FHSS Radio Design

T. C. McDermott, N5EG

Spread Spectrum Seminar

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Outline

- Design Objectives
- System Level Requirements
- Implementation Options
- Implementation Details
- Status

Design Objectives

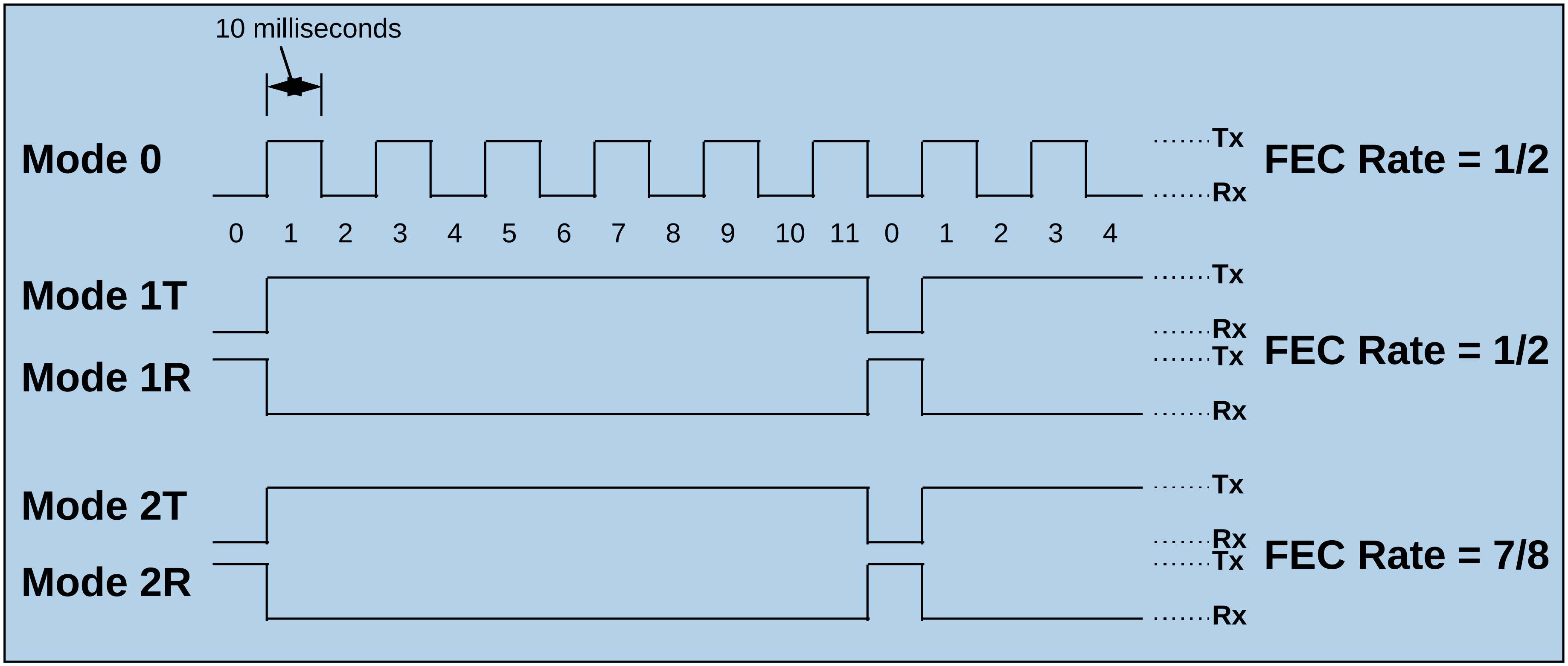
- Provide ~ ISDN throughput (128 kb/s)
  - with options for greater throughput
- Path length of 20 miles
- For Internet Protocol (IP) frames
- Minimal disruption of existing users
  - 902-926 MHz
- Accommodate reasonable number of simultaneous users
- Provide point-to-point and hub functions
- Ethernet Interface to Computer
- Future - Router Functionality Supporting TCP/IP

System Level

- Time-Division Half-Duplex (TDHD) is cost effective
  - No duplexers needed
  - Single antenna, feedline
- Radio to transmit for 10 milliseconds, then receive for 10 milliseconds
  - Minimize latency with fast switching
- Normally, time slots alternate between transmit and receive.
- Possible to have more transmit slots than receive slots when traffic is asymmetrical
  - Potentially doubles throughput

Throughput

- **Modulation format: QPSK**
- **Symbol rate: 300 ksym/s**
- **Raw bit rate = 2 * 300k = 600 kb/s**



Mode 0, 1, 2: new hop each 10 msec slot

Throughput Calculations

$$\text{Mode 0: } 600\,\text{kb/s} \bullet \frac{1}{2} \bullet \frac{1}{2} \bullet \frac{8.83}{10} = 132.45\,\text{kb/s}$$

$$\text{Mode 1: } 600\,\text{kb/s} \bullet \frac{1}{2} \bullet \frac{11}{12} \bullet \frac{8.83}{10} = 242.825\,\text{kb/s}$$

$$\text{Mode 2: } 600\,\text{kb/s} \bullet \frac{7}{8} \bullet \frac{11}{12} \bullet \frac{8.83}{10} = 424.94375\,\text{kb/s}$$

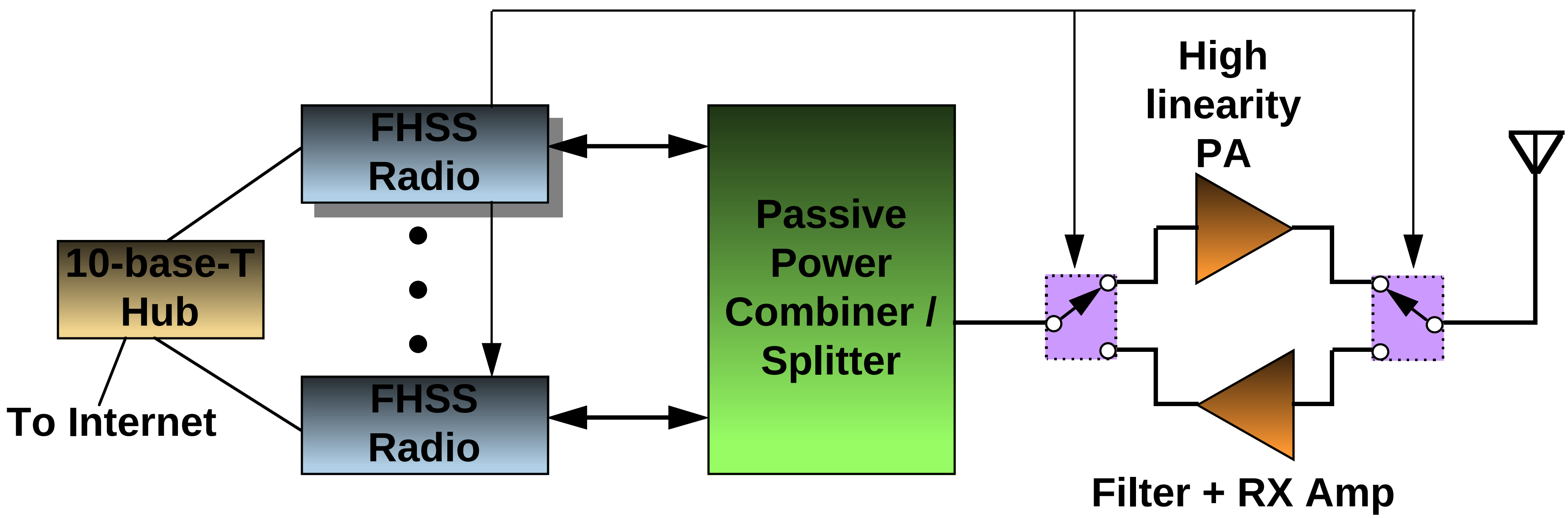
FEC Rate

Overhead Factor

Transmit Density

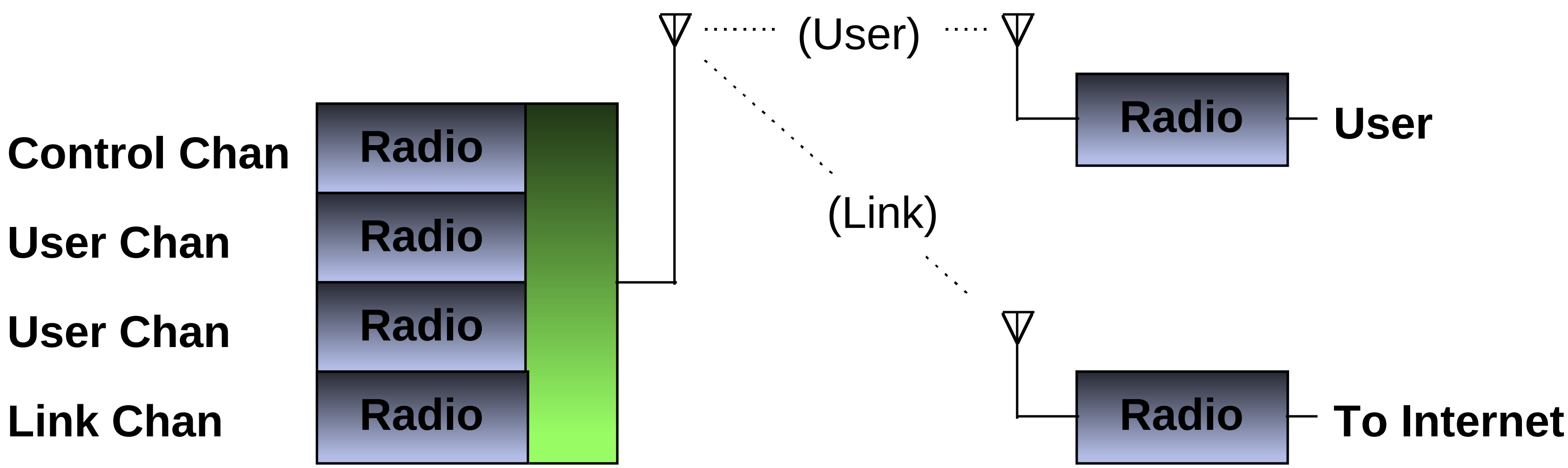
Hubbing Configuration

- **Multiple radio configuration is useful (hub)**
  - **Concentrate users onto a single Internet connection**
  - **Provide link to a remote Internet connection**
- **Requires Synchronization between T/R switching of radios**
  - **All radios transmit, receive at same time (Mode 0)**
  - **One radio is in control**



Hub Functions

- **Multiple access (one radio is control channel, assigns users to data radios)**
- **Remote linking (occupy one data radio as link)**
- **Spreading sequence the same for all radios, but each starts at a different sequence *offset***



