Advanced Modulation Techniques for Telemetry

A Short Course at the
International Telemetering Conference
Las Vegas, NV • October 23, 2017

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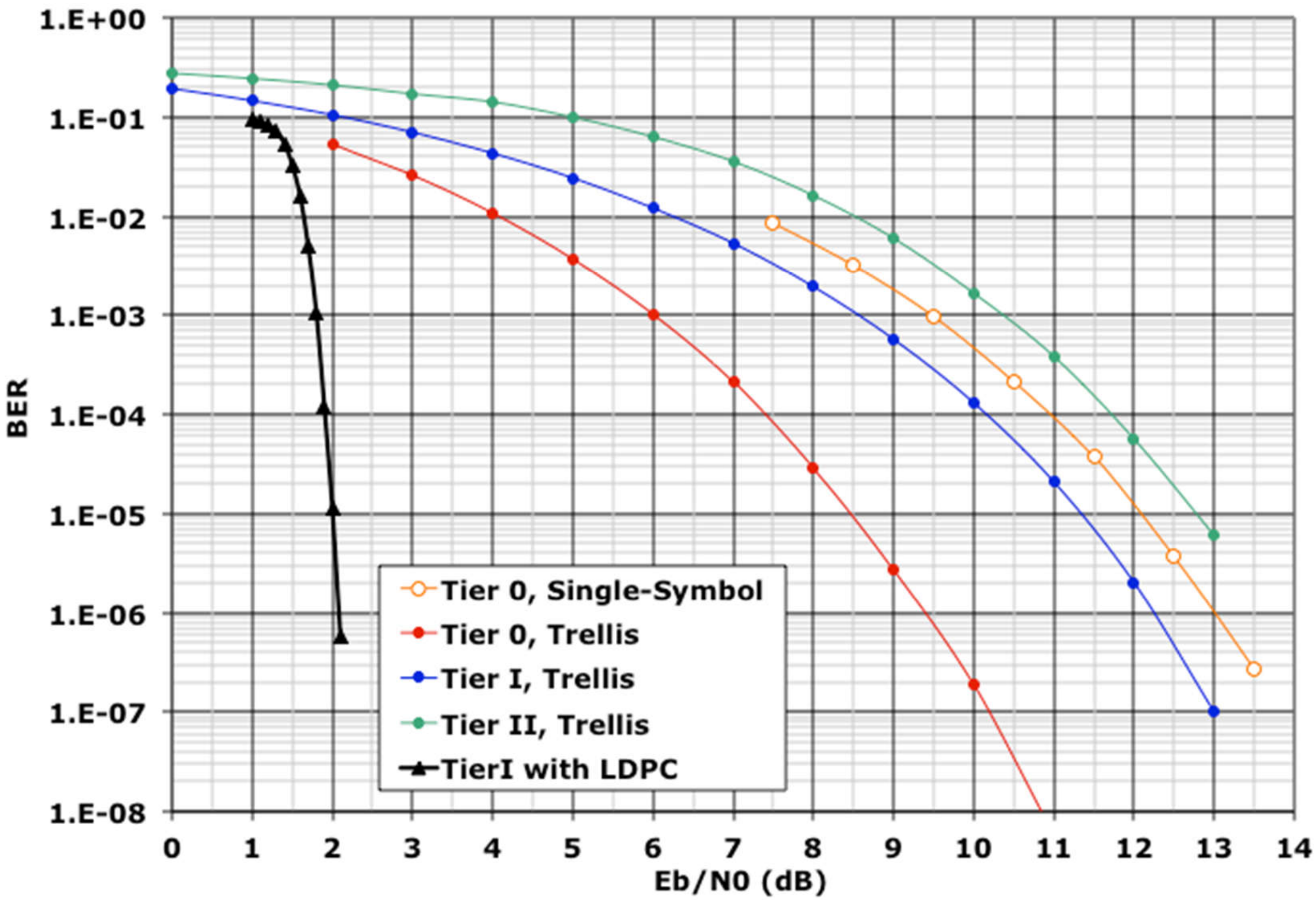
Course Outline

