Telemetry Smorgasbord

A Little Taste of Everything

Terry Hill, Quasonix

Spring 2020

Course Outline – Day 1

- Performance Metrics
- Continuous Phase Modulation (CPM)
  - Tier 0
  - Tier I
  - Tier II
- Demodulation
  - Trellis vs. Single-Symbol
  - Data Quality Metric
  - Synchronization

Course Outline – Day 2

- Demodulation
  - Trellis vs. Single-Symbol
  - Data Quality Metric
  - Synchronization
- Channel Impairments
  - Adjacent Channel Interference
  - Multipath Propagation
- Impairment Mitigation Techniques
  - Adaptive Equalization
  - Diversity Combining
  - Best Source Selection

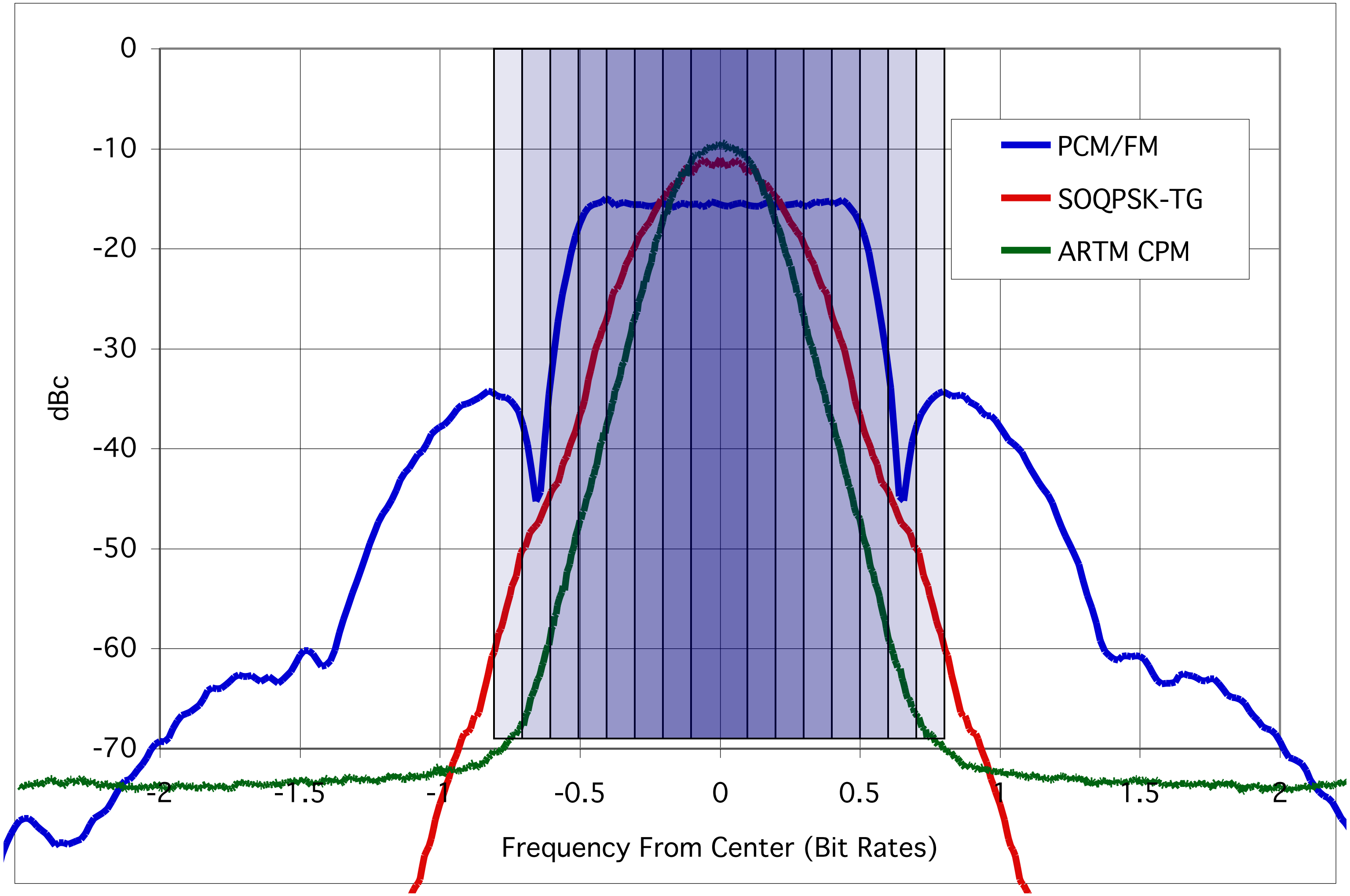
Course Outline – Day 3

- Impairment Mitigation Techniques
  - Adaptive Equalization
  - Diversity Combining
  - Best Source Selection
  - Best Channel Selection
  - Space-Time Coding
  - Forward Error Correction (FEC)
- Using All the Tools Together
- Performance Comparison & Summary
- Link Budgets

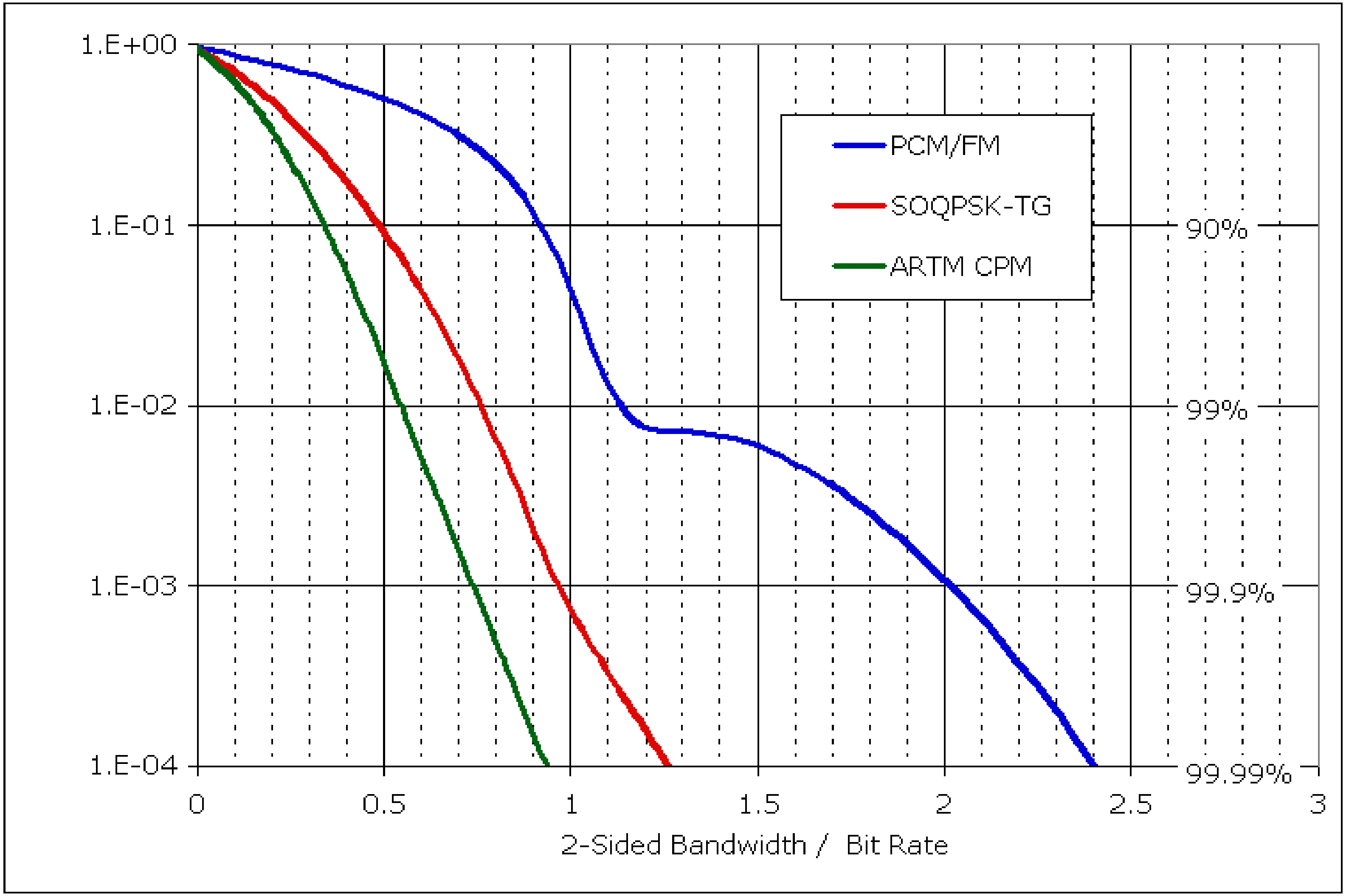
Performance Metrics

- Bandwidth Efficiency
  - How much (or how little) spectrum do I need?
- Information Fidelity
  - How many of the bits are correct?
- Bandwidth-Power plane

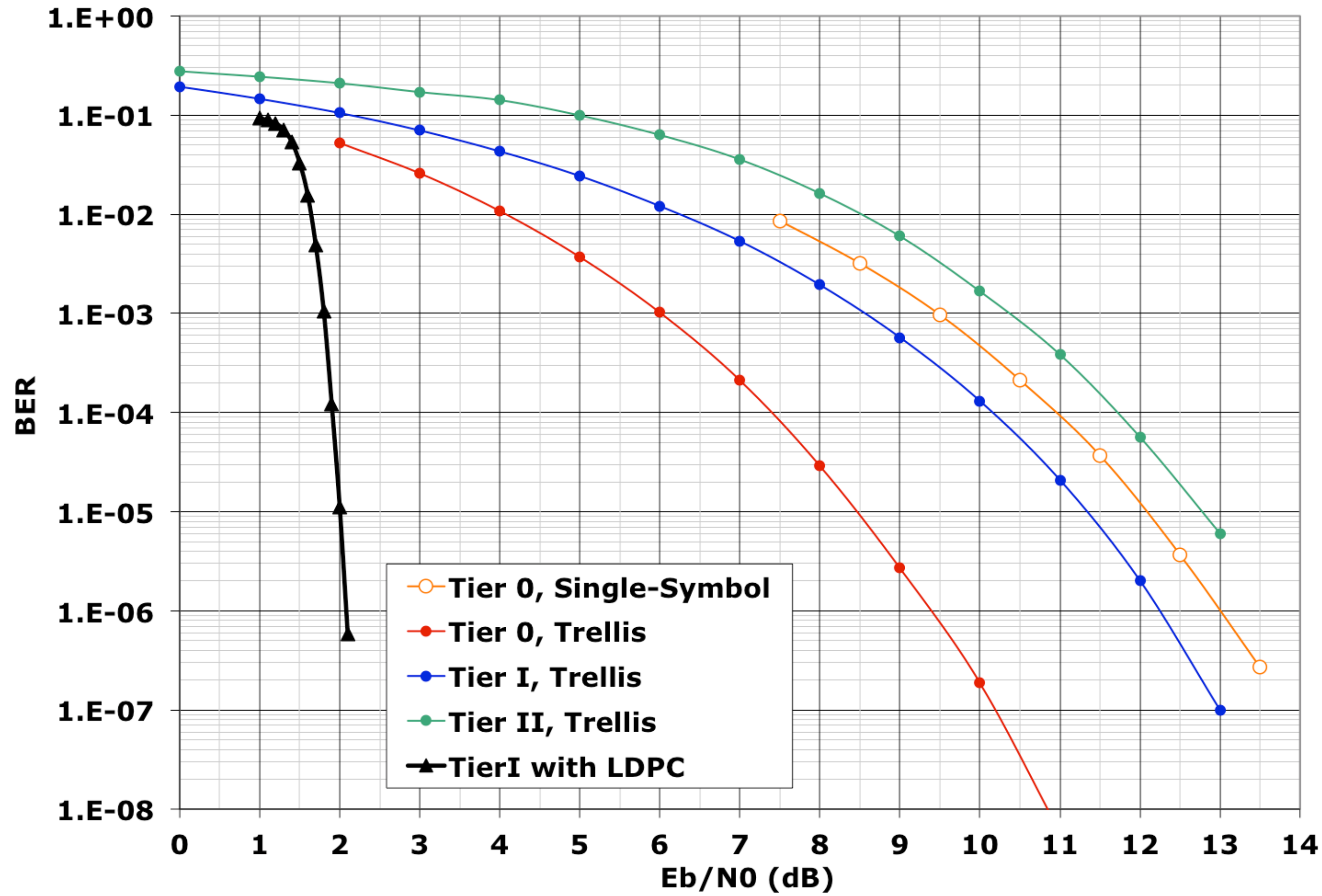
Power Spectral Density (PSD)