System Gain Requirements

Assumptions

Tx Output Power = 1.0 watt

Tx Antenna gain = 6 dB, Cable loss = 3 dB

Rx Antenna Temperature = 293K

Rx Antenna gain = 8 dB, cable loss = 3 dB

Frequency = 915 MHz, Rx BW = 600 KHz

Rx NF = 8.0 dB

Calculations

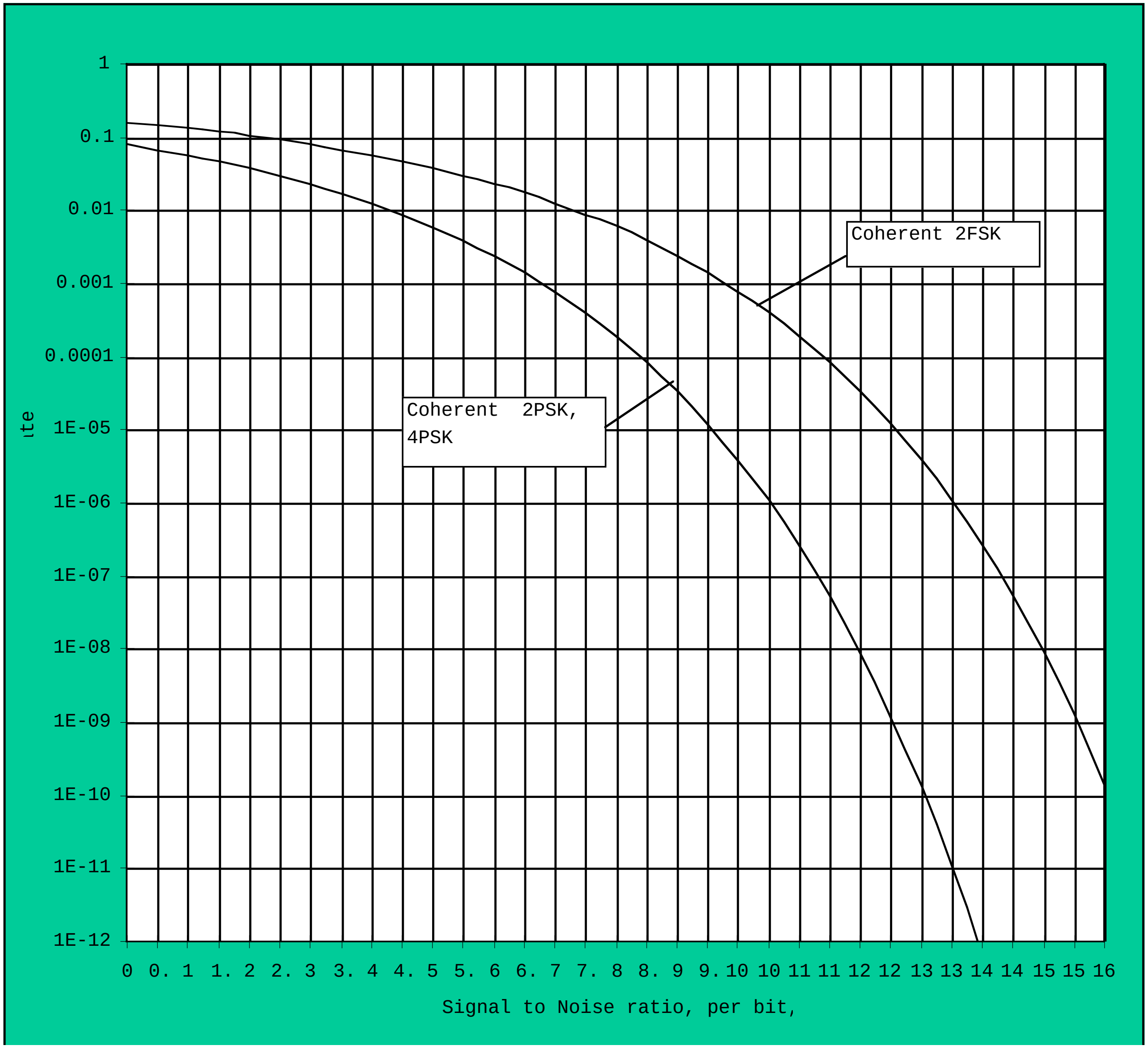
- **Tx ERP = 2.0 watts**
- **Rx Noise Temperature = 438.4K**
- **S/N at Rx = +21.1 dB.**
  (Eb/No = +18.1 dB for QPSK)

Eb/No Requirement

For BPSK or QPSK, a BER of 10^{-6} requires + 10.5 dB Eb/No

BER of 10^{-9} requires +12.5 dB Eb/No

***Differential* QPSK degrades 2.3 dB, thus a BER of 10^{-6} requires +12.8 dB Eb/No**



Implementation Margin

Available Eb/No = +18.1 dB

Needed Eb/No at 10^{-6} is +12.8 dB

- **Implementation Margin = 5.3 dB.**

Can improve Eb/No requirement by using Forward Error Correction (FEC).

Convolutional Codes (3-bit soft):

Rate 1/2, 10^{-6} BER, needed Eb/No = 5.1 + 2.3 dB

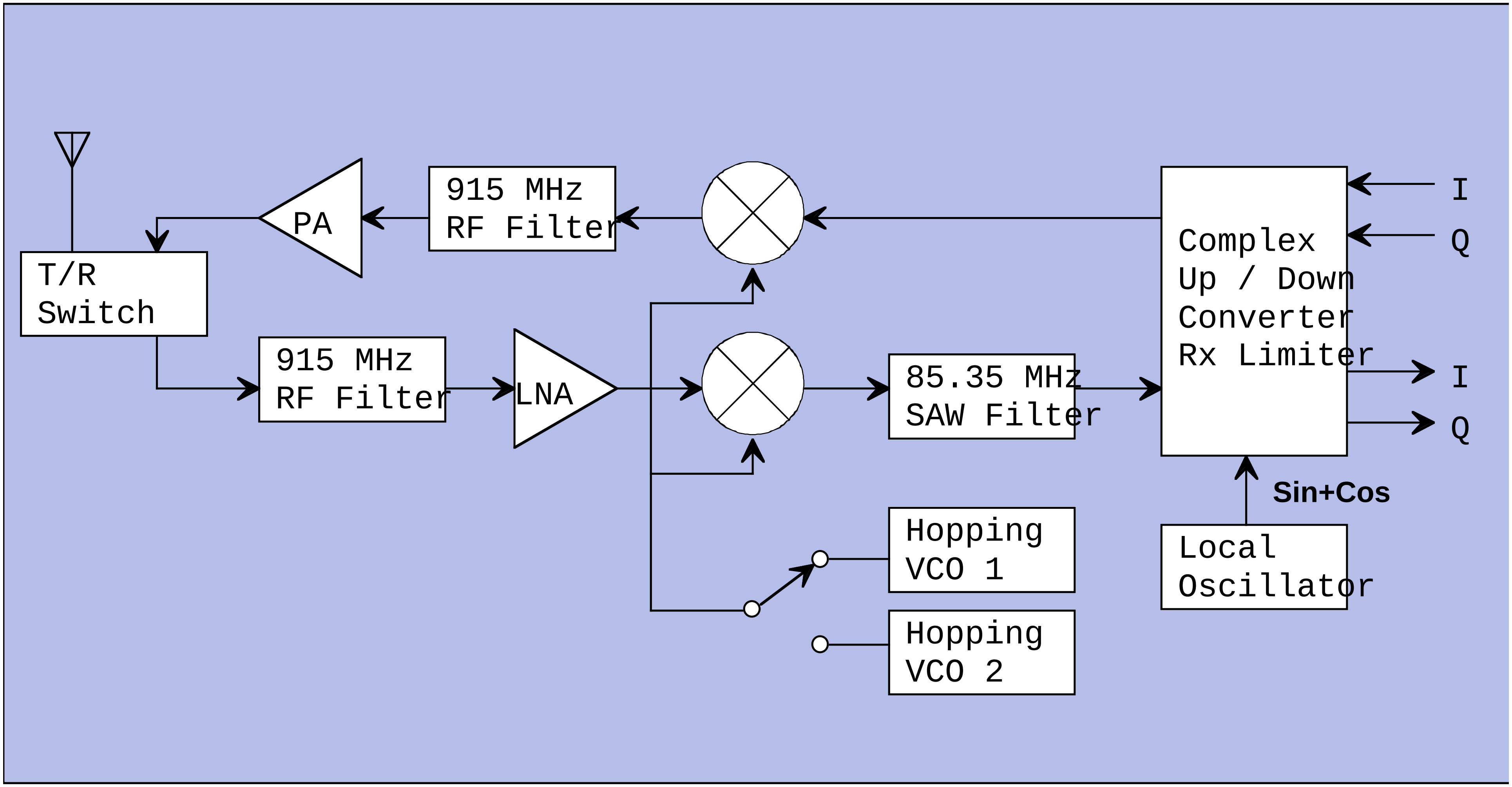
Rate 7/8, 10^{-6} BER, needed Eb/No ~ 6.7 + 2.3 dB

- **Implementation Margin = <u>10.7 dB</u> (rate 1/2)**
- **Implementation Margin = <u>9.1 dB</u> (rate 7/8)**

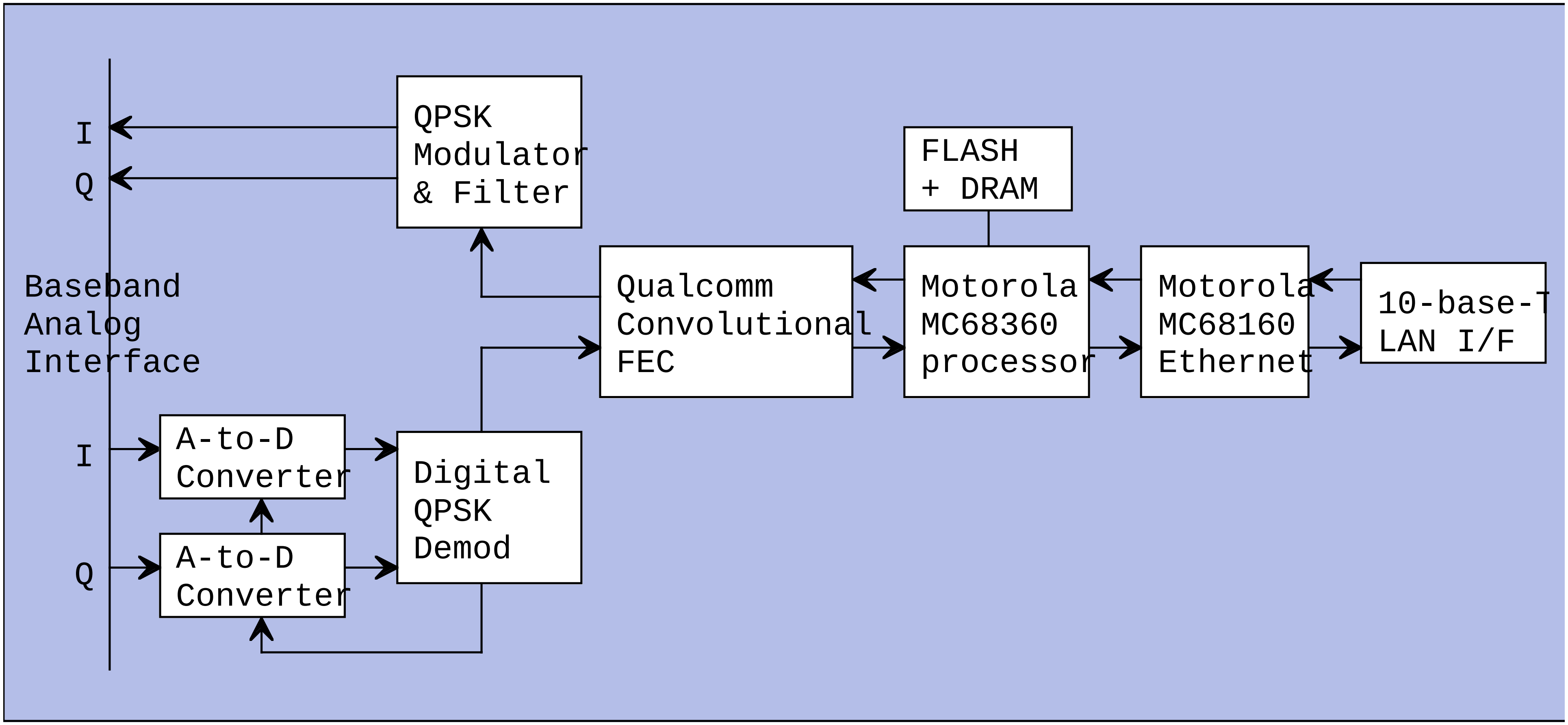
Feedline Loss at 900 MHz

- **RG58 = 16 dB / 100 feet**
- **RG8 = 6.7 dB / 100 feet**
- **9913 = 4.2 dB / 100 feet**