- Performance Metrics
- Continuous Phase Modulation (CPM)
  - Tier 0
  - Tier I
  - Tier II
- Demodulation
  - Synchronization
- Channel Impairments
  - Adjacent Channel Interference
  - Lunch
  - Multipath Propagation
- Impairment Mitigation Techniques
  - Diversity Combining
  - Adaptive Equalization
  - Best Source Selection
  - Space-Time Coding
  - Forward Error Correction (FEC)
- Using All the Tools Together
- Performance Comparison & Summary

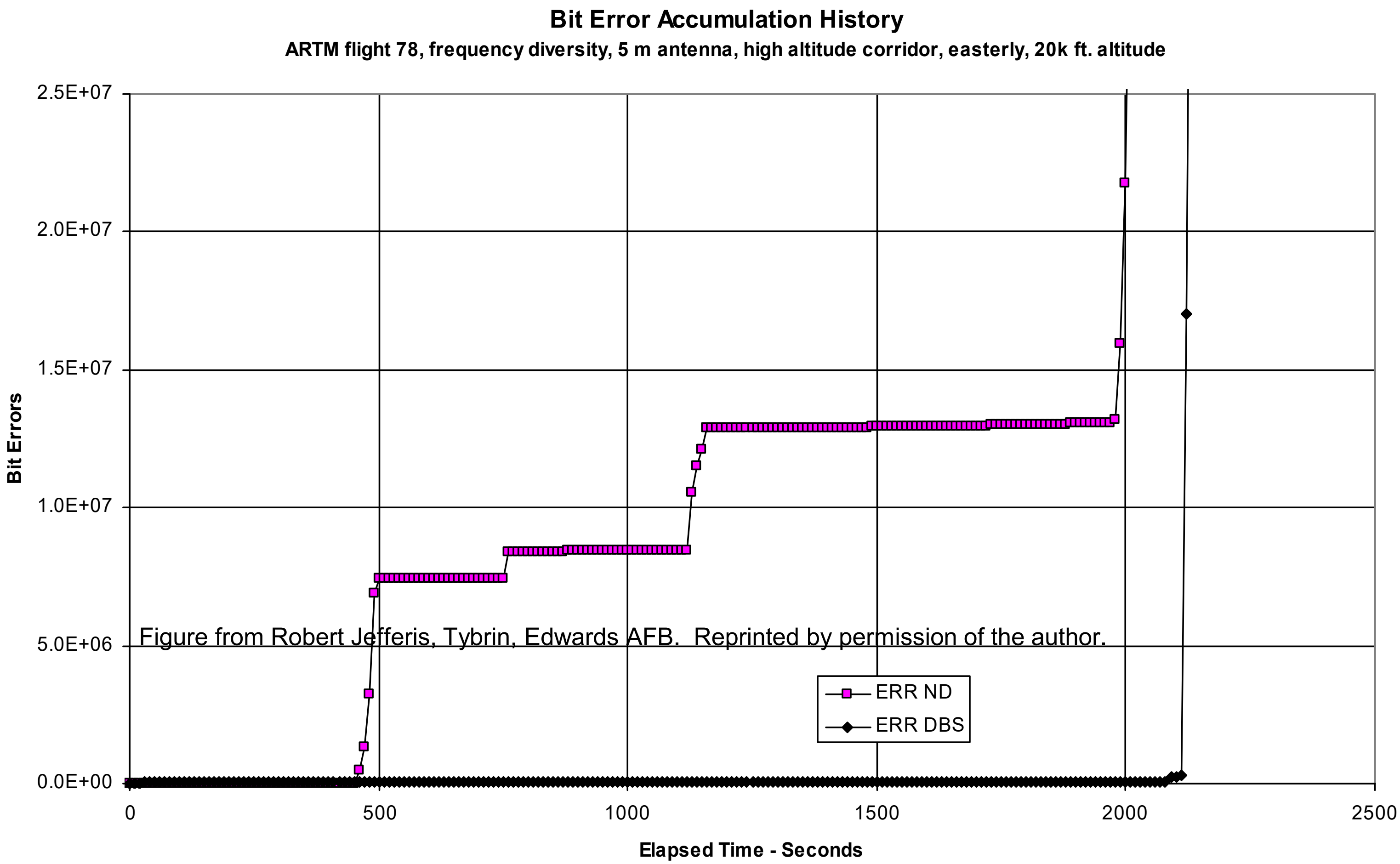
Performance Metrics

- Information Fidelity
  - Additive White Gaussian Noise (AWGN) channels
    - Bit Error Probability (BEP) or Bit Error Rate (BER)
  - Bursty (dropout) channels
    - Cumulative error count
    - Link Availability
- Bandwidth Efficiency
  - Power spectral density
  - Fractional Out-of-band Power
  - Channel spacing with adjacent channel interference (ACI)
- Bandwidth-Power plane