Fractional Out-of-band Power

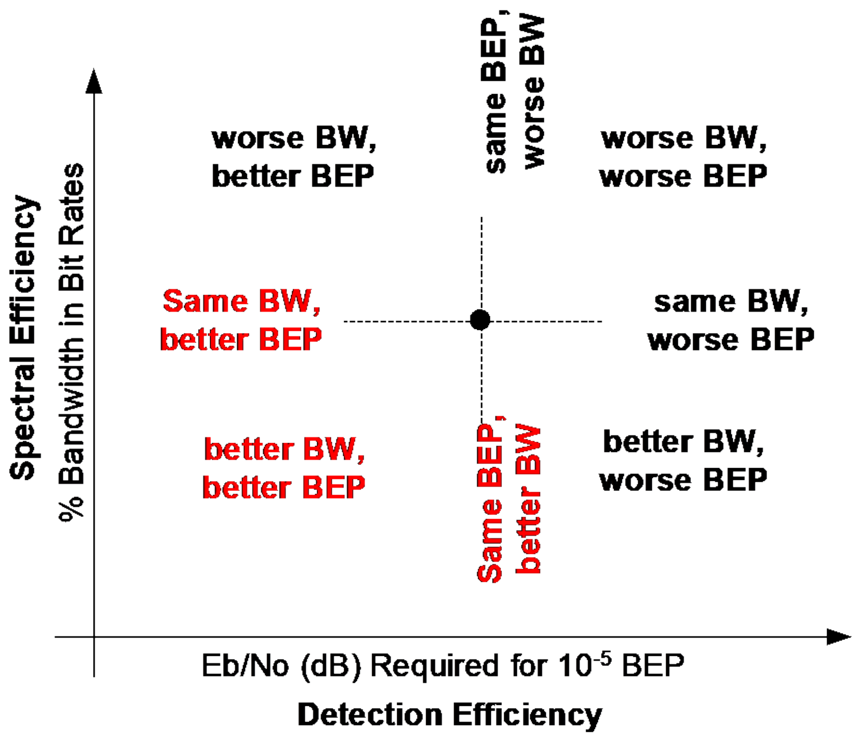


BER Performance Comparison

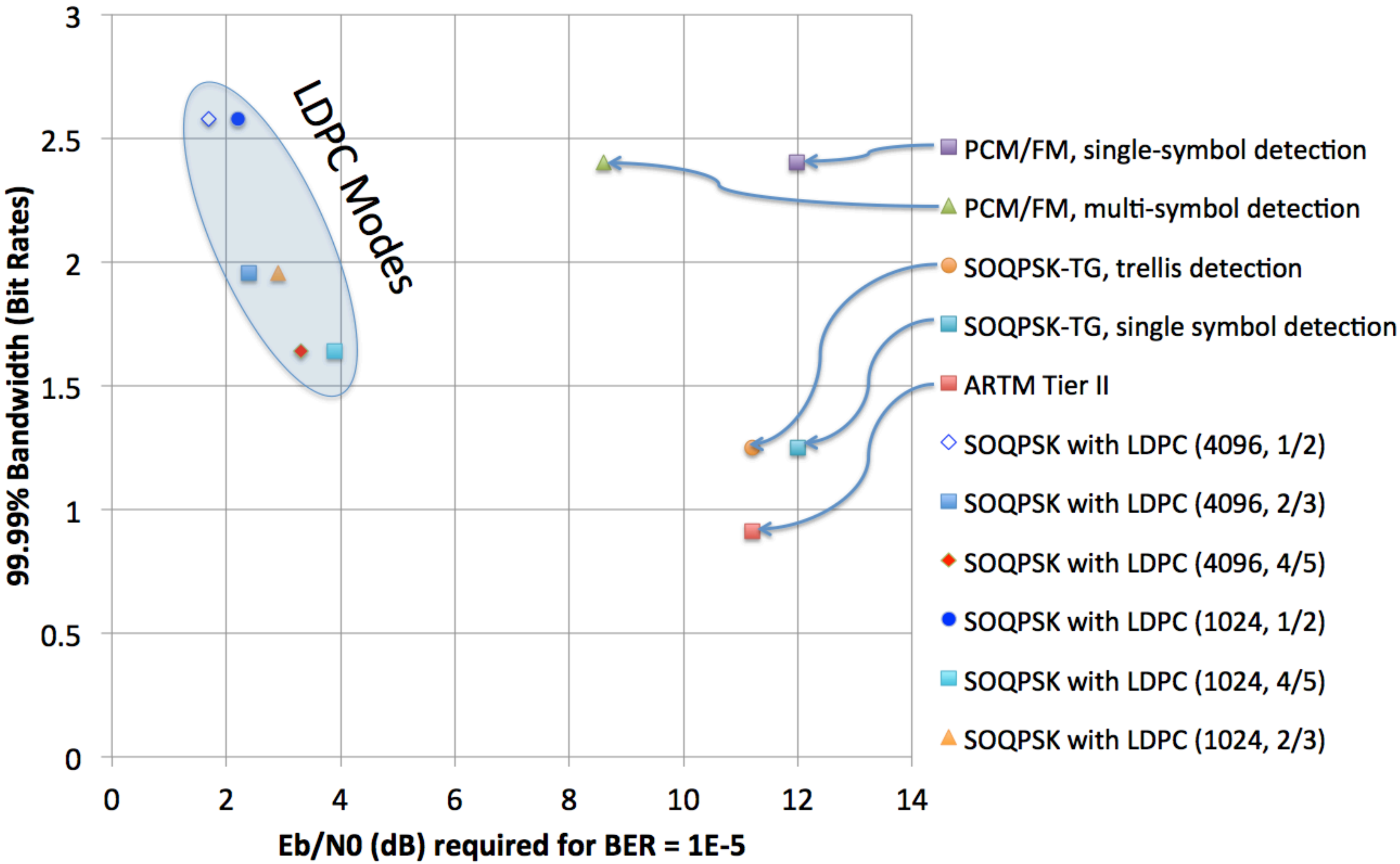


Bandwidth-Power Plane

- Simultaneous representation of
  - Bandwidth Efficiency (Bandwidth normalized to Bit Rate)
  - Power Efficiency (Eb/No required to achieve 10^{-5} BEP)



Today's Modulation Tour



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Continuous Phase Modulation

The Modulation Universe

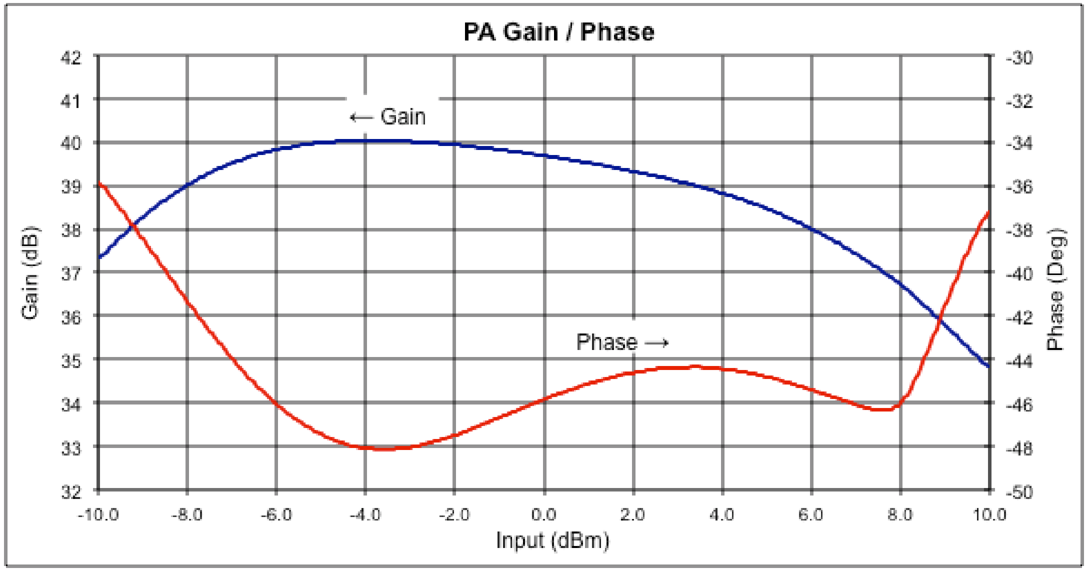
- Analog, Digital
- Amplitude modulation
- Quadrature amplitude modulation
- Angle modulations
  - Frequency modulation
  - Phase modulation

Angle Modulations

- Includes both frequency modulation and phase modulation
- Some have an amplitude modulation component
  - BPSK
  - QPSK
  - Offset QPSK
- Some are constant envelope
  - Binary FM
    - FSK, MSK, premod filtered MSK, GMSK
  - M-ary FSK
  - SOQPSK
  - Multi-h continuous phase modulation
  - No amplitude variation
- Saturated power amplifiers are ideal for <u>constant envelope waveforms</u>

Saturated Power Amplifiers

- DC-to-RF conversion efficiency is important
  - Minimizes cooling requirements
  - Maximizes battery life
- Maximizing efficiency demands nonlinear operation
- Non-linear operation creates AM-AM and AM-PM conversion:



Constant Envelope Modulations

- Before ARTM (Tier 0)
  - PCM/FM
  - "Legacy" waveform for telemetry
- Advanced Range Telemetry (ARTM) Program
  - ARTM Tier 1
    - Proprietary Feher-patented FQPSK
      - FQPSK-B, Revision A1
      - FQPSK-JR
    - SOQPSK-TG
      - Equivalent in performance to FQPSK
      - Non-proprietary
  - ARTM Tier 2
    - Multi-h CPM (M=4, L=3RC, h1 = 4/16, h2 = 5/16)
- PCM/FM, SOQPSK and Multi-h CPM are all *continuous phase modulations* (CPM)

CPM Notation and Parameters

$$s(t) = \sqrt{2E/T}\cos[2\pi f_o t + \phi(t,\overline{\alpha}) + \phi_o]$$

$$\phi(t,\overline{\alpha}) = 2\pi h \int_{-\infty}^{t} \sum_{i=-\infty}^{+\infty} \alpha_i g(\tau - iT)\,d\tau \quad -\infty < t < +\infty$$

- Where α_i represents an M-ary symbol sequence
  - α_i derived from input bits d_i
- h is the modulation index
- g(t) is the frequency pulse shape in the interval $0 < t < LT$
  - L = 1 is "full response" signaling
  - L > 1 yields "partial response"
- CPM is a modulation with memory due to the constraint of continuous phase. Further memory is introduced with L > 1.

ARTM Tier 0 (PCM/FM) (CPFSK)

The way things were

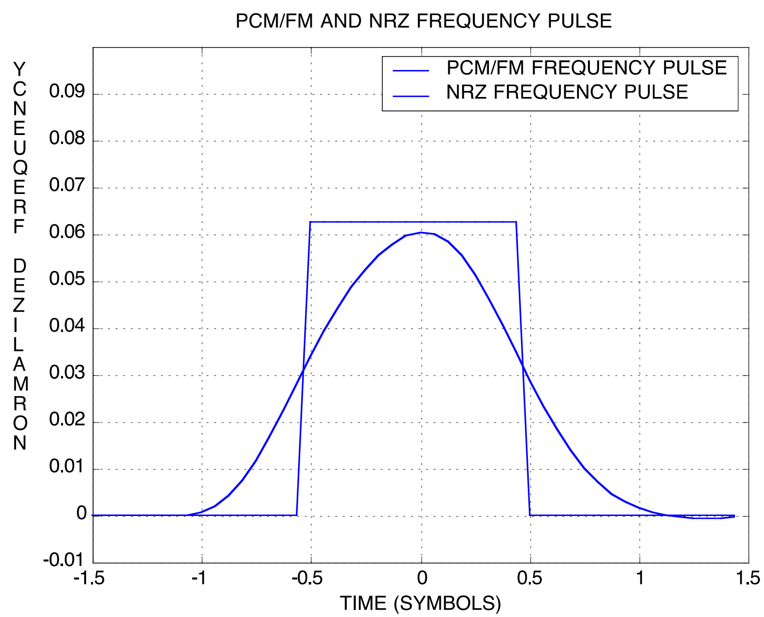
Tier 0 in CPM Notation

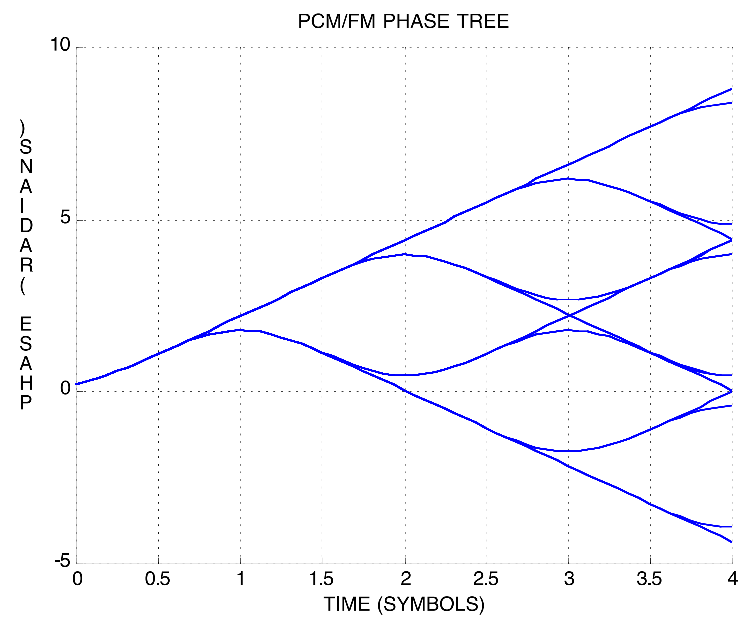
$$s(t) = \sqrt{2E/T}\cos[2\pi f_o t + \phi(t,\overline{\alpha}) + \phi_o]$$

$$\phi(t,\overline{\alpha}) = 2\pi h \int_{-\infty}^{t} \sum_{i=-\infty}^{+\infty} \alpha_i g(\tau - iT)\,d\tau \quad -\infty < t < +\infty$$

- M = 2 (binary)
- $\alpha_i = 2d_i - 1$
  - $d_i = \{0, 1\}$, $\alpha_i = \{-1, +1\}$
- h = 0.7
- g(t) is the normalized impulse response of a high order Bessel filter with 3 dB bandwidth = 0.7 * bit rate
  - Normalized such that the integral over all time = 1/2