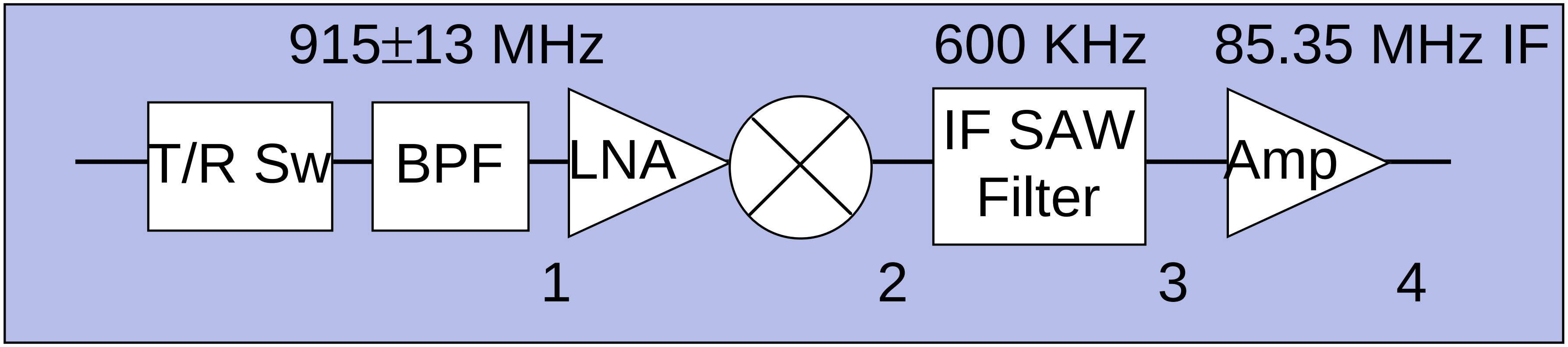
IF & RF Diagram



Baseband Diagram



Receiver Front-End Calculations



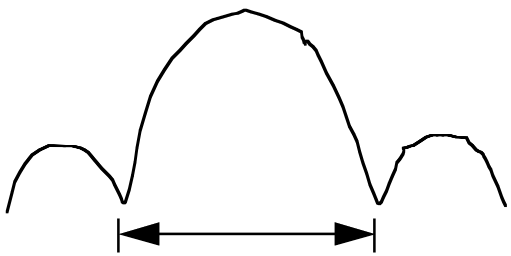
Stage		1	2	3	4
		Filter+T/R	LNA+Mix	IF filter	IF Post Amp
Noise Figure (dB)		0	5.5	0	8
Gain (dB)		-3	28	-15	18
Pout (dBm)		-111	-83	-98	-80
Input Power (dBm)	-108				
Cascade NF (dB)					7.84
Temperature (C)	25				
BW (kHz)	650				
Noise Power (dBm)	-108				
Noise voltage (uV)	0.9	(@ 50 ohms)			

Frequency-Hopping VCOs

- **Frequency Hopping is achieved by altering the Local Oscillator frequency. Otherwise, the radio looks like a non-SS radio.**
- **Key issue is ‘settling time’ of the VCO’s.**
- **This radio changes frequency each 10 milliseconds.**
- **If there is one VCO, it must settle much, much faster than 10 milliseconds -- this is very difficult.**
- **Solution: use 2 VCO’s. One slews to a new frequency whilst the other is being utilized. This allows 10 milliseconds settling time.**
- **3 VCO’s would allow 20 msec settling time, etc.**

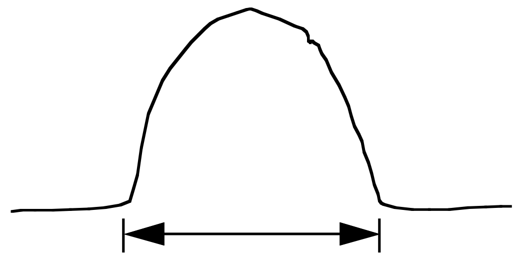
Data Rate vs. SAW bandwidth

Transmit Spectrum - No filtering



2x Symbol Rate

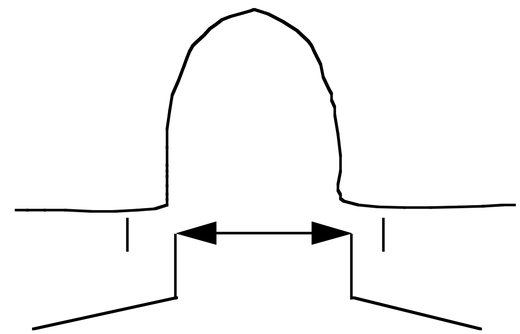
Transmit Spectrum - alpha = 1 filtering



2x Symbol Rate

α = 1.0, 300 ksym/s
=> 600 kHz

Transmit Spectrum - alpha < 1 filtering



(1+α) x Symbol Rate

α = 0.4, 300 ksym/s
=> 420 kHz

Low-alpha raised-cosine filters narrow the emission bandwidth, minimize interference from adjacent channels

FHSS - key issues

- Top three:
  - Speed
  - Speed
  - Speed
- VCO lockup time

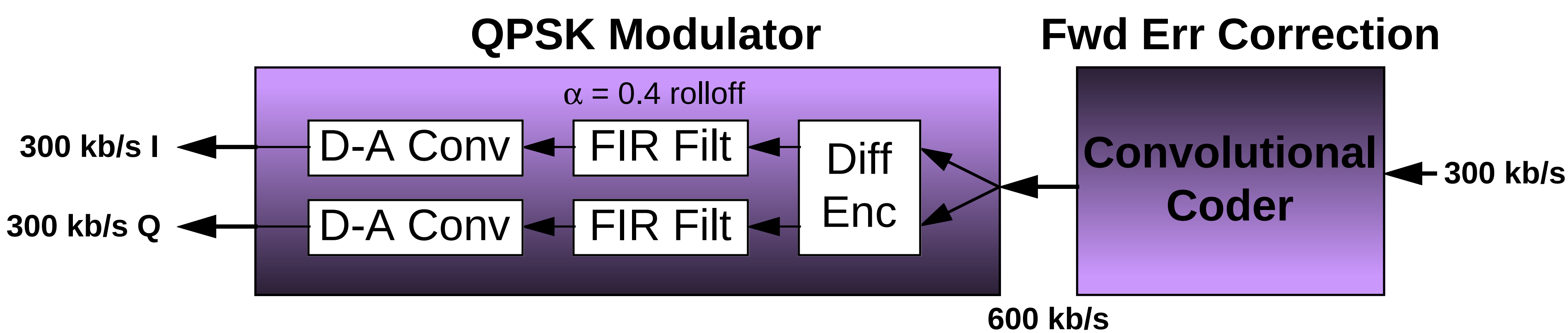
  ⇒ Multiple VCOs
- Carrier Recovery Lockup Time

  ⇒ Memorize (compute) frequency error [make a really good guess]
- Symbol Recovery Lockup Time

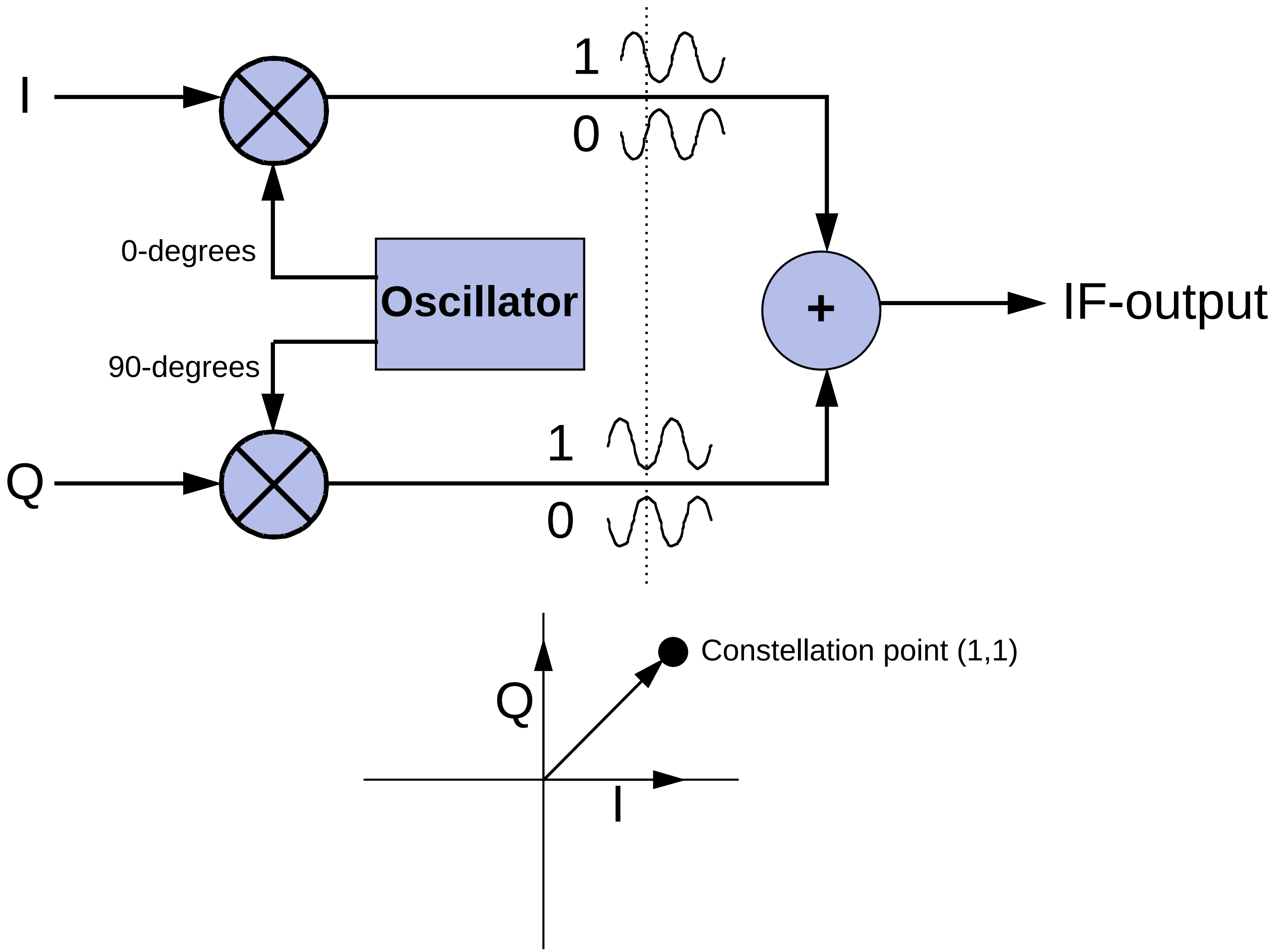
  ⇒ Usually faster than carrier recovery lockup time

