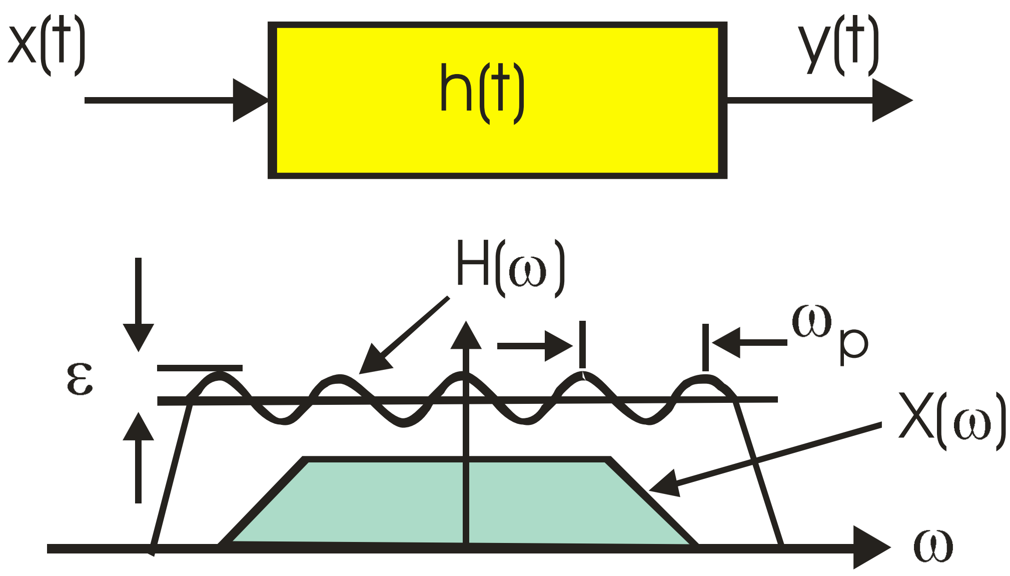
Algorithm Noise Due to Finite Arithmetic and Coefficient Noise



Algorithm Noise due to Finite Arithmetic Scaling Noise



Signal Through Filter with Gain Distortion



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

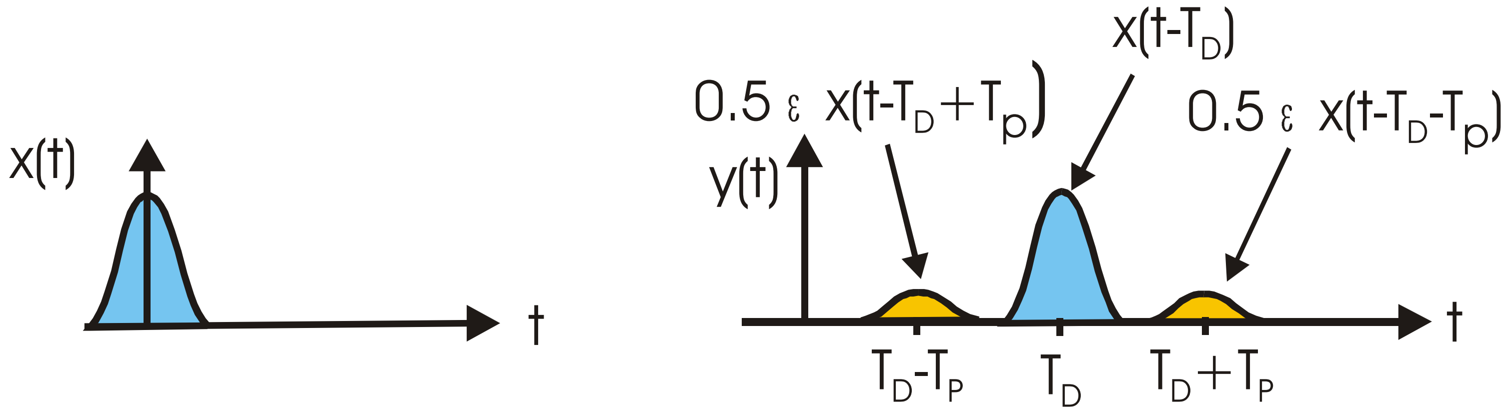
Model of Gain Distortion

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

$$\begin{aligned}
Y(\omega) &= X(\omega)\, H(\omega) = X(\omega)[1 + \varepsilon \cos(\omega T_p)] \\
&= X(\omega) + \varepsilon X(\omega) \cos(\omega T_p) \\
&= X(\omega) + 0.5\, \varepsilon\, X(\omega) \exp(j\omega T_p) + 0.5\, \varepsilon\, X(\omega) \exp(-j\omega T_p)
\end{aligned}$$

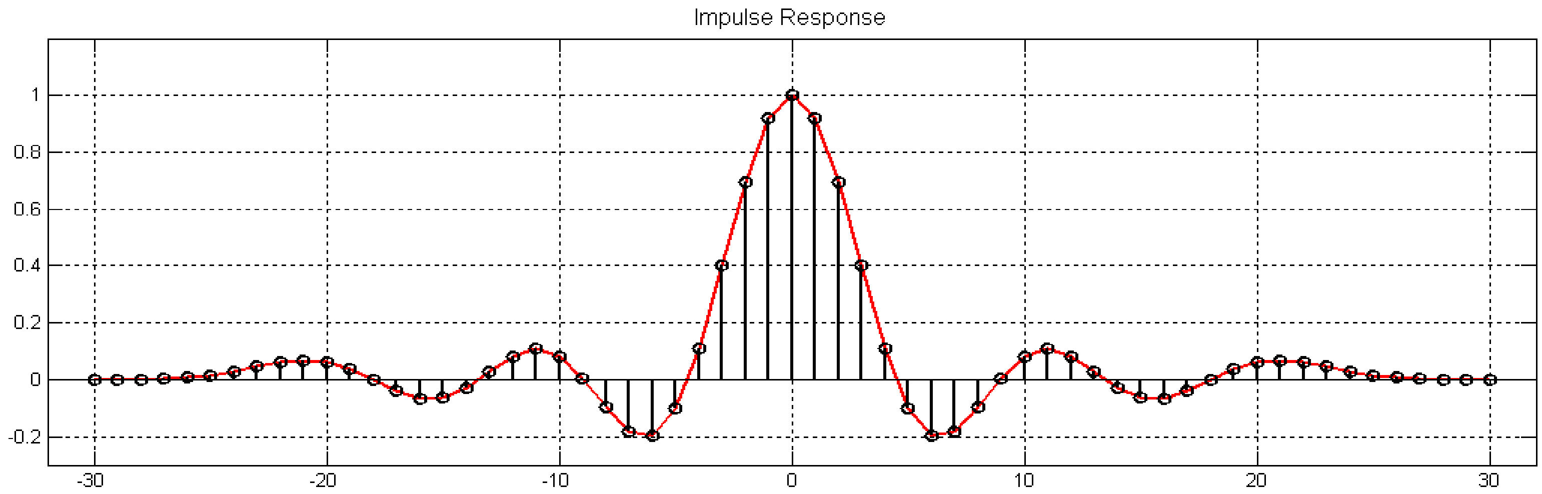
$$y(t) = x(t) + \underbrace{0.5\, \varepsilon\, x(t+T_p) + 0.5\, \varepsilon\, x(t-T_p)}_{\text{Paired Echos}}$$

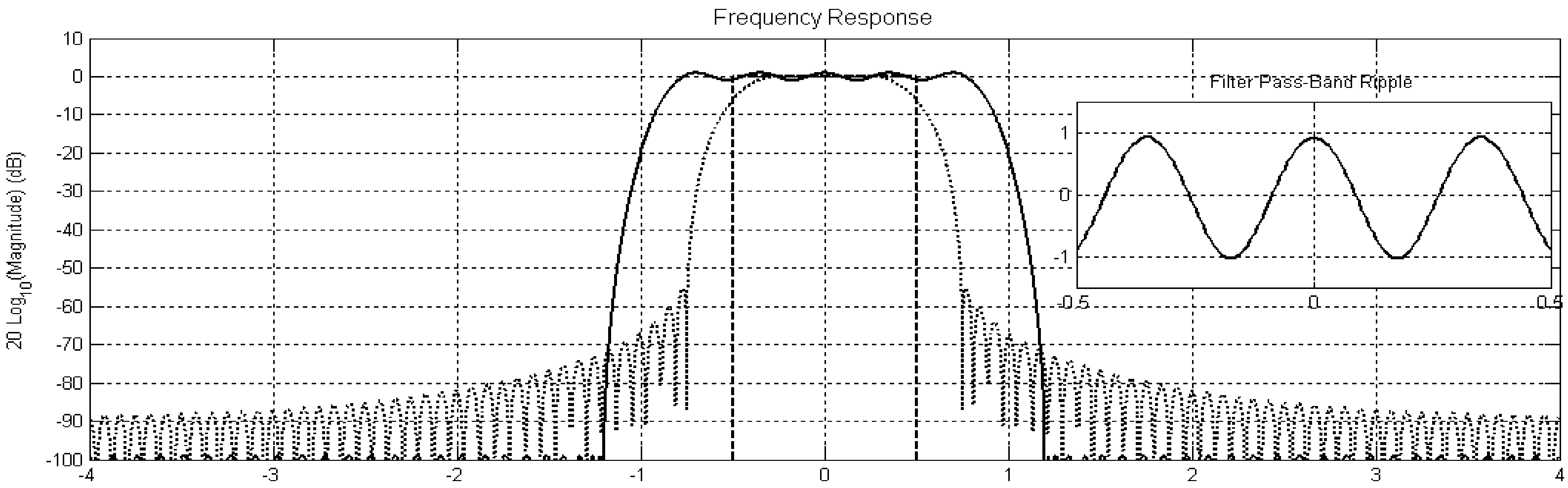
Pre-and-Post Echoes



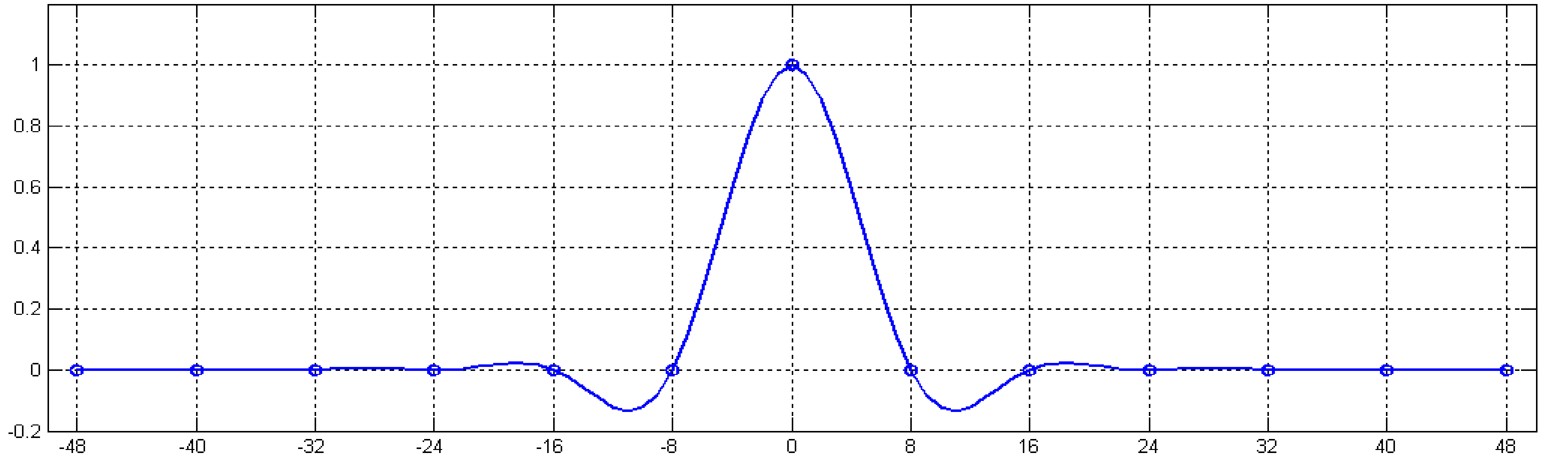
Paired Echos: The Effect of Passband Ripple