PCM/FM as a Phase Modulation





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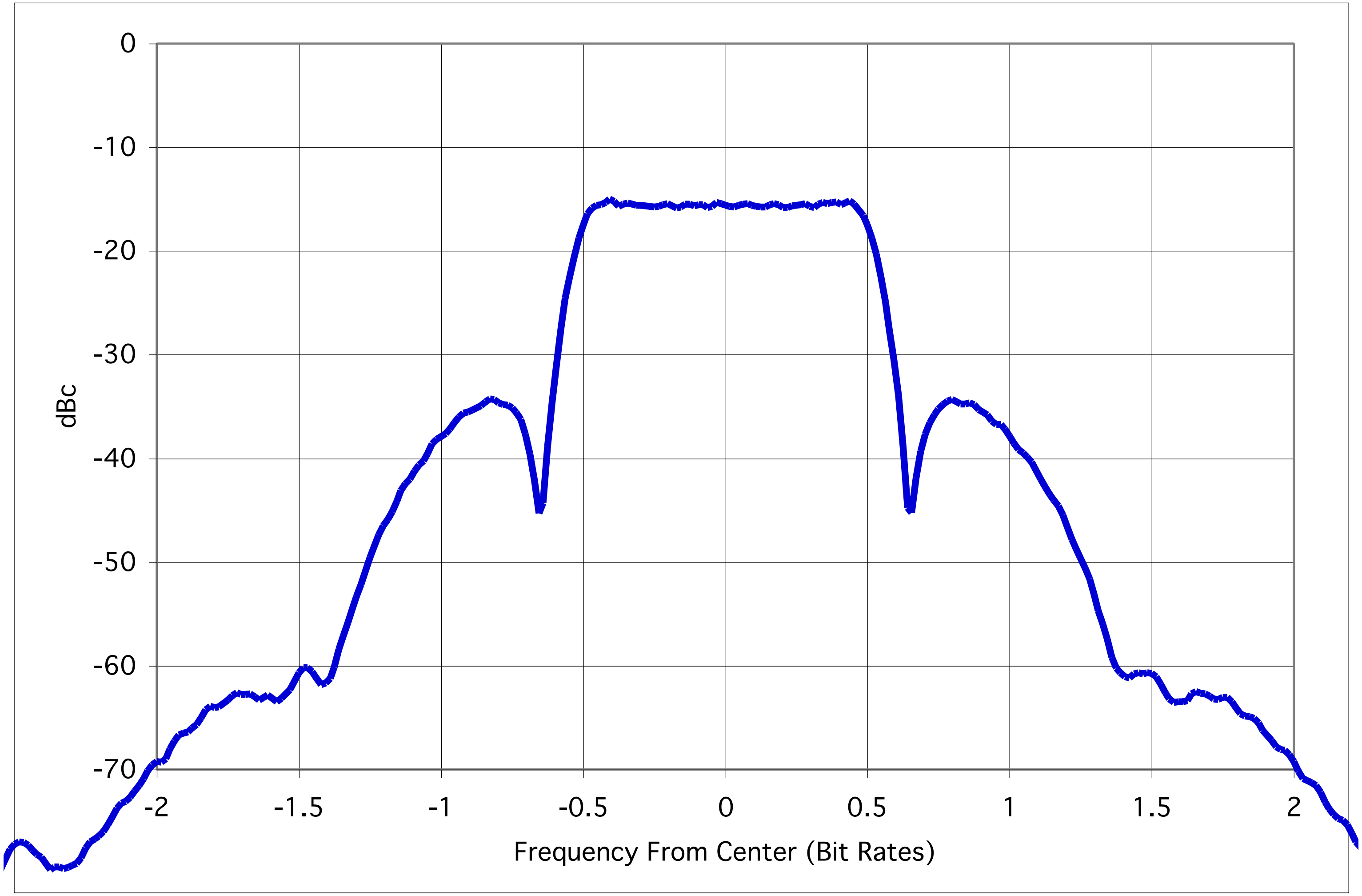
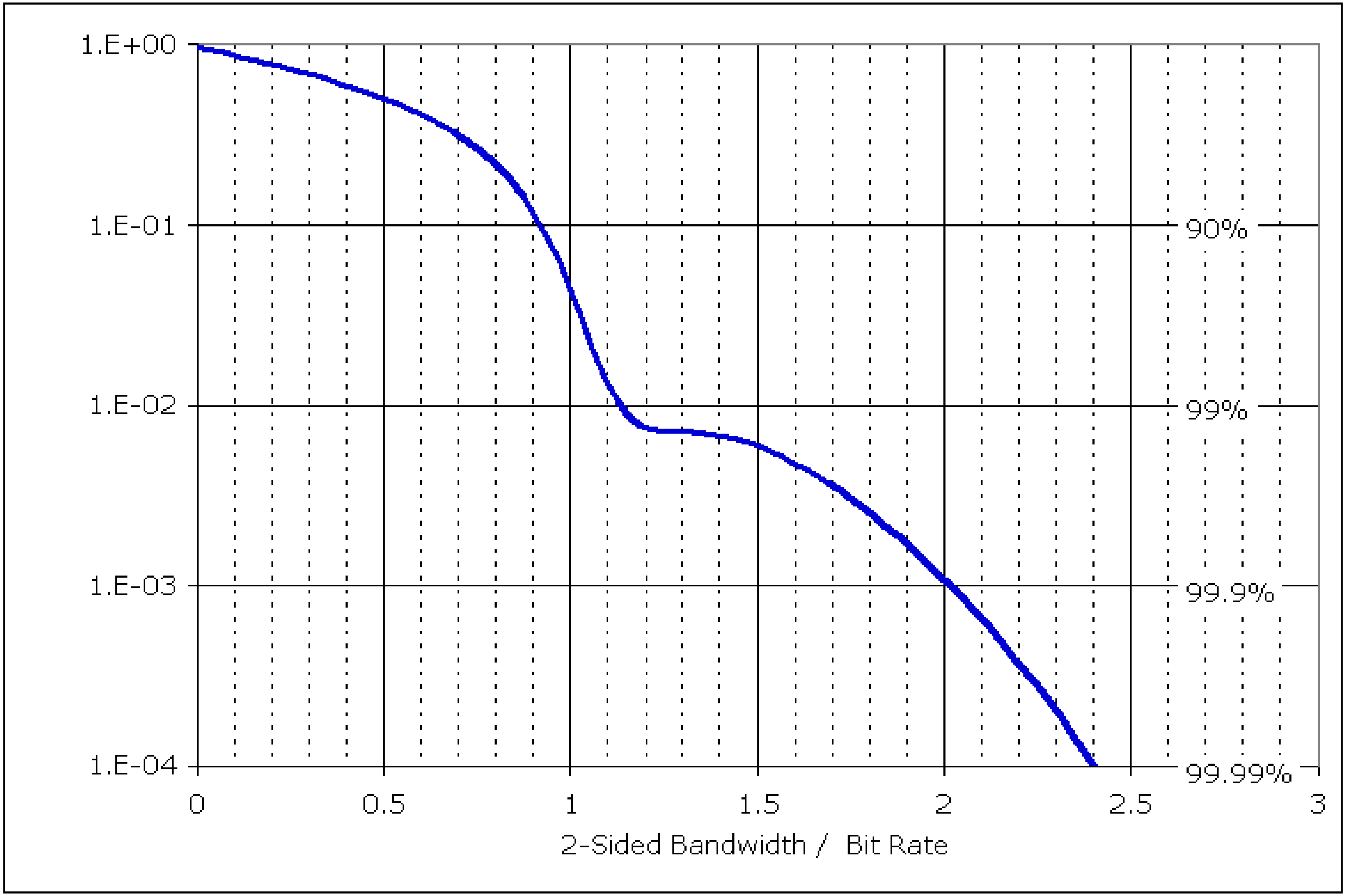
Power Spectral Density (PSD)



Fractional Out-of-band Power



PCM/FM Summary

- Legacy waveform
  - Equipment is ubiquitous
- Constant envelope
- Several practical implementations
- 99.9% bandwidth: 2.03 times bit rate

M	α_i	h	g(t)
2	{-1, +1}	0.7	Normalized impulse response of a high order Bessel filter with 3 dB bandwidth = 0.7 * bit rate

ARTM Tier I (SOQPSK-TG)

The way things are

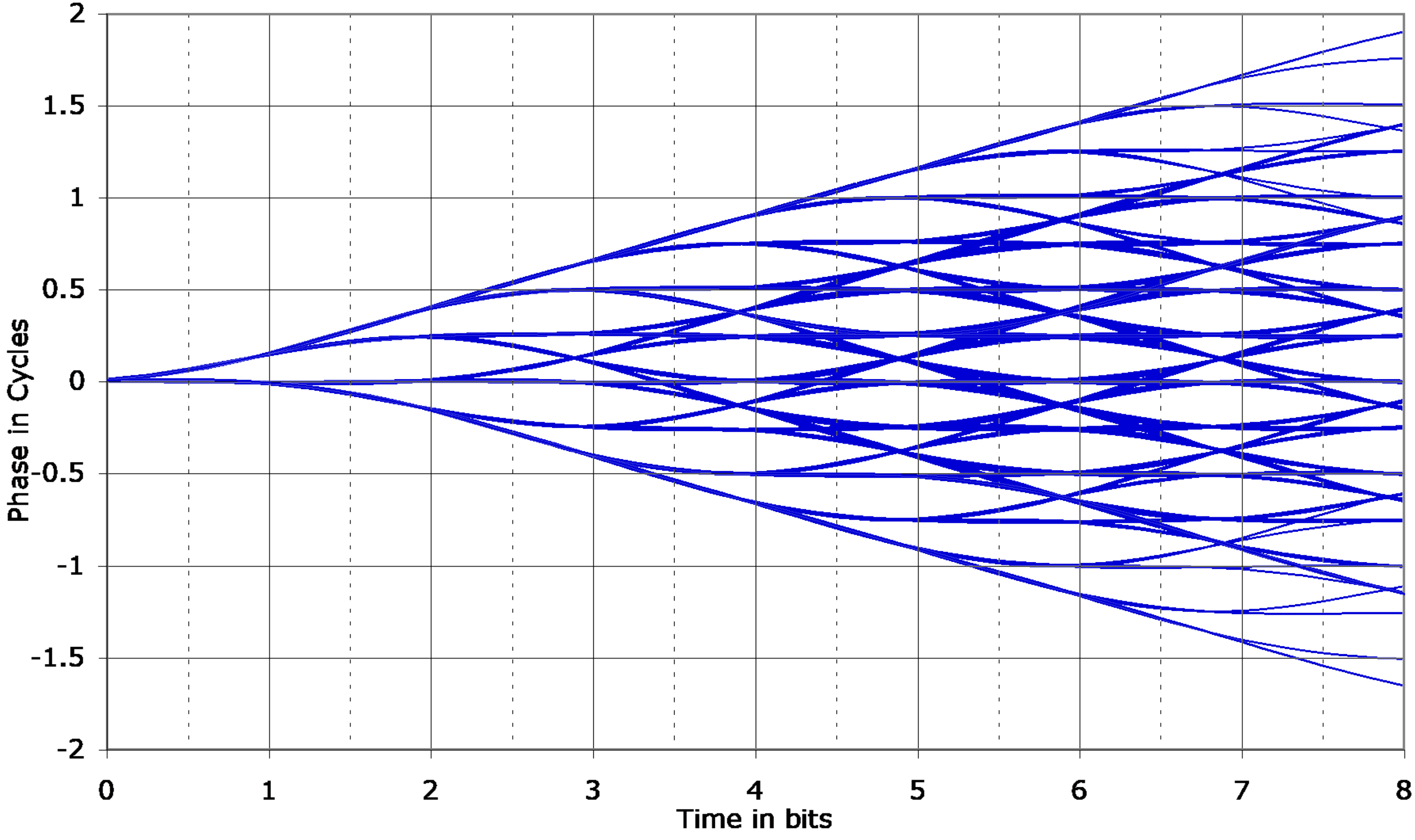
SOQPSK in CPM Notation

$$s(t) = \sqrt{2E/T}\cos[2\pi f_o t + \phi(t,\overline{\alpha}) + \phi_o]$$

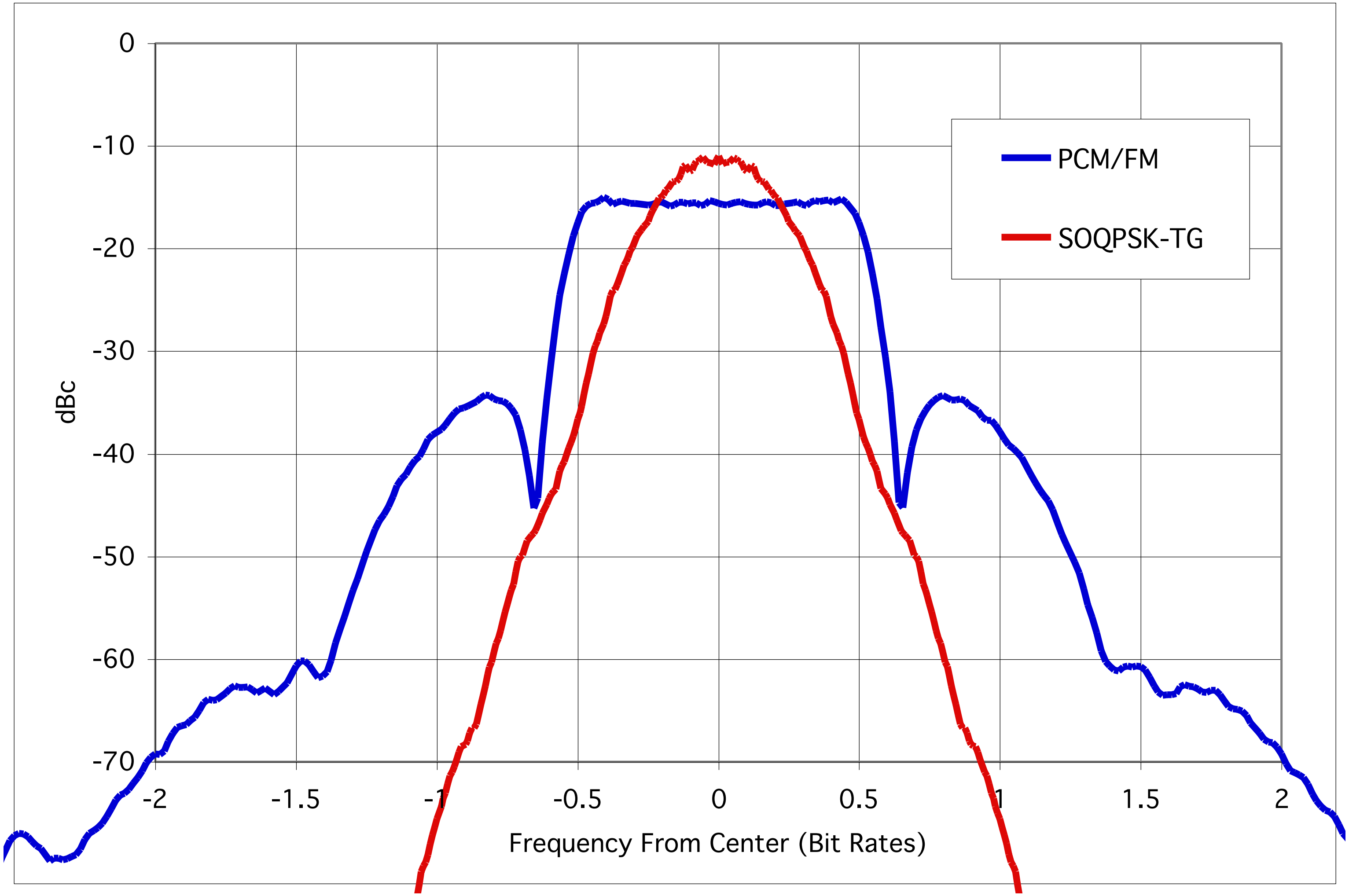
$$\phi(t,\overline{\alpha}) = 2\pi h \int_{-\infty}^{t} \sum_{i=-\infty}^{+\infty} \alpha_i g(\tau - iT)d\tau \quad -\infty < t < +\infty$$

- M = 3 (ternary)
- $\alpha_i = (-1)^{i+1}\frac{a_{i-1}(a_i - a_{i-2})}{2}$; $\alpha_i = \{-1, 0, +1\}$
  - $a_i = 2d_i - 1$
  - $a_i = \{-1, +1\}$, $d_i = \{0, 1\}$
- h = 0.5
- g(t) = windowed impulse response of spectral raised cosine
  - Normalized such that the integral over all time = 1/2