FEC / QPSK Modulator

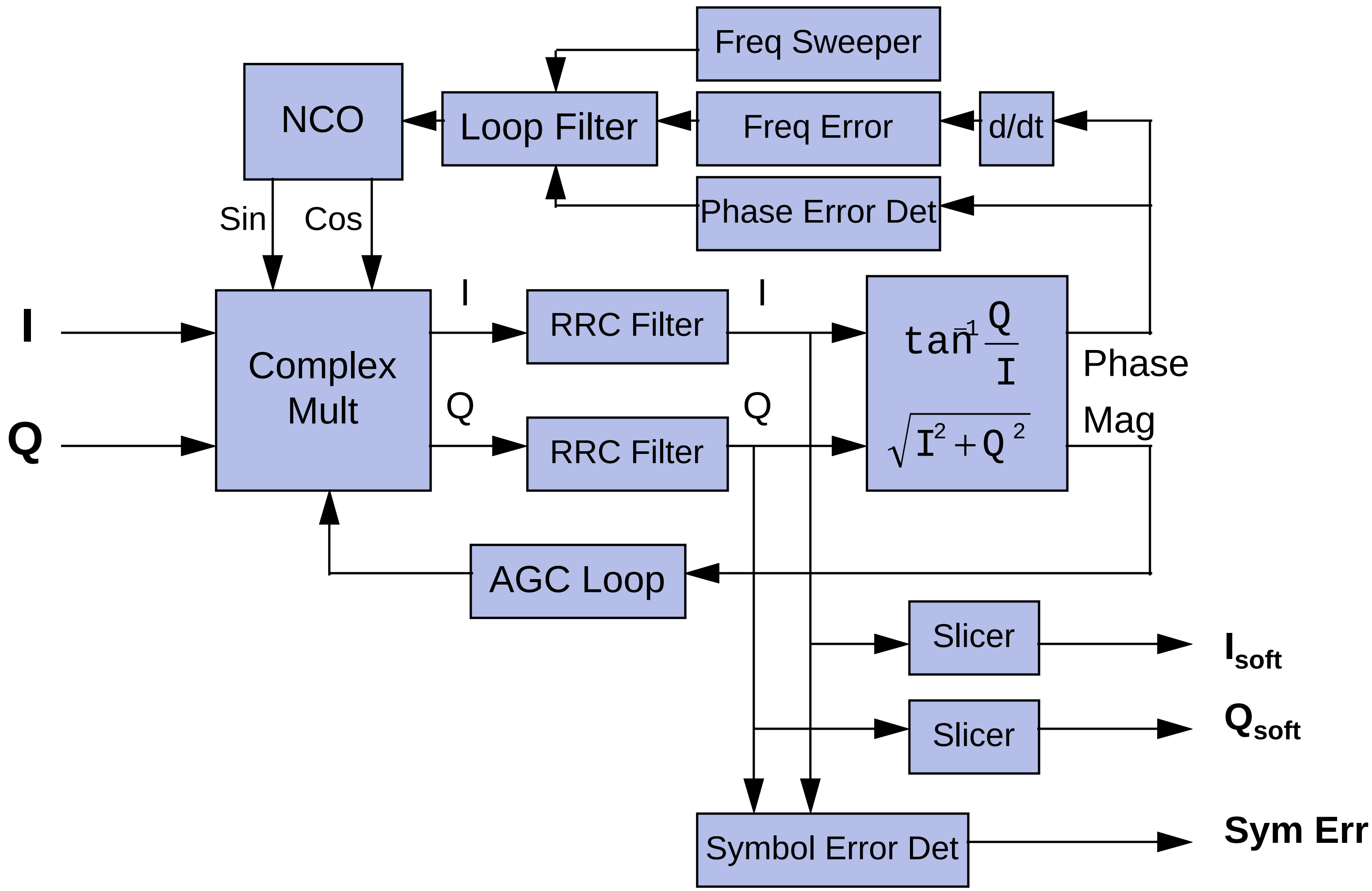
- **FEC doubles the bit rate (for rate = 1/2). Input is 300 kb/s, output is 600 kb/s.**
- **Each 'pair' of bits are used to select one of four phase states, producing 300 ksym/s.**
- **QPSK modulator filters the baseband signals, and differentially-encodes them. This coding means that the phase output *difference* is proportional to the symbol value.**



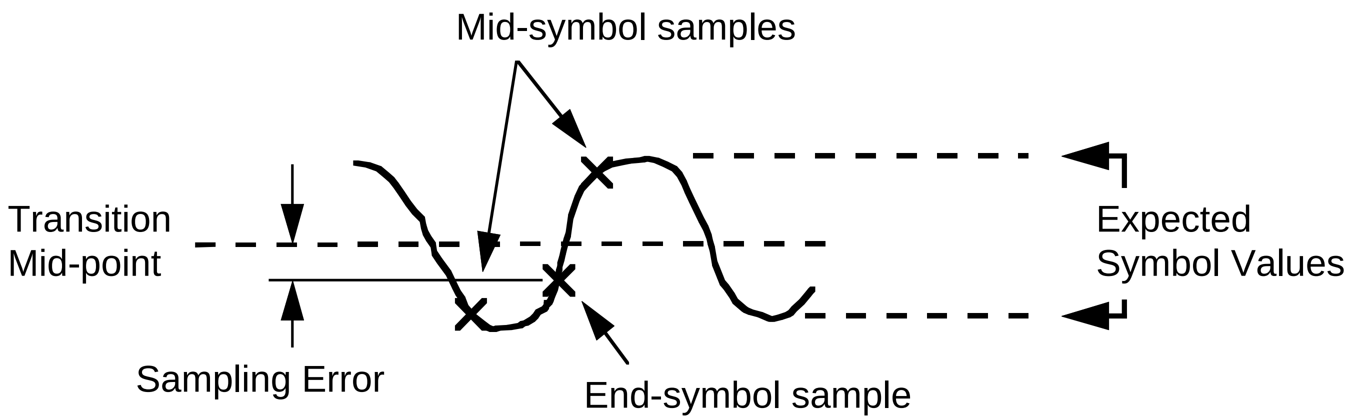
QPSK Upconversion



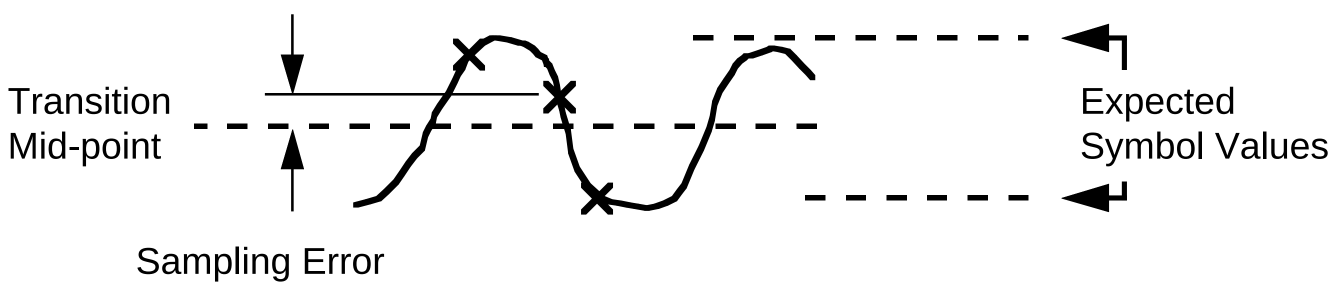
QPSK Demodulator HSP50210



Clock Recovery



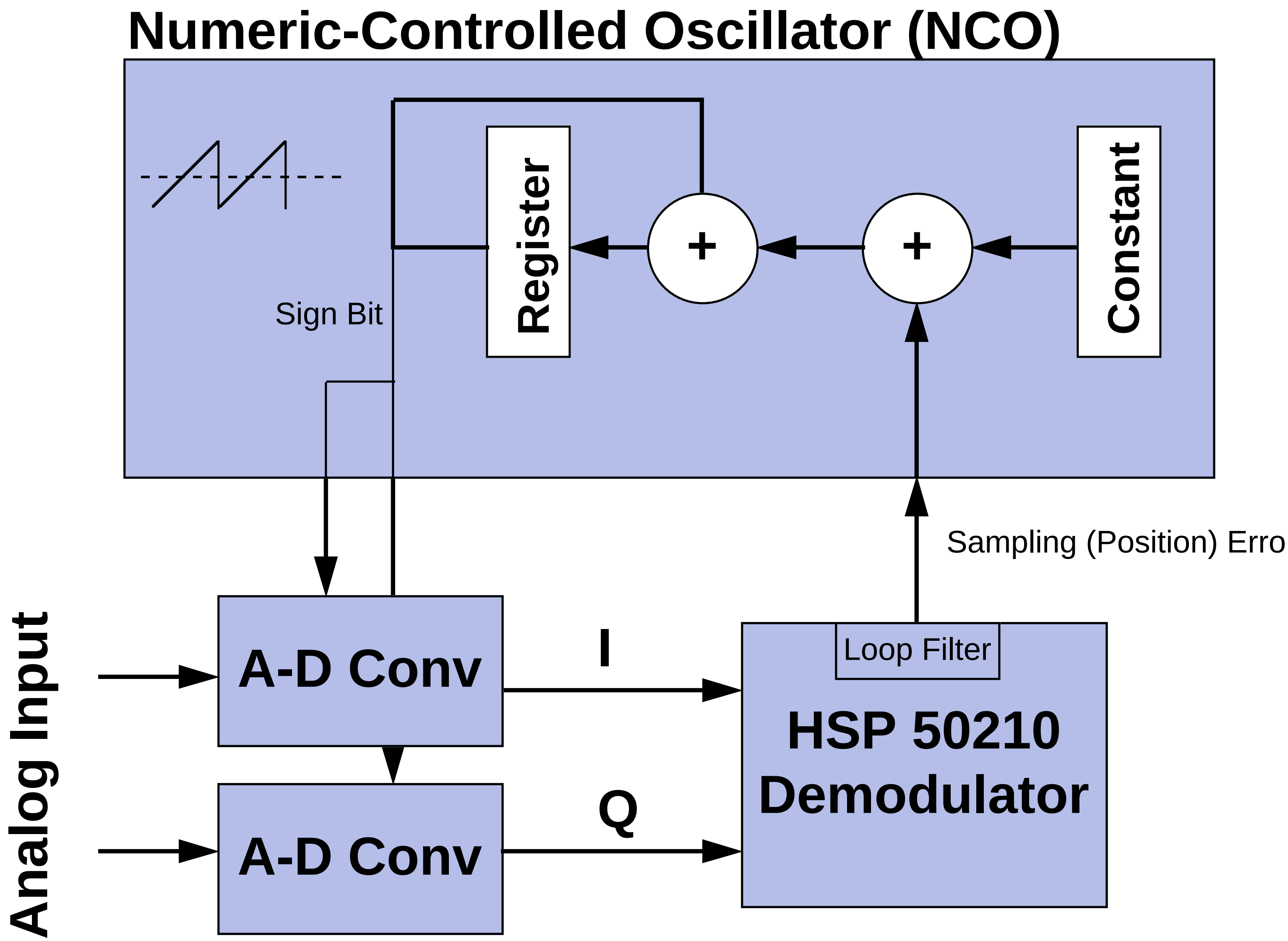
Sampling too early (positive slope)



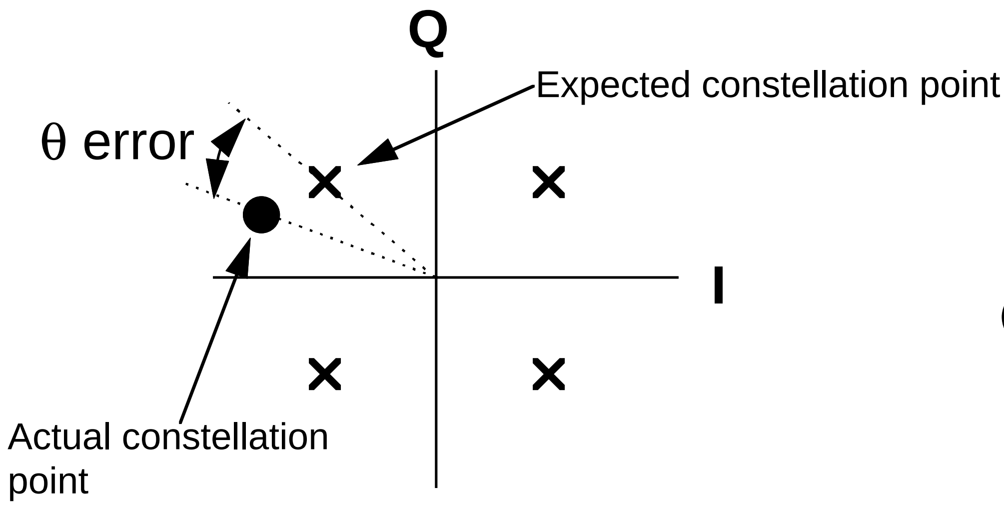
Sampling too early (negative slope)

Sign of error term depends on direction of slope as well as early / late timing of the sample