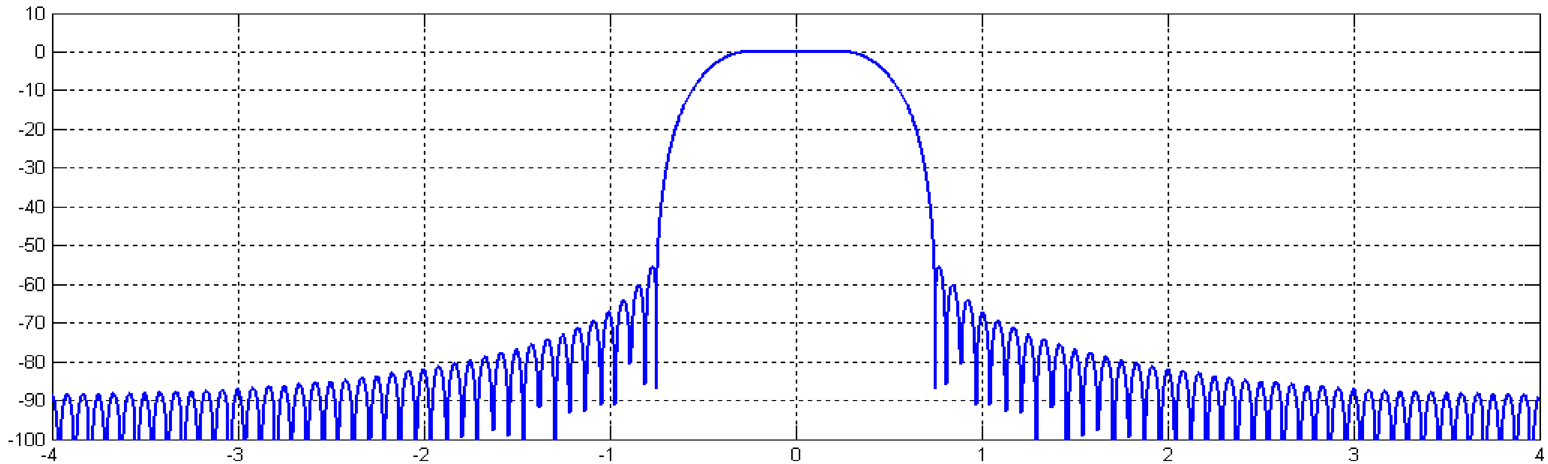
Nyquist Pulse Time and Frequency



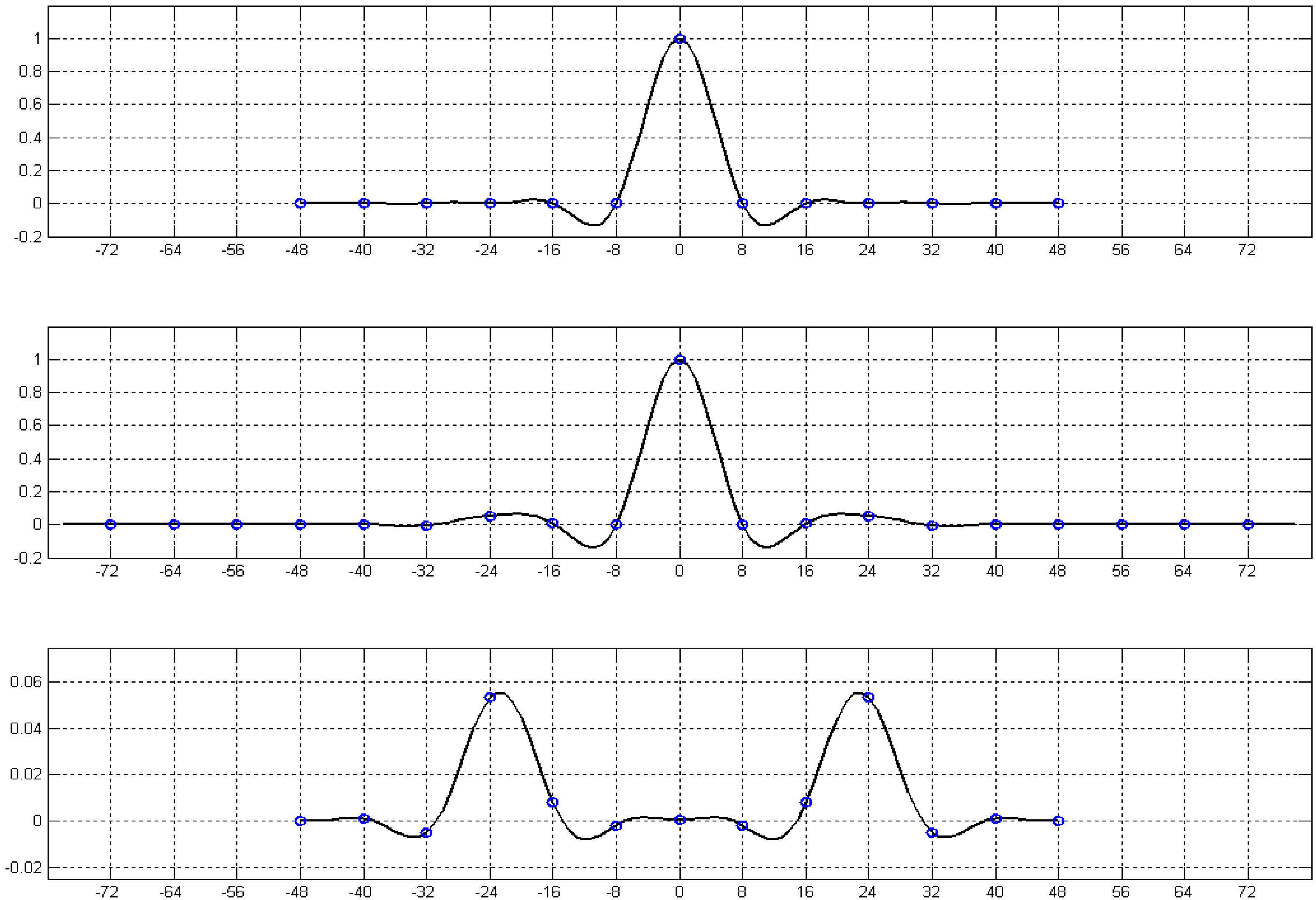


Pulse: Time and Frequency

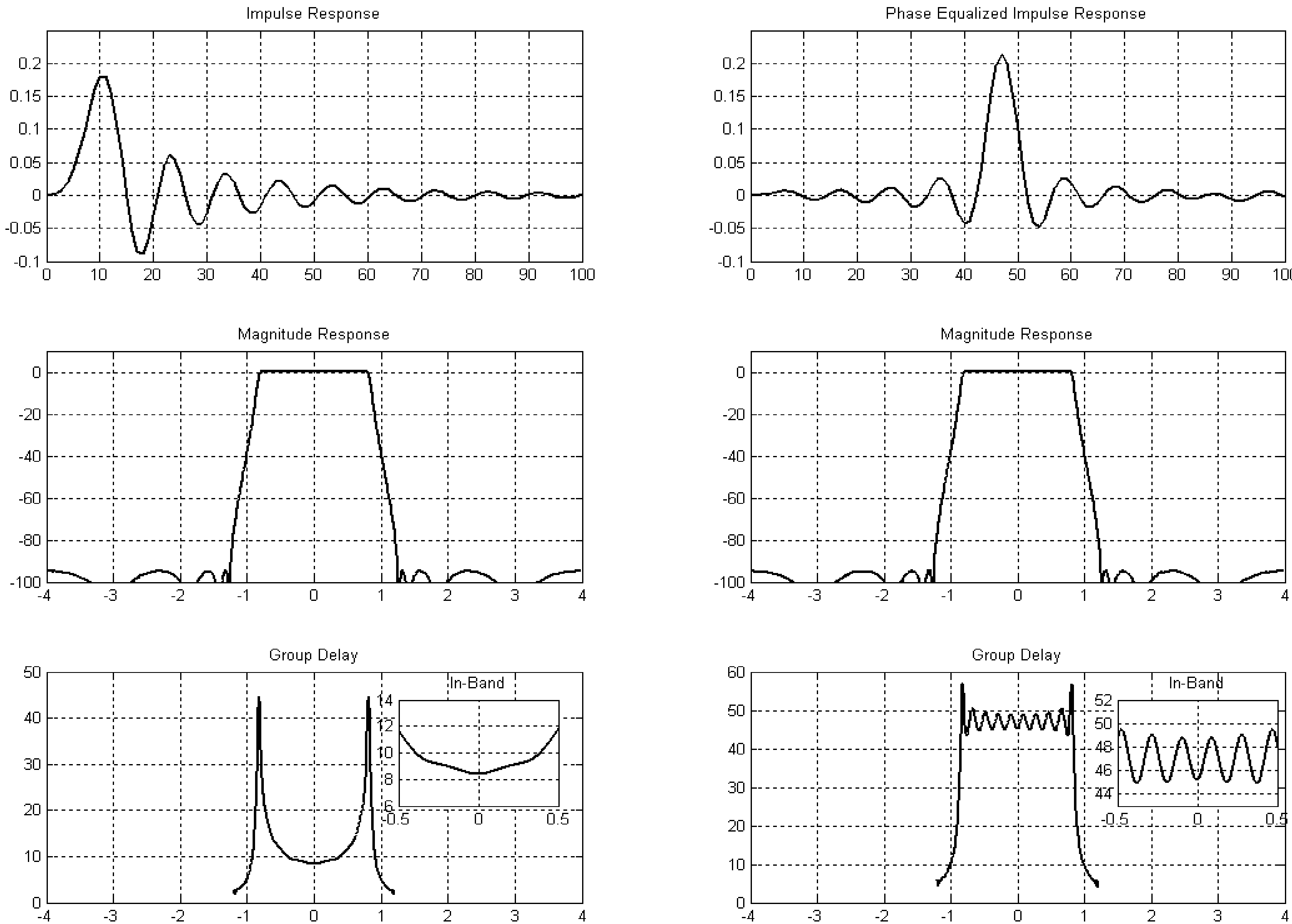




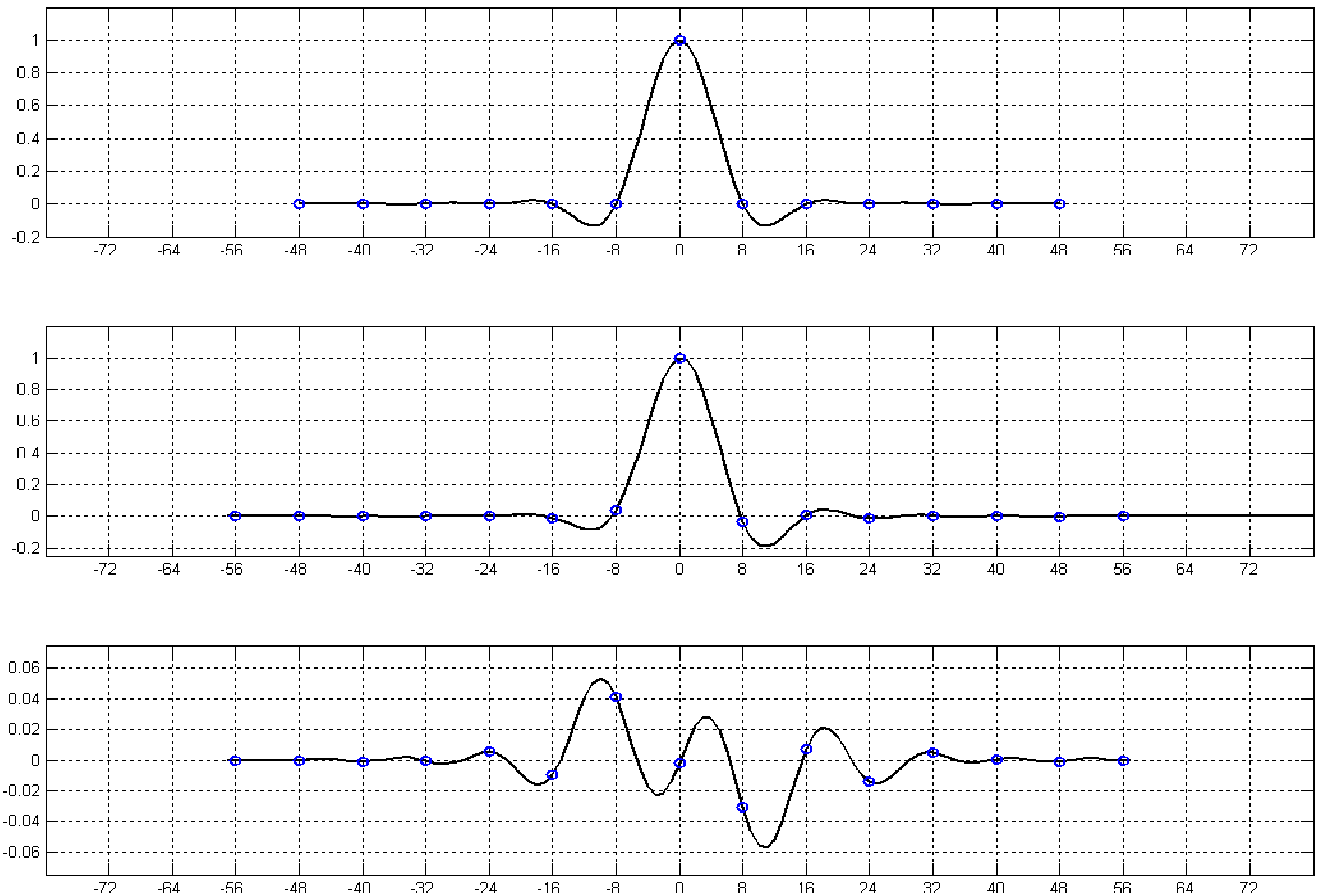
Pulse Response and ISI Component



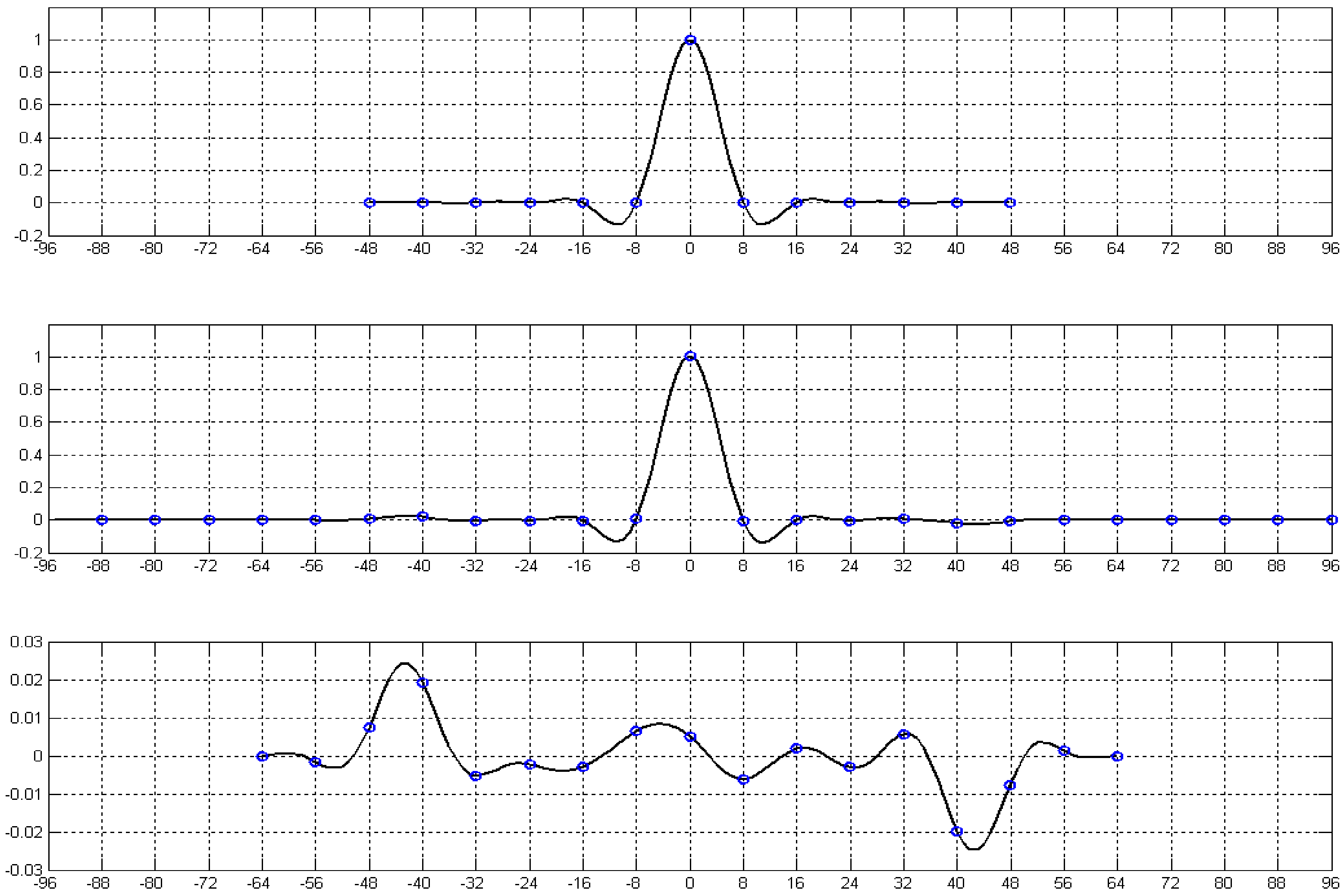
Recursive Filter Time & Frequency



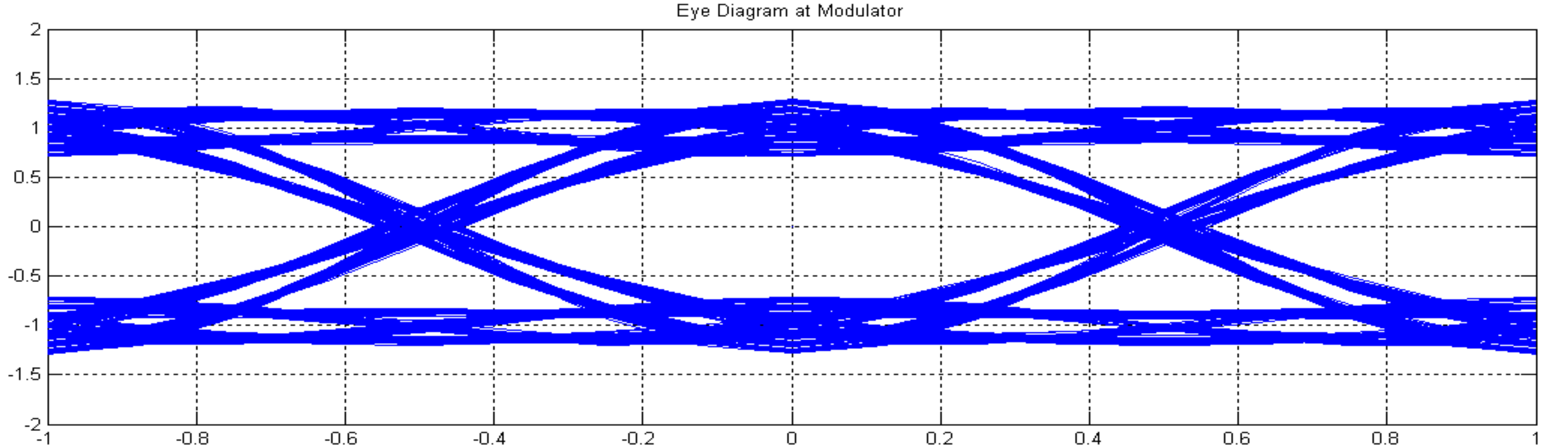
Pulse Response and ISI Component

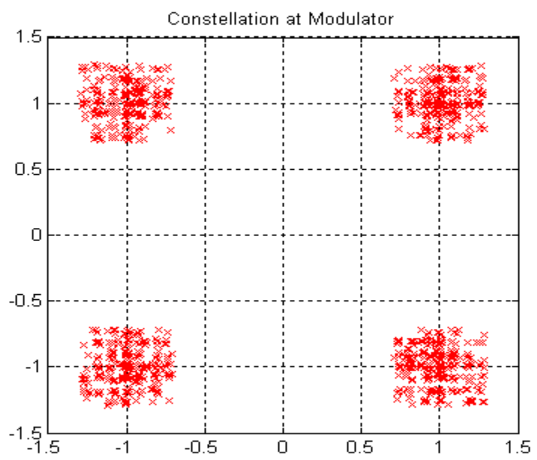


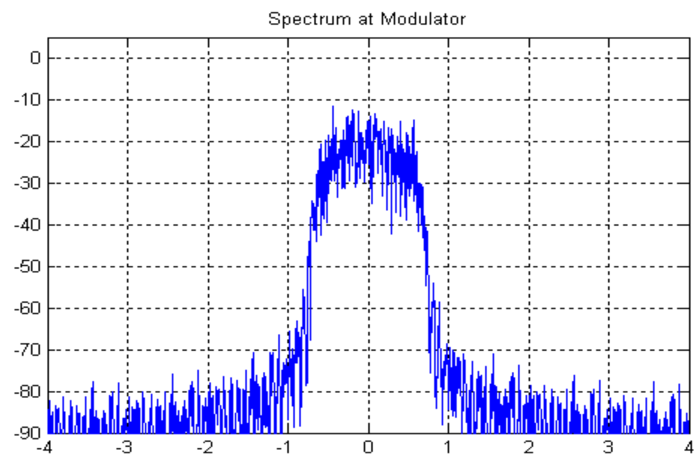
Pulse Response and ISI Component



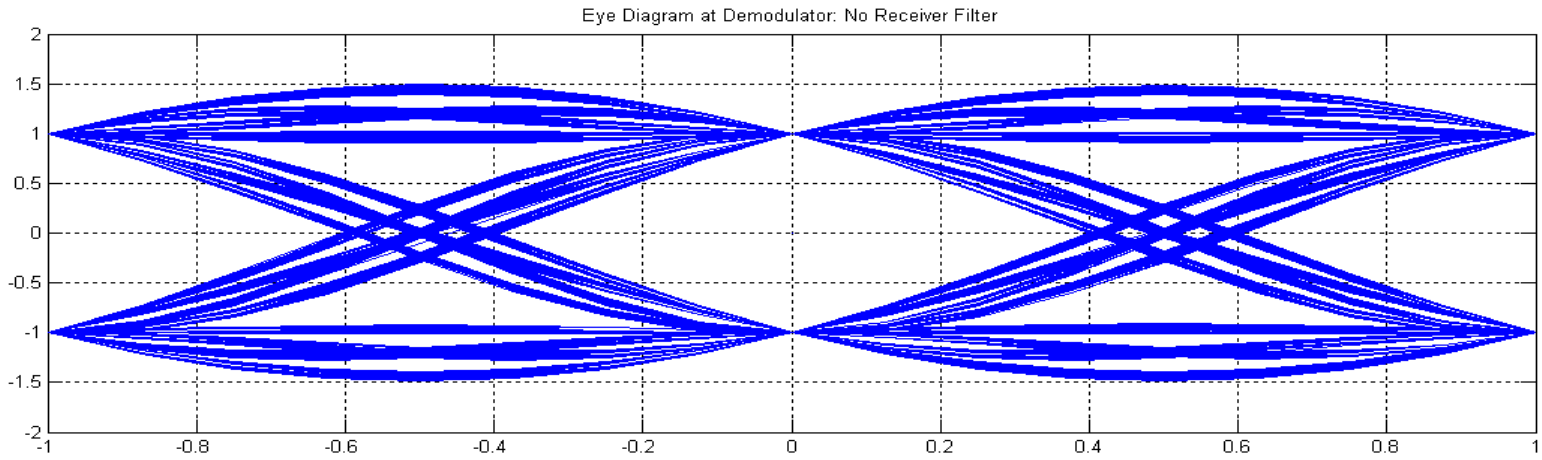
QPSK Modulator Eye-Diagram, Constellation, and Spectrum

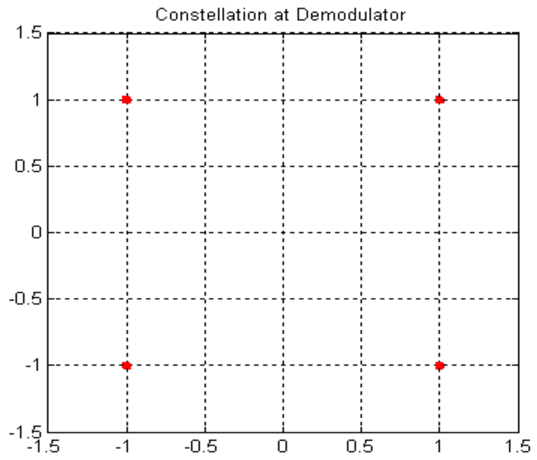


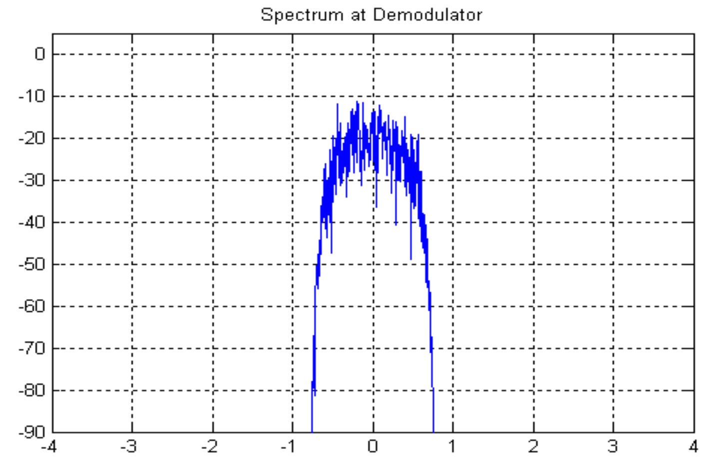




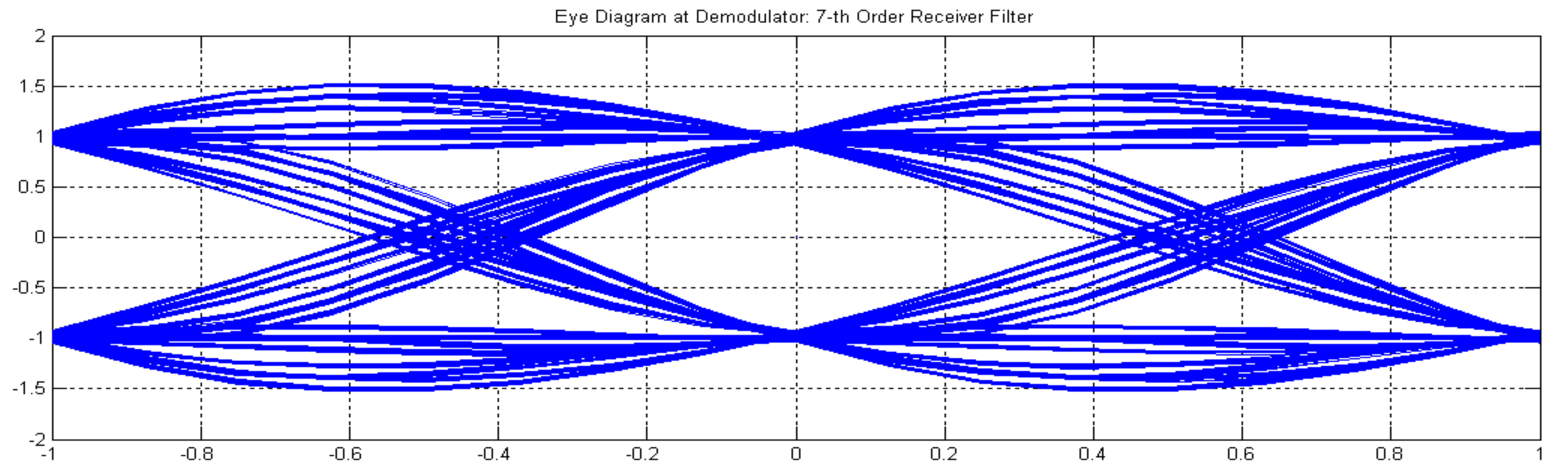
QPSK Demodulator, Eye-Diagram Constellation, and Spectrum

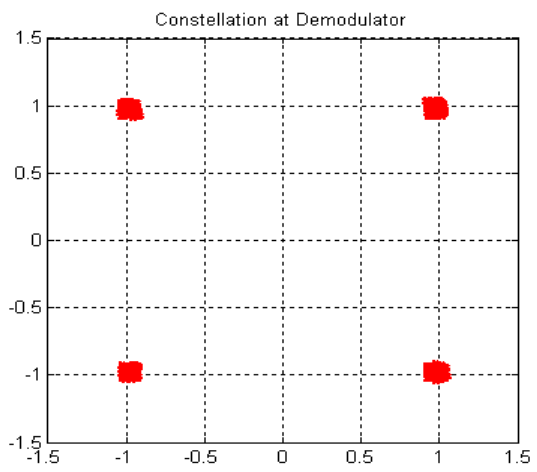


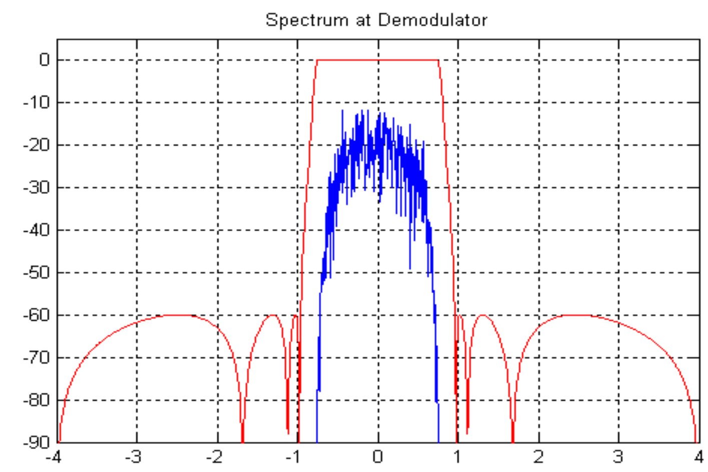




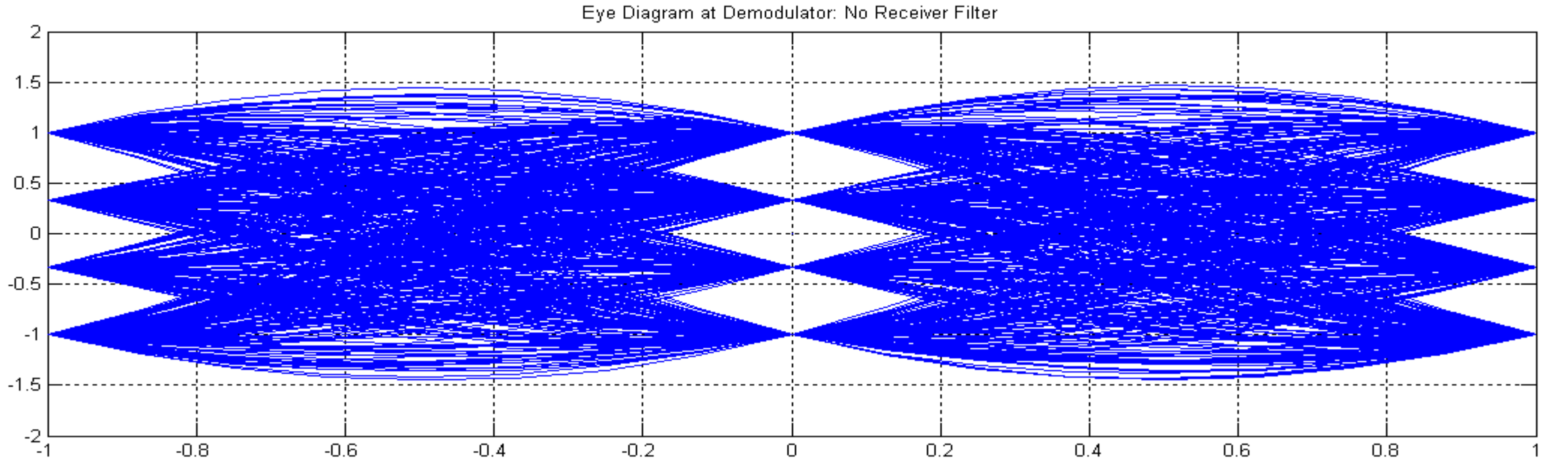
QPSK Demodulator with RCVR Filter

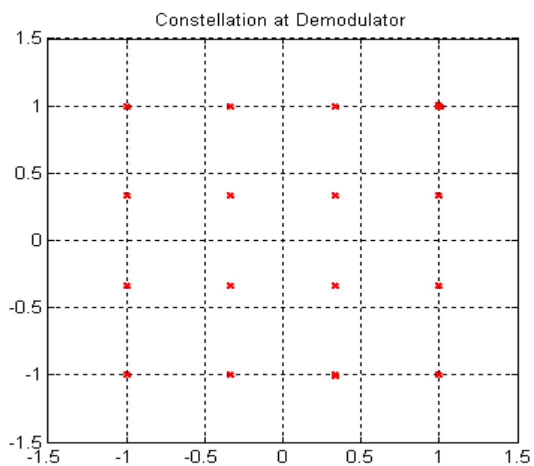


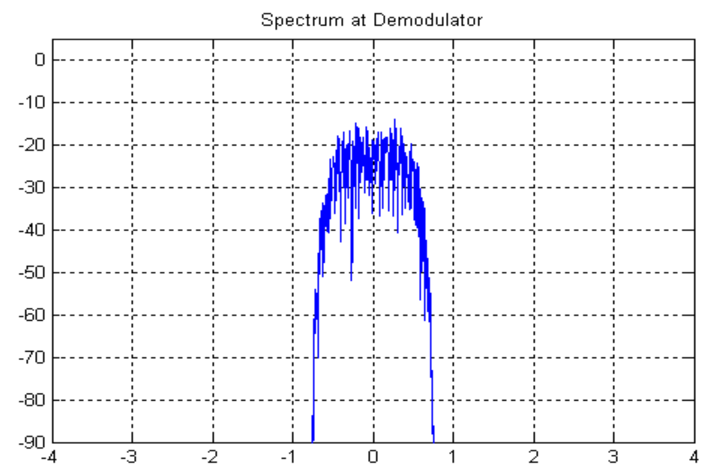




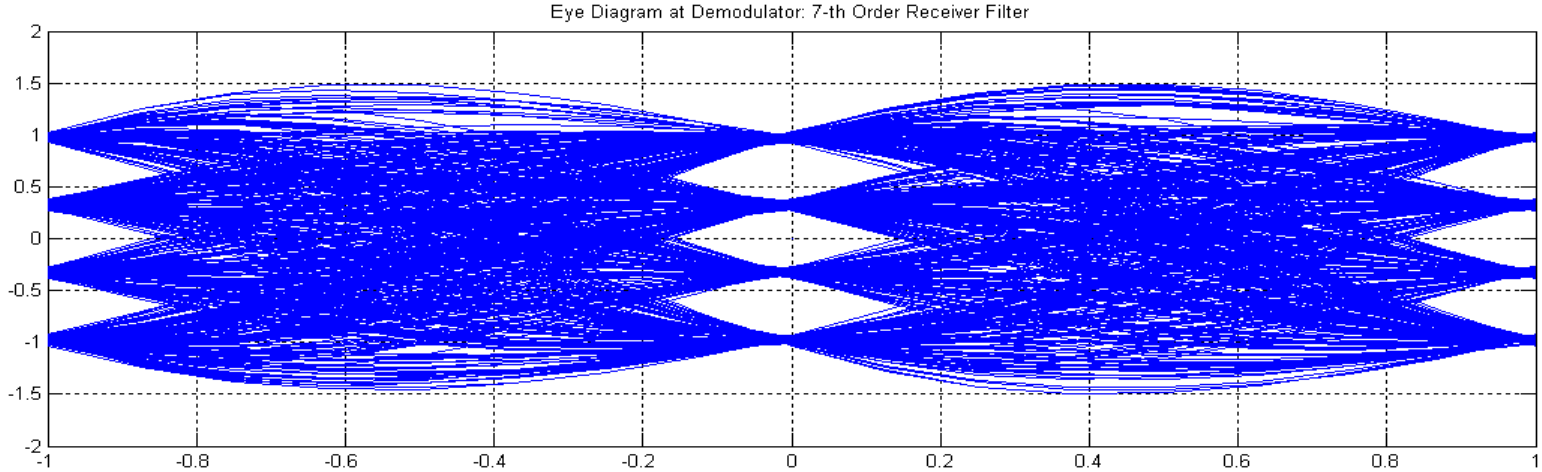
16-QAM Modulator Eye-Diagram, Constellation, and Spectrum