BER Performance Comparison



Cumulative Error Counts in Bursty Channels



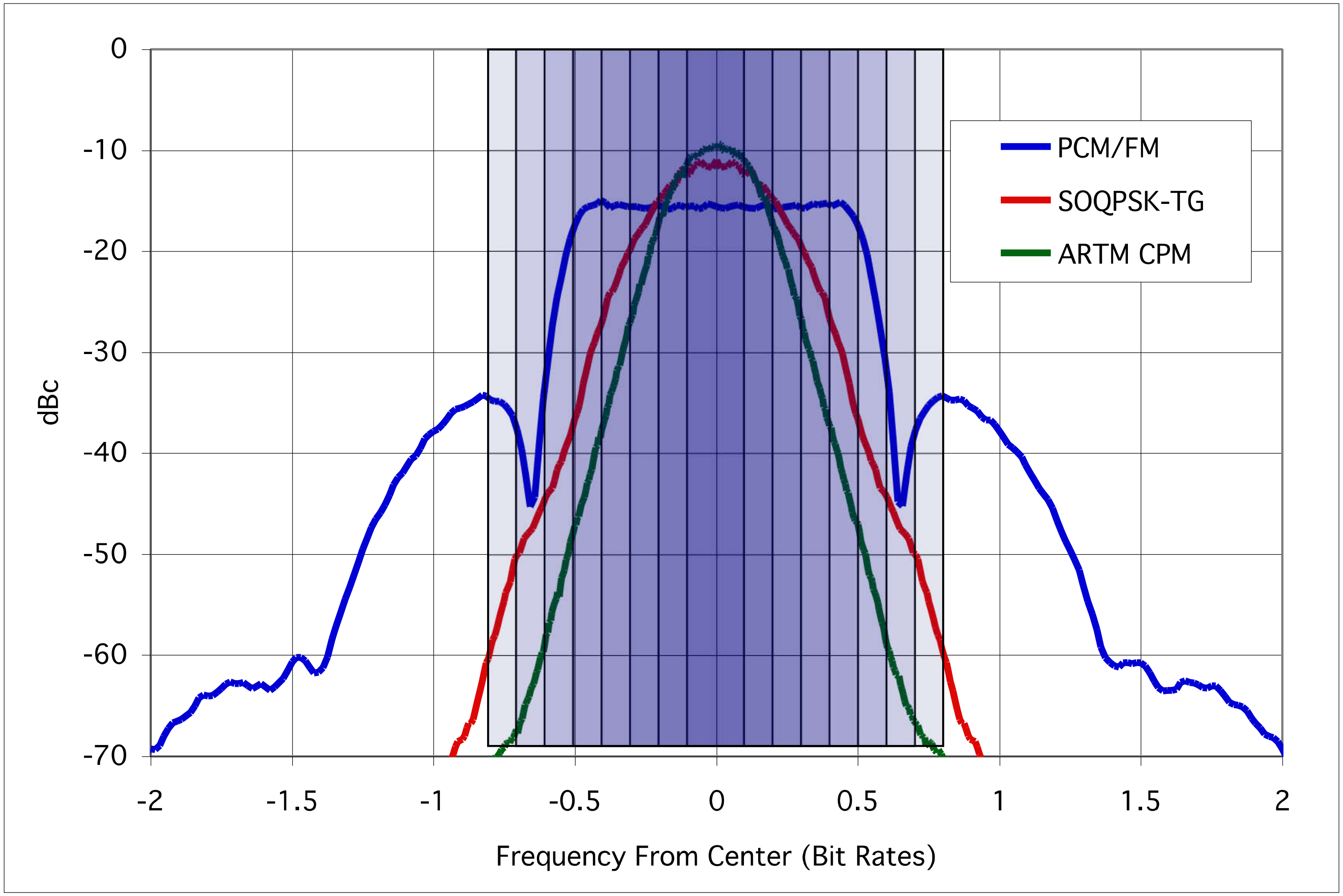
Performance Metrics

- ***Link Availability (LA)*** – % of the time that the instantaneous BER over 1 sec blocks is less than 10^{-5}.