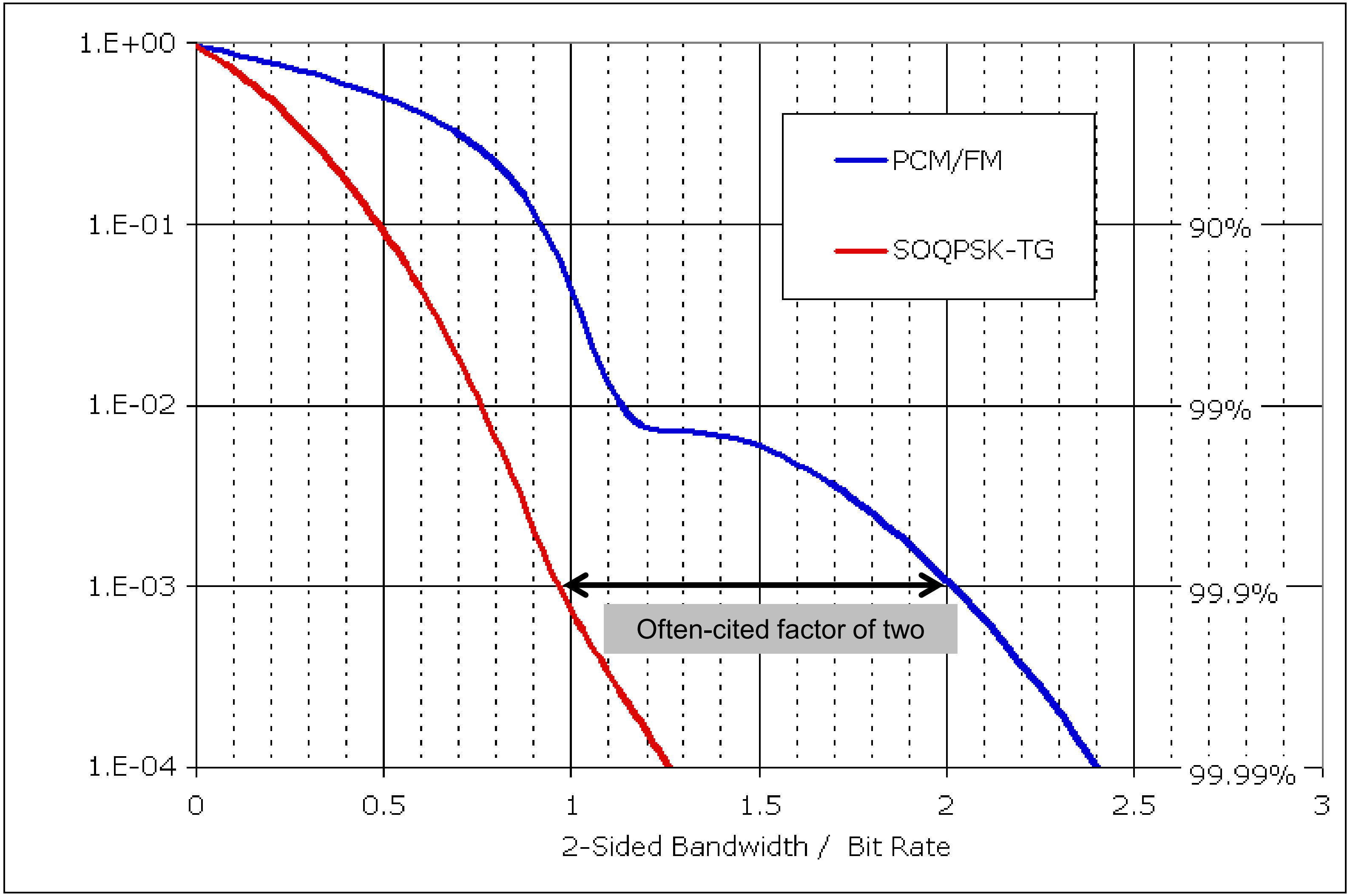
SOQPSK-TG Phase Tree



Measured PSD (Tier 0 & 1)



Fractional Out-of-band Power



Shaped Offset QPSK Summary

- Constant envelope, CPM waveform
- Adjustable shaping factor for BW and detection efficiency trade-off
- Improved spectral containment over OQPSK
- Compatible with standard OQPSK receivers and demodulators
- Adopted as an ARTM Tier I waveform
- 99.9% bandwidth: 0.98 times bit rate
- Interoperable with FQPSK

M	α_i	h	g(t)
3	{-1, 0, +1}	0.50	Normalized windowed impulse response of a spectral raised cosine

ARTM Tier II (ARTM CPM) (Multi-h CPM)

The way things can be

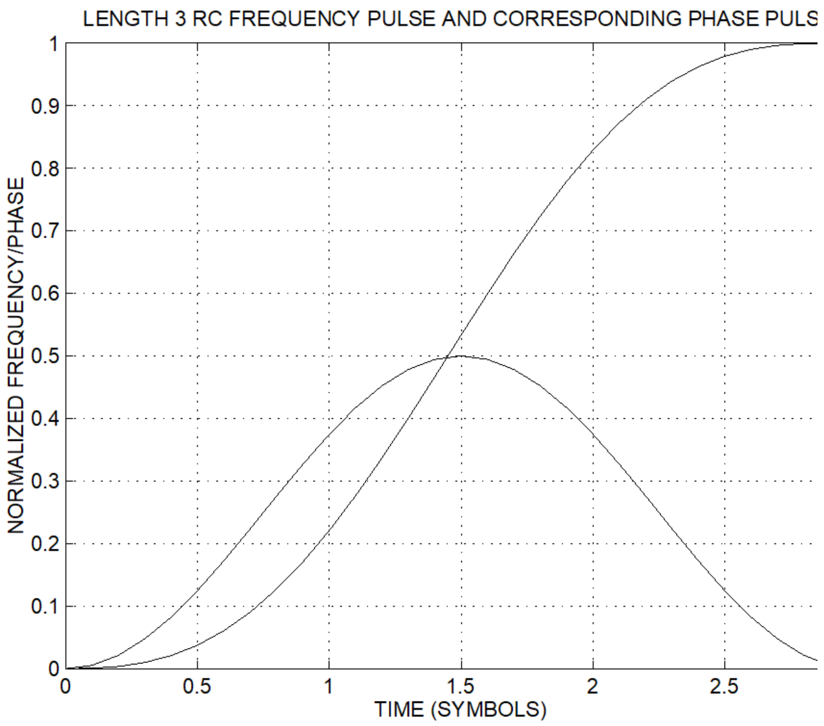
ARTM Tier II in CPM Notation

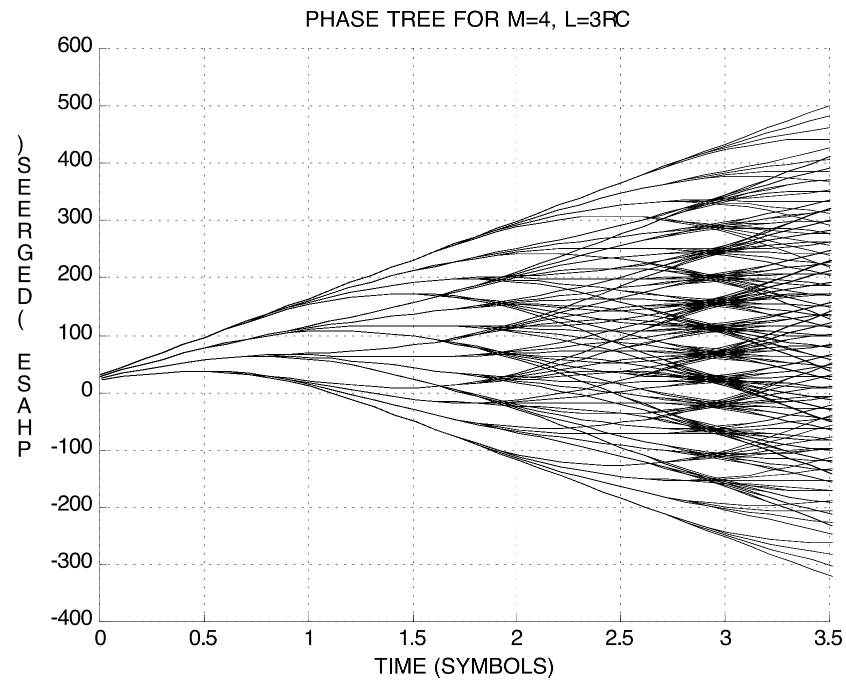
$$s(t) = \sqrt{2E/T}\cos[2\pi f_o t + \phi(t,\overline{\alpha}) + \phi_o]$$

$$\phi(t,\overline{\alpha}) = 2\pi h \int_{-\infty}^{t} \sum_{i=-\infty}^{+\infty} \alpha_i g(\tau - iT)\,d\tau \quad -\infty < t < +\infty$$

- M = 4 (quaternary)
- $\alpha_i = 2\,[2d_{1i} + d_{0i}] - 3$
  - $\alpha_i = \{-3, -1, +1, +3\}$
  - $d_i = \{0, 1\}$
- h = {4/16, 5/16}, alternating
- g(t) = raised cosine, 3 symbols (6 bits) in duration
  - Normalized such that the integral over all time = 1/2

Frequency Pulse & Phase Tree





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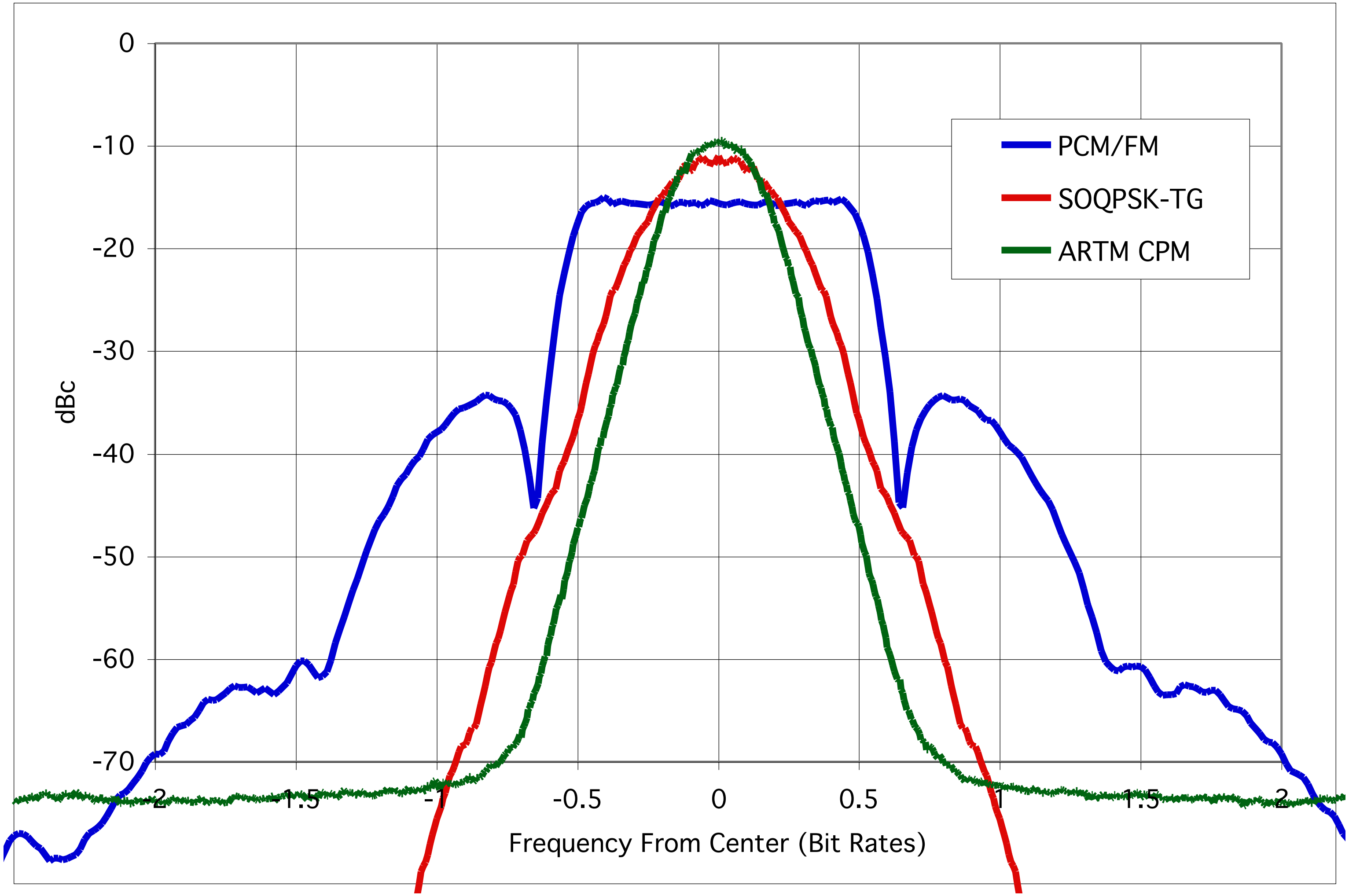
PSD (Tier 0, I, & II)