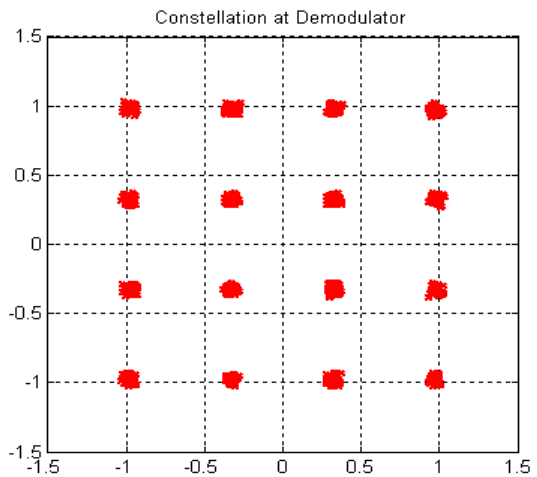


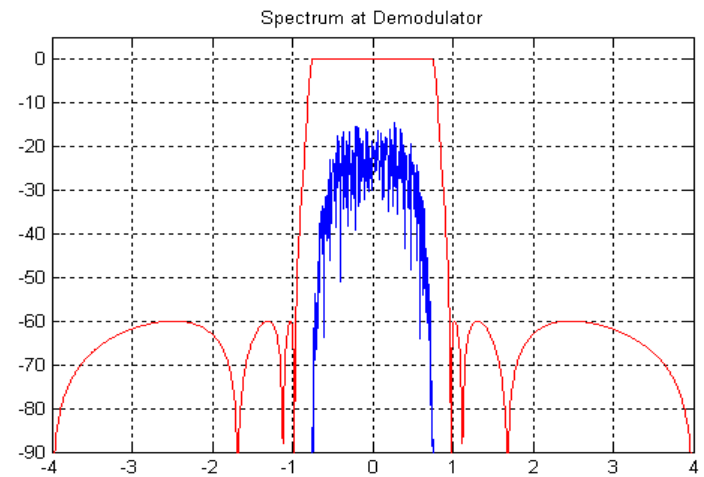




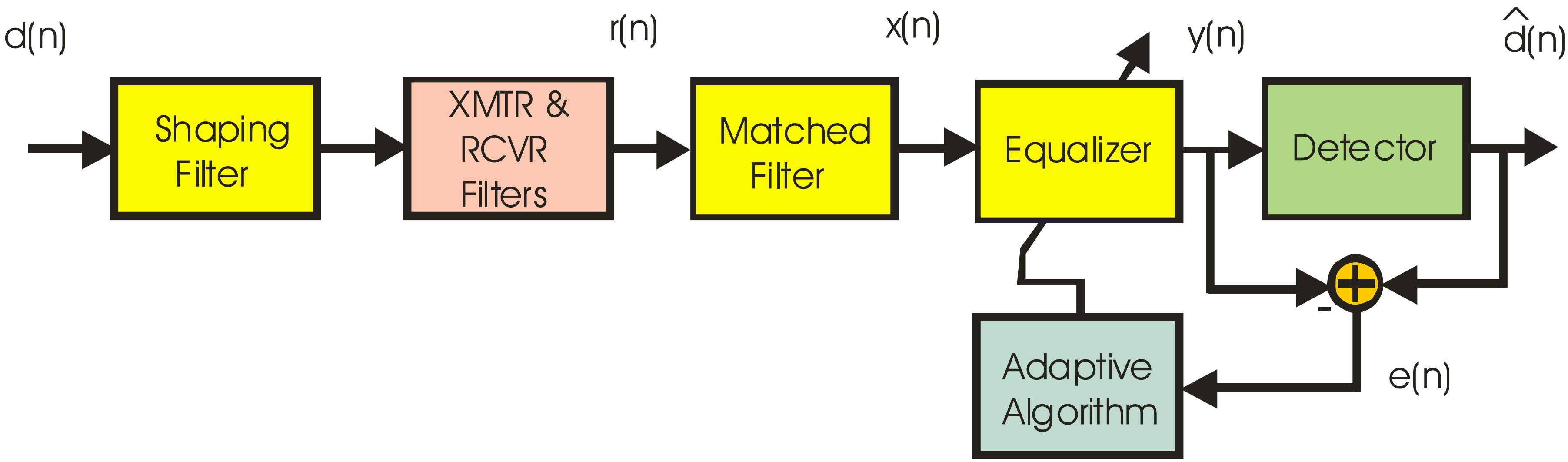
16-QAM Demodulator with RCVR Filter



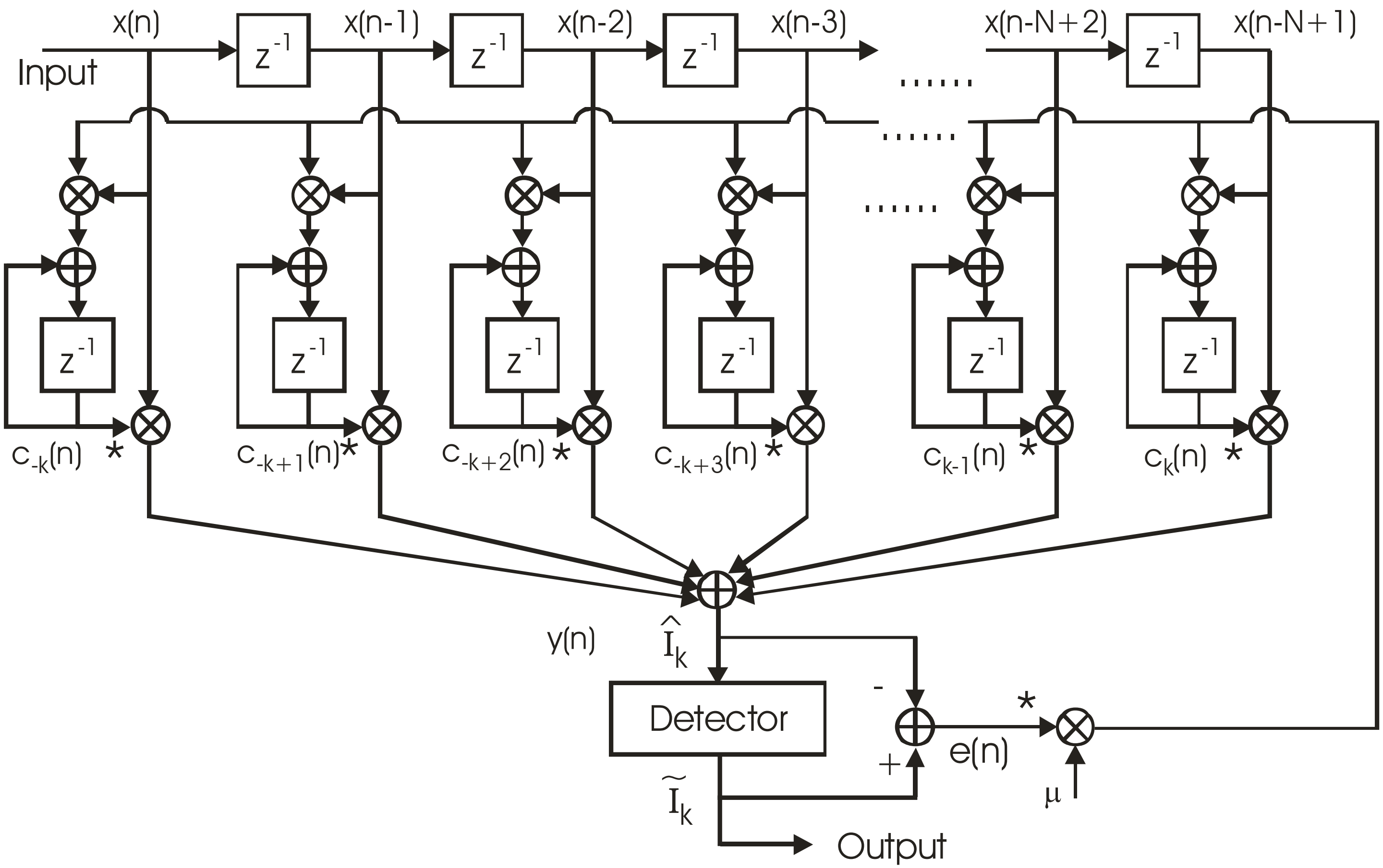




Signal Flow Path in XMTR & RCVR

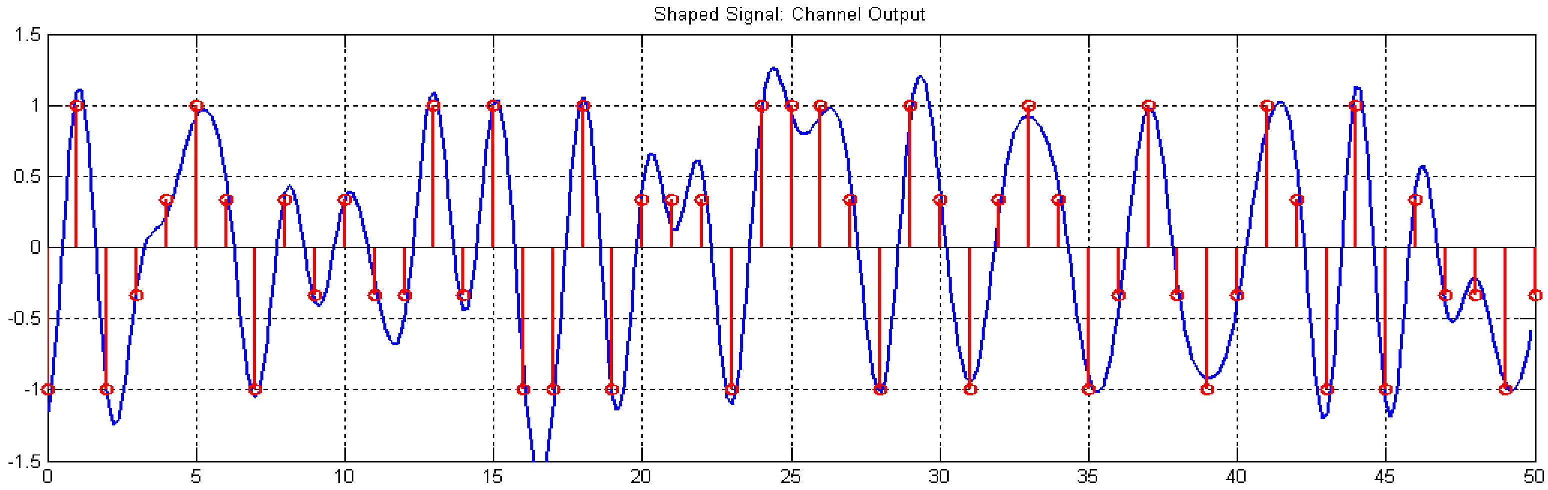


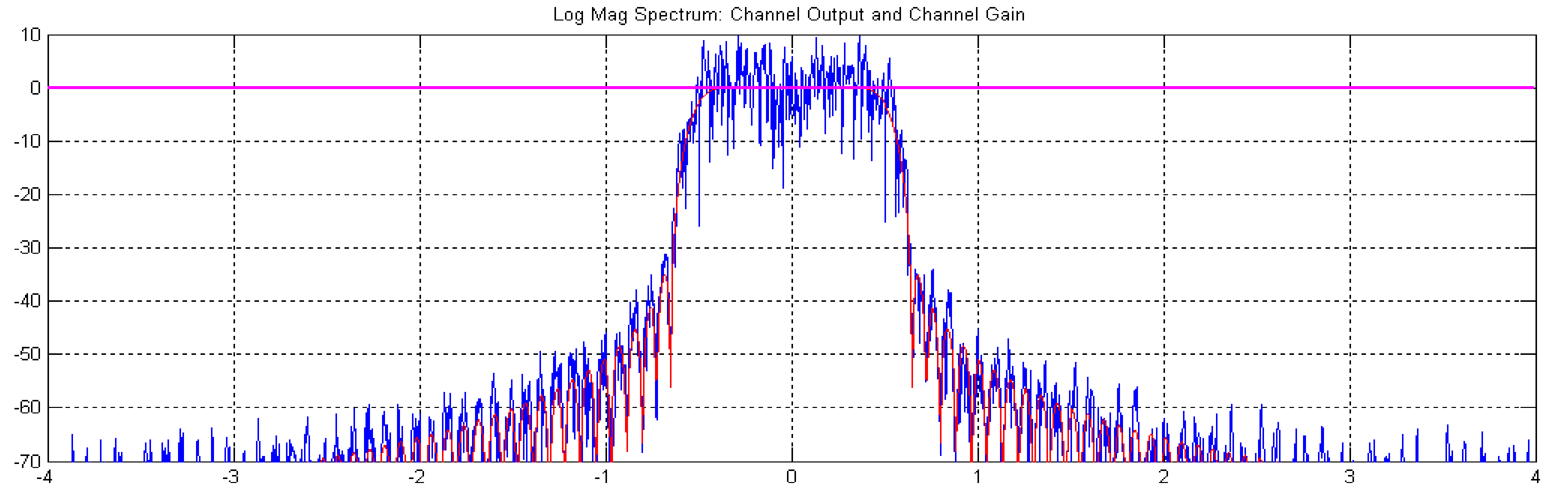
Decision Directed, Gradient Descent (LMS) Tapped Delay Line Equalizer



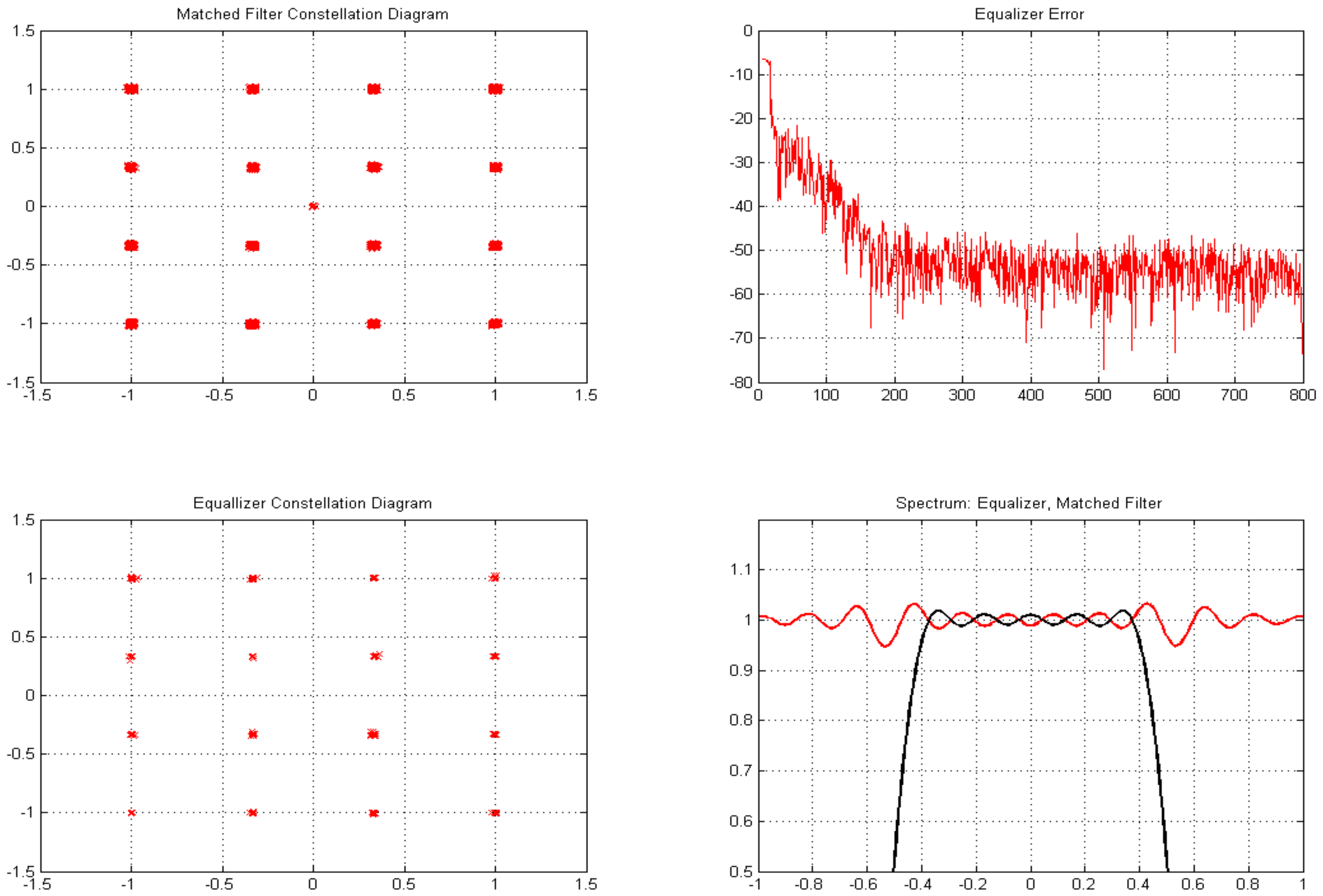
Received Signal and Spectrum

No Channel Distortion



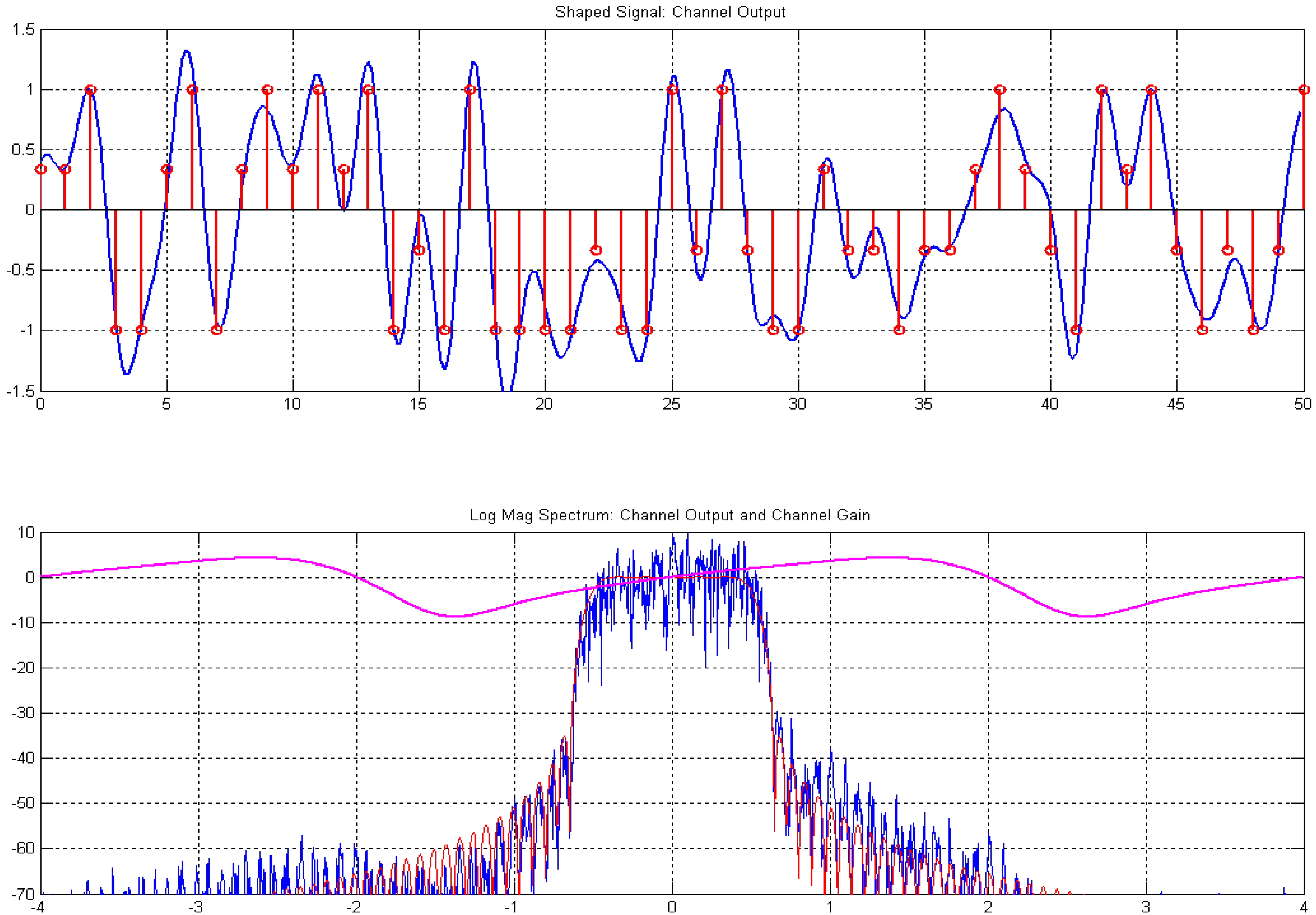


Constellation: Equalizer Input and Output

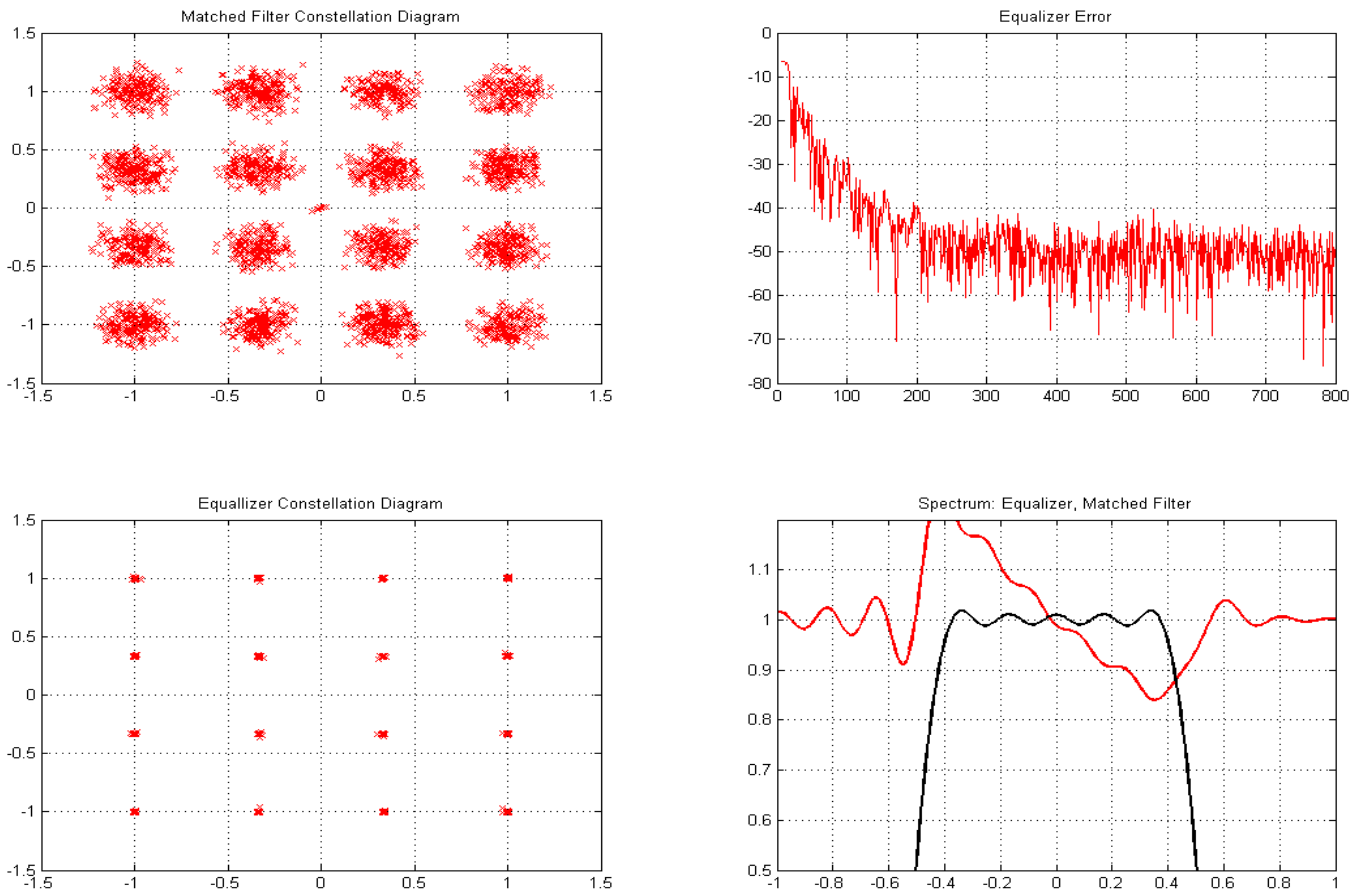


Received Signal and Spectrum

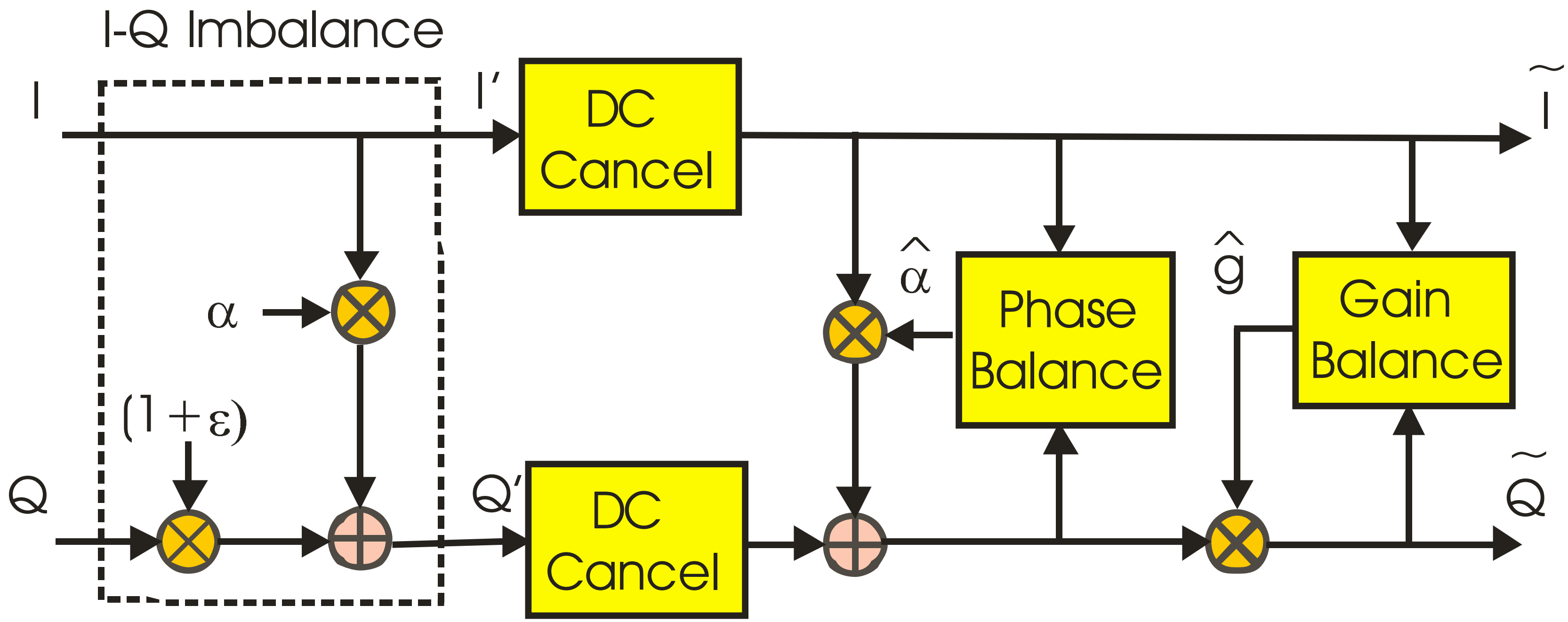
With Channel Distortion



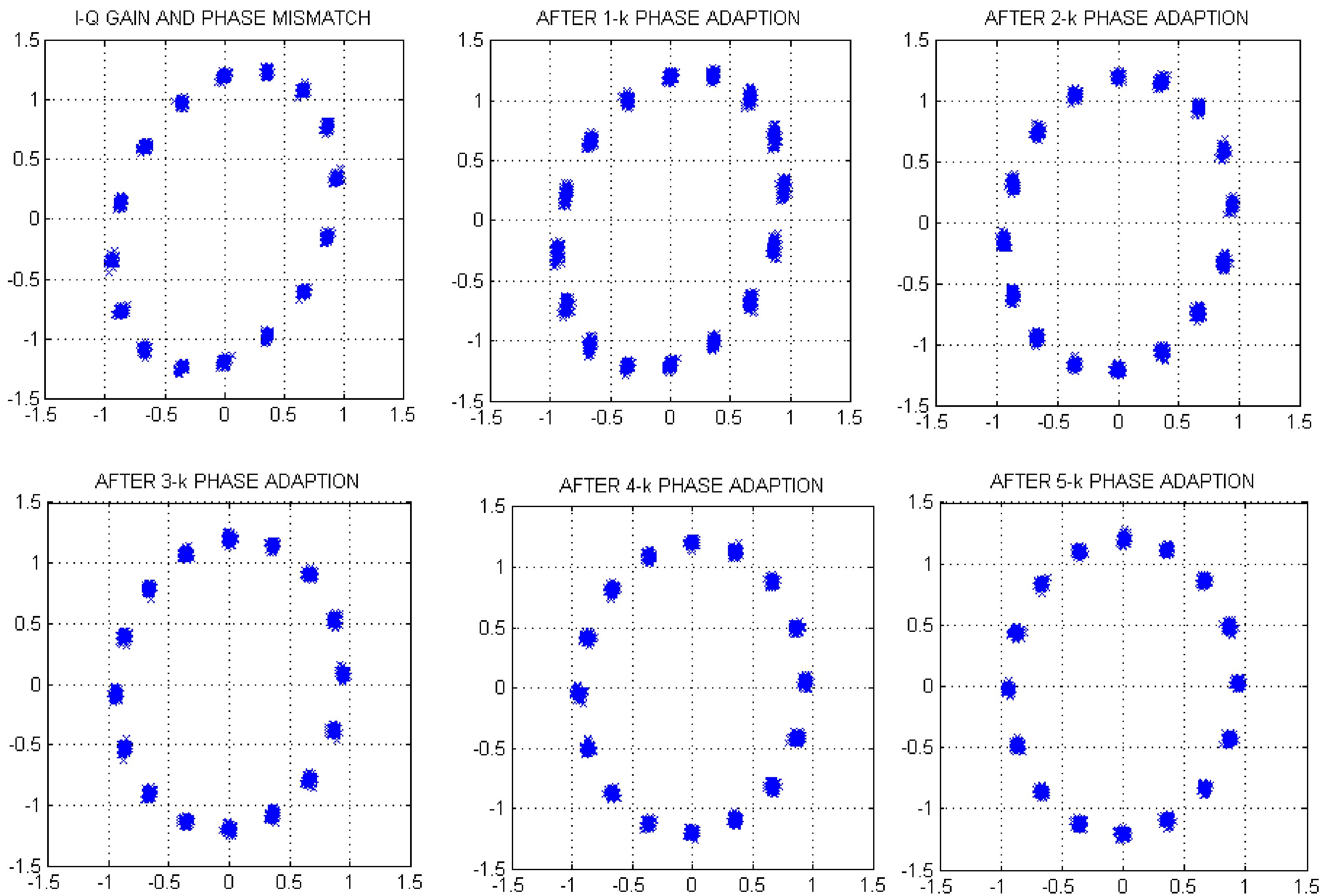
Constellation:
Equalizer Input and Output