- ***Video Availability (VA)*** - % of time video is available (picture on time/ total time x 100)
- These two metrics are not the same. Video system sensitivity and its response to bit errors can have significant impact on VA performance.

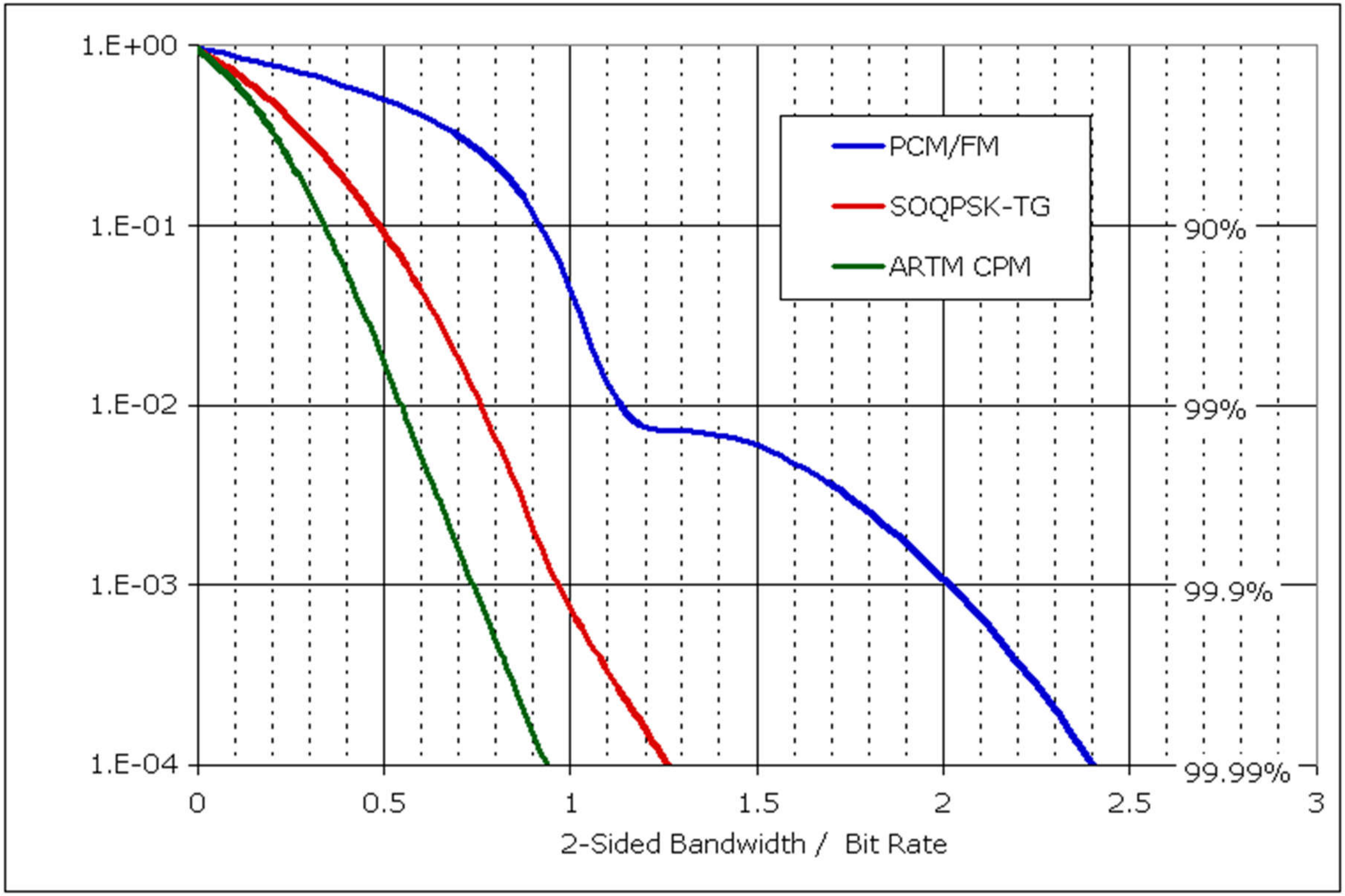
Which Bandwidth?