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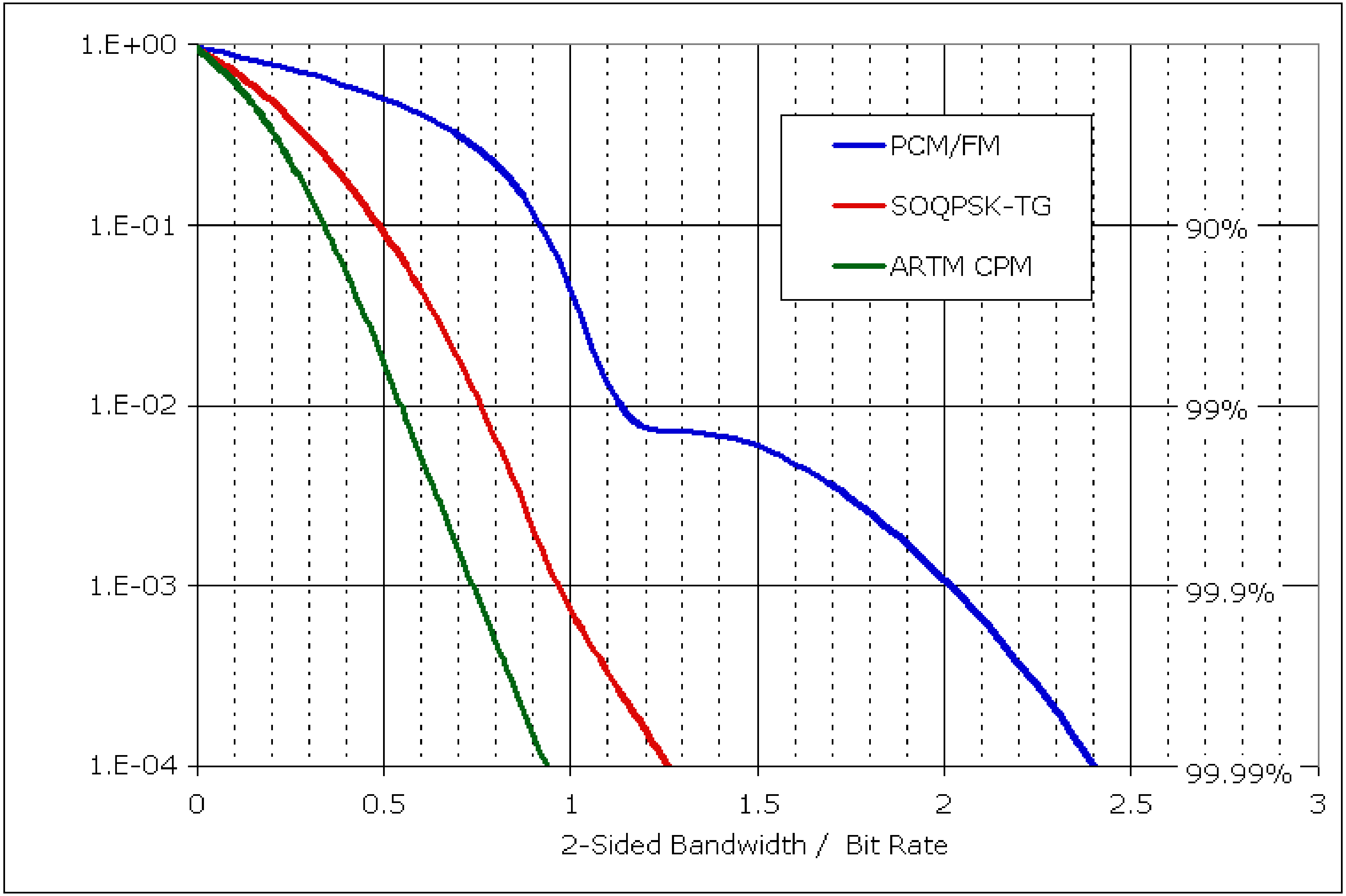
Fractional Out-of-band Power



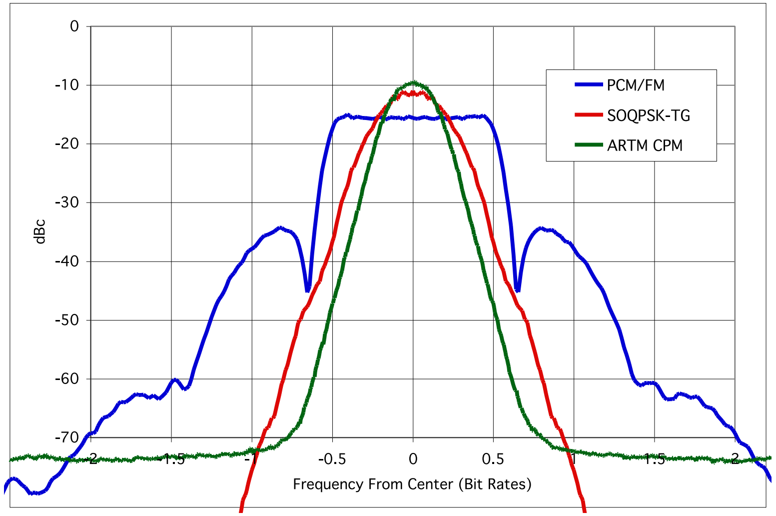
Tier II Multi-h CPM Summary

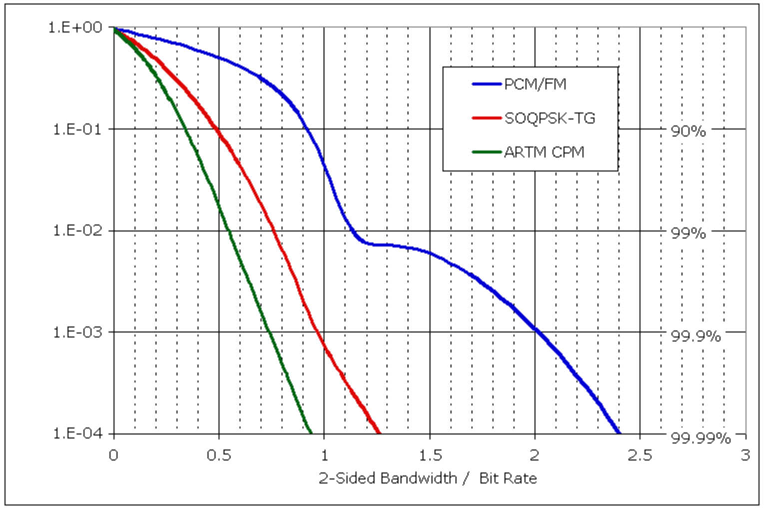
- Similar detection efficiency to PCM/FM.
- Constant envelope waveform is ideal for efficient non-linear PA’s.
- Enhanced performance gained by increasing demodulator complexity.
- 99.9% bandwidth: 0.75 times bit rate

M	α_i	h	g(t)
4	{-3, -1, +1, +3}	{4/16, 5/16}	Normalized raised cosine, 3 symbols (6 bits) long

Side by Side Summary

Tier	M	α_i	h	g(t)	99.9% BW
0	2	{-1, +1}	0.7	Normalized impulse response of a high order Bessel filter with 3 dB bandwidth = 0.7 * bit rate	2.03
I	3	{-1, 0, +1}	0.5	Normalized windowed impulse response of a spectral raised cosine, 8 bits long	0.98
II	4	{-3, -1, +1, +3}	{4/16, 5/16}	Normalized raised cosine, 3 symbols (6 bits) long	0.75





Demodulation

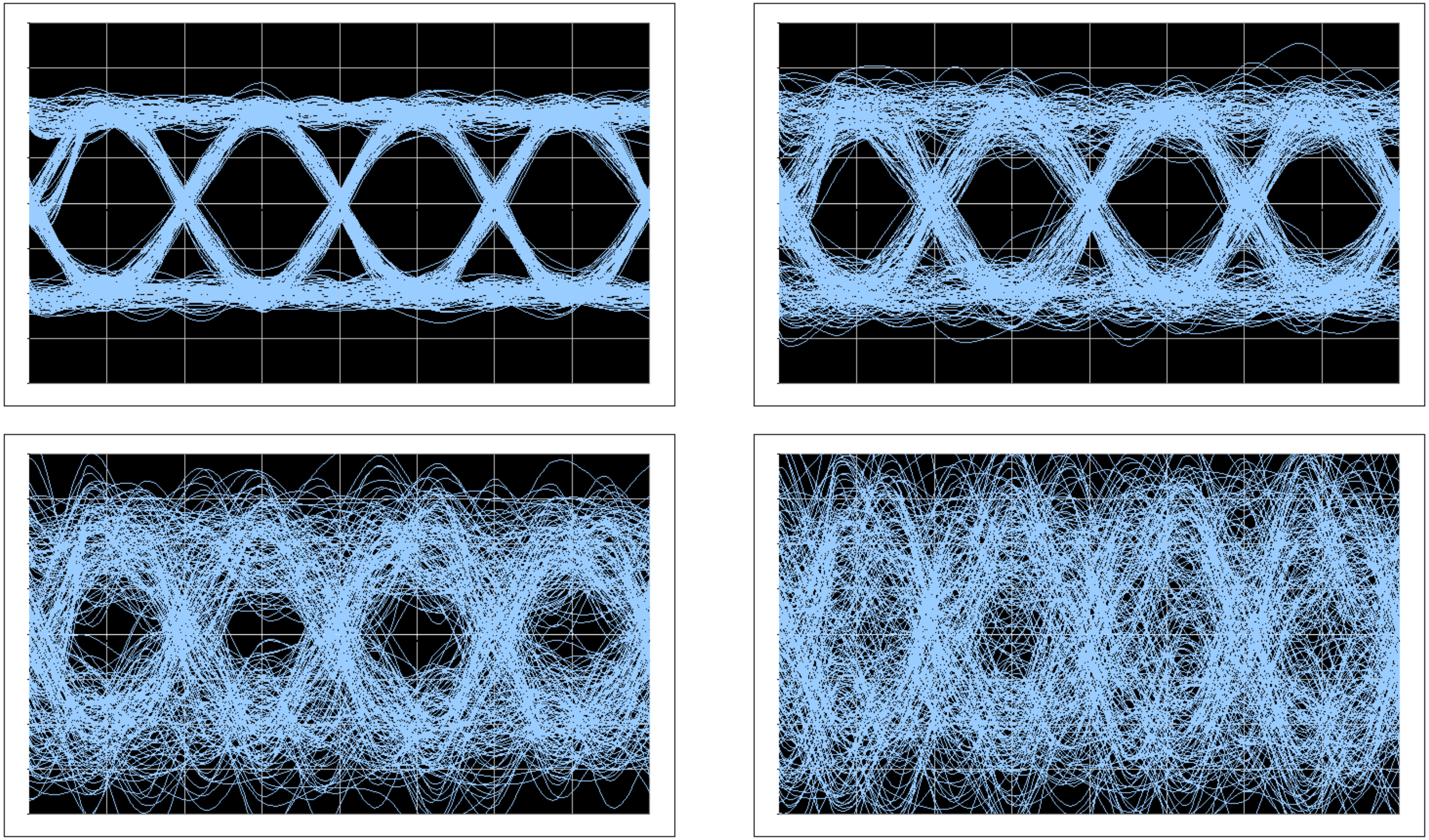
Demodulation

- As the shop manual says, “Installation is reverse of removal.”
- Demodulation is intrinsically more difficult
  - Unknown carrier frequency
  - Unknown carrier phase
  - Unknown clock frequency and phase
  - Signal corruption
    - Noise
    - Interference
    - Multipath
    - Doppler shift
- Multiple techniques can be applied

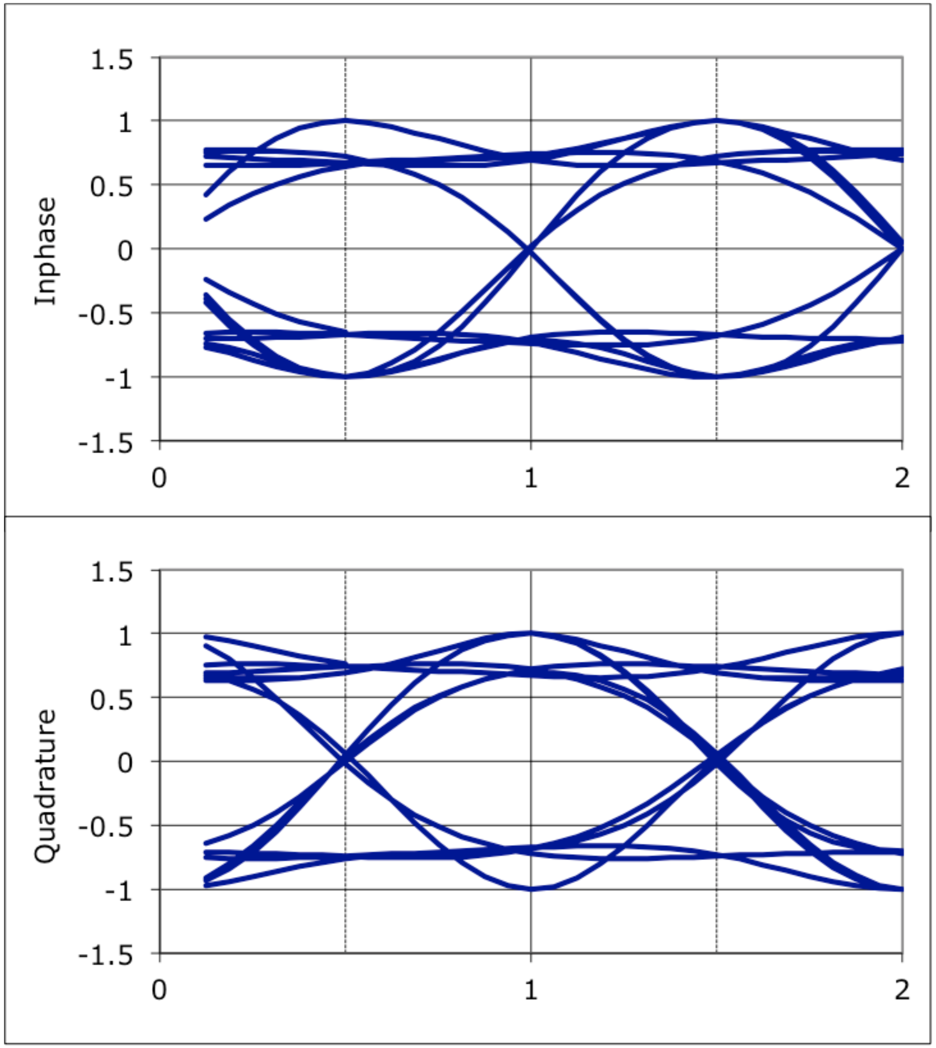
Single-Symbol Demodulation

- Tier 0
  - Legacy (nearly exclusive in 20th century)
  - Simple to build
  - Robust to signal defects and channel impairments
  - ~3.5 to 5 dB short of theoretical limit
- Tier I
  - Requires optimization for **S**OQPSK
  - Weakly synchronized
  - Requires high SNR for acquisition
  - ~1.0 to 1.5 dB short of theoretical limit
- Tier II
  - No practical single-symbol detectors