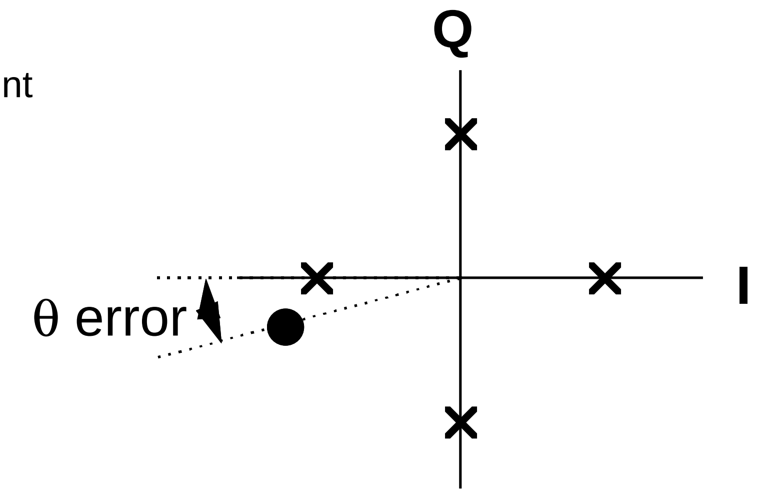
Clock Recovery Process



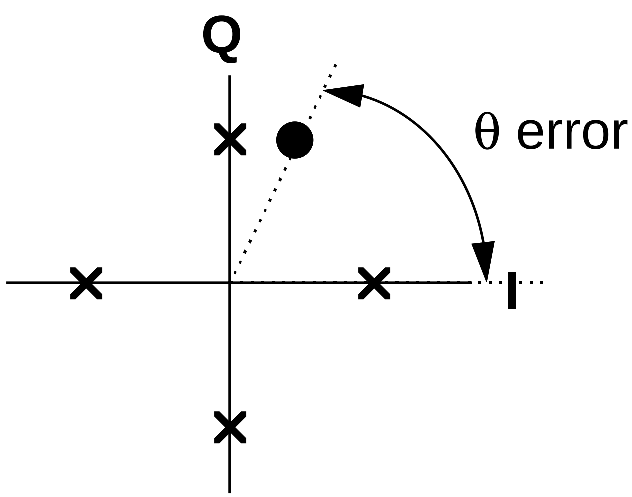
Carrier Recovery



Initial Constellation



Rotation by 45 degrees



Multiplication by 4

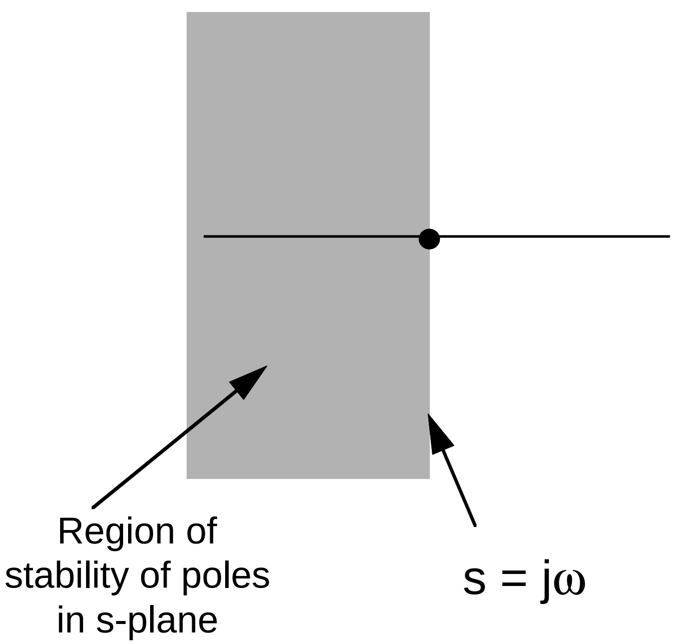
1. Rotation,
2. Multiplication by 4.
This Removes modulation components from the error term, and references error to the zero-phase position.

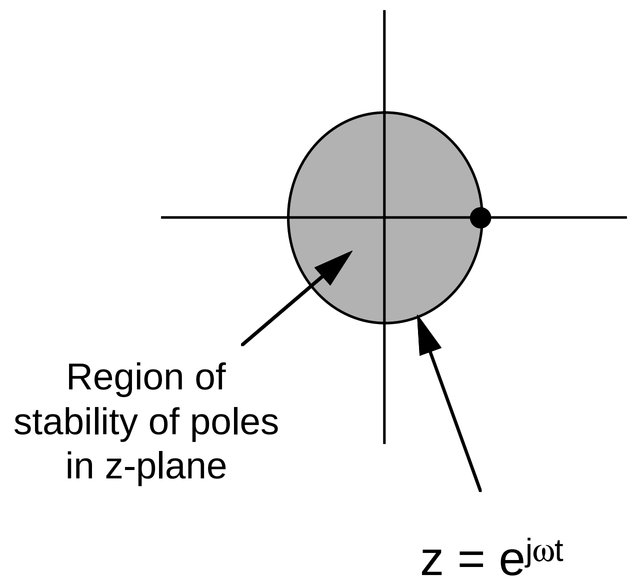
Carrier Recovery

- Carrier Error Detector implements 'Frequency Error' term (how much the phase rotates each sample).
- If the loop is too far off-frequency, the phase error accumulation increases too fast and the loop cannot lock.
- Sweep-aided acquisition allows the carrier reference oscillator to 'sweep' up and down in frequency. When the frequency gets close enough, the sweeper disconnects, and the loop acquires by phase alone.
- Sweeping takes a long time, and is to be avoided (except maybe during link setup).

s-plane vs. z-plane

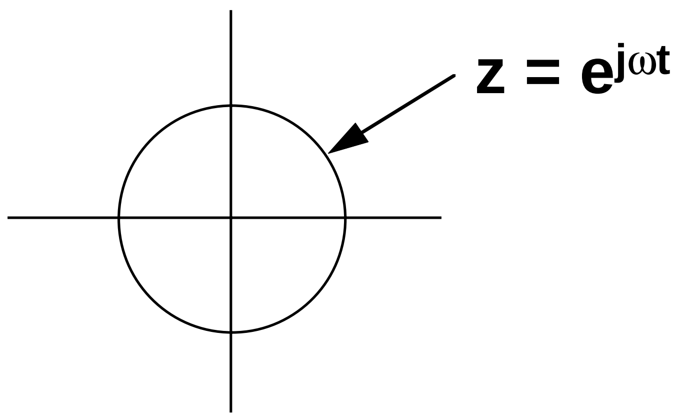
- **Frequency analysis on s-plane is conducted over jω (the imaginary axis).**
- **Left-hand plane of s-plane maps to unit-disk of z-plane**
- **Thus, frequency analysis on z-plane is conducted over unit circle**



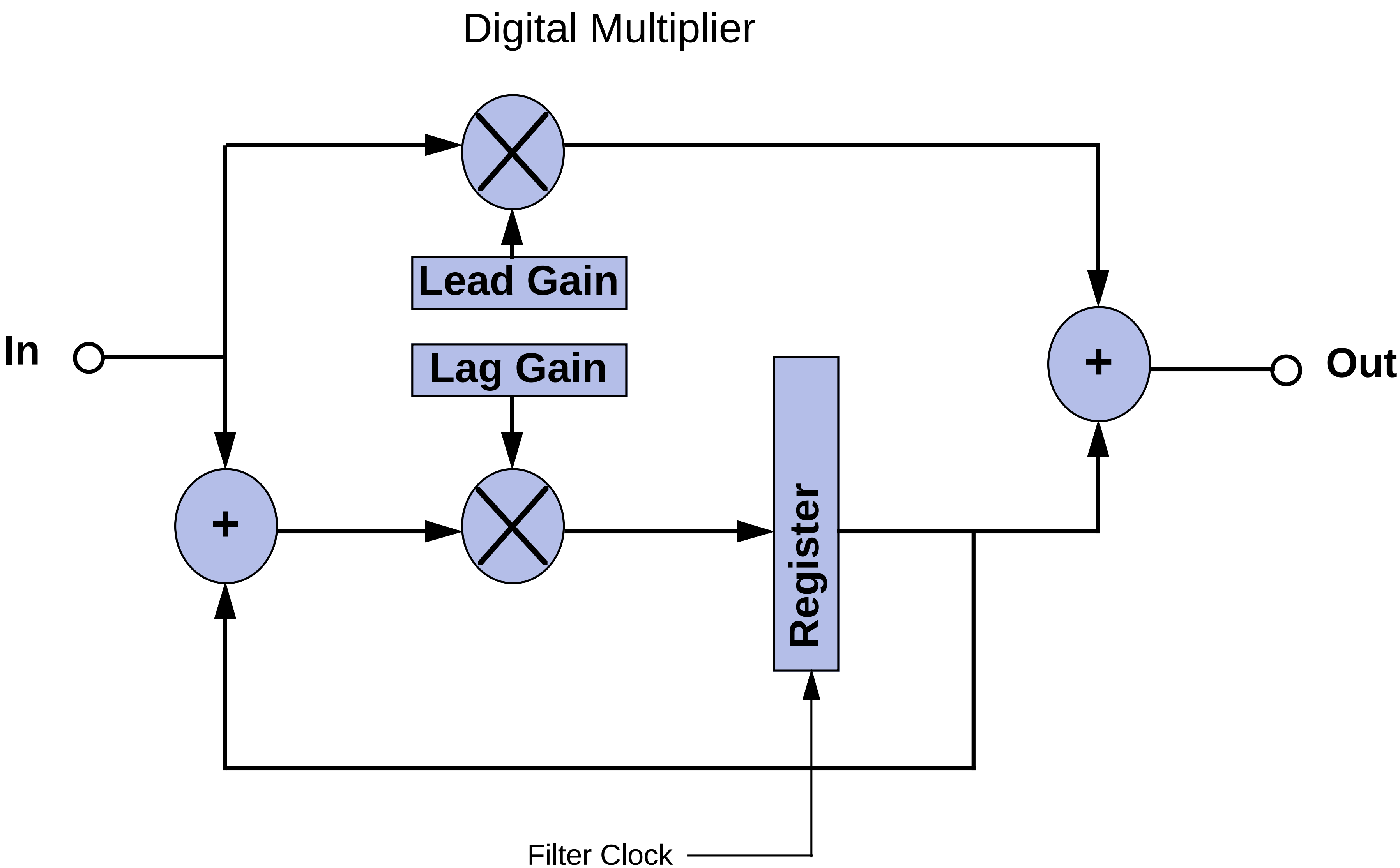


Loop Filter Analysis

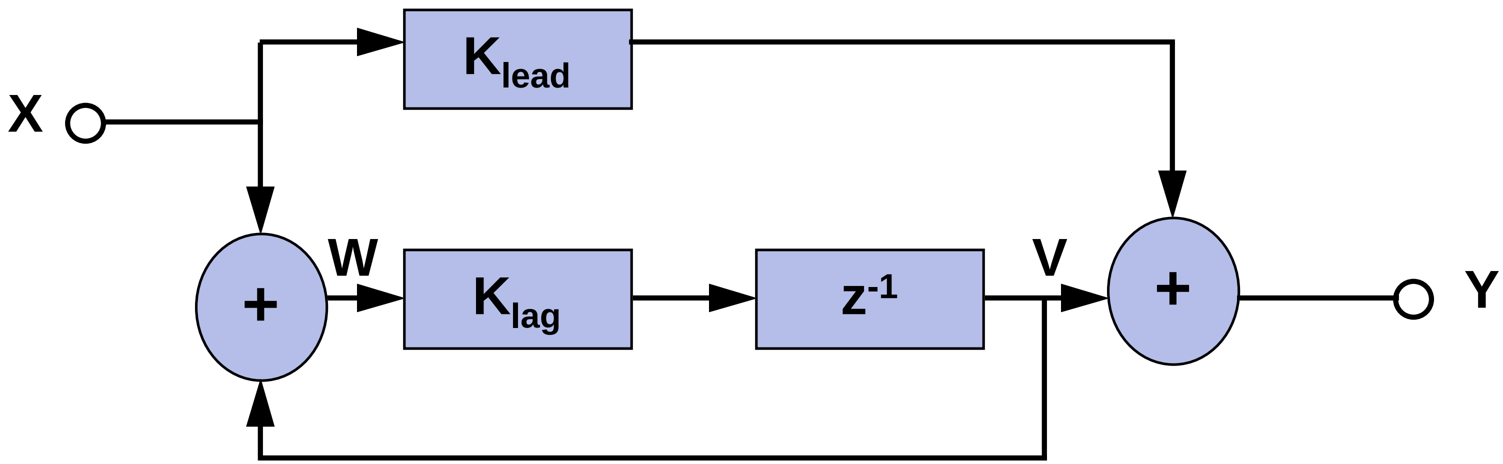
- **Frequency & Phase Response of digital filters most easily analyzed in Z-domain**
- **Apply Z-transform by inspection (a register is equivalent to multiplying by z^{-1})**
- **Derive Amplitude & Phase by evaluating H(z) on the unit circle in the Z-plane [substituting $z = e^{j\omega t}$ and varying ω from zero to $2\pi/t$]**
- **Excel spreadsheet can evaluate and plot results.**