- Fixed level
  - -60 dBc is common
  - -25 dBm is “standard” in IRIG-106
- Fractional out-of-band power
  - 99%, 99.9%, 99.99% are all used
- Minimum frequency separation
  - Accounts for receive-side effects
    - Receiver IF filtering
    - Demodulator interference tolerance
    - Relative levels of interfering signals
    - Depends on application

Power Spectral Density (PSD)

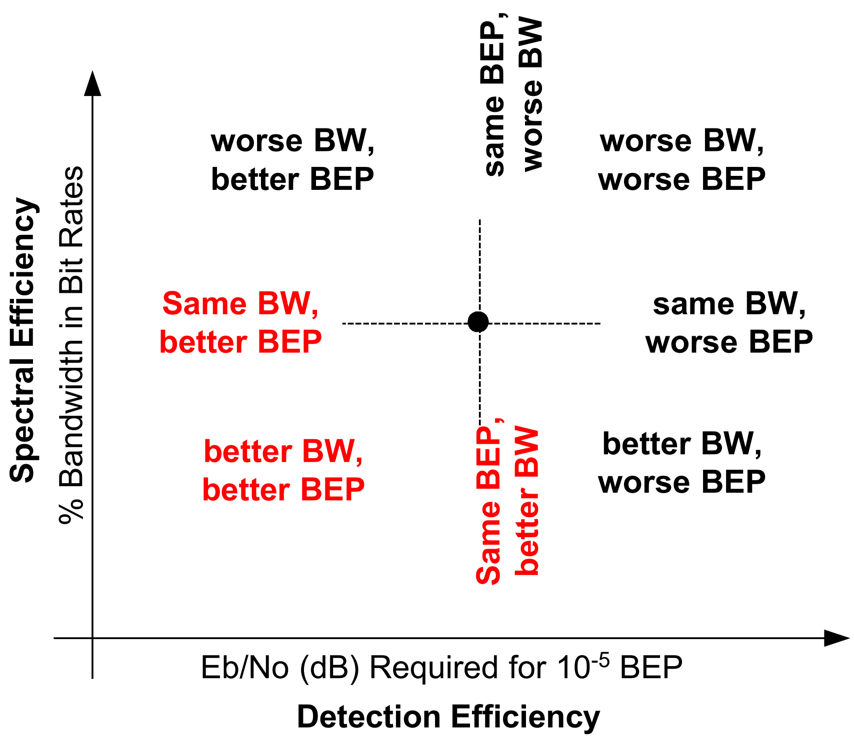


Fractional Out-of-band Power