Tier 0 Frequency Detection

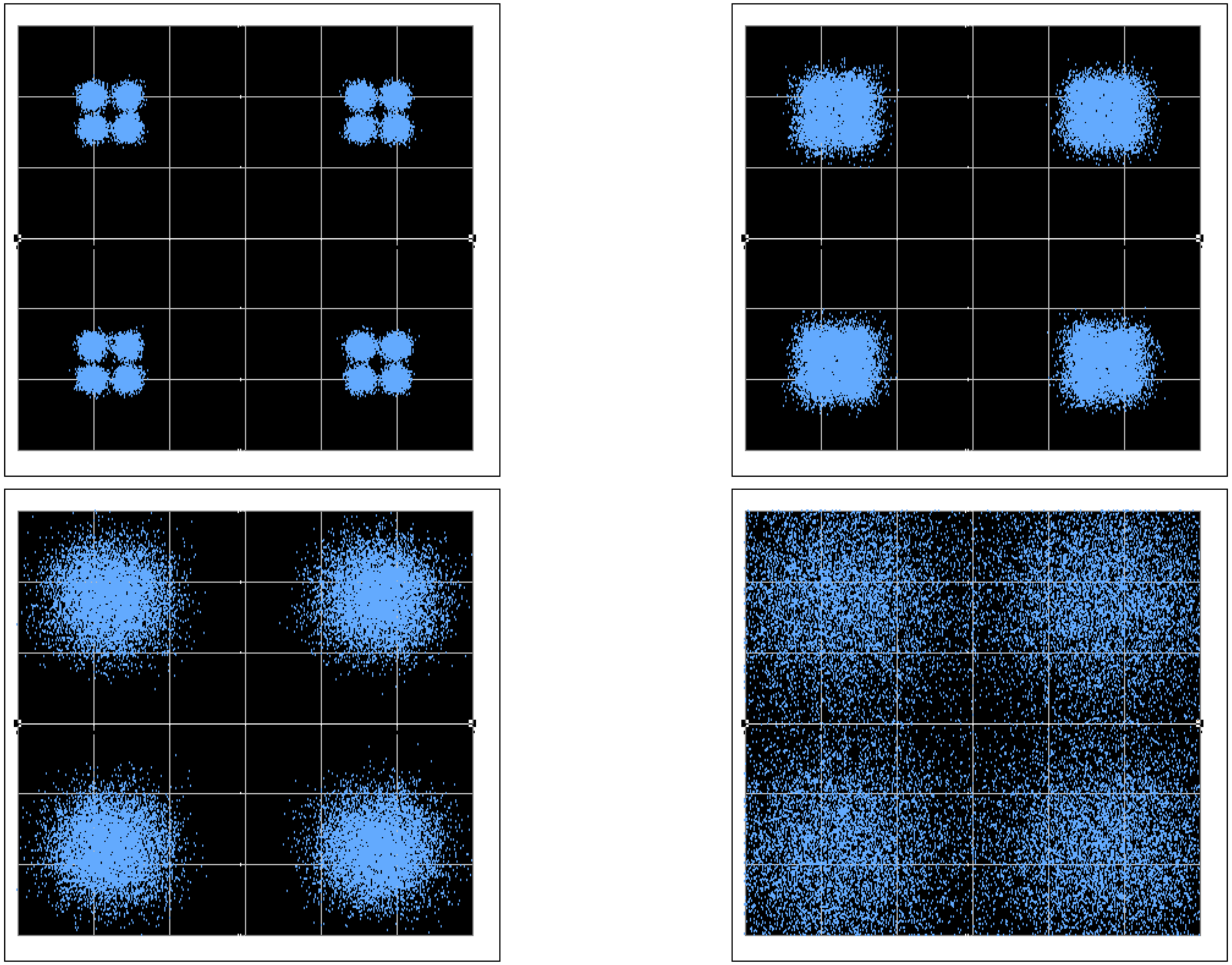


SOQPSK-TG Eye Patterns



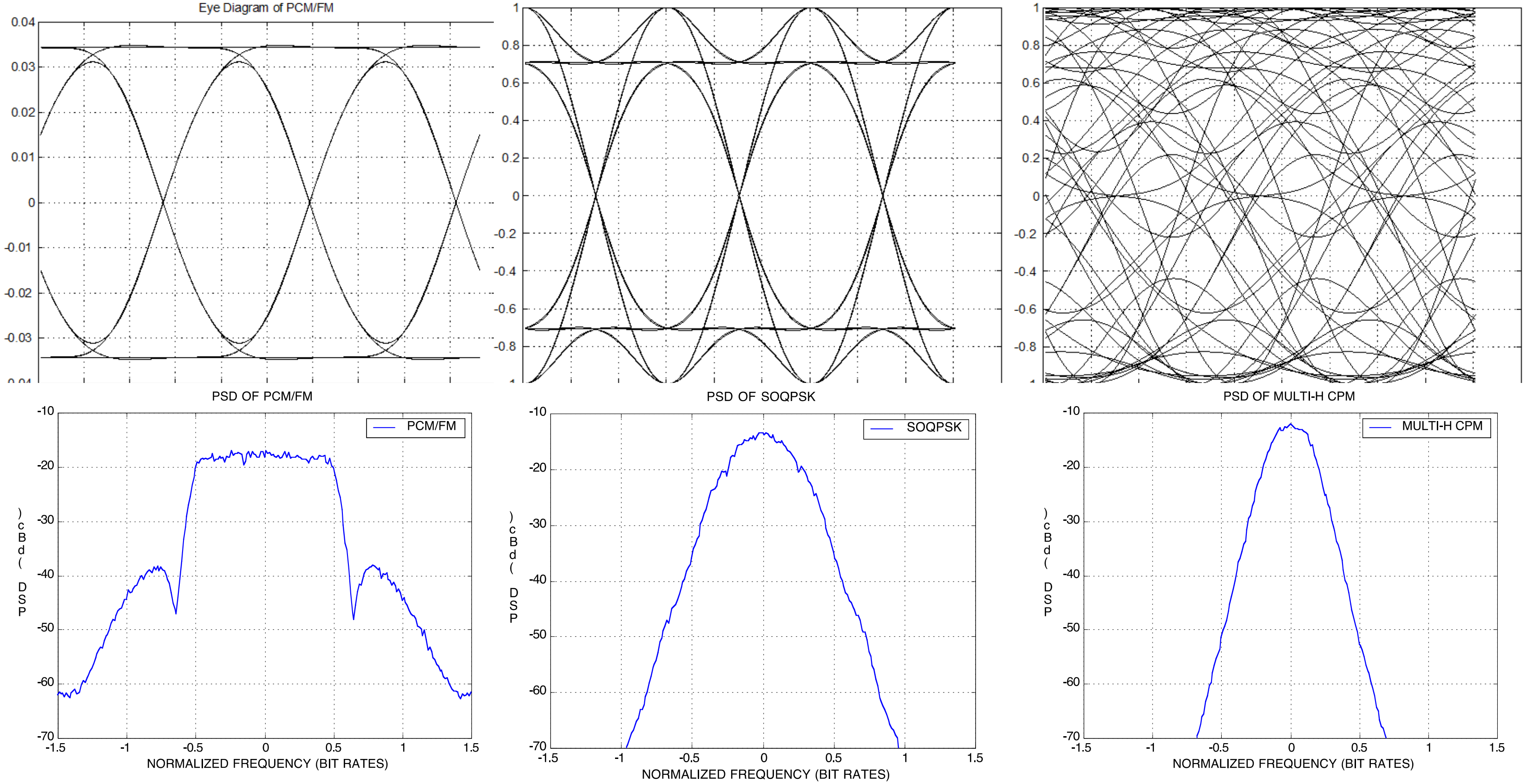
- Single-symbol detection ignores memory inherent in waveform
- Can be detected by conventional (non-shaped) offset QPSK demod
- I&D detector endures additional loss due to waveform mismatch

SOQPSK Constellations



Waveform Comparison

PCM/FM (1x) SOQPSK (2x) Multi-h CPM (2.5x)



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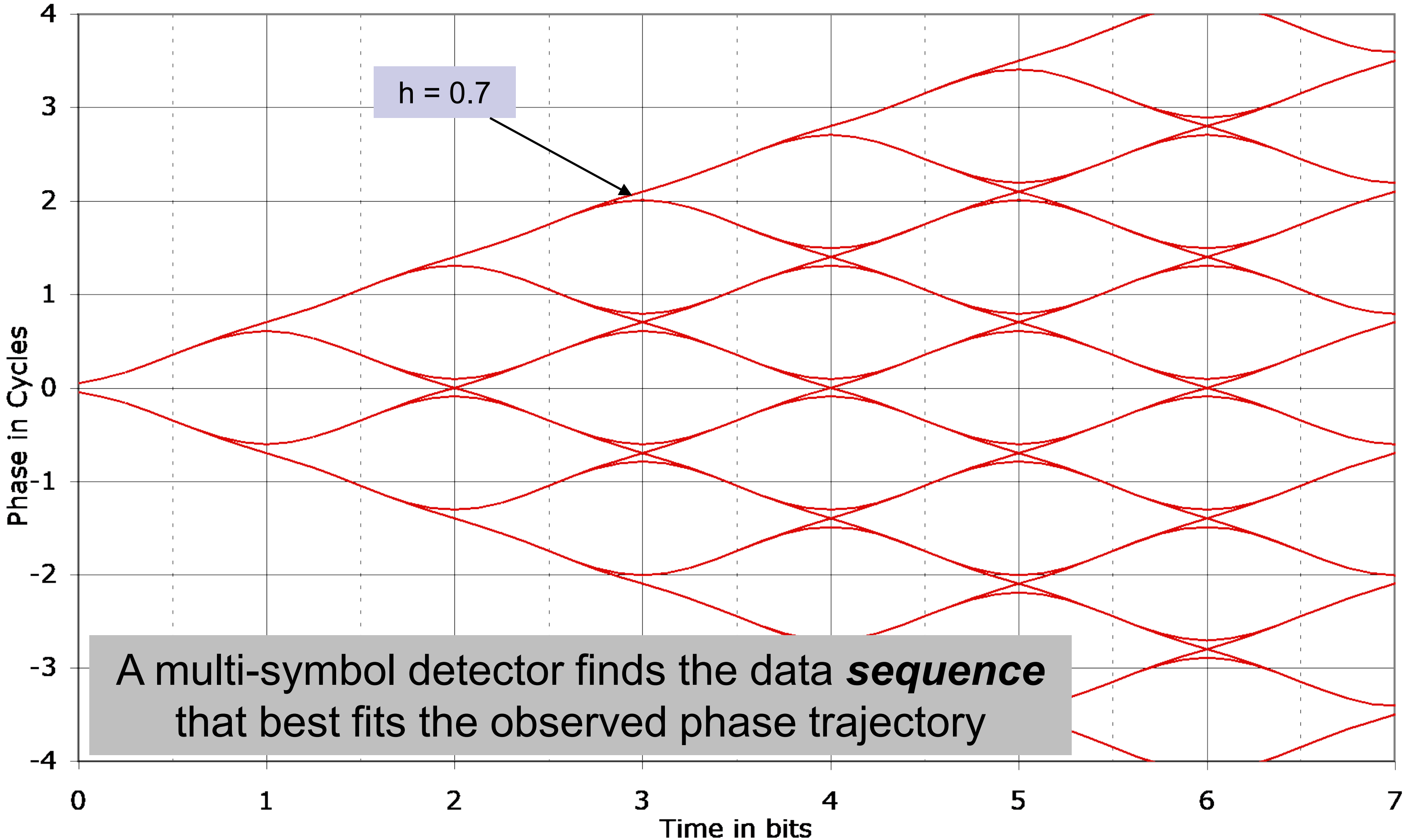
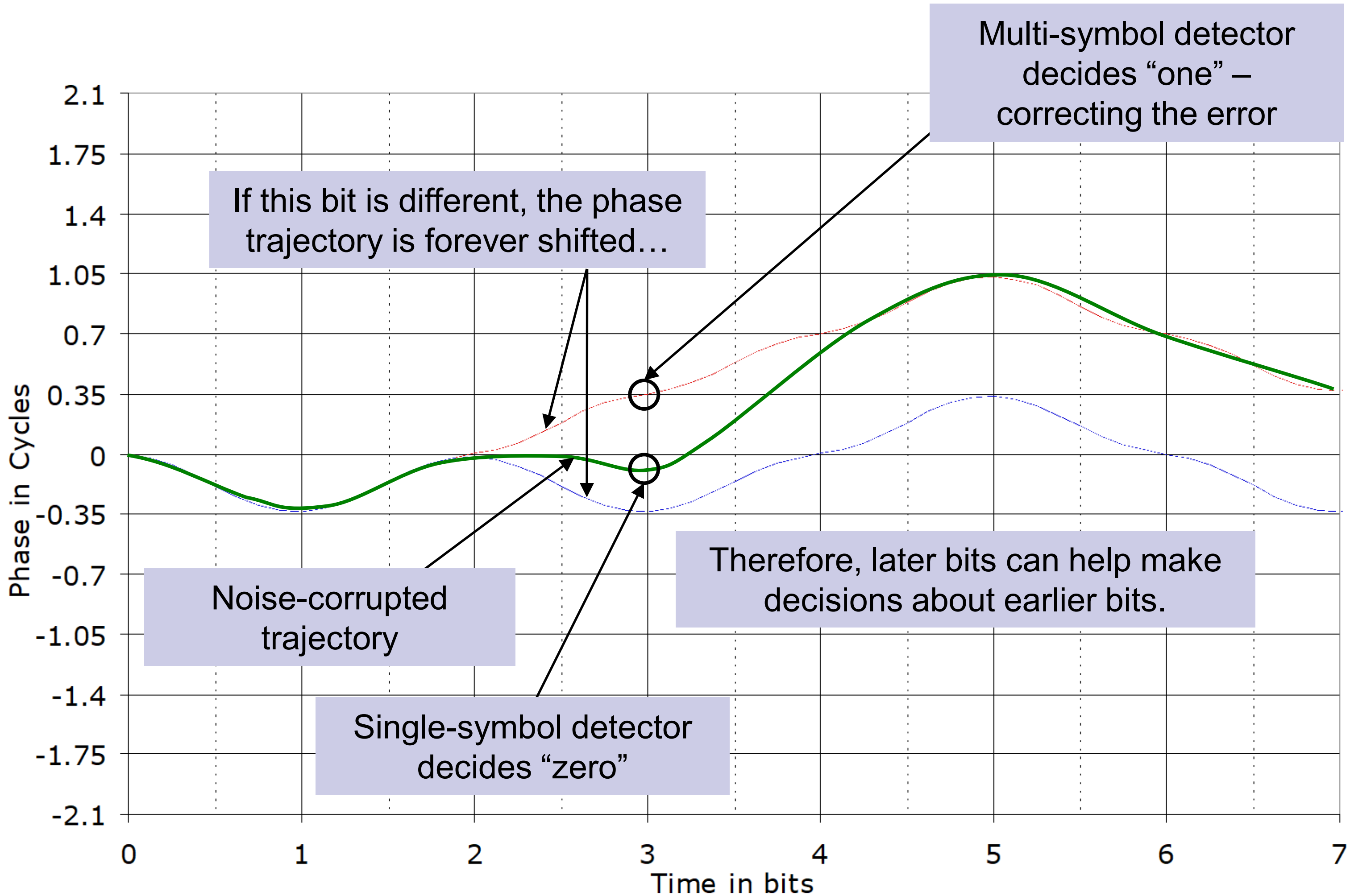
Trellis Demodulation Overview

- Tier 0
  - Invented in 1974, introduced in 2001
    - Osborne & Luntz, “Coherent and Noncoherent Detection of CPFSK”, IEEE T-COM, August 1974
  - Requires significant signal processing power
  - Signal defects and channel impairments require attention
    - DSP techniques can be applied to solve these issues
  - Operates within 0.2 dB of theoretical limit
- Tier I
  - Strong, rapid synchronization
  - Operates within 0.2 dB of theoretical limit
- Tier II
  - Mandatory for practical implementation

Tier 0 Phase Tree



Why Does It Matter?