Lead Lag Filter



Filter Analysis



$$Y = K_{lead}\, X + V$$

$$V = K_{lag}\, W\, z^{-1}$$

$$W = X + V$$

$$V = K_{lag}\,(X + V)\, z^{-1} = K_{lag}\, X\, z^{-1} + K_{lag}\, V\, z^{-1}$$

$$V\,(1 - K_{lag}\, z^{-1}) = X\, K_{lag}\, z^{-1}$$

$$V = X\, \frac{K_{lag}\, z^{-1}}{1 - K_{lag}\, z^{-1}}$$

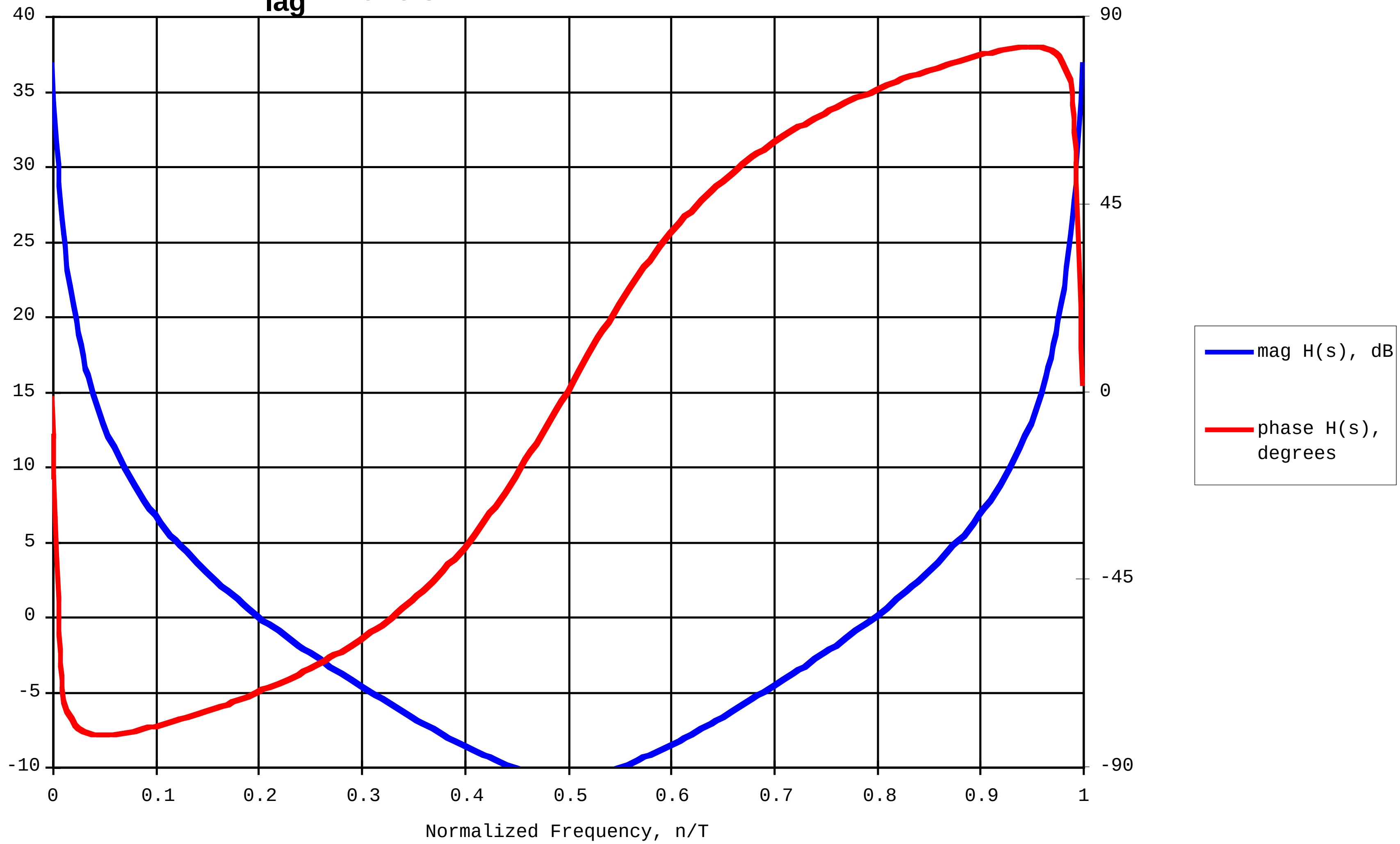
$$Y = X\, K_{lead} + X\, \frac{K_{lag}\, z^{-1}}{1 - K_{lag}\, z^{-1}}$$

$$H(z) = \frac{Y}{X} = \frac{K_{lag} + K_{lead}\,(1 - K_{lag})\, z^{-1}}{1 - K_{lag}\, z^{-1}}$$

Loop Filter Performance

$K_{lead} = 20$

$K_{lag} = 0.98$



NCO - Phase response

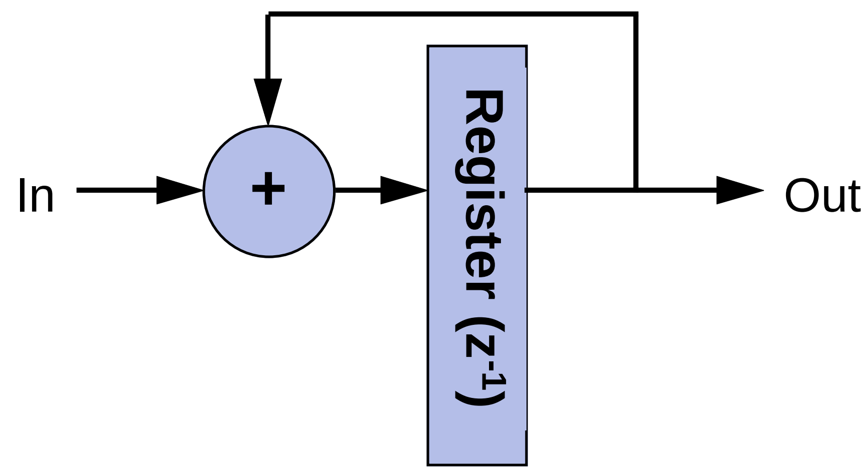
- **NC-VCO converts error signal to *accumulating* phase (i.e.: frequency).**
- **Need to derive relationship of output phase to input error signal.**

$$Out = (In + Out)z^{-1}$$

$$zOut = In + Out$$

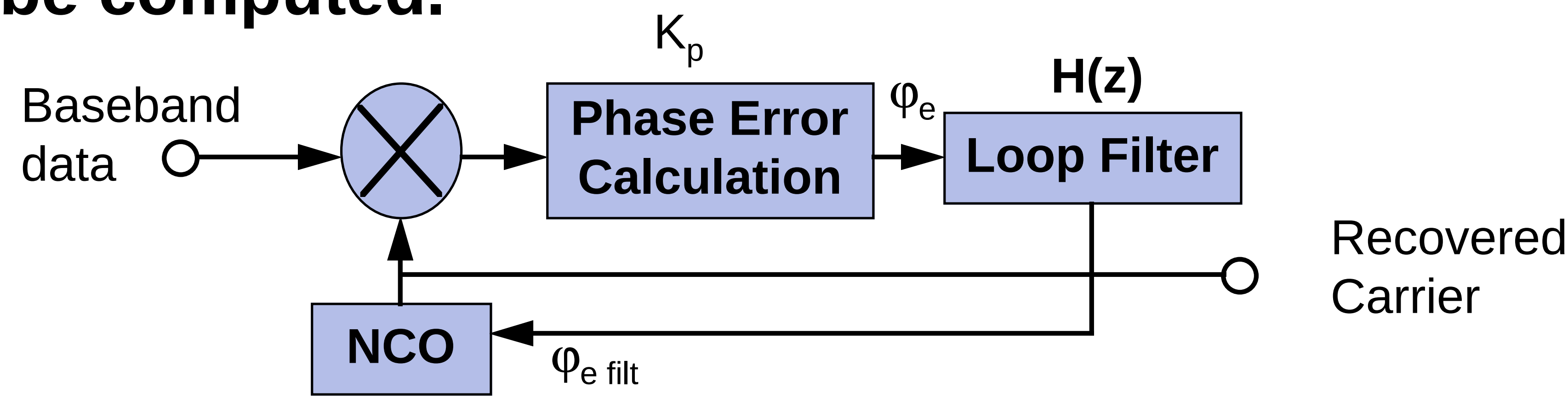
$$(z-1)Out = In$$

$$\frac{Out}{In} = \frac{1}{z-1}$$



(thus: phase = integral of frequency vs. time)

- **Loop Filter resides inside Carrier Recovery Loop. Closed-loop transfer function needs to be computed.**