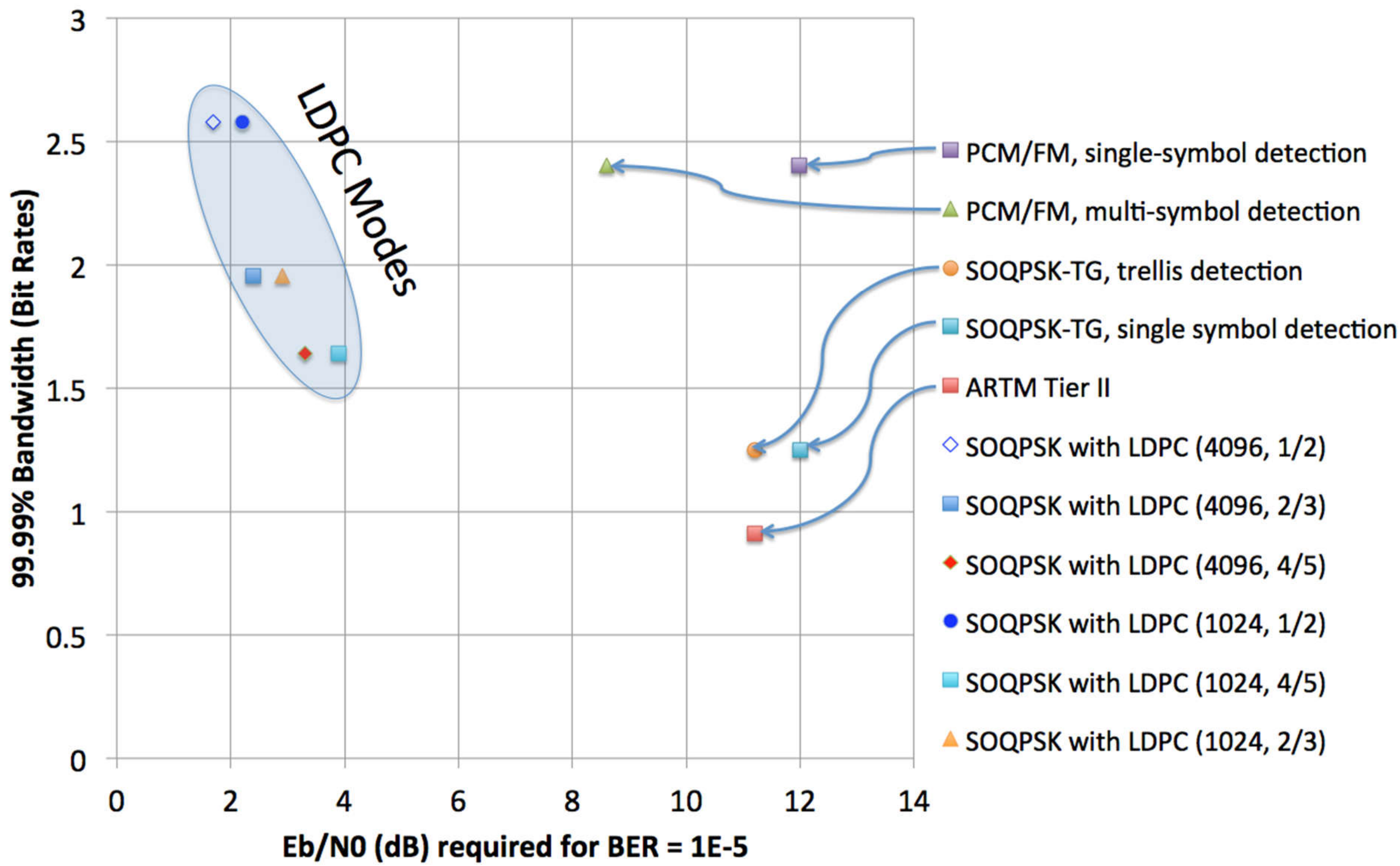


Bandwidth-Power Plane

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



Today's Modulation Tour



Continuous Phase Modulation

The Modulation Universe

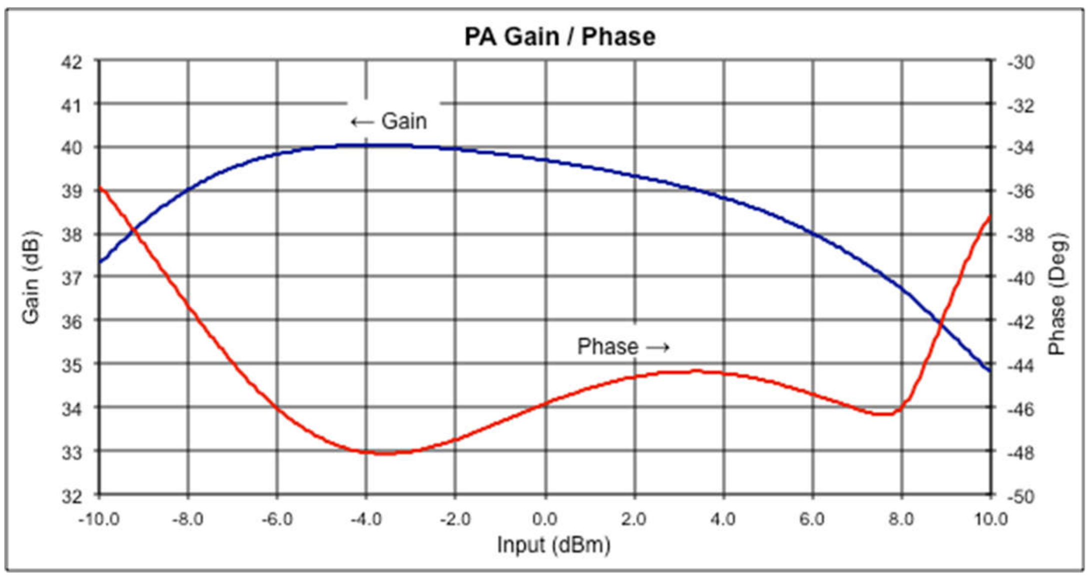
- Analog, Digital
- Amplitude modulation
- Quadrature amplitude modulation
- Angle modulations
  - Frequency modulation
  - Phase modulation

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.