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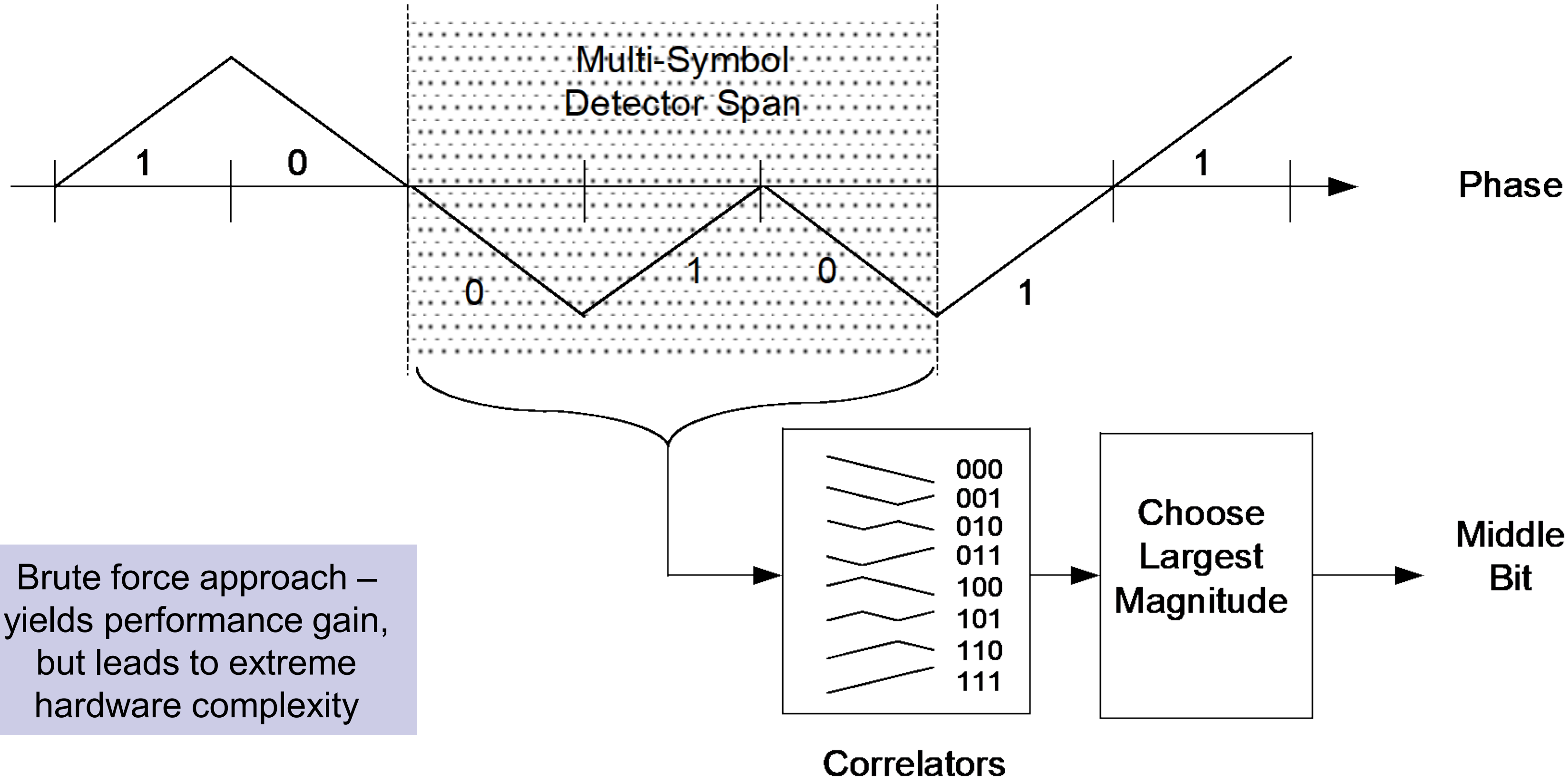
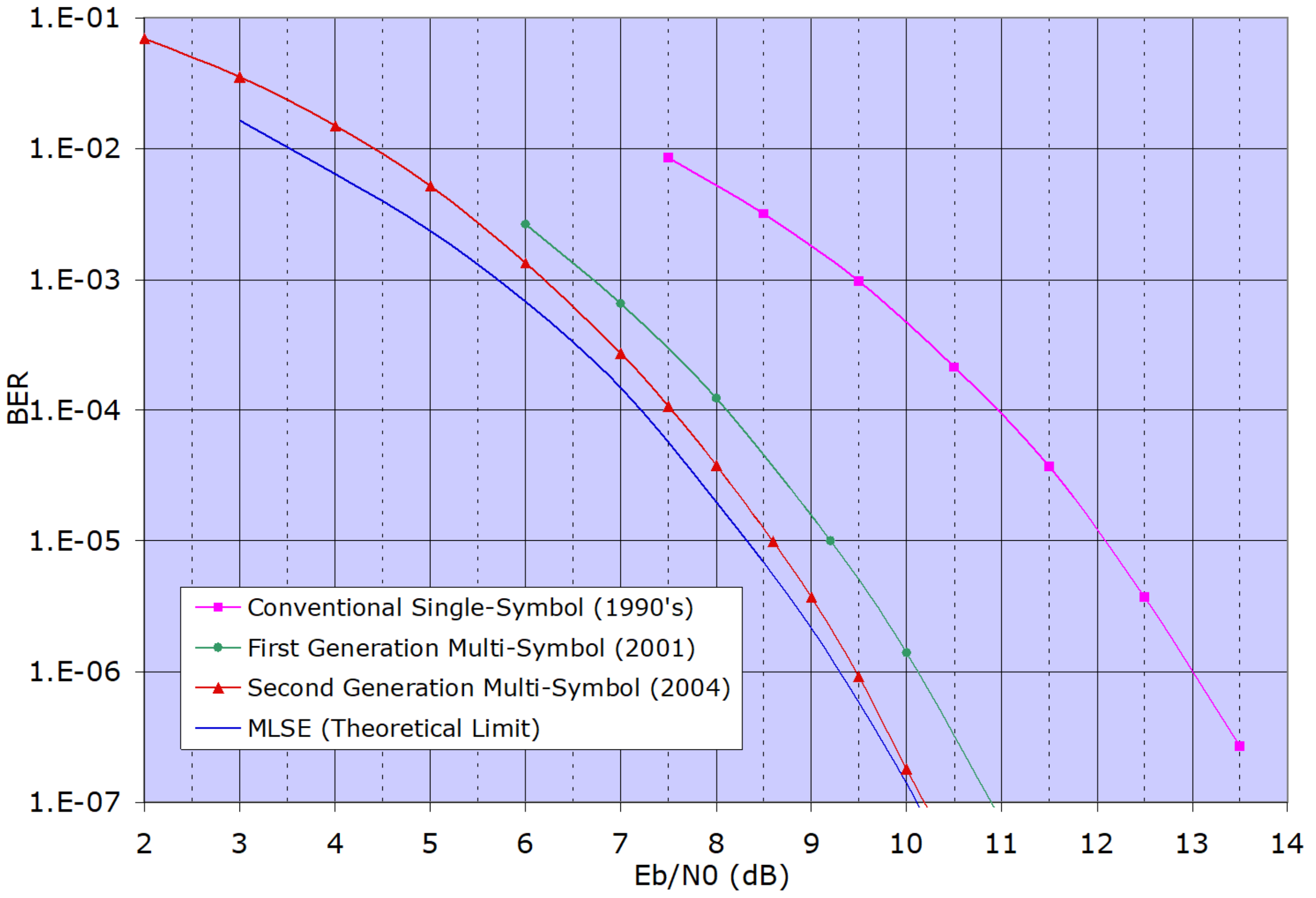
Multi-Symbol Detector Example

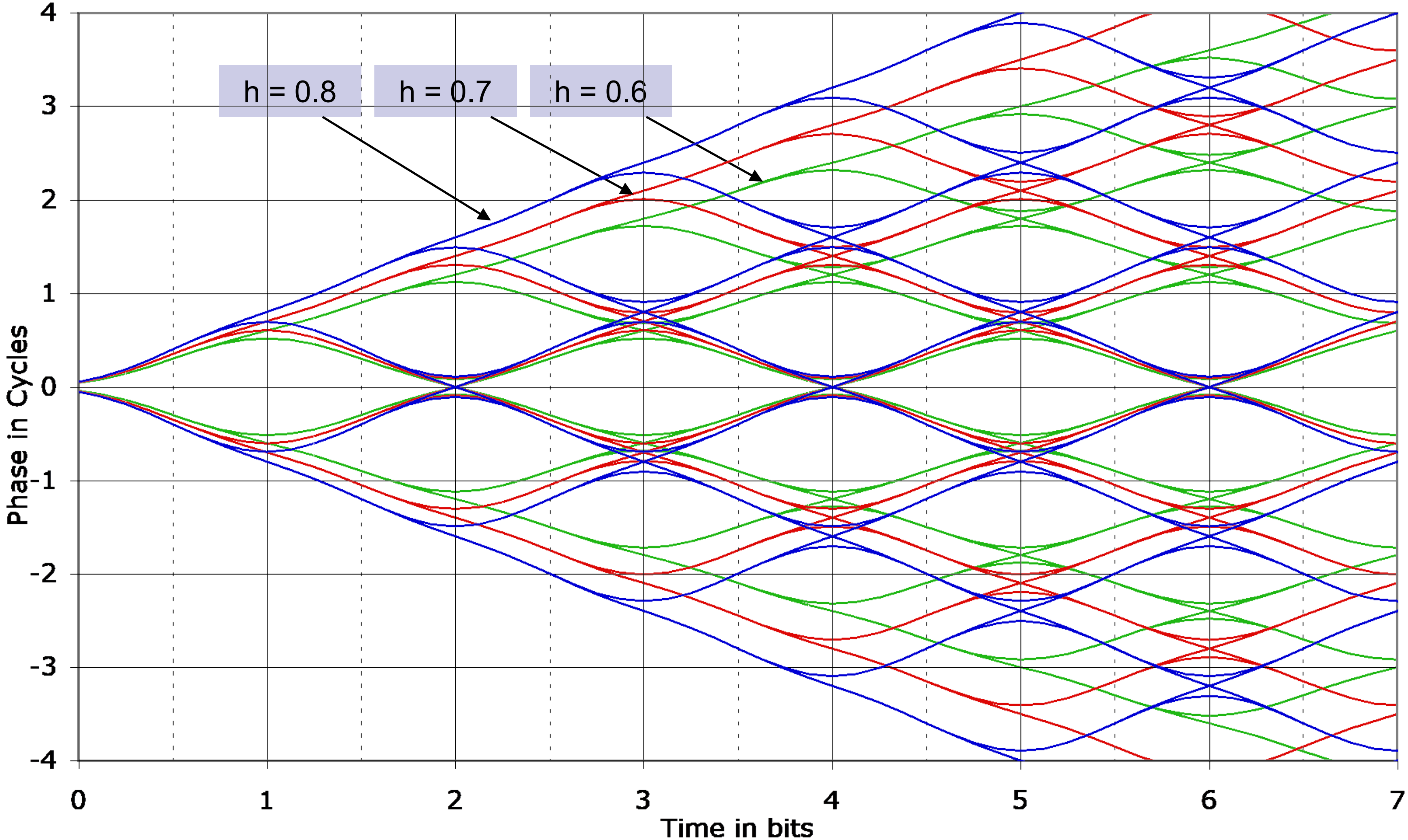


Brute force approach – yields performance gain, but leads to extreme hardware complexity