$$\varphi_o = N\,H\,(\varphi_i - \varphi_o)$$

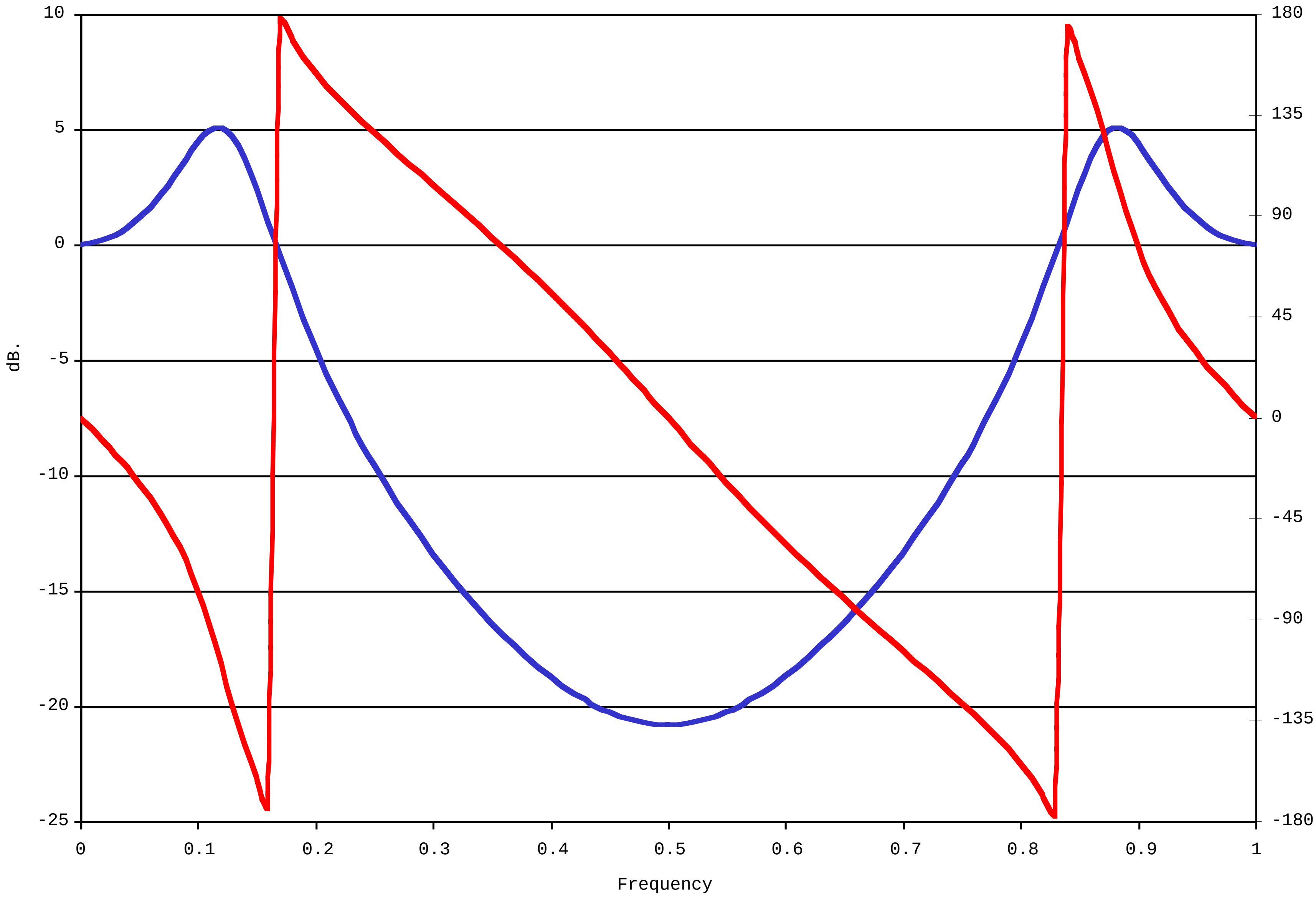
$$\varphi_o(1 + NH) = NH\,\varphi_i$$

$$\frac{\varphi_o}{\varphi_i} = \frac{NH}{1 + NH}$$

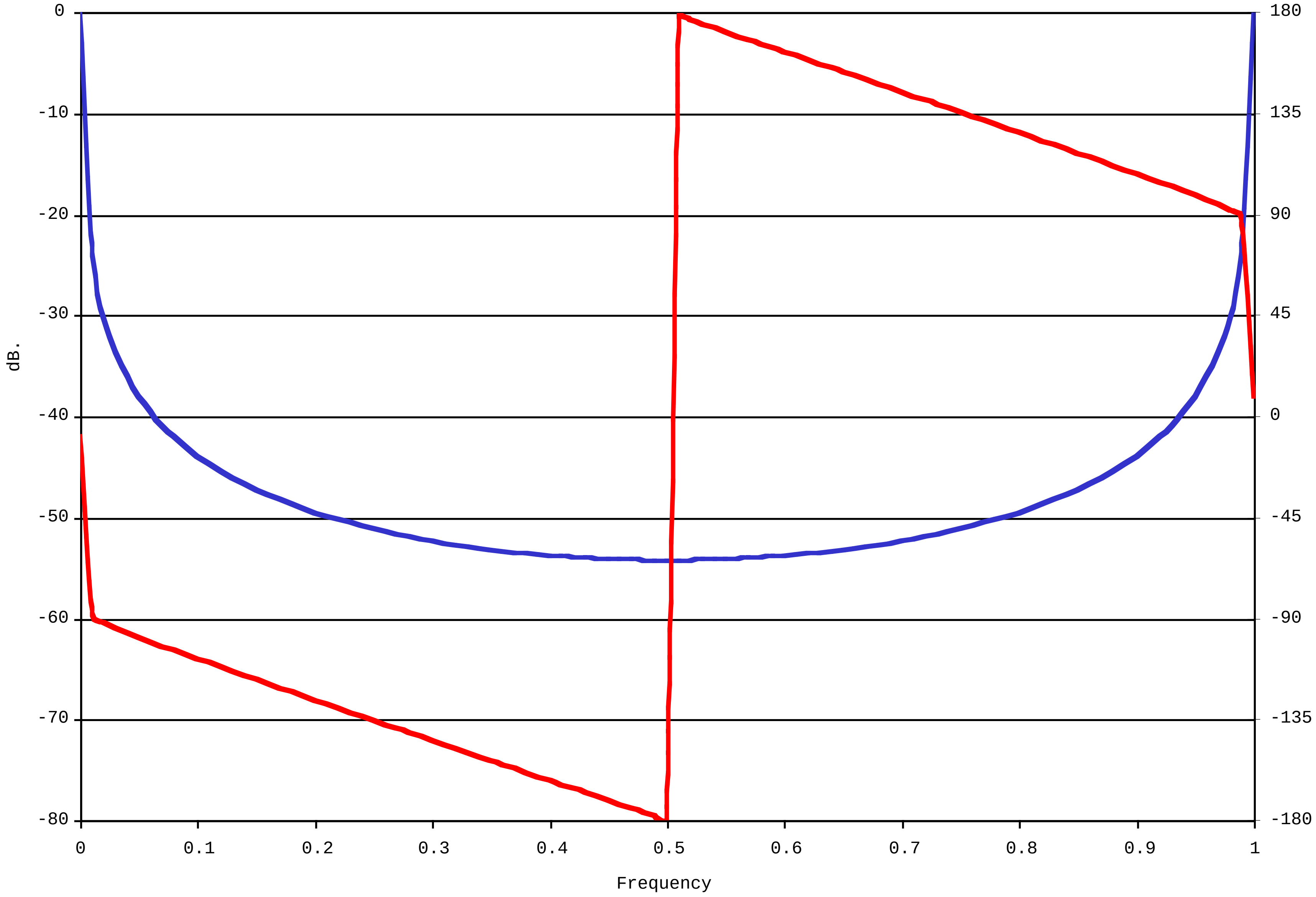
$$N = \frac{K_p}{z-1}$$

$$\boxed{\frac{\varphi_o}{\varphi_i} = \frac{K_p H(z)}{z - 1 + K_p H(z)}}$$

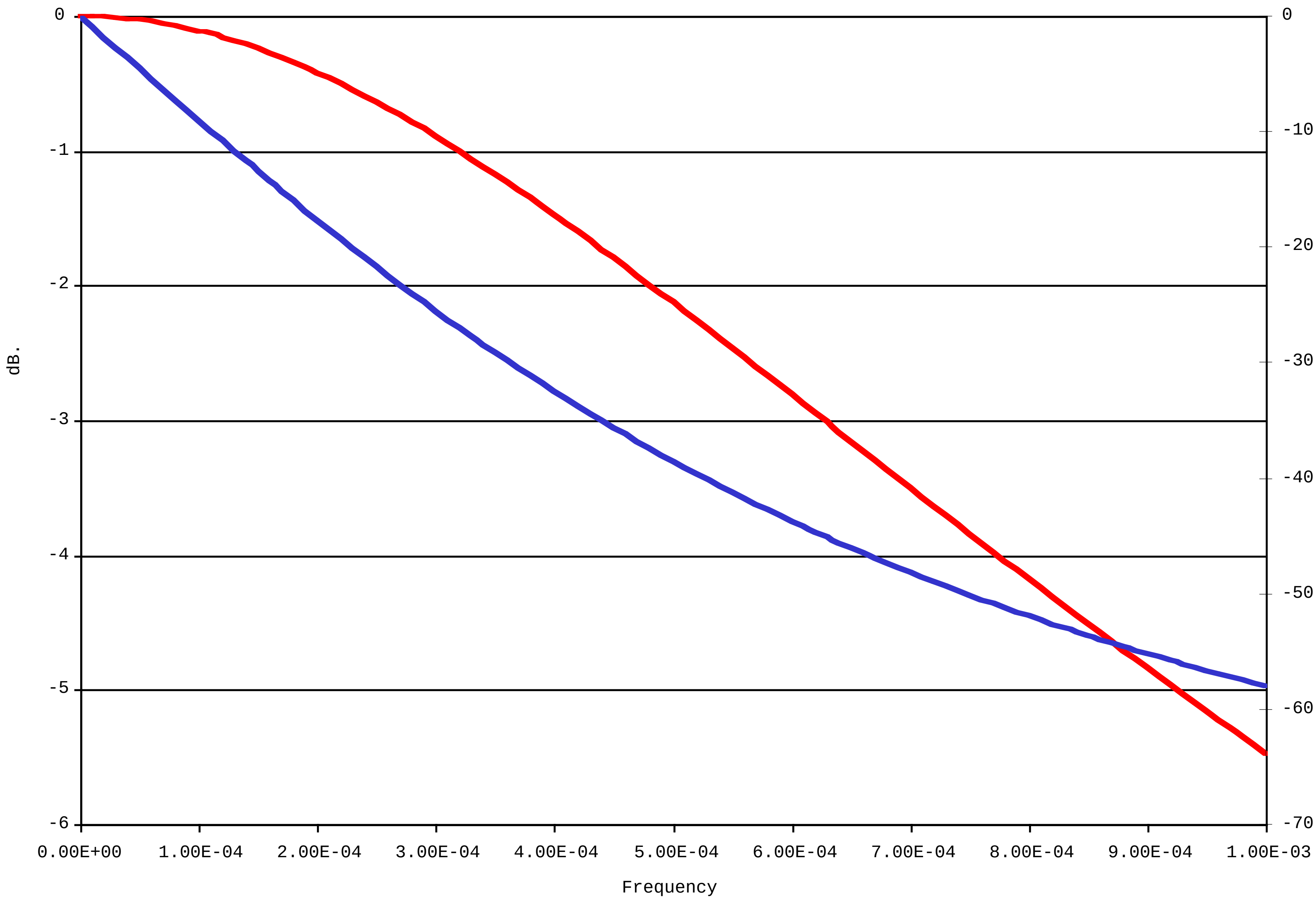
A poor choice for filter constants



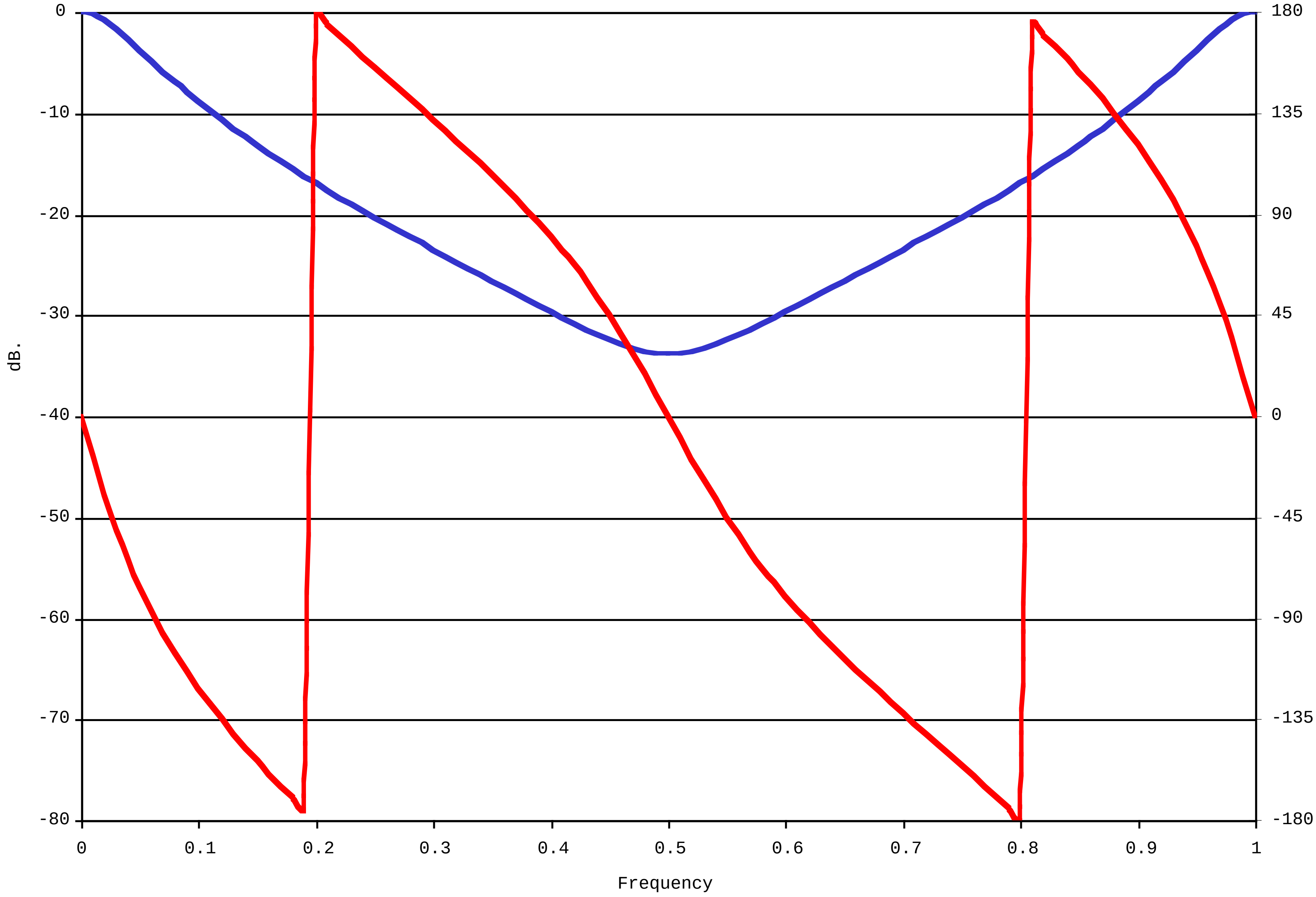
Loop Response - Track Mode



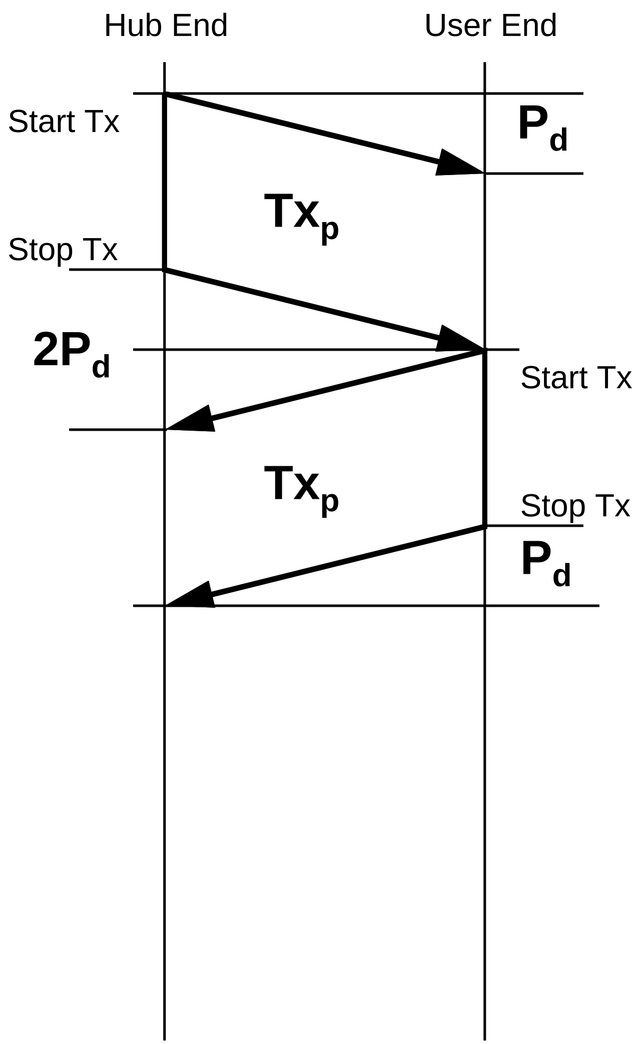
Track Mode - High Resolution



Loop Response - Acquisition Mode



Overall T/R timing



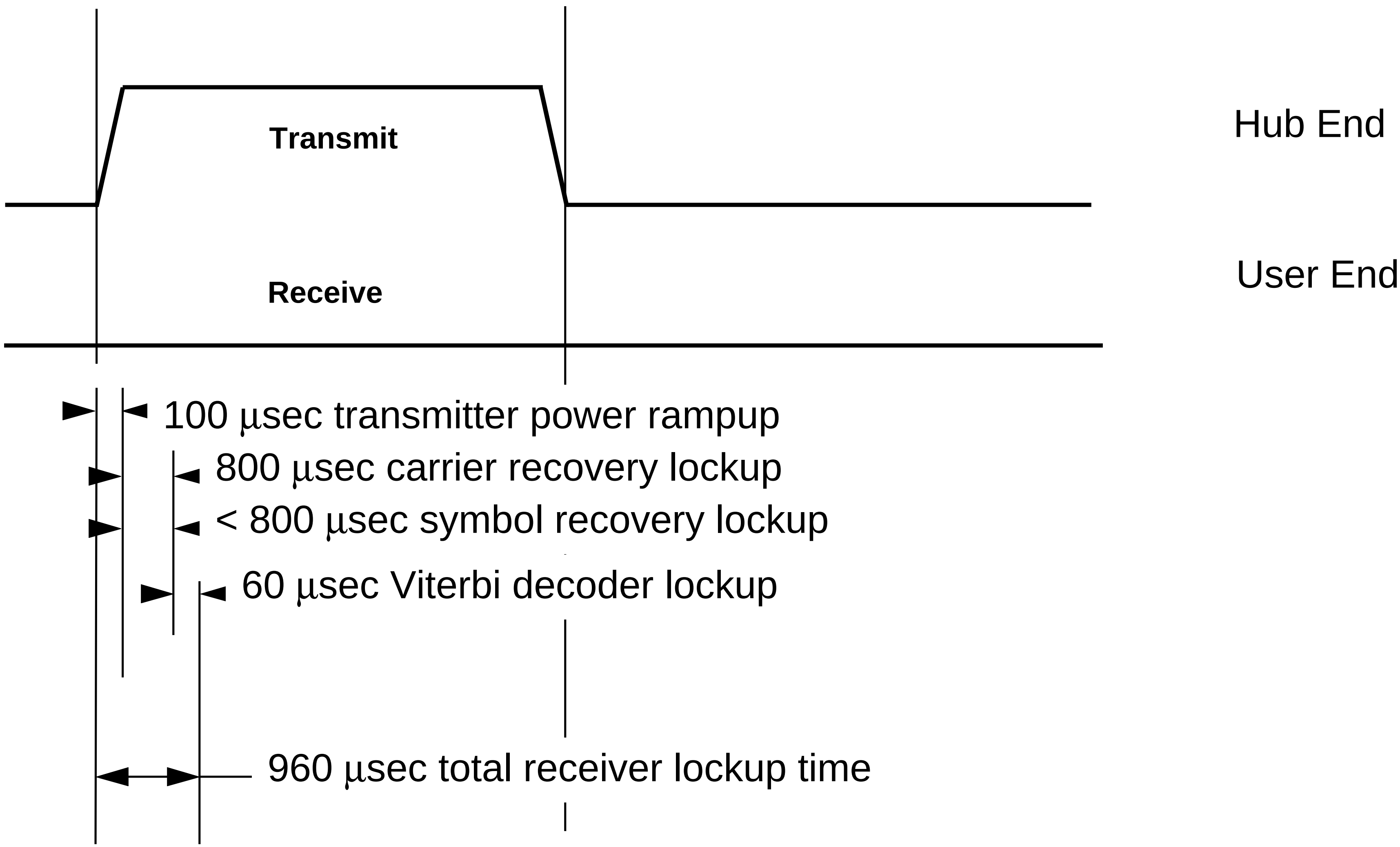
$$(T + R)cycle = 2P_d + 2Tx_p$$

$$Tx_p = Tcycle - P_d$$

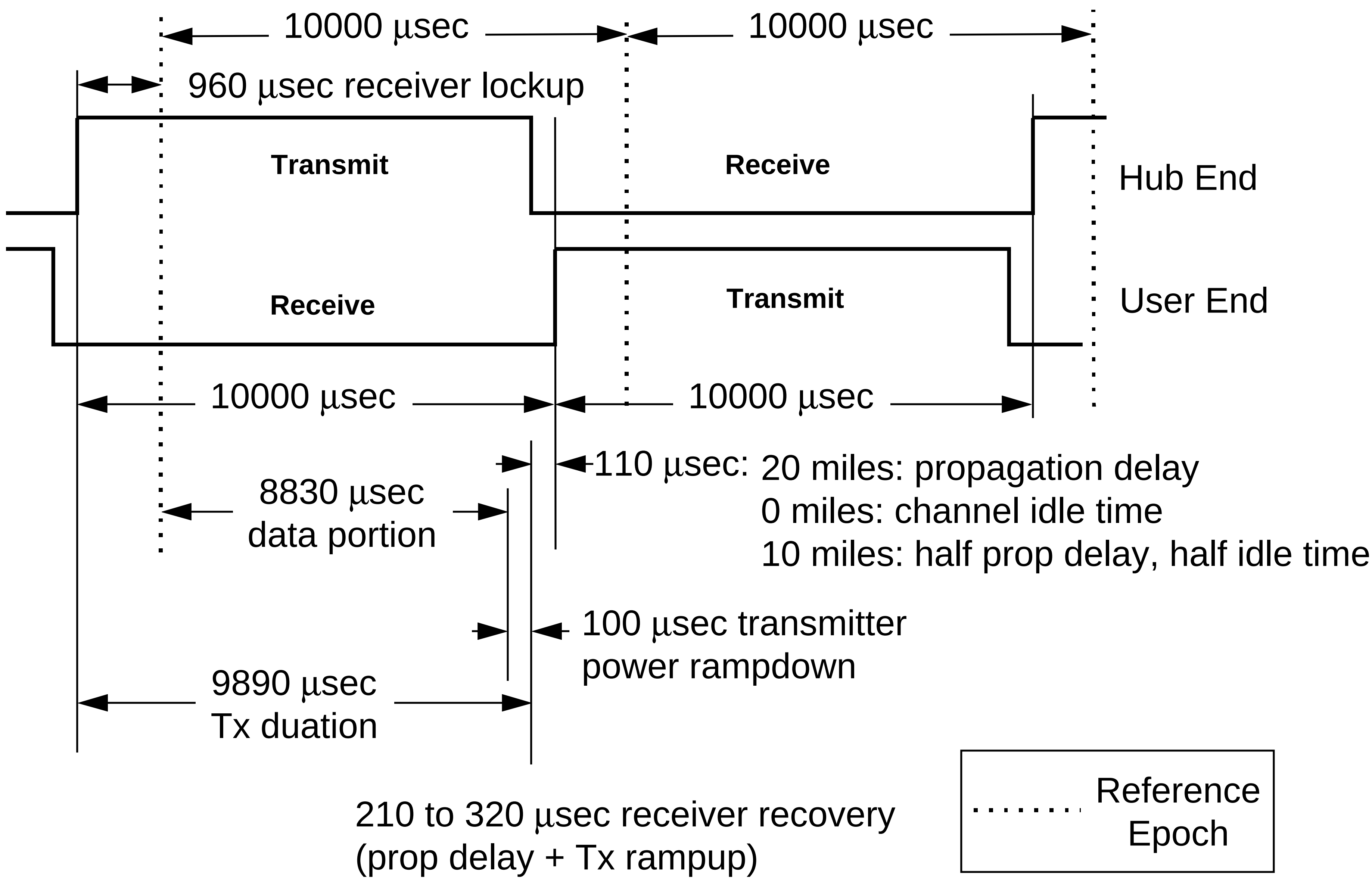
For P_d = 110 μsec (20 miles):
Tx_p = 10 msec - 110 μsec
= 9890 μsec transmit duration

Receiver recovery time = 2 P_d
= 220 μsec (+ tx ramp time)

Receiver Acquisition Timing



Detailed Timing



T/R timing

- **Hub establishes 10.000 millisecond period from it's internal clock.**
- **Timing epoch is the opening FLAG from the Hub radio transmit frame, 960 μsec after the transmission starts.**
- **User radio establishes timing by listening for the hub epoch, smooths arrival times.**
- **Transmitter ramp-up and ramp down consume 100 milliseconds each.**
- **Transmission duration is 9,890 μsec, data portion is 8830 μsec.**
- **Propagation delay is measured during link startup. Hub computes the delay, communicates to user.**