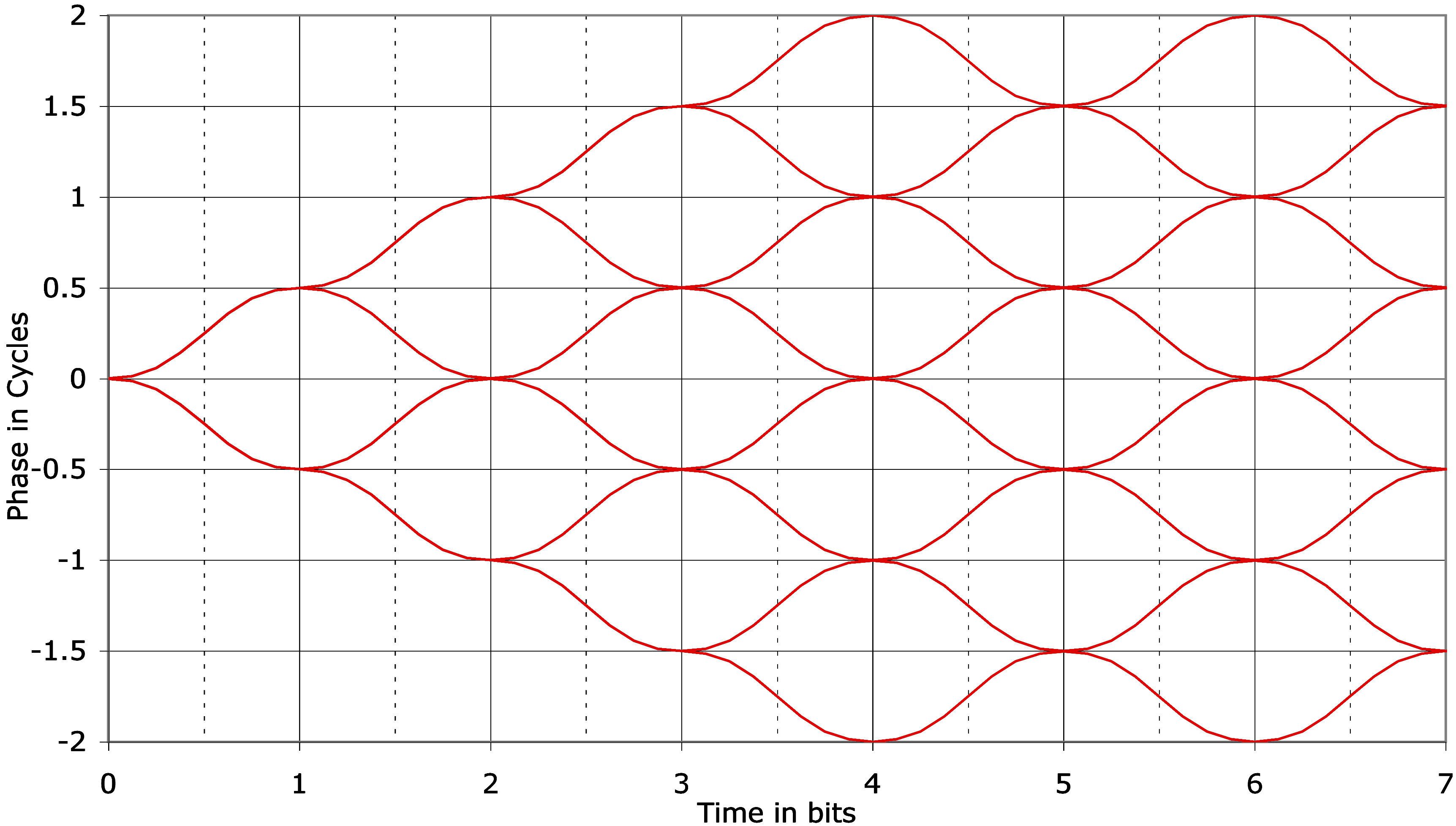
Key Parameters of CPM

- M – Order of Modulation (2-ary, 4-ary, etc.)
- g(t) - Frequency Pulse (Rectangular, Raised Cosine, etc.)
- L – Length of Frequency Pulse
- h – Modulation Index
- Increase Spectral Efficiency by
  - Increasing M
  - Reducing h
  - Increasing L
  - Choosing Smoother Frequency Pulse Shape
- In general, increasing spectral efficiency decreases detection efficiency