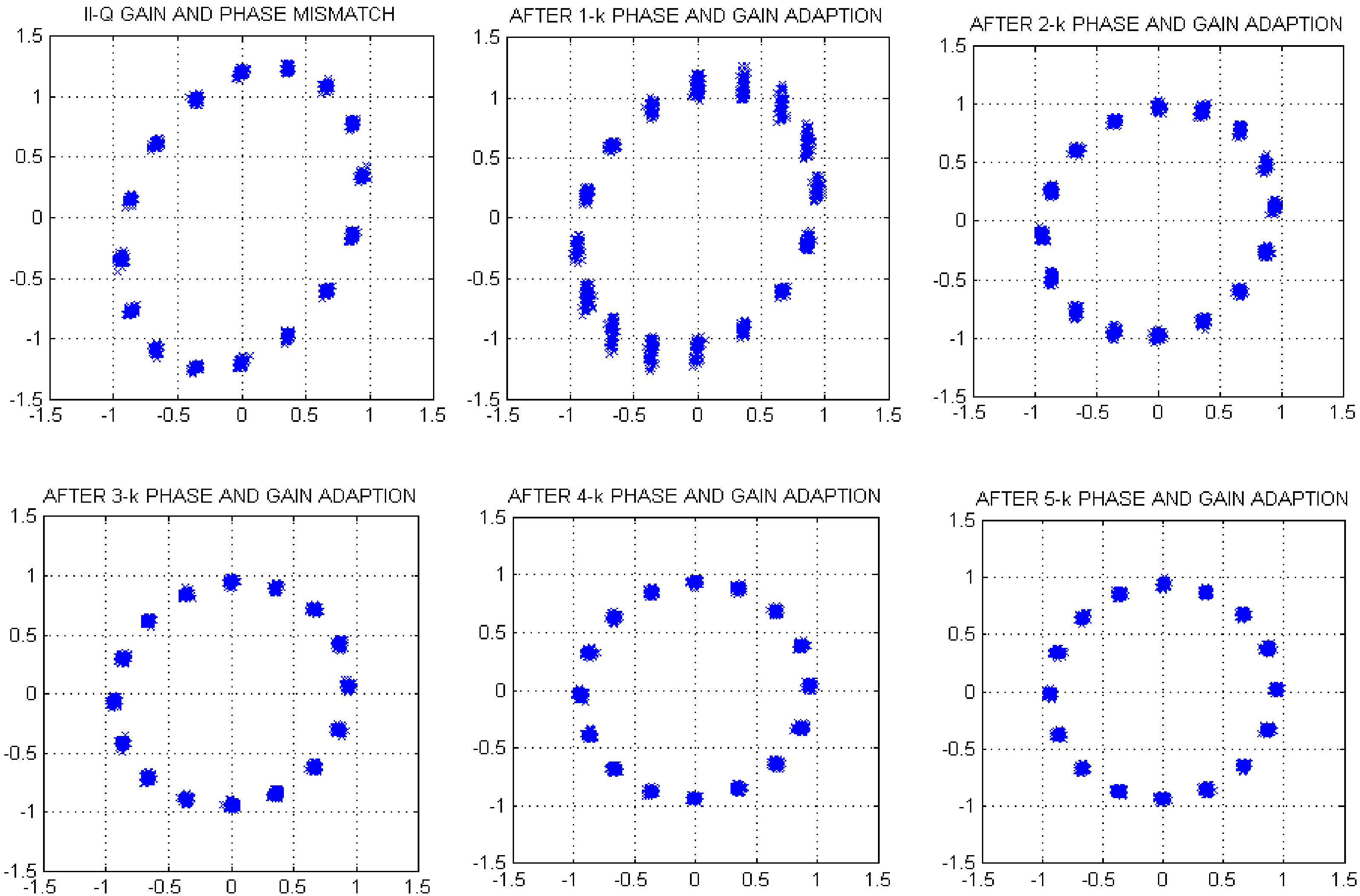
I-Q Imbalance Requires DC Cancellers



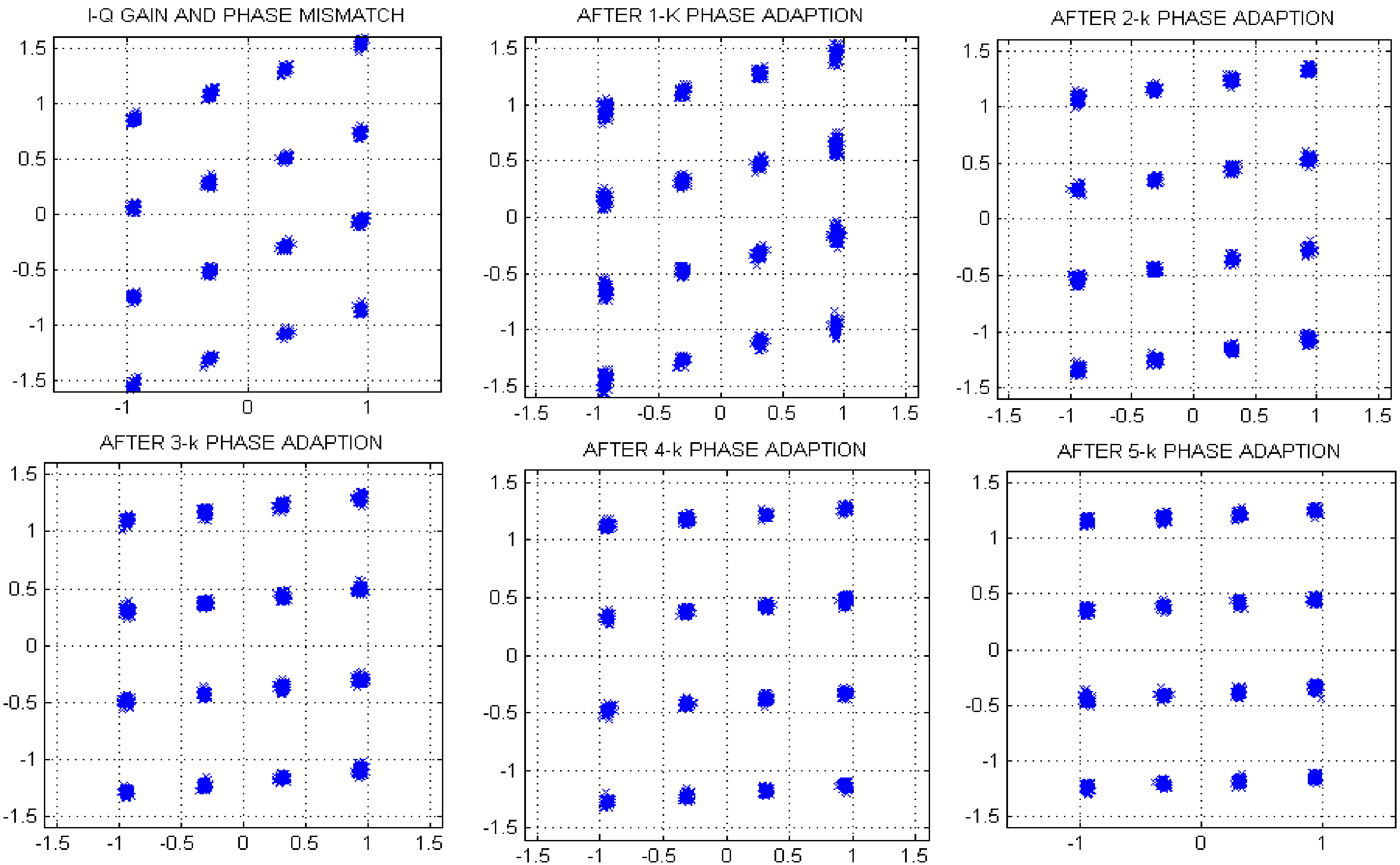
Sequence of 16-Phase Constellations During Phase Balancing



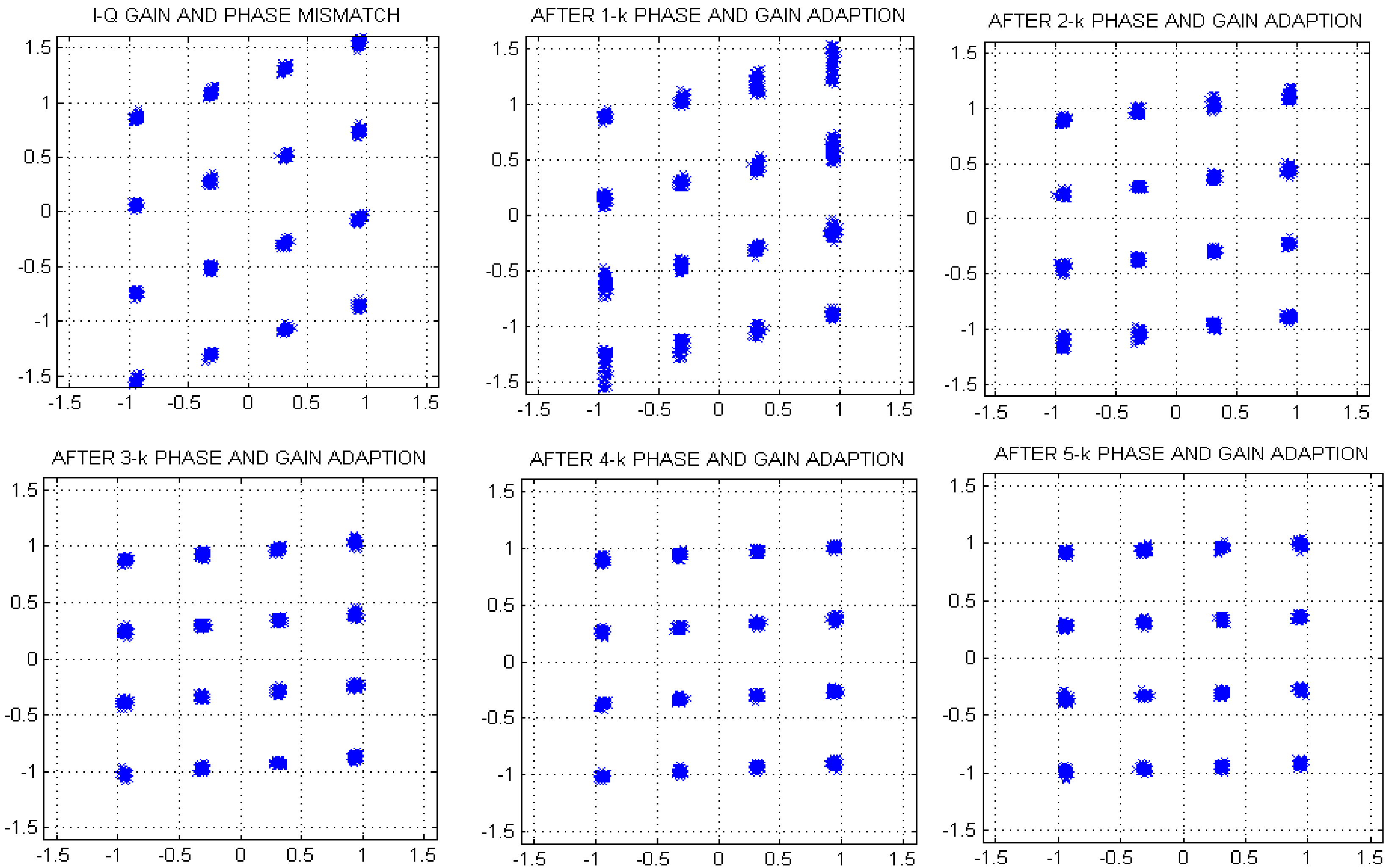
Sequence of 16-Phase Constellations During Gain and Phase Balancing



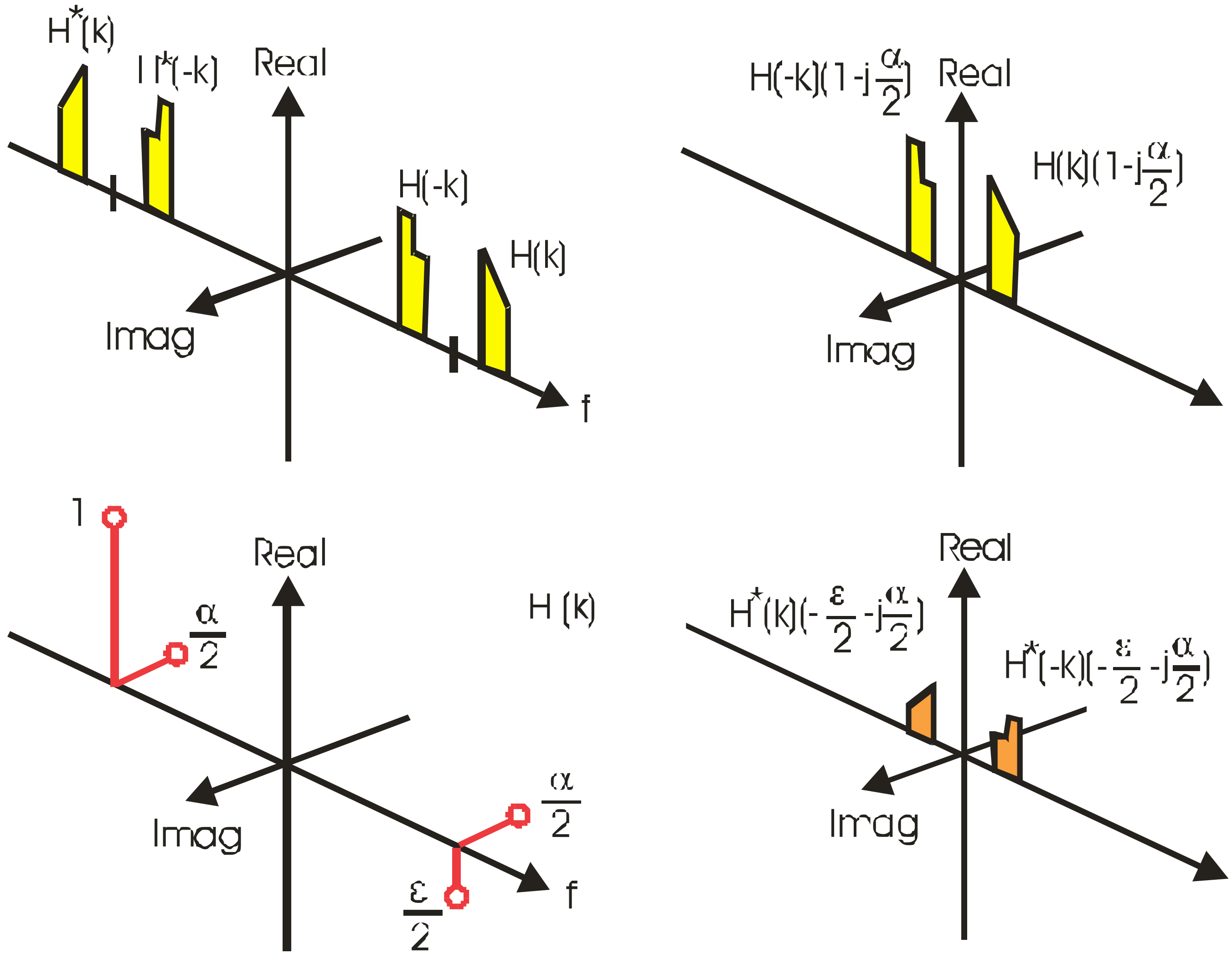
Sequence of 16-QAM Constellations During Phase Balancing



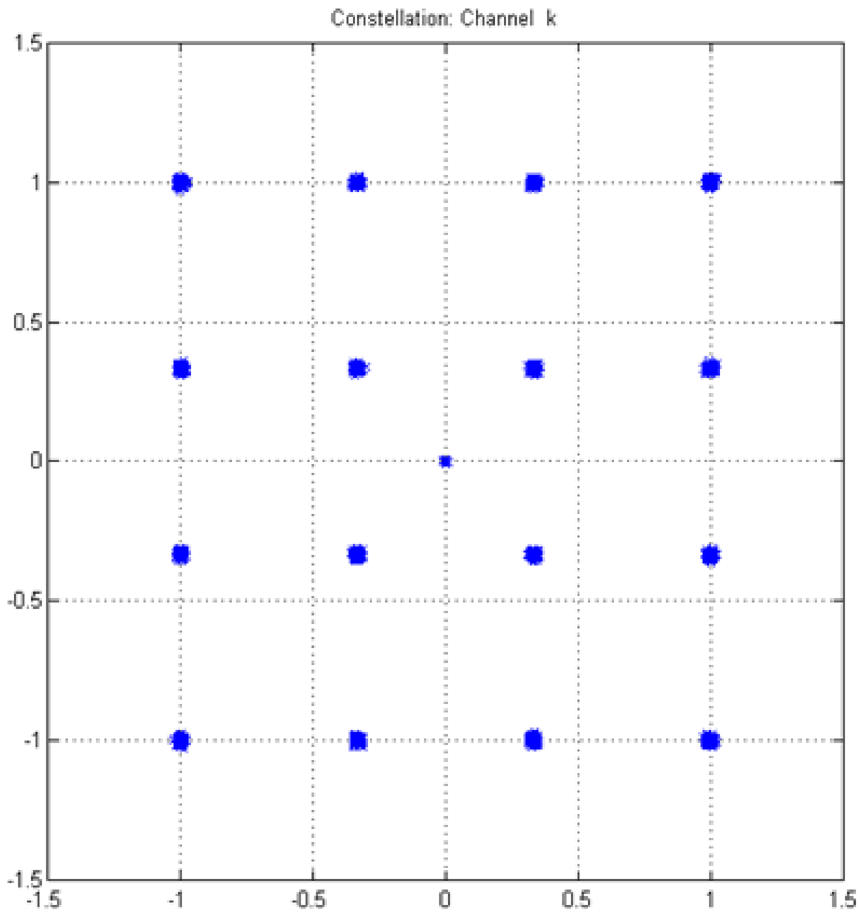
Sequence of 16-QAM Constellations During Phase and Gain Balancing

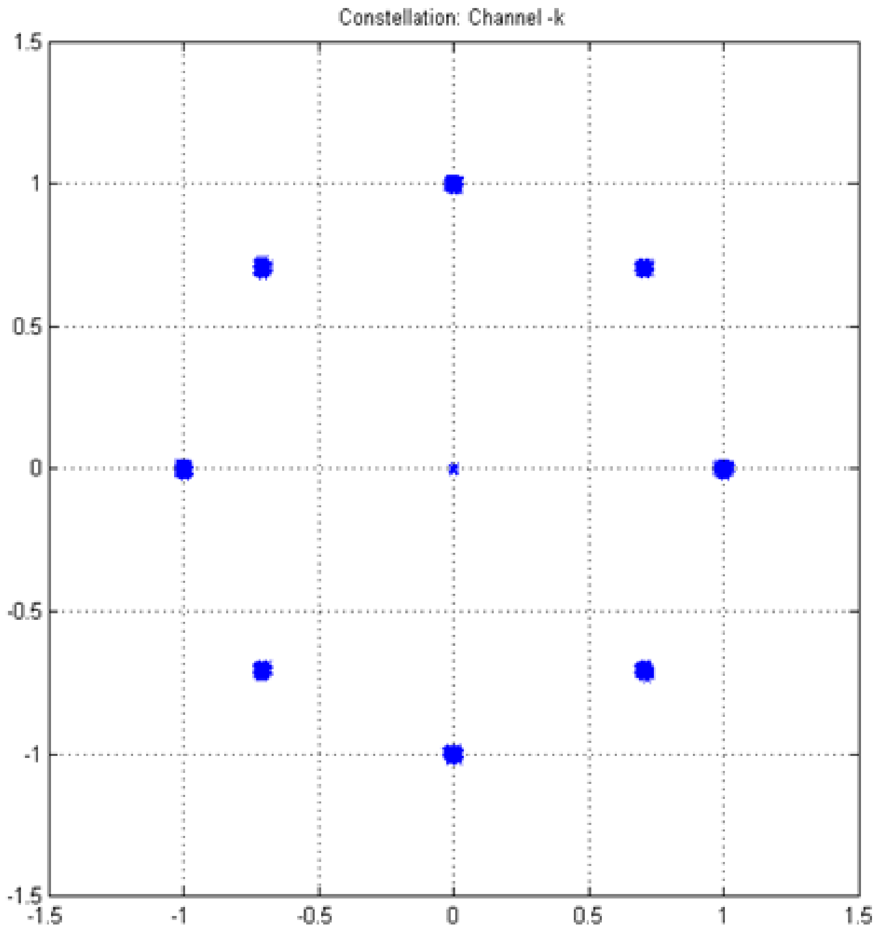


Spectral Images Due to I-Q Mismatch

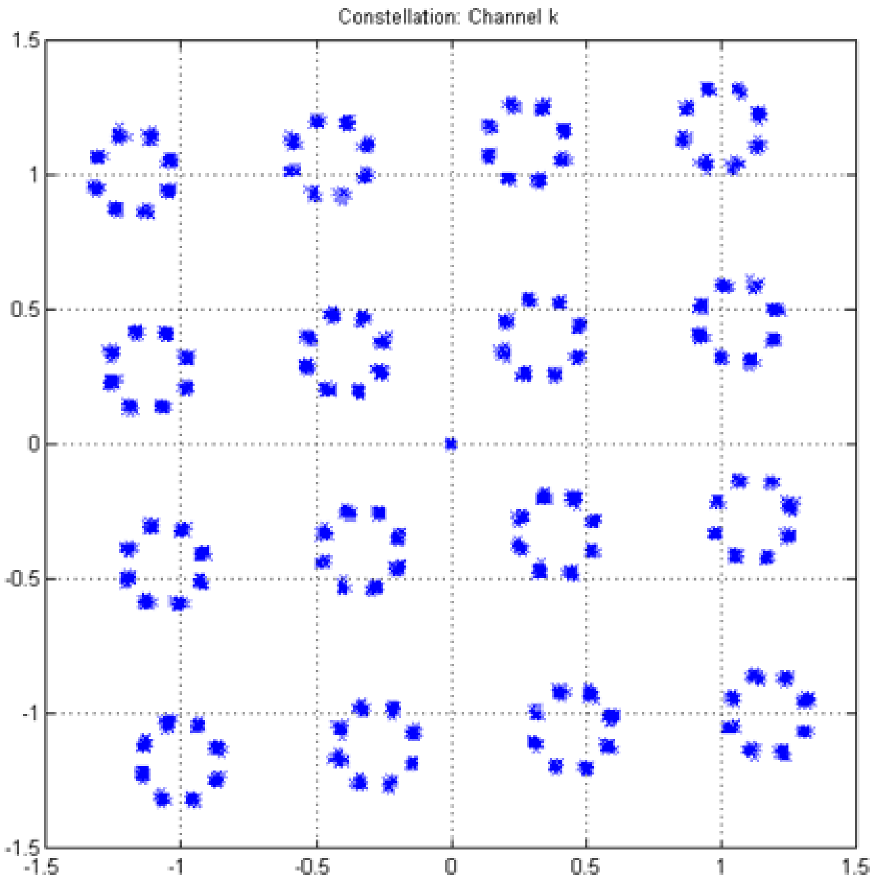


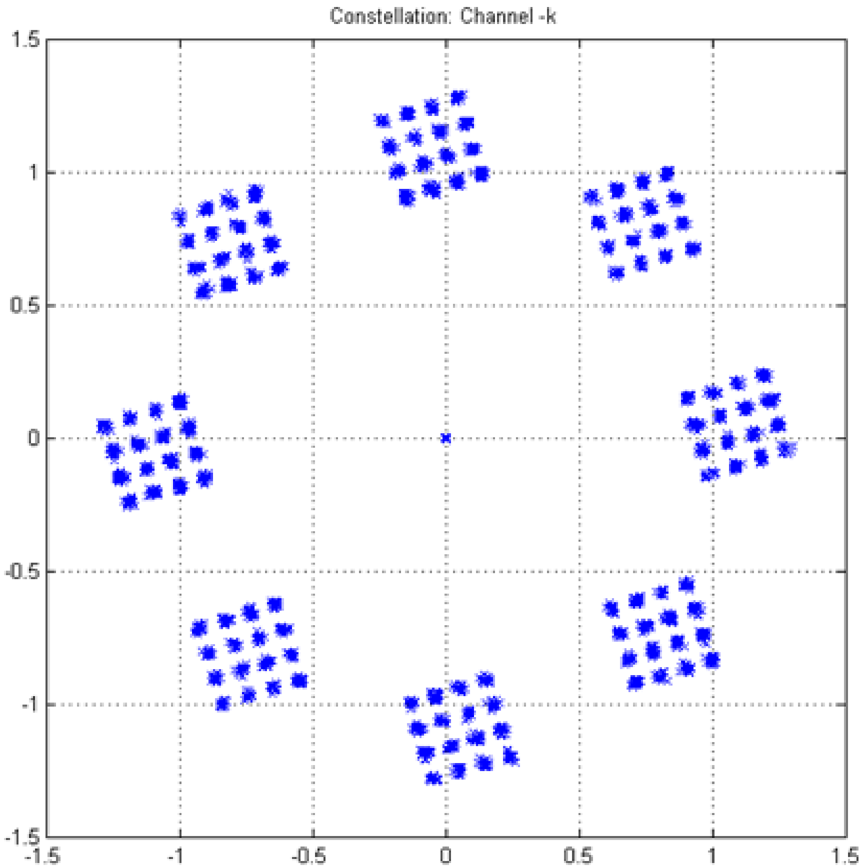
Constellations of Channel +k and -k



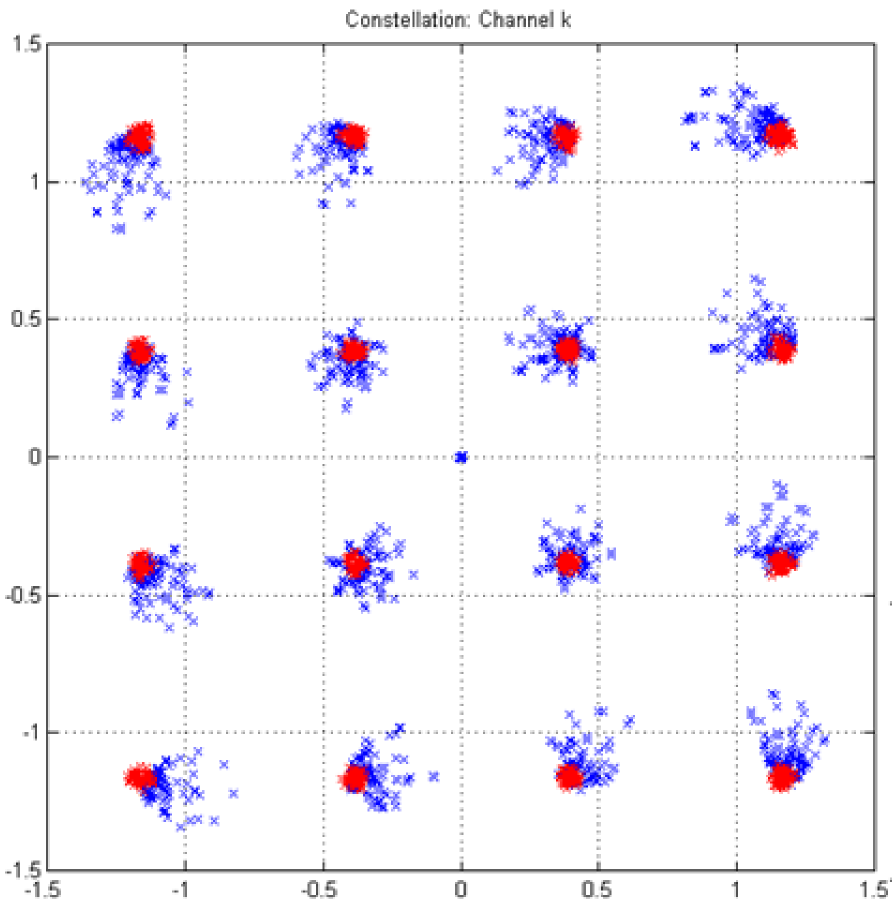


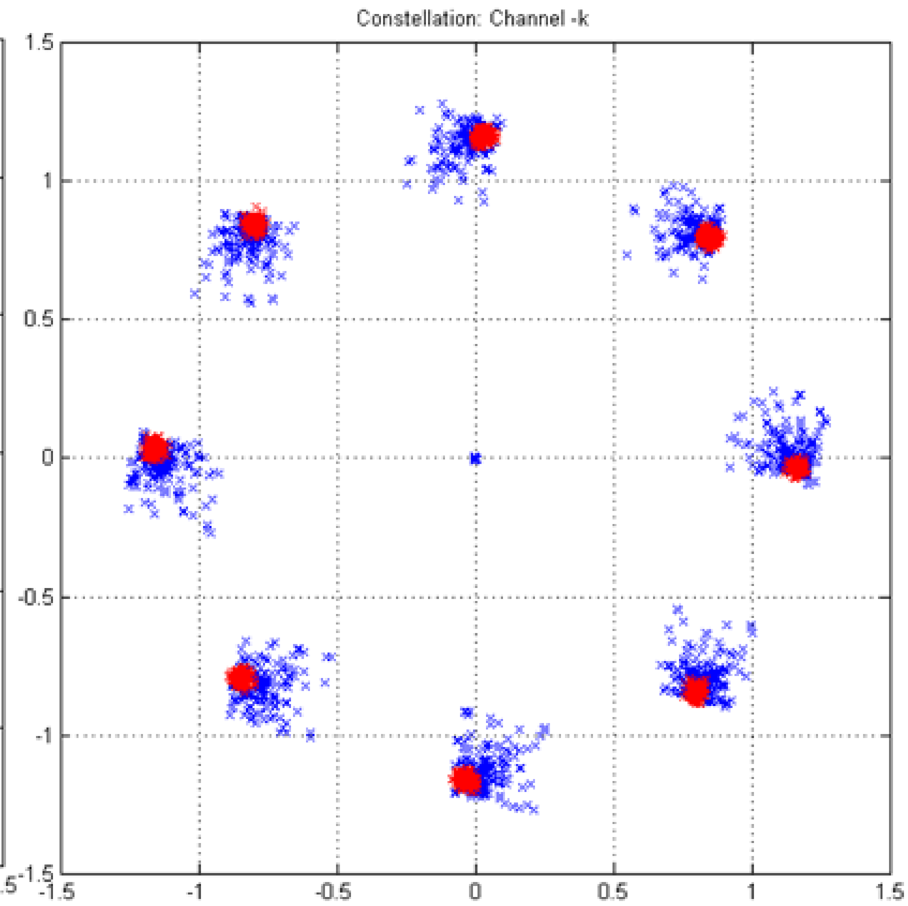
Crosstalk Between Channels k and –k Due to gain and Phase Imbalance