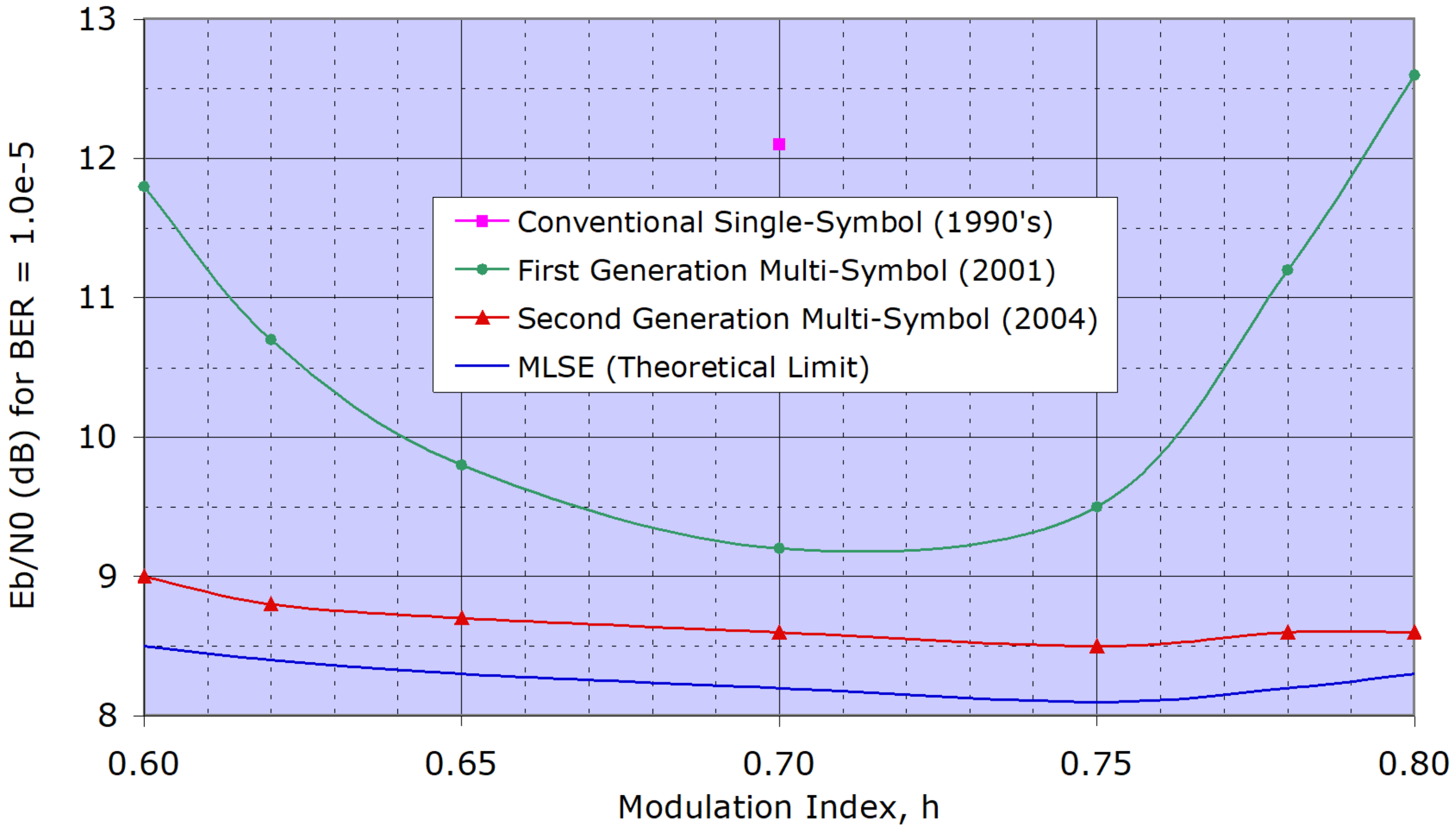
Tier 0 BER Performance



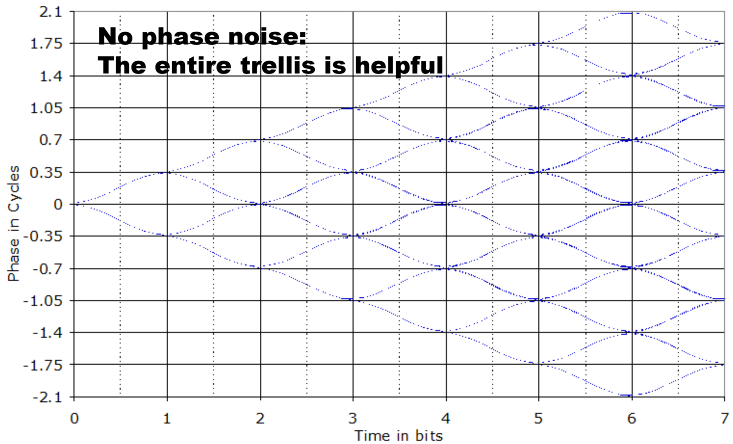
Legacy PCM/FM Transmitters

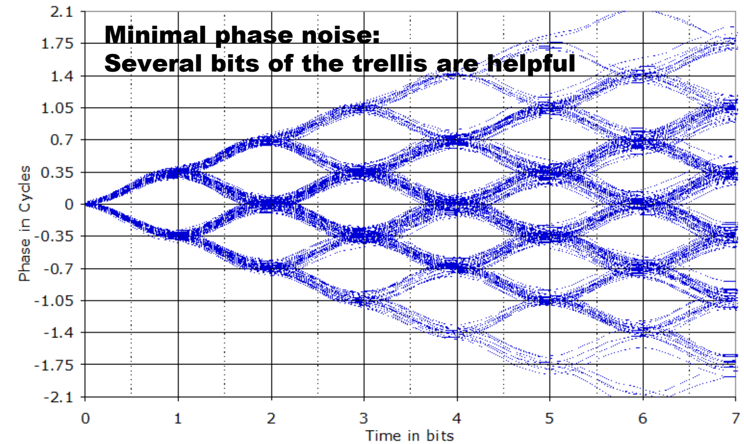


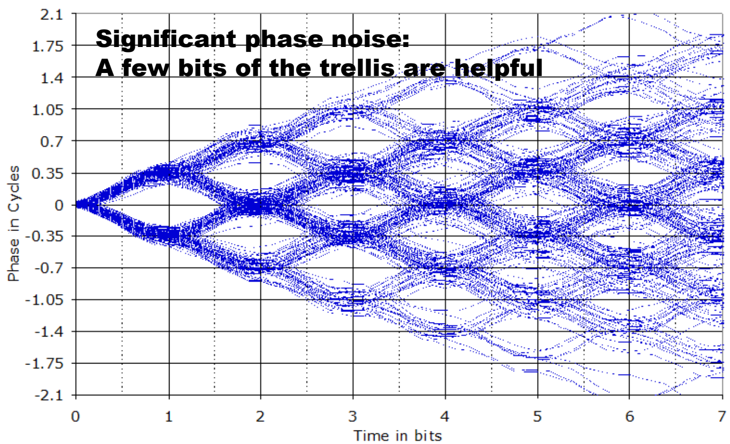
Effect of TX Deviation Error

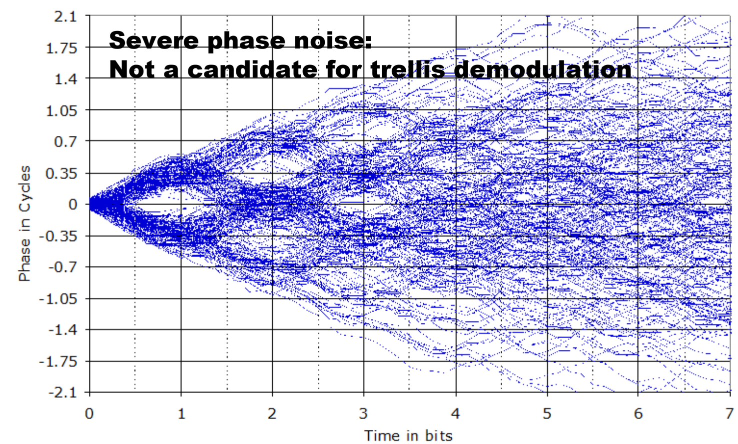


What About Phase Noise?









Phase Noise

- Trellis demodulation is based on the assumption that the signal is following a predictable path through the trellis.
- If this is not true (due to high phase noise), then a trellis demodulator may not provide the expected performance gain
- Most often an issue at low bit rates
- Some trellis demods handle this case by modifying the trellis calculations.

SOQPSK Detection

- Can be detected by conventional (non-shaped) offset QPSK demod
- Non-matched filtering loss of about 2 dB
- Butterworth lowpass filter is reasonable approximation to matched filter
- Trellis detection is optimum, but more complex

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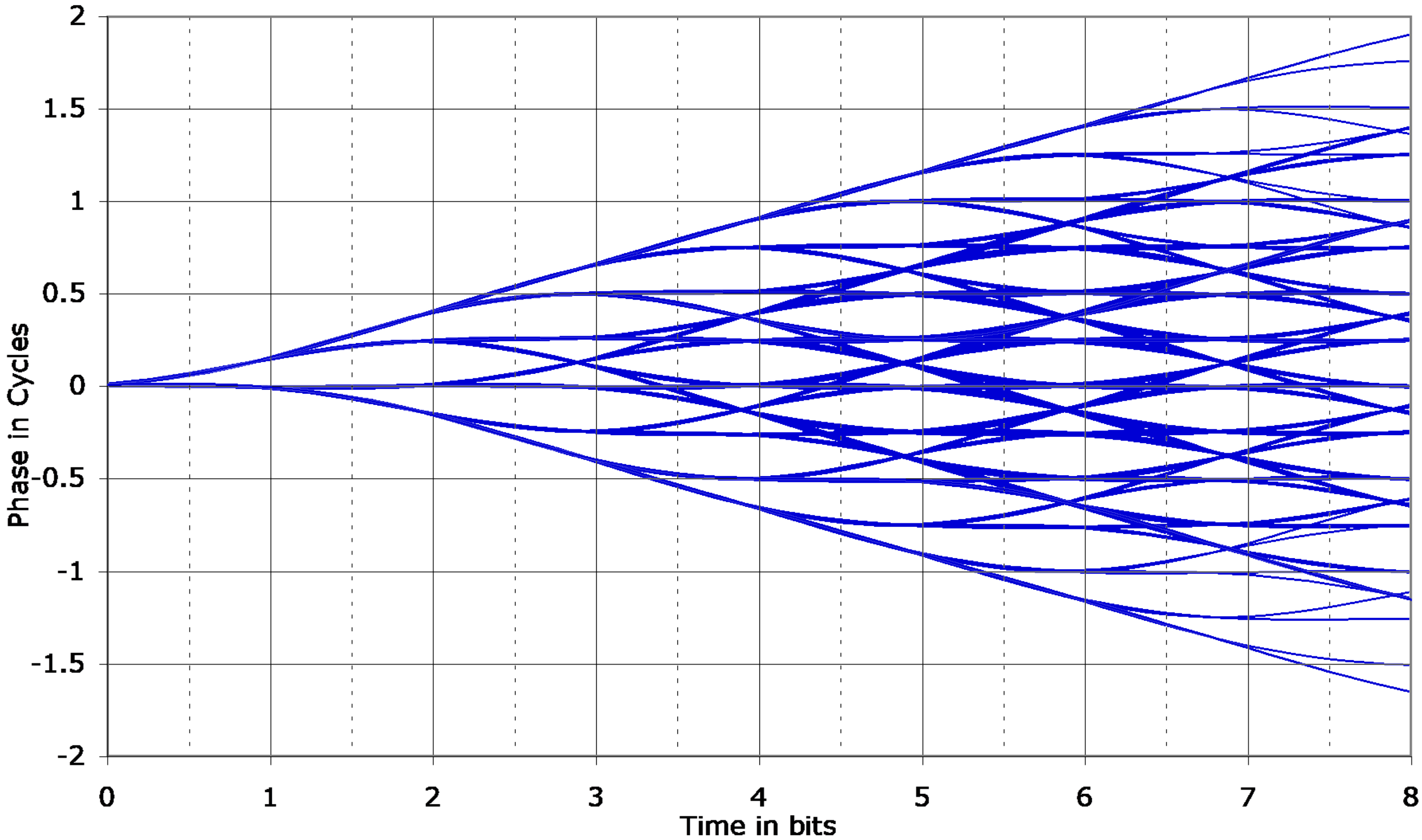
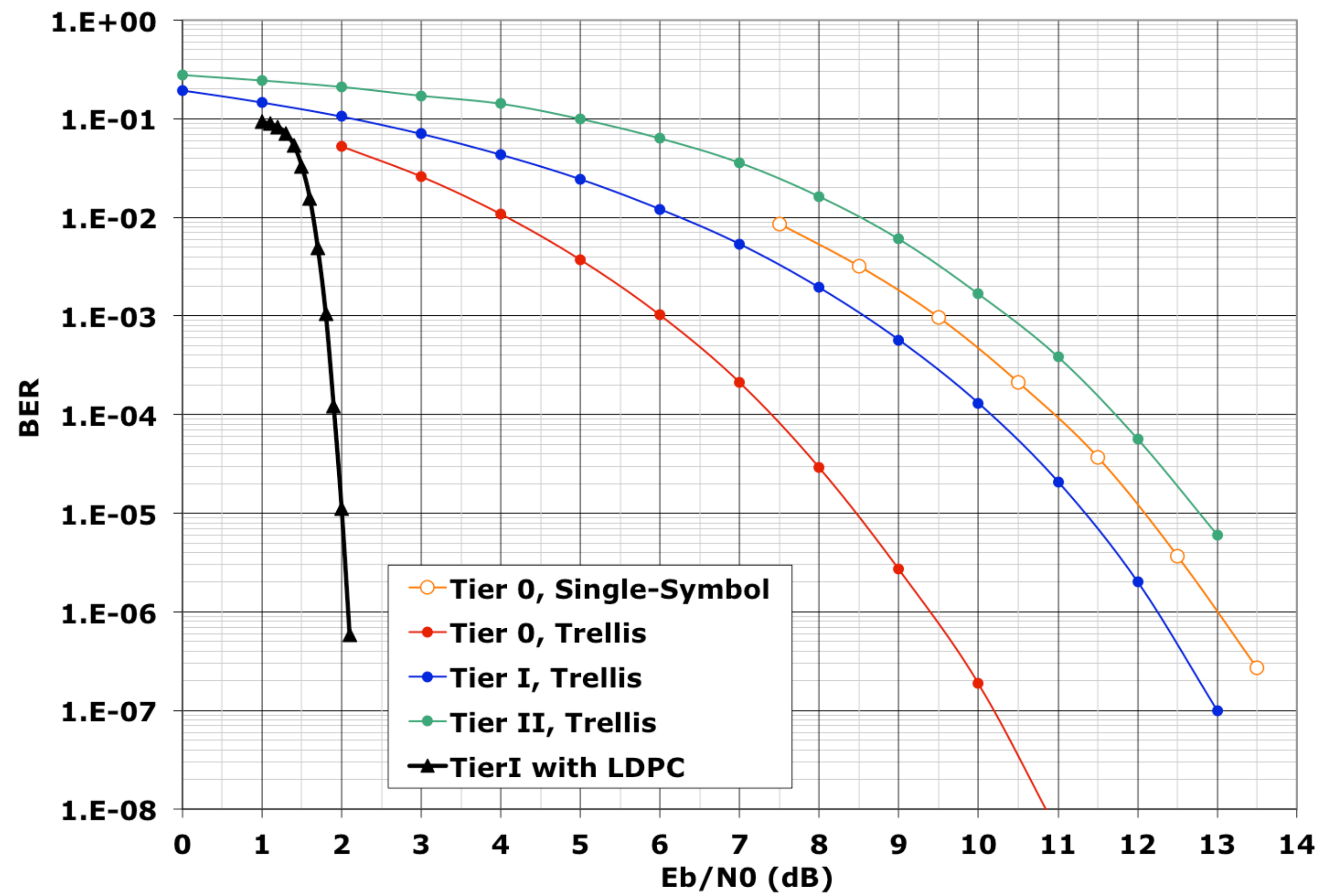
SOQPSK-TG Phase Tree



Multi-h CPM Detection

- Modulator intentionally creates severe inter-symbol interference
  - 3-symbol RC premod filter
- Symbol-by-symbol detection is essentially useless
- Trellis detection is required

BER Performance Comparison



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  - Multipath Propagation
- Impairment Mitigation Techniques
  - Adaptive Equalization
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