CPM Characteristics

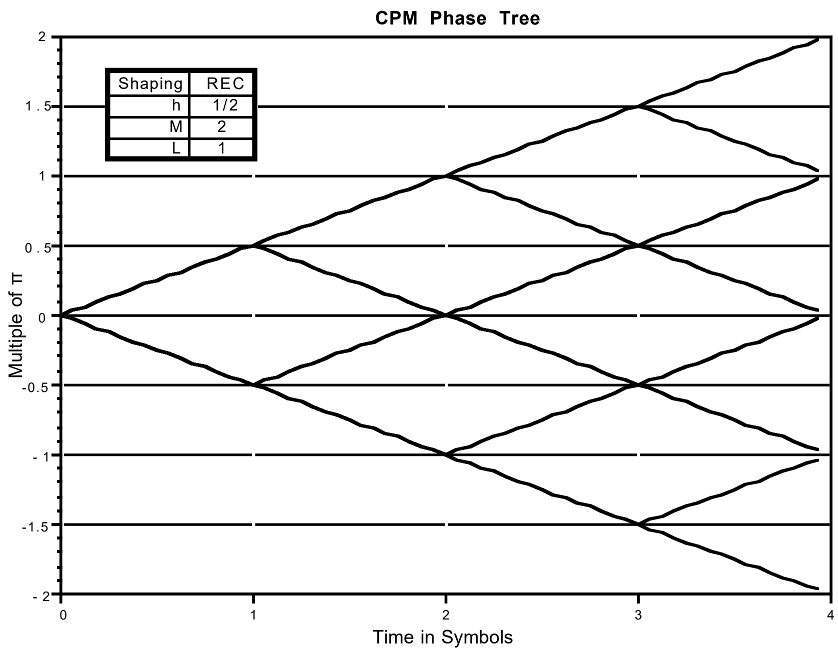
- Continuous Phase
- Constant envelope
- Signals are described by their phase trajectories
  - Phase tree representation is complete
- PSD and BER can be "traded" by
  - Varying h, modulation index
  - Changing g(t), the frequency pulse shape
- Phase trellis decoder is optimum for any variant of CPM