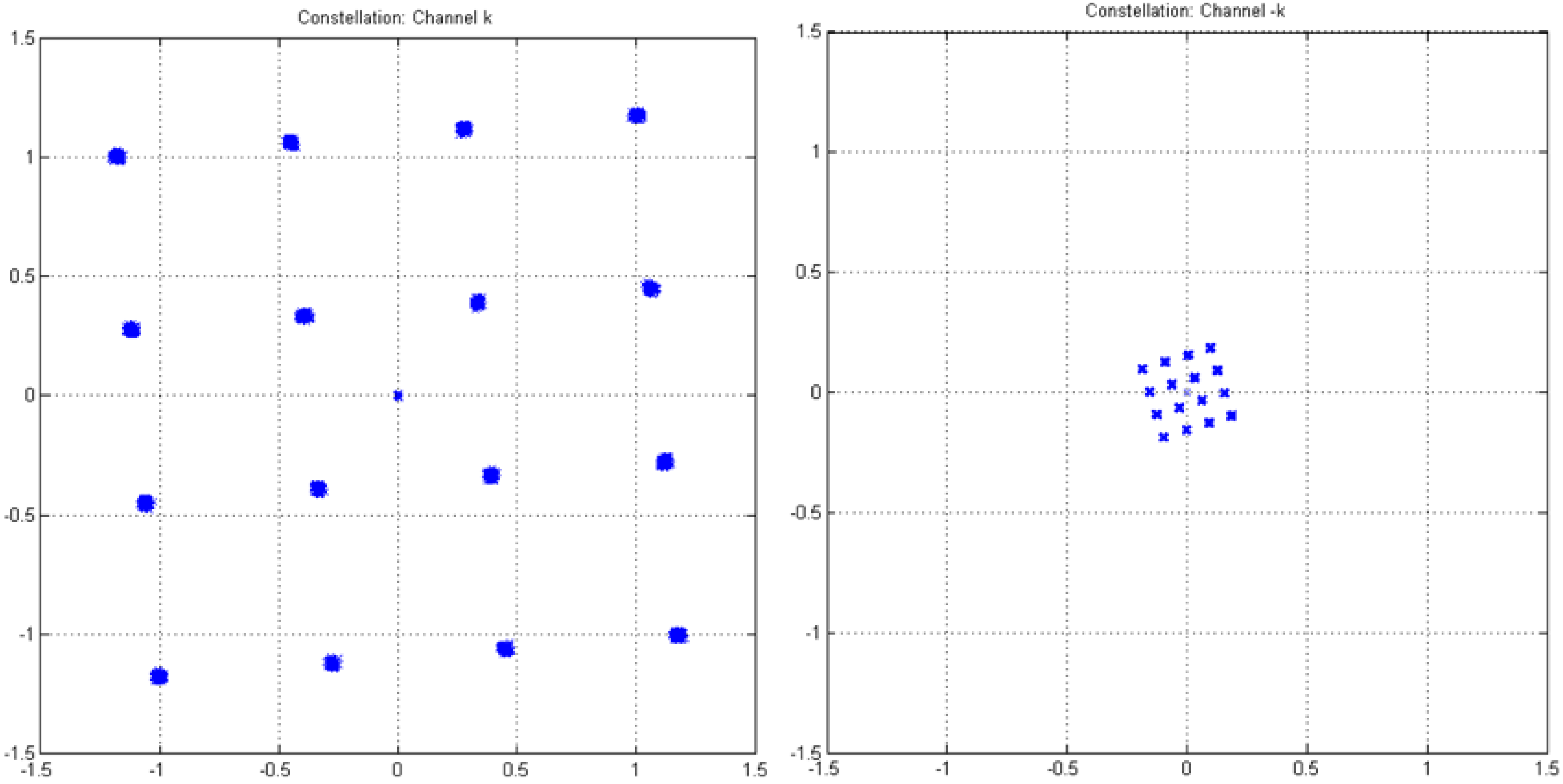


Constellation after Gradient Descent Correction of Gain and Phase Imbalance

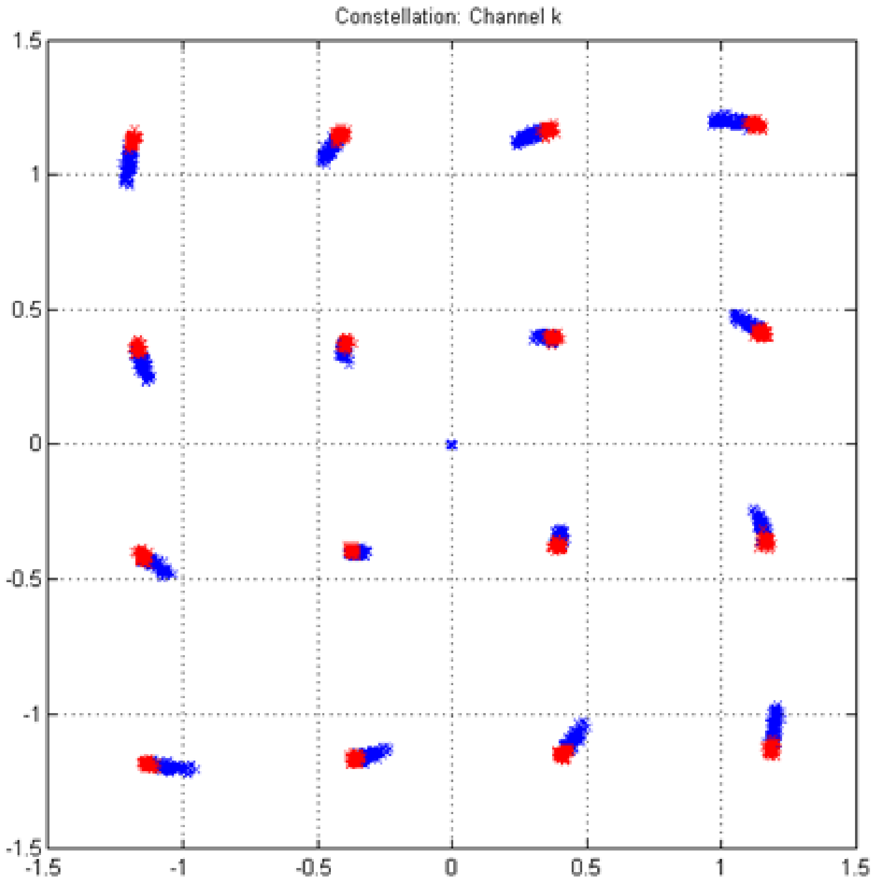


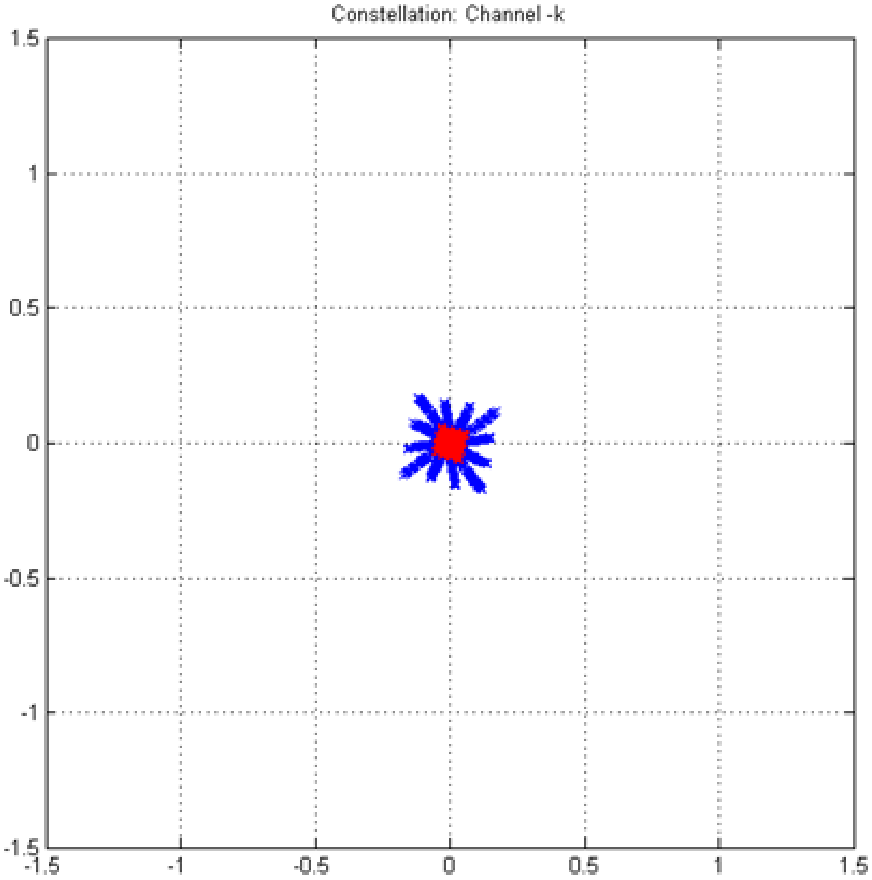


Crosstalk Between Channel k and Empty Channel –k

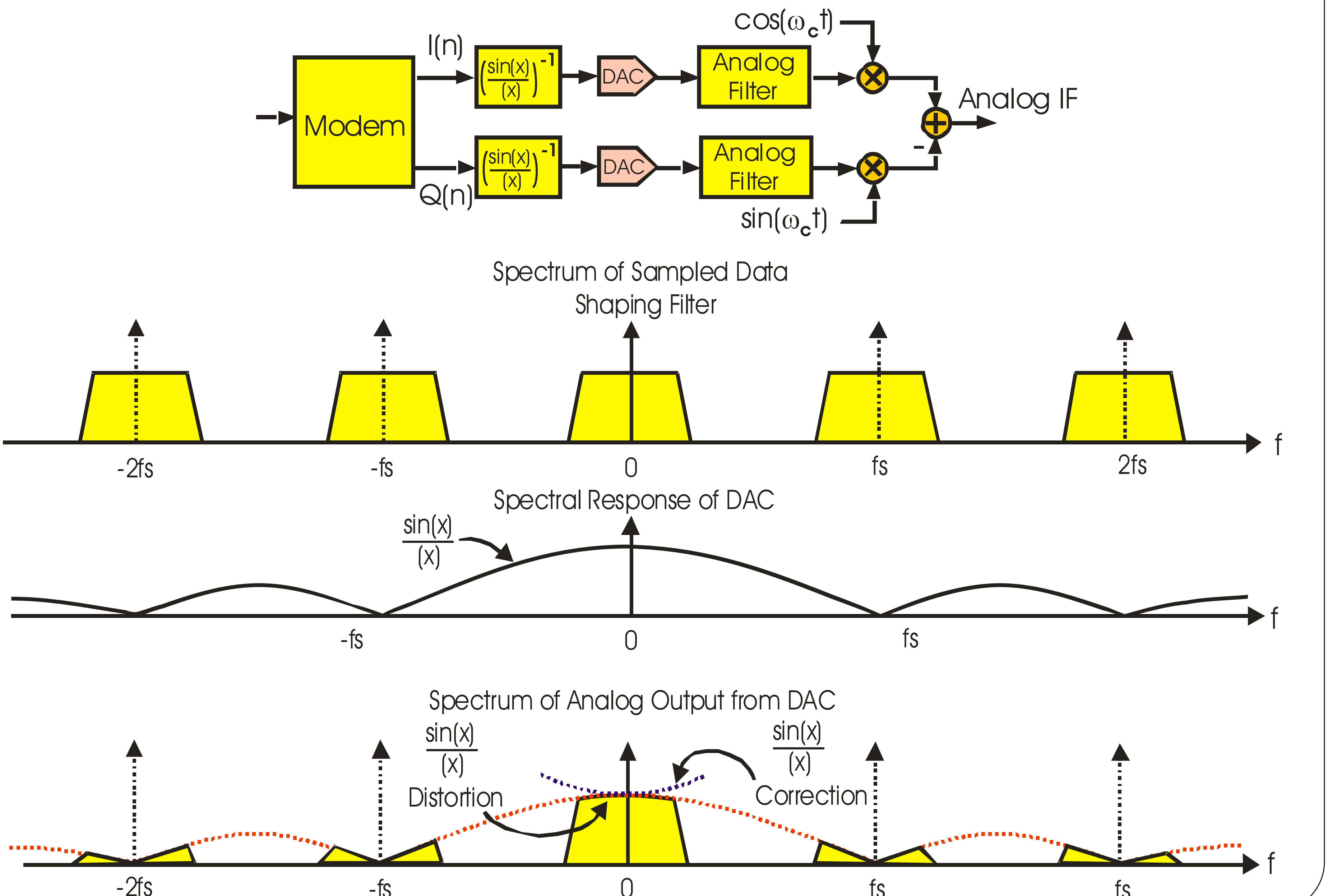


Constellation after Gradient Descent Correction of Gain and Phase Imbalance

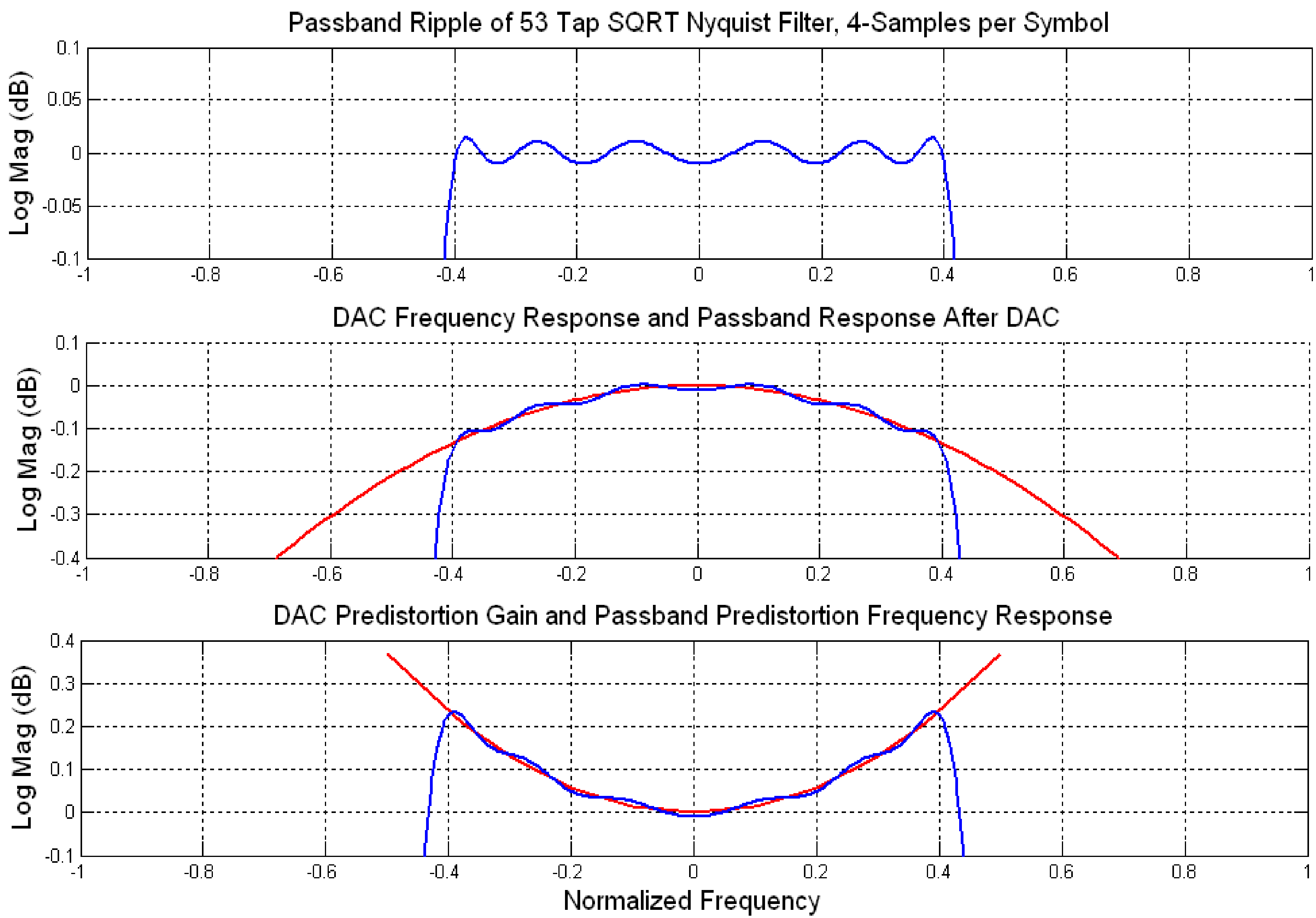




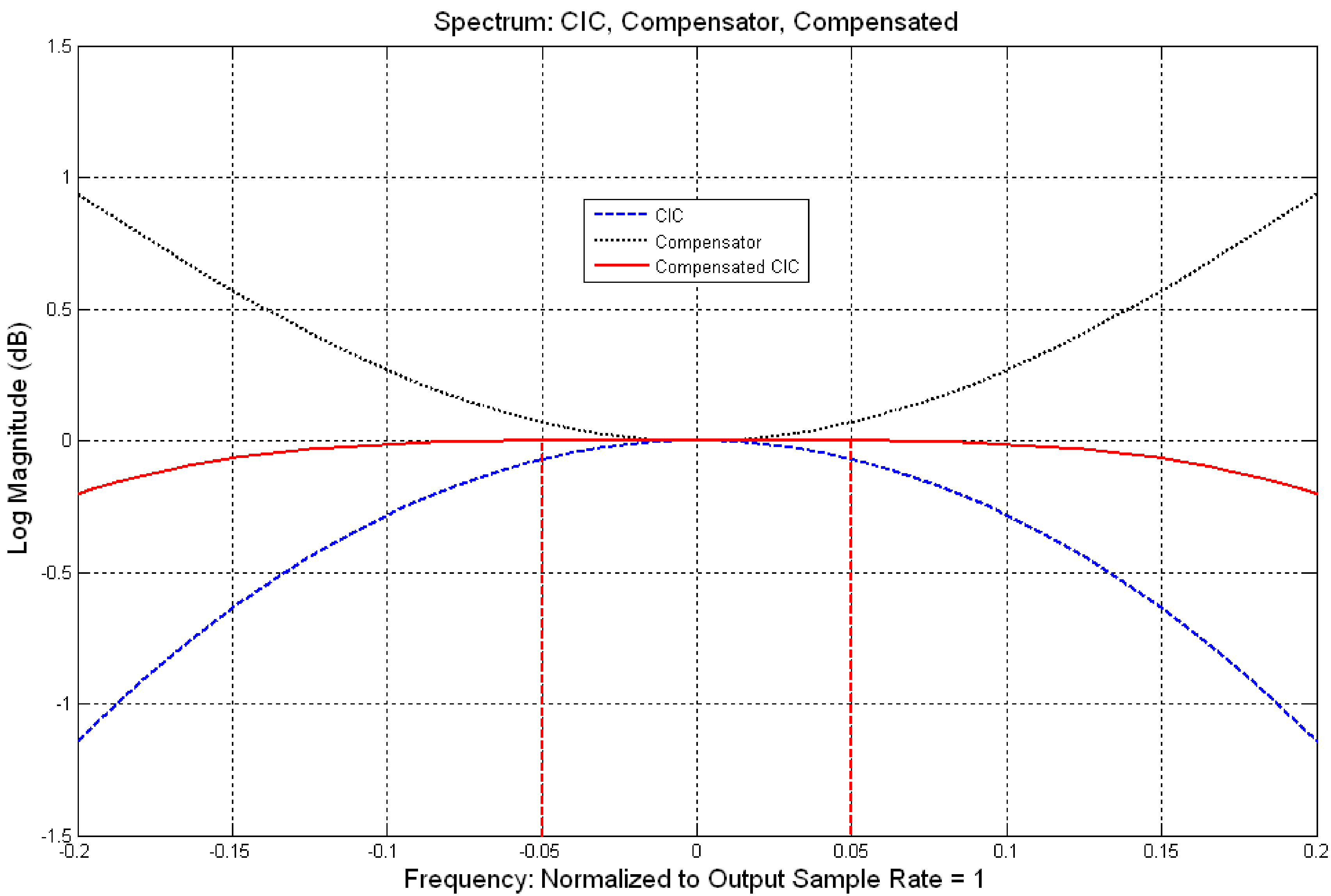
DAC Sin(x)/(x) Baseband Distortion



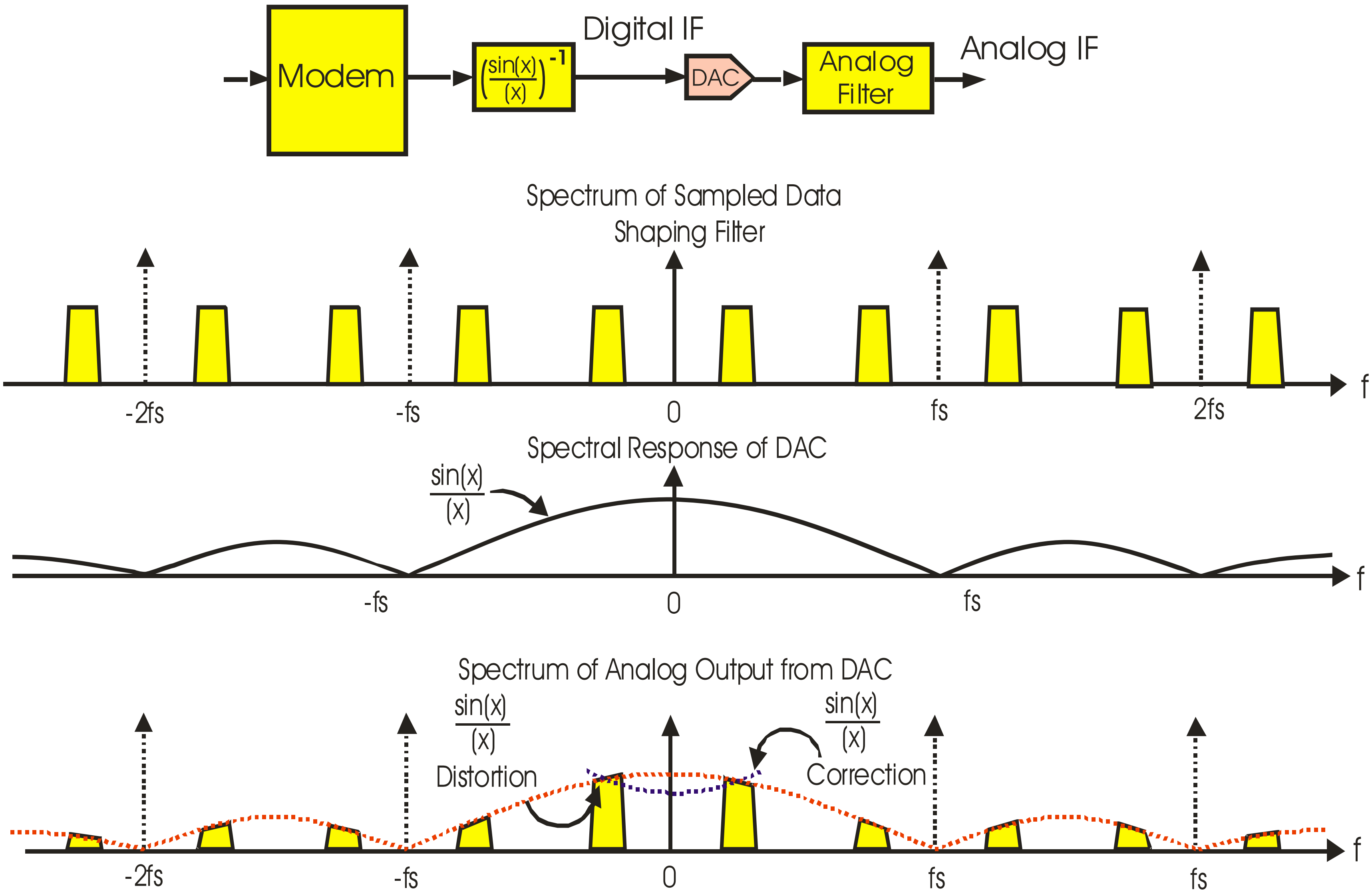
Baseband Filter DAC Predistortion



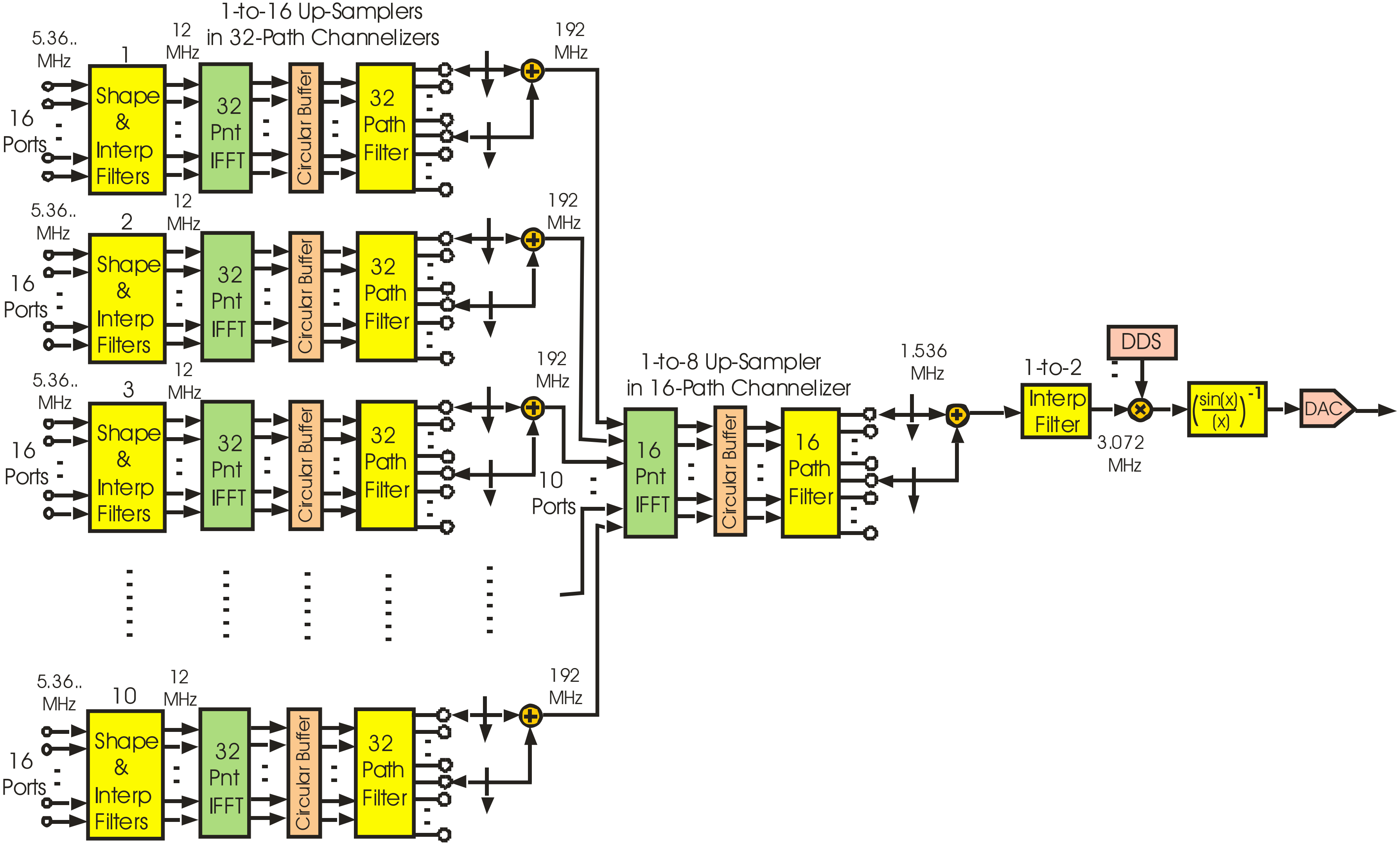
CIC $[\mathrm{Sin}(x)/(x)]^P$ Compensator



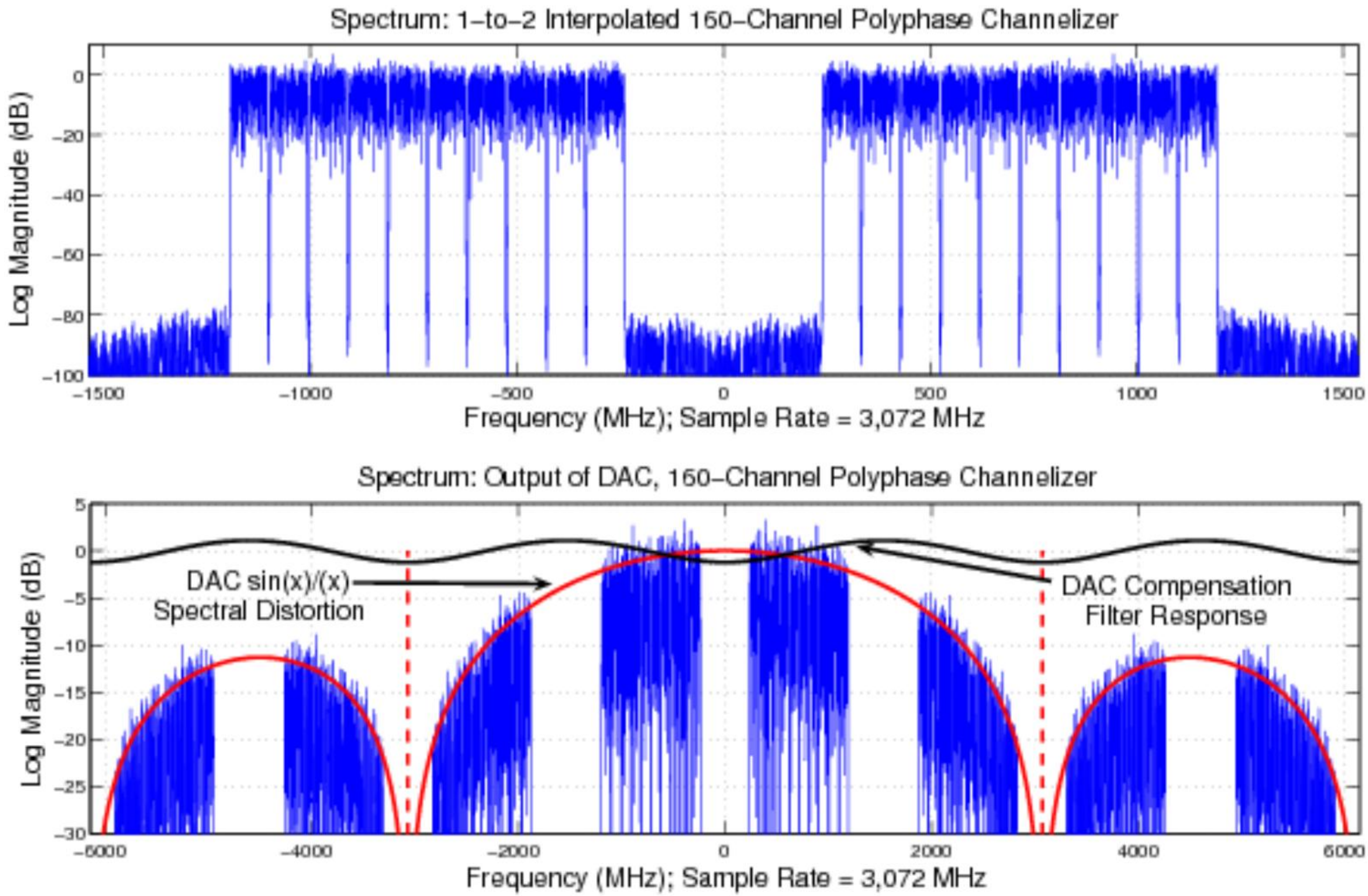
DAC Sin(x)/(x) Digital IF Distortion



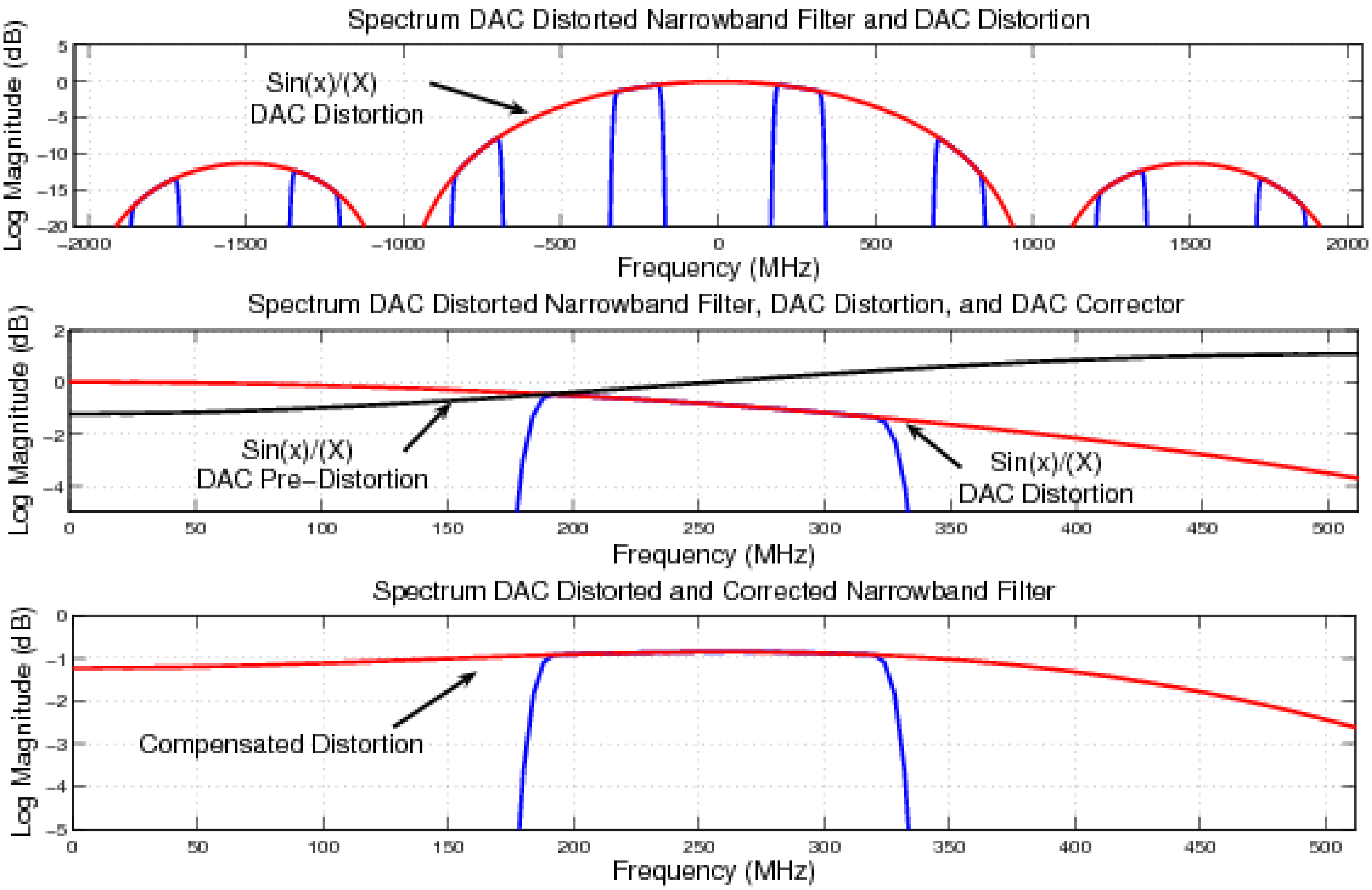
Sin(x)/(x) Predistortion



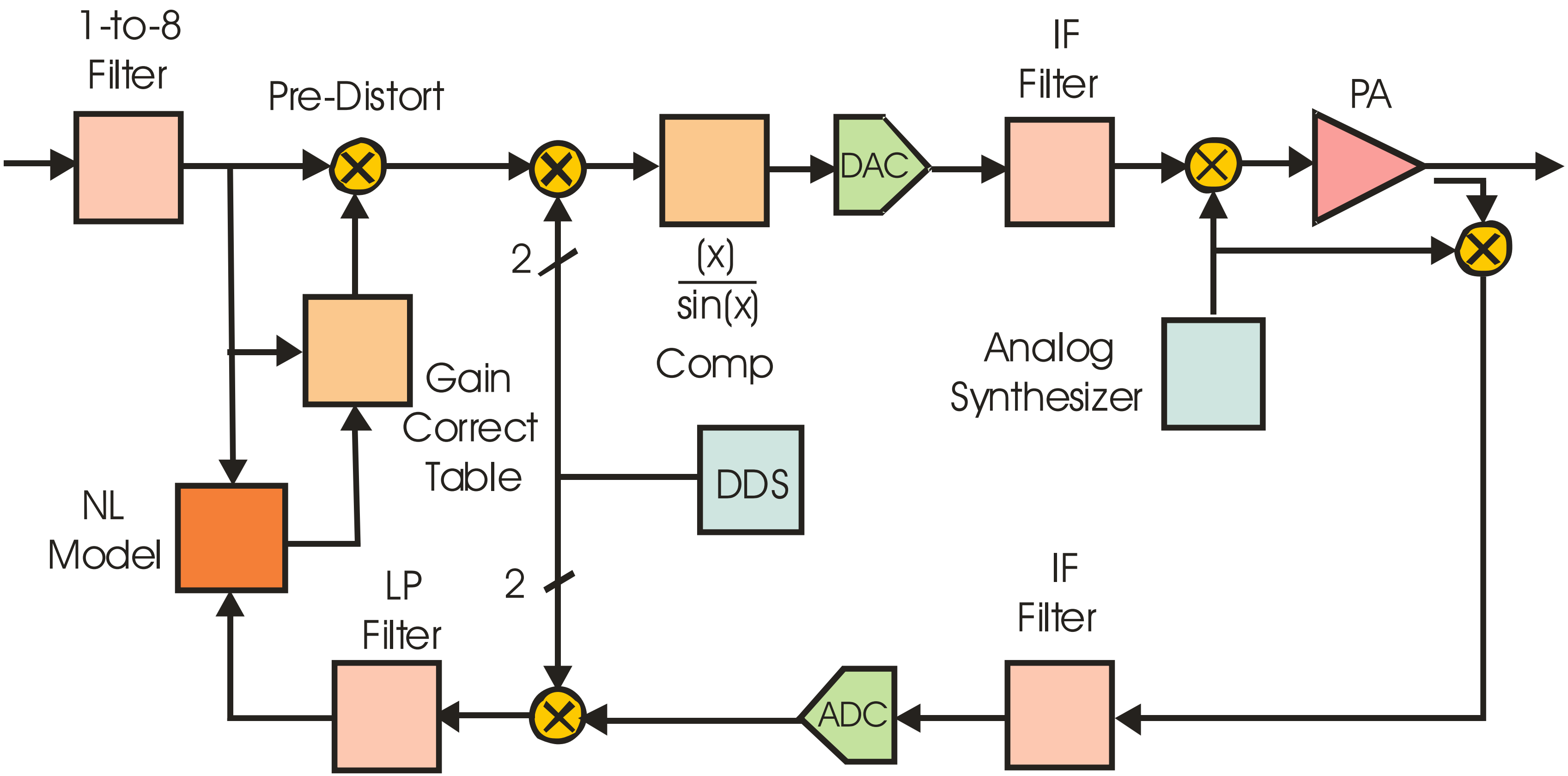
DAC SIN(X)/X CORRECTION



DAC Sin(x)/(x) IF Predistortion



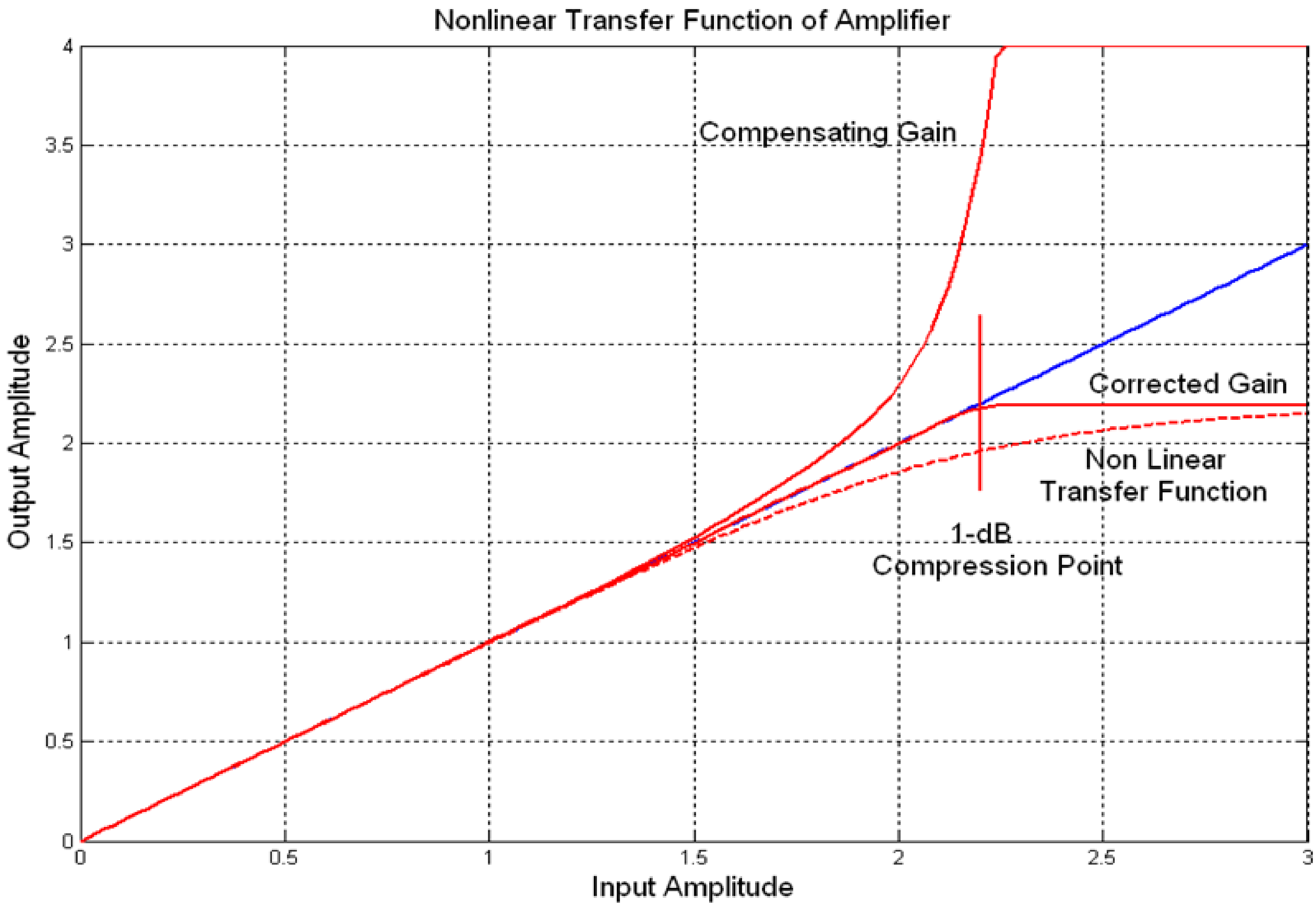
Power Amplifier Linearization



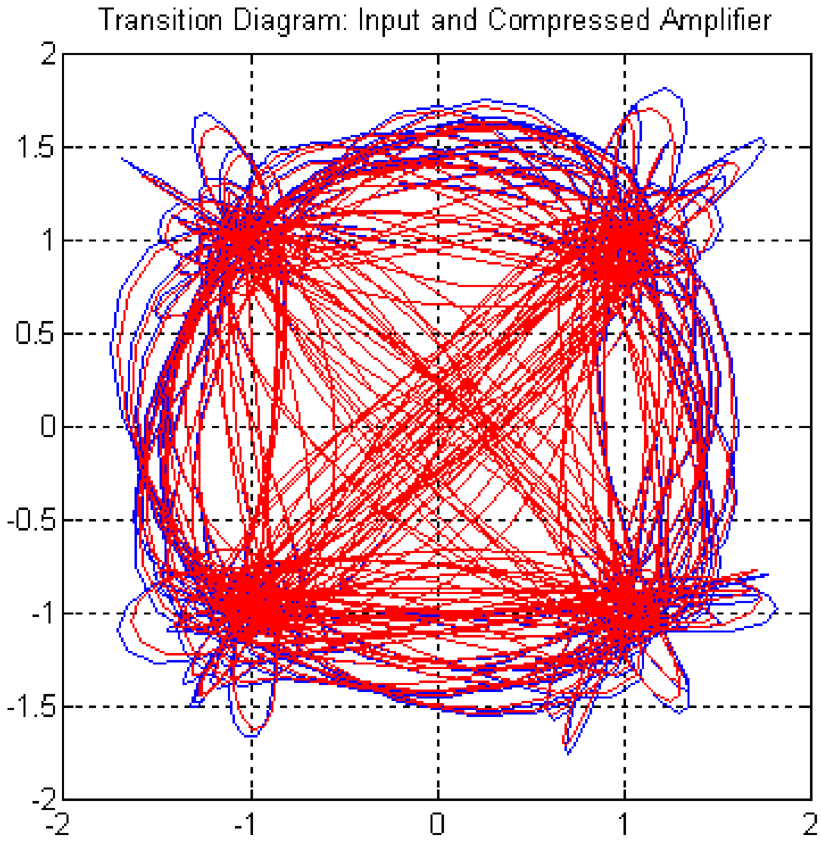
PA Linearization

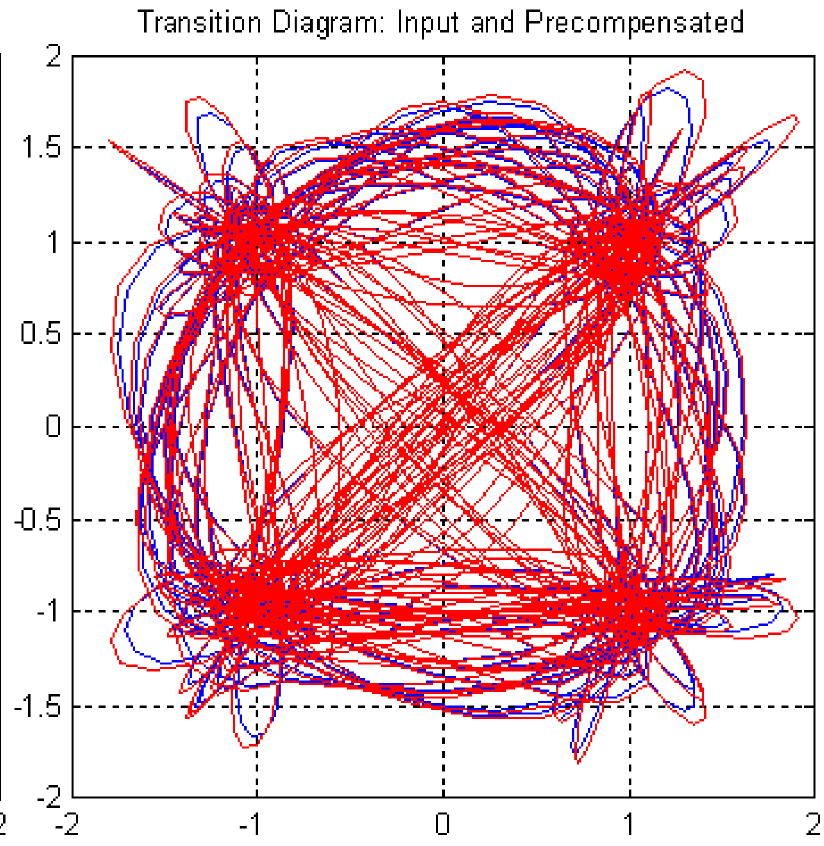
Peak-to-Average Ratio Control

Non Linear Amplifier and Pre-Compensating Gain

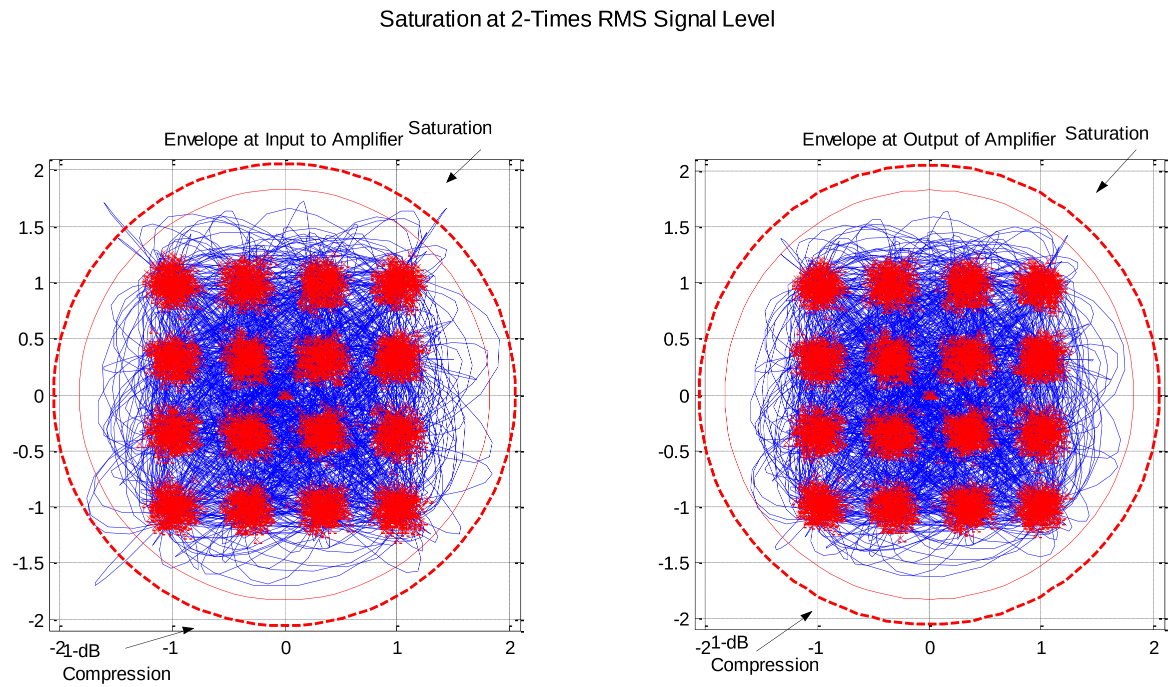


Transition Diagram Input and Output of Amplifier and Input and Output of Precompensator

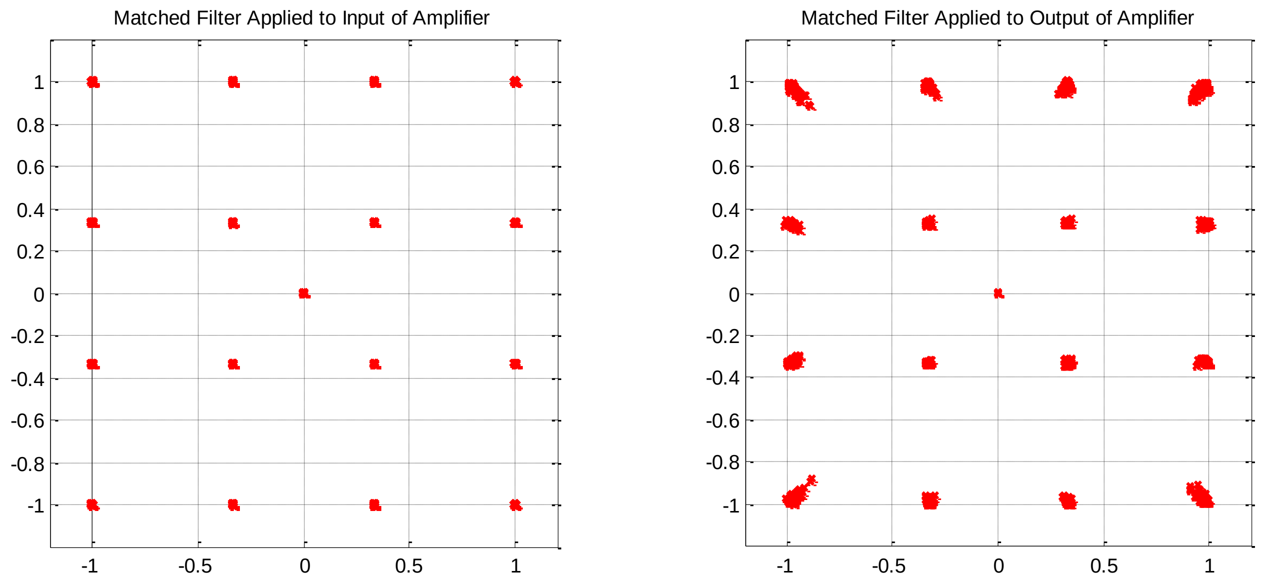




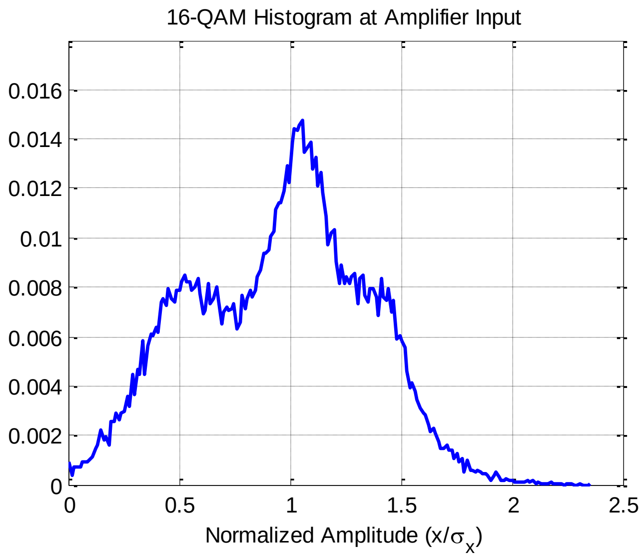
16-QAM Input and Output Envelopes. Saturation and 1-dB Compression Circles

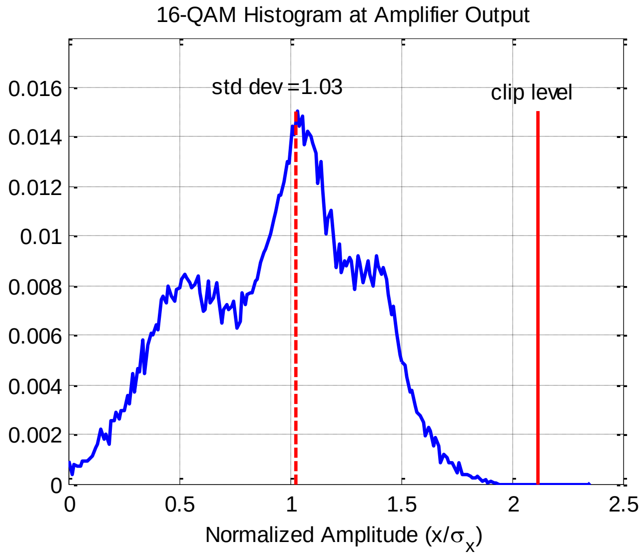


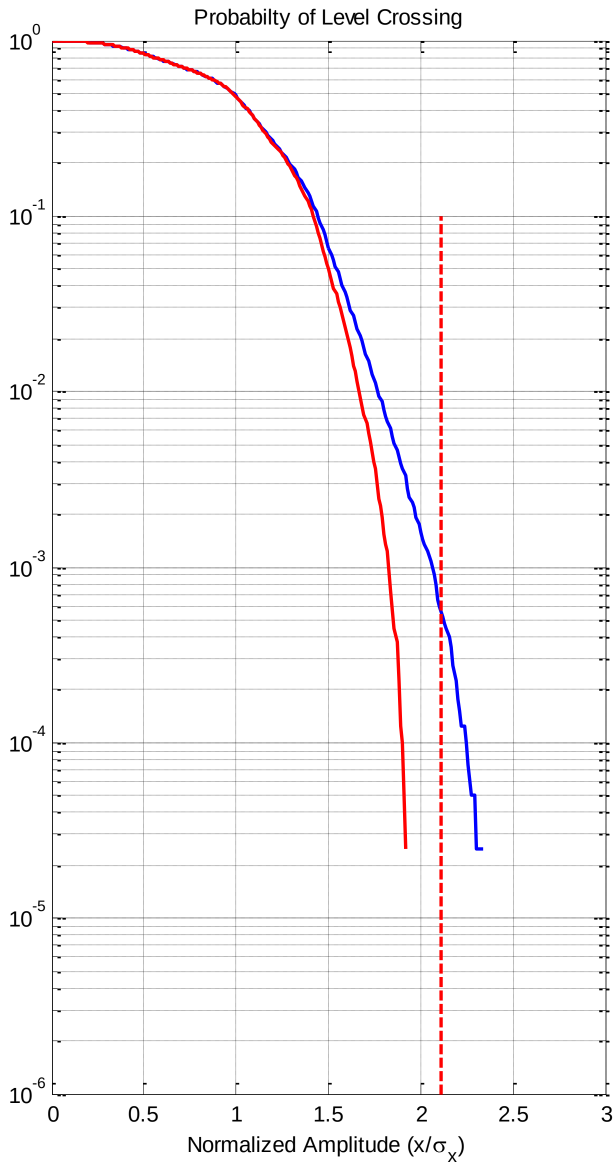
Limiting Amplifier Effect on Received QAM Constellation



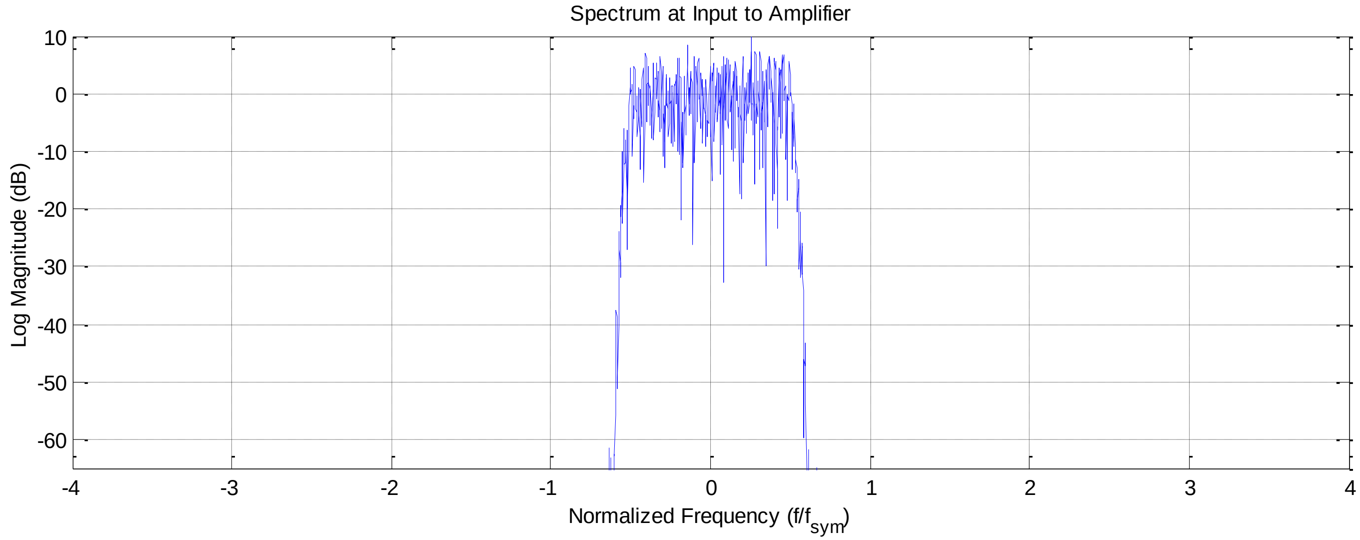
16-QAM (α=0.2) Envelope Statistics

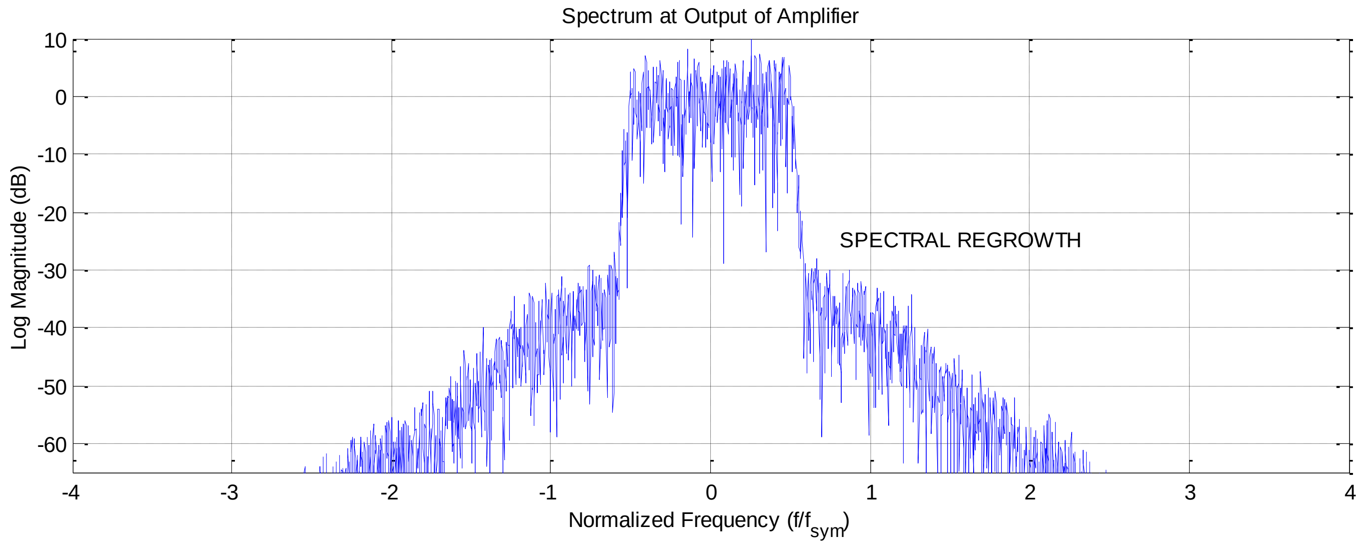




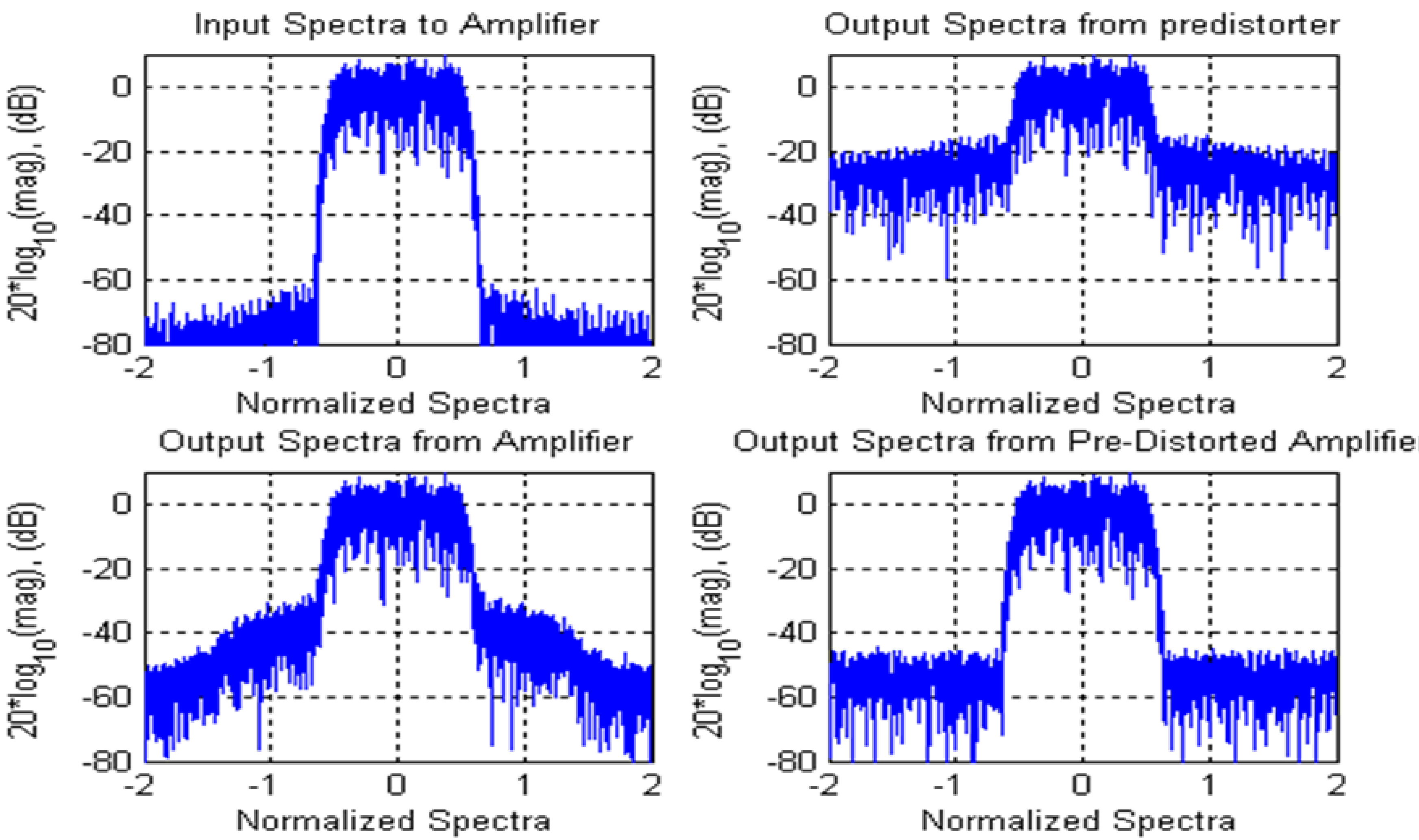


Limiting Amplifier Effect on Signal Spectra

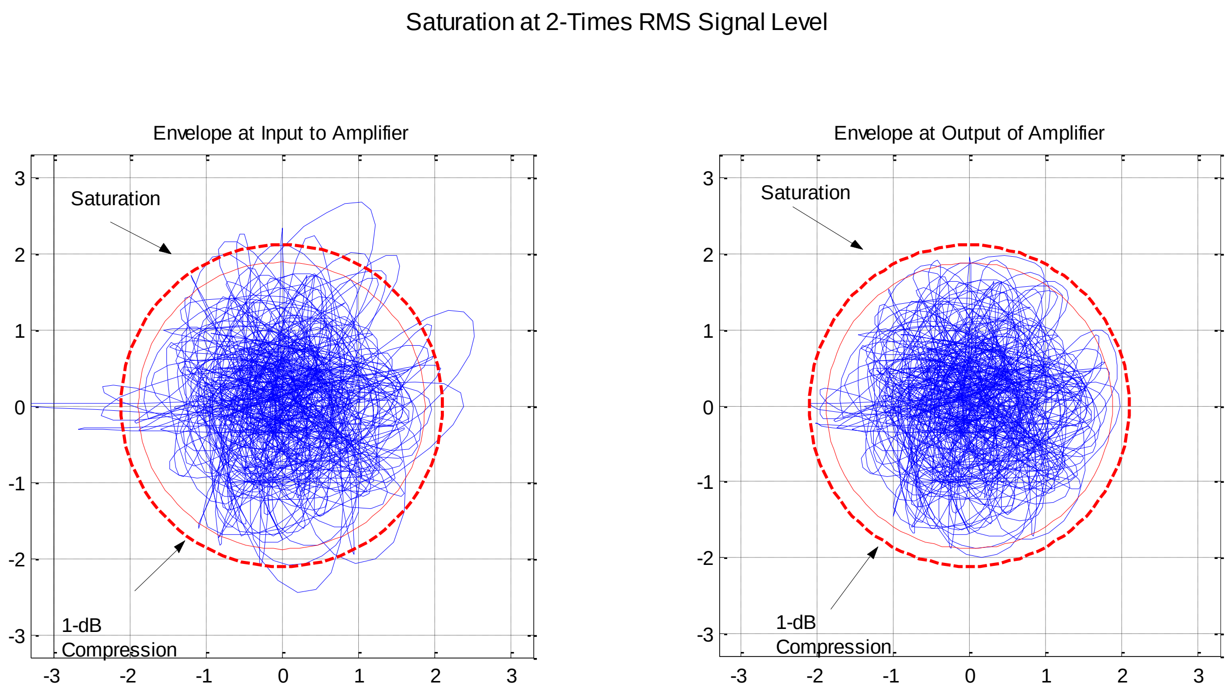




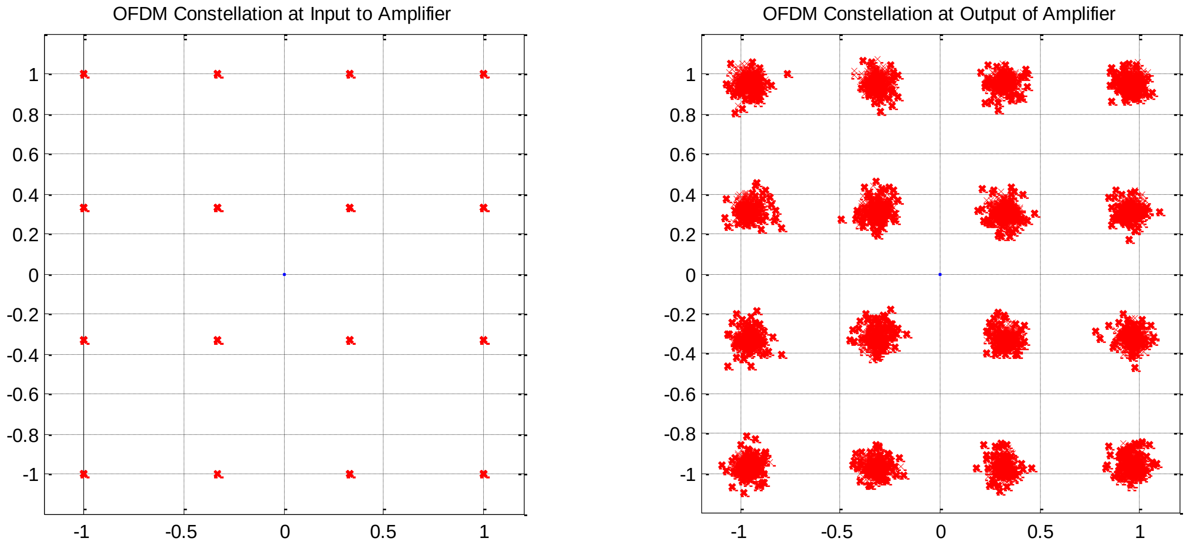
Spectra: Input and Output of Amplifier and Output of Pre-Compensator and Pre-Compensated Amplifier



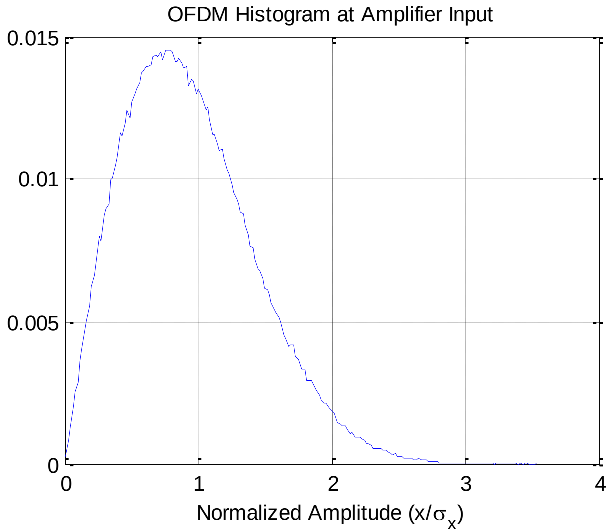
OFDM Input and Output Envelopes: Saturation and 1-dB Compression Circles

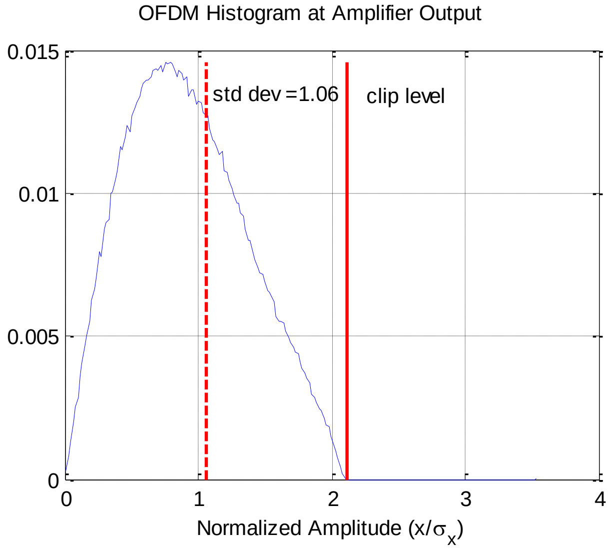


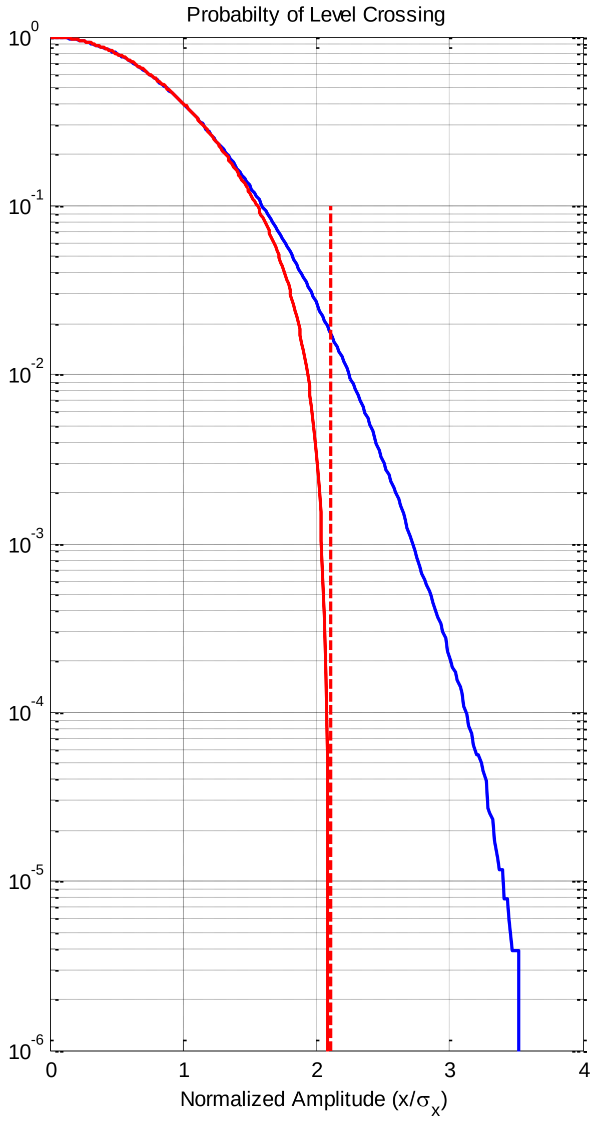
Limiting Amplifier Effect on OFDM Constellation



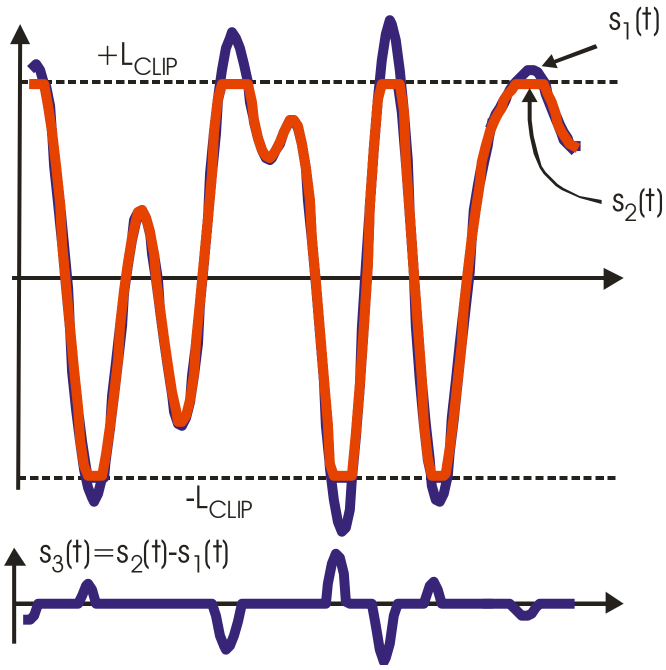
OFDM Envelope Statistics

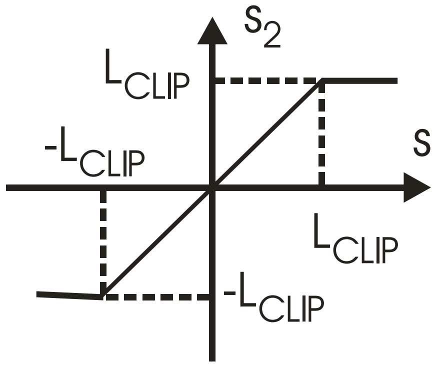


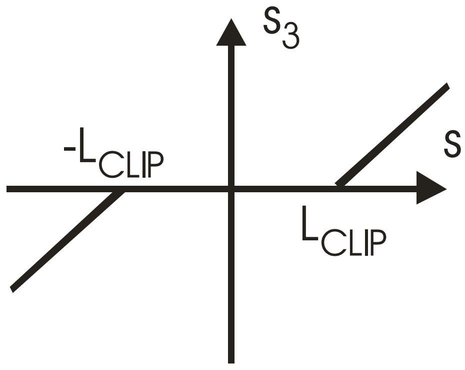




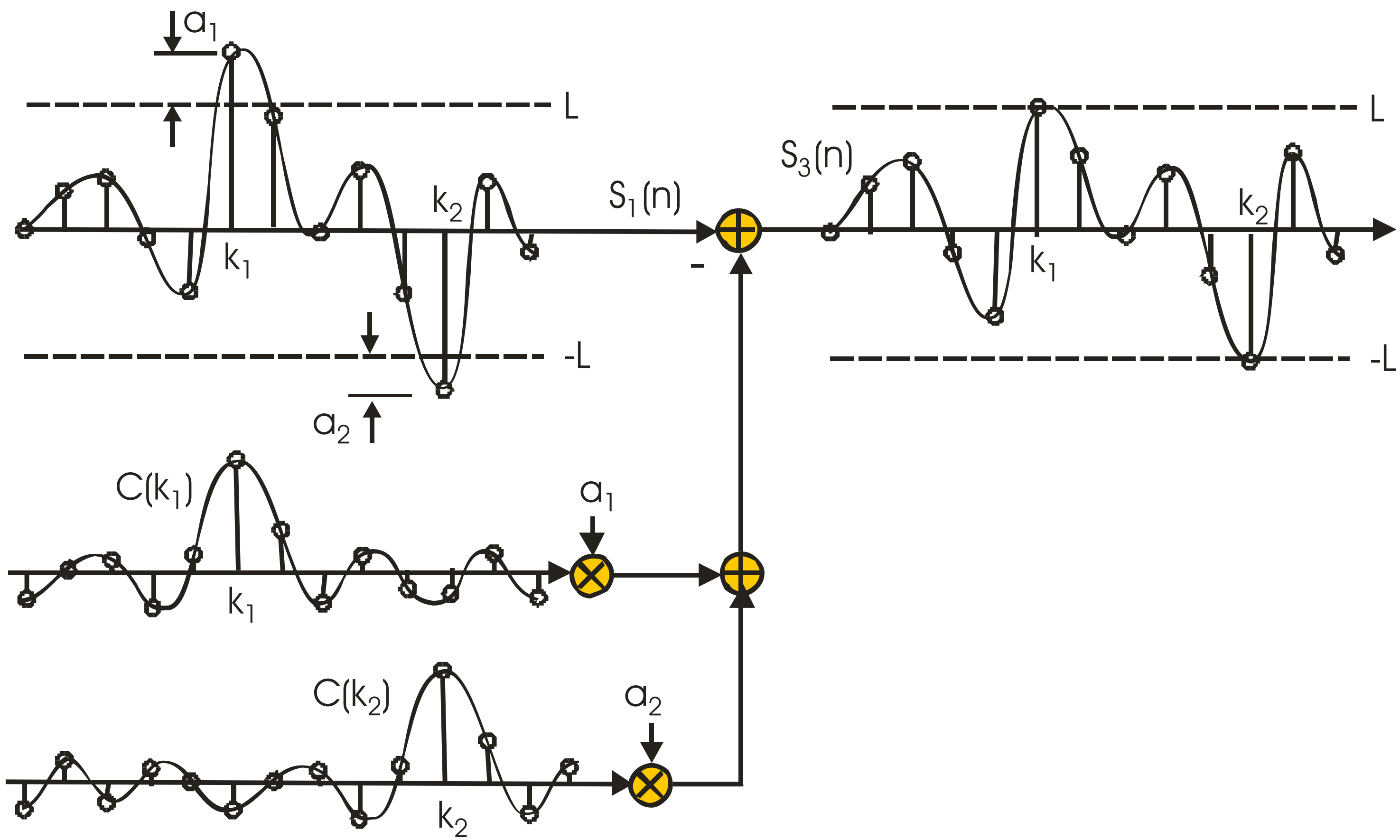
To Clip or Not to Clip: That is the Question!



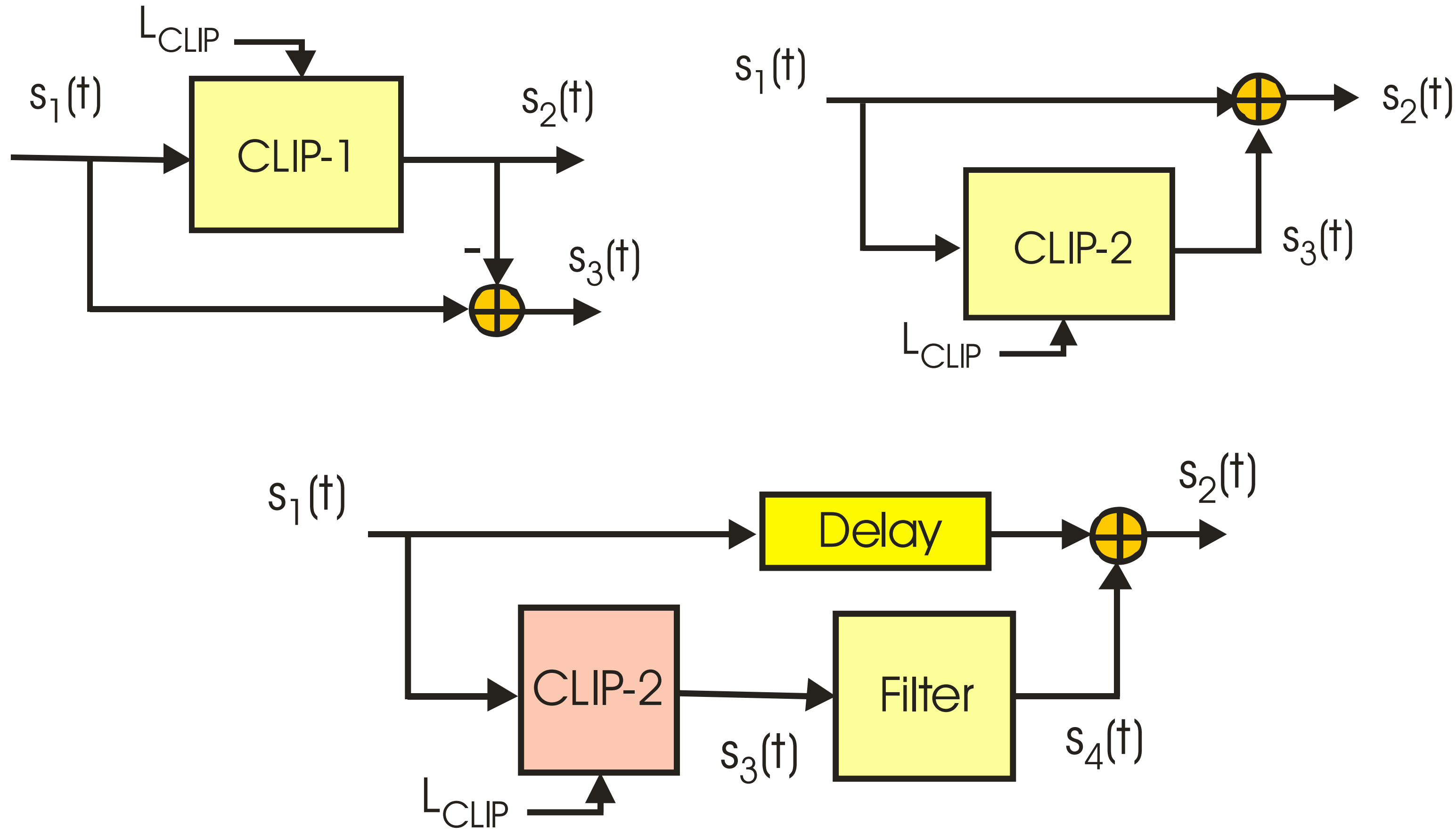




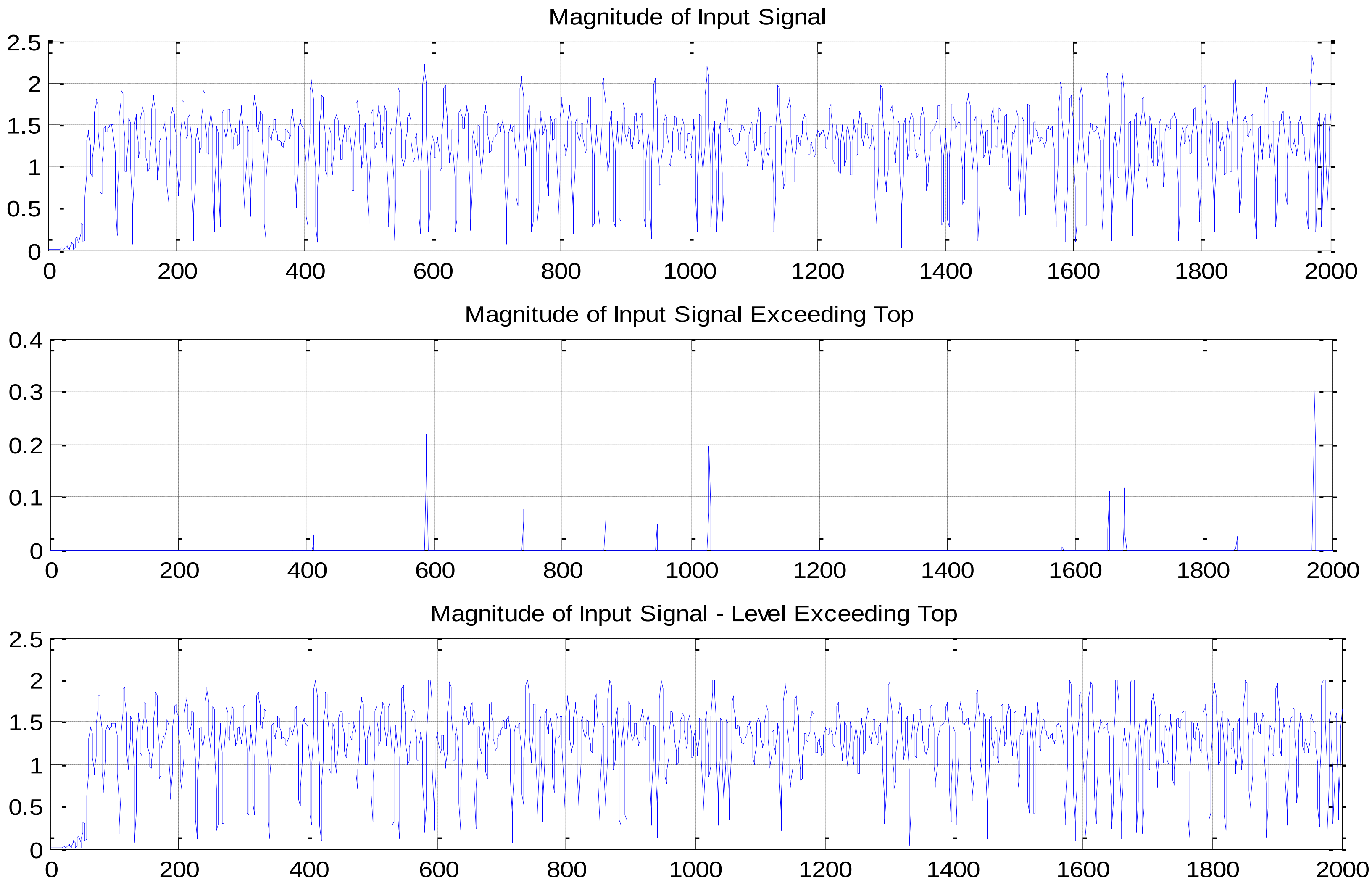
Band Limited Subtractive Clipping



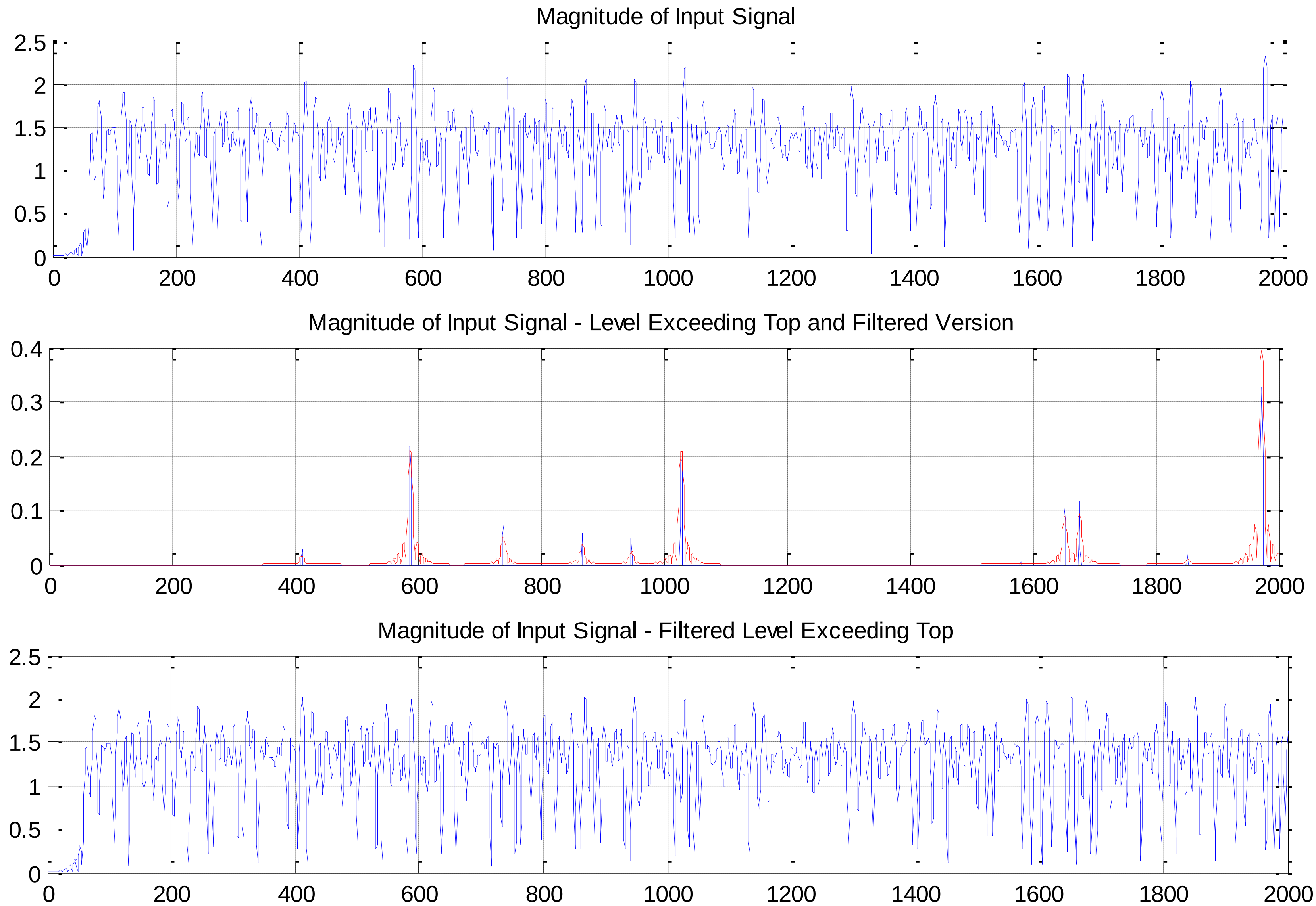
Band-Limited Clipping



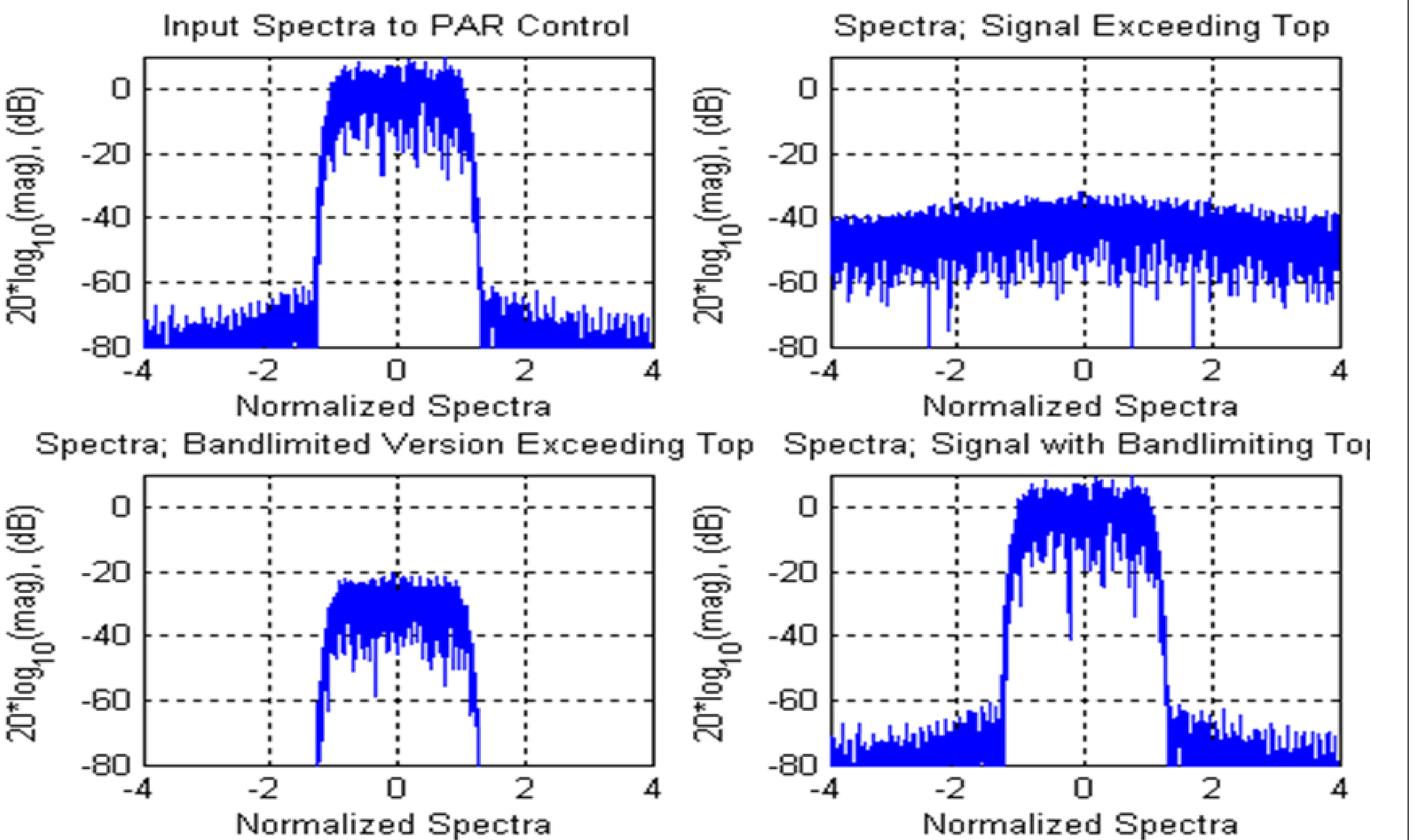
Input Signal, Clipping Component and Clipped Signal



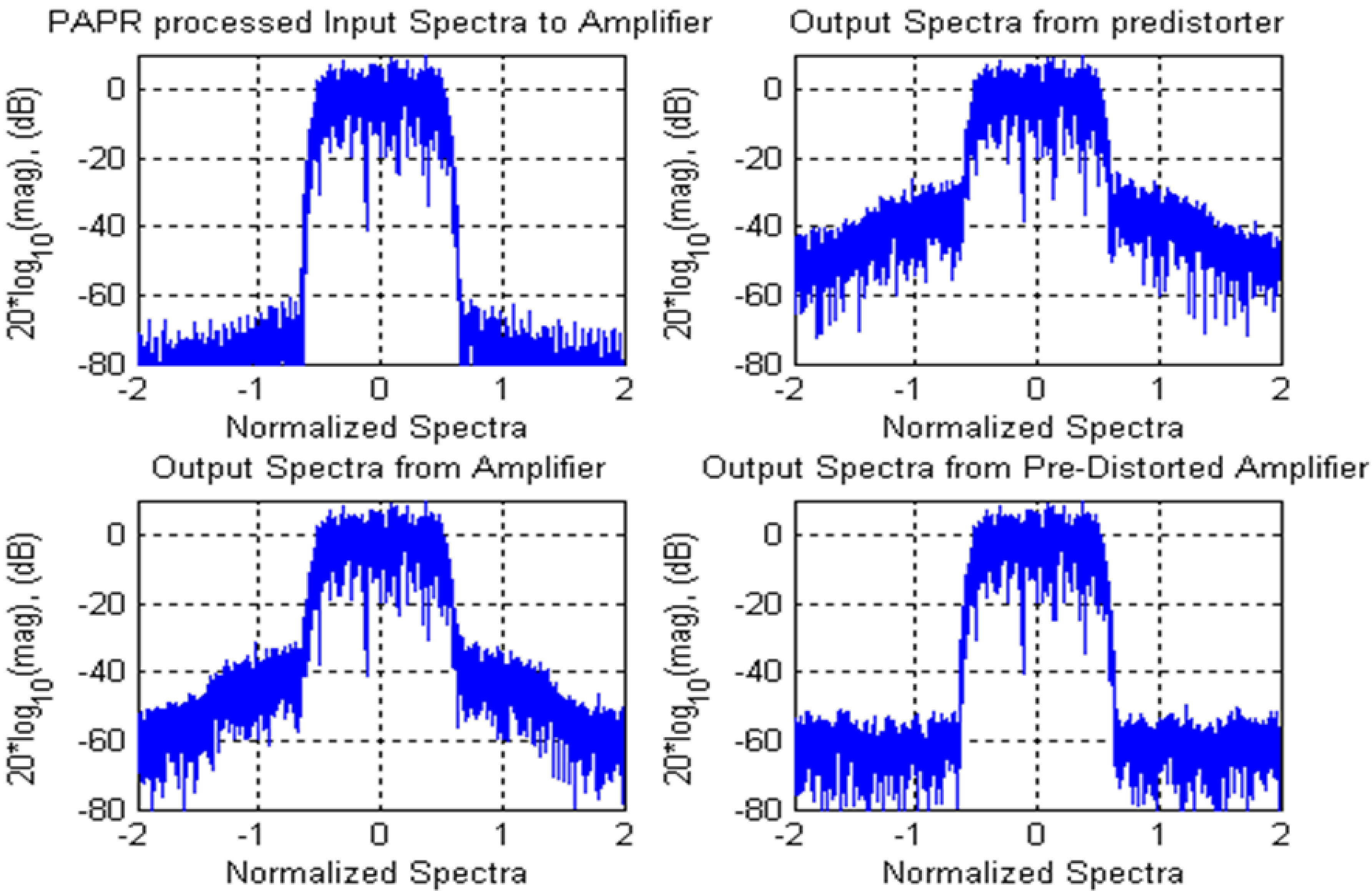
Spectra: Input Signal, Band Limited Clipping Component and Clipped Signal



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

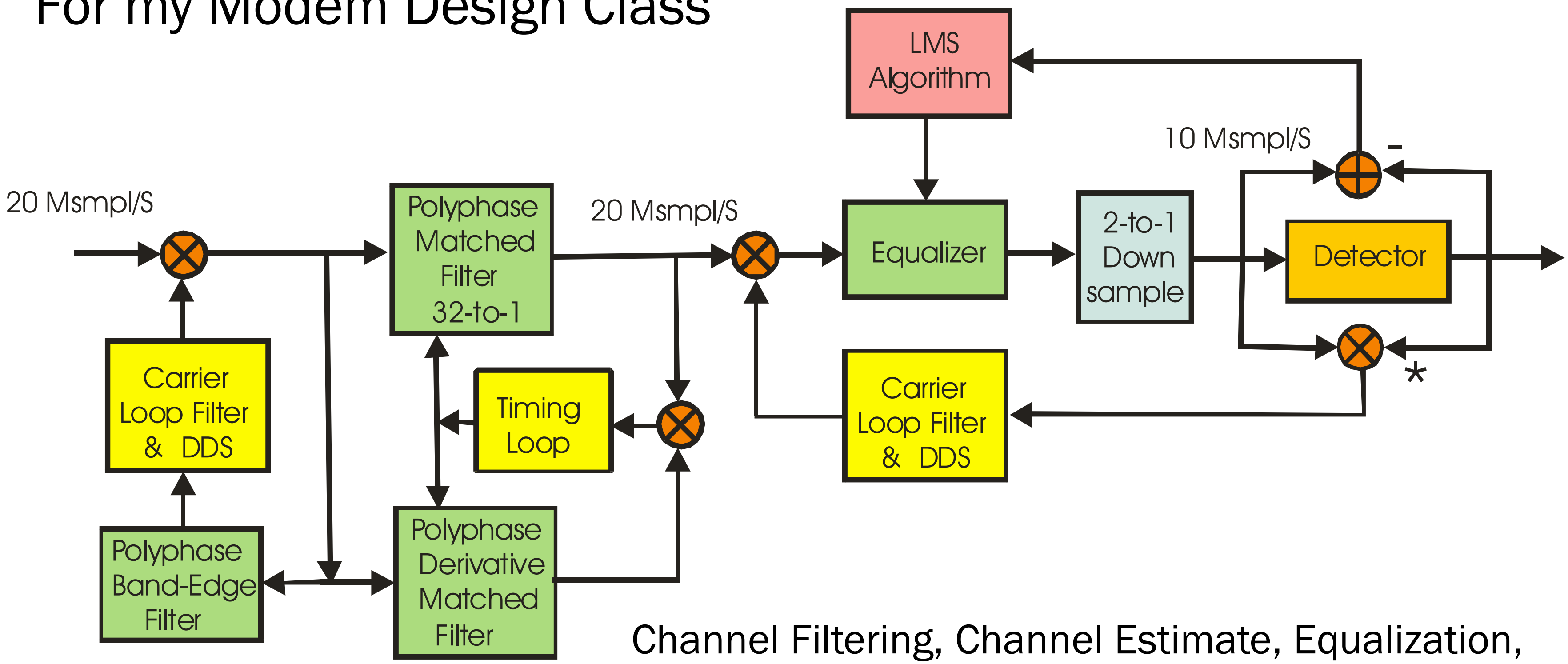


Spectra: Input and Output of Amplifier and Output of PAPR Controlled and Pre-Compensator and Pre-Compensated Amplifier

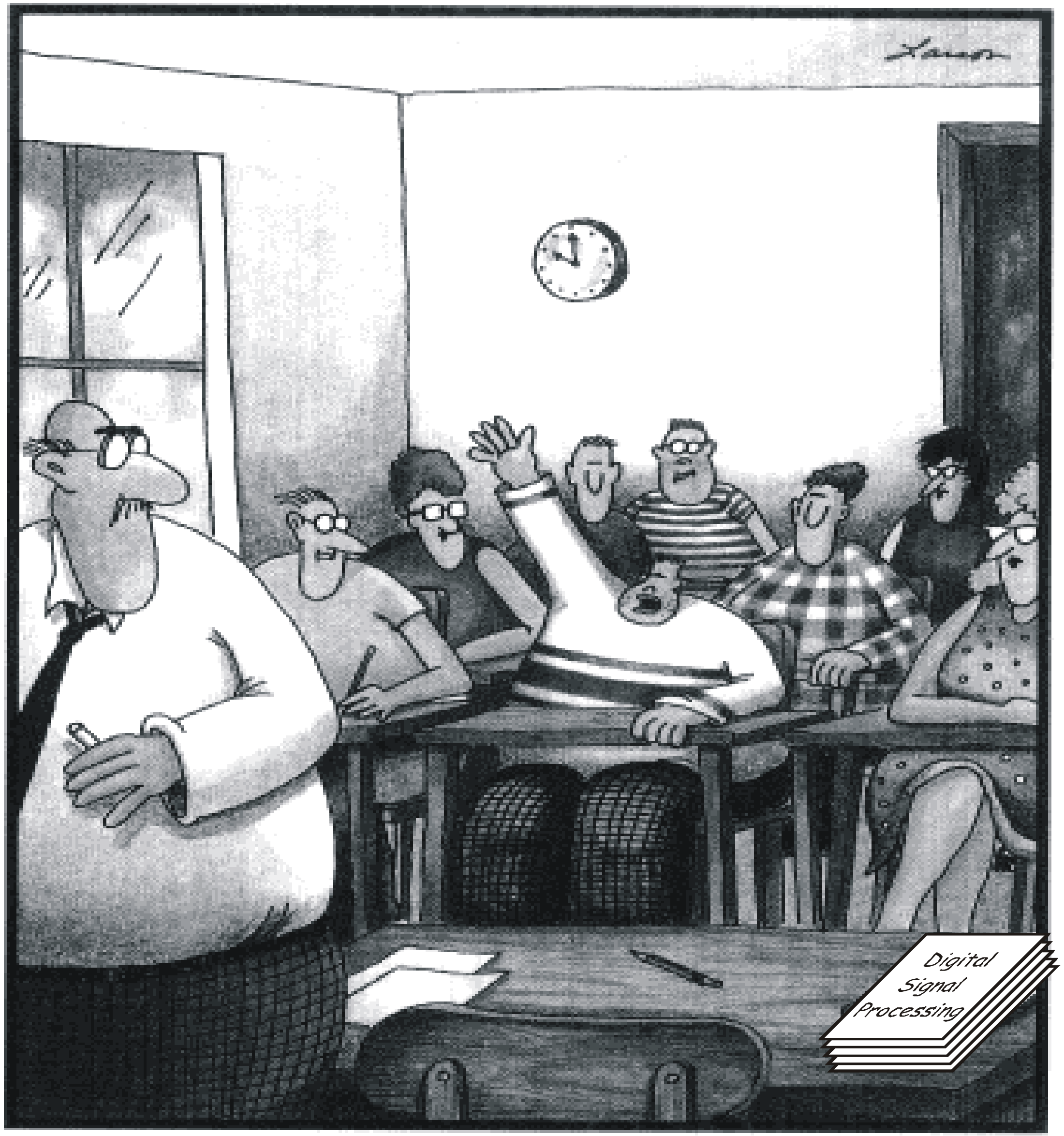


DSP Radio (DSP Everywhere!)

Actually, A design Project
For my Modem Design Class

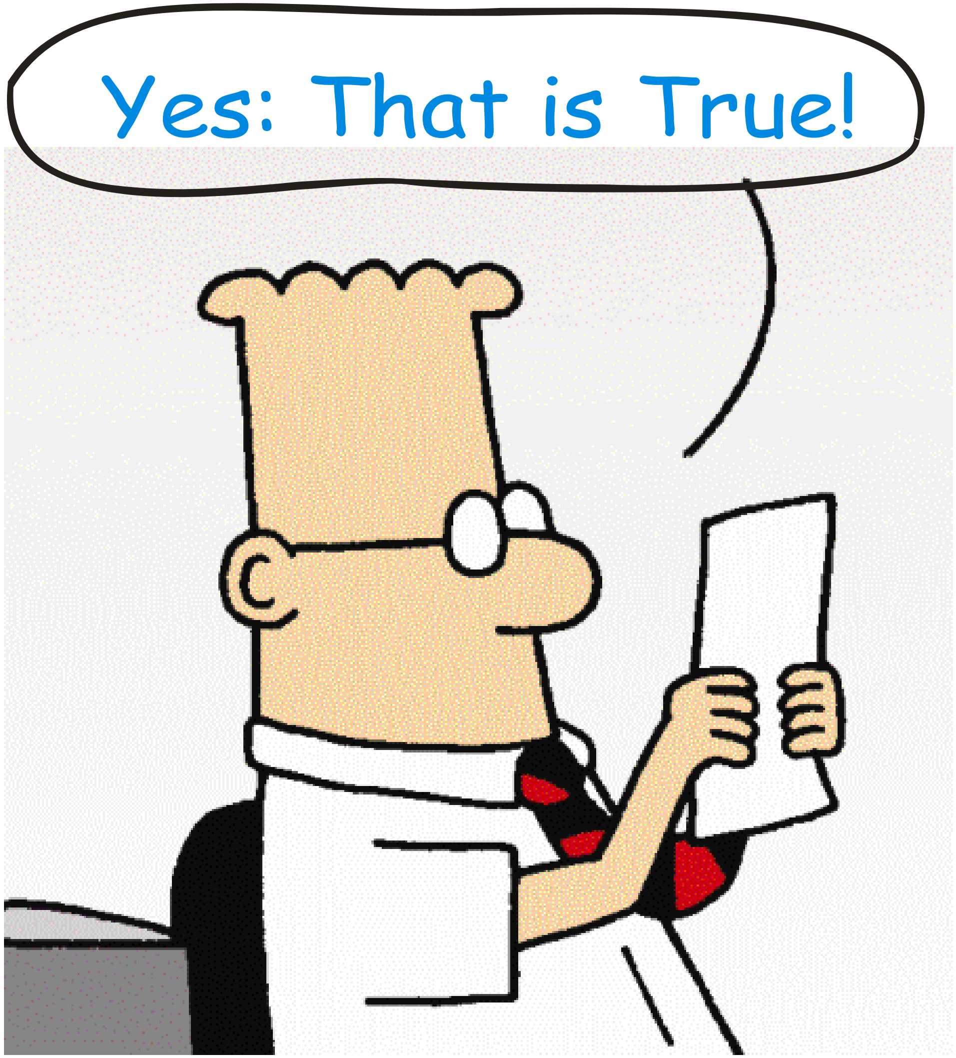


Channel Filtering, Channel Estimate, Equalization, AGC, DC-Cancelling, I-Q Balance, Line Canceller, Interference Canceller, Matched Filter, SNR Estimate, Band Edge Filter, Frequency Lock Loop, Carrier Lock Loop, Interpolator, Timing Lock Loop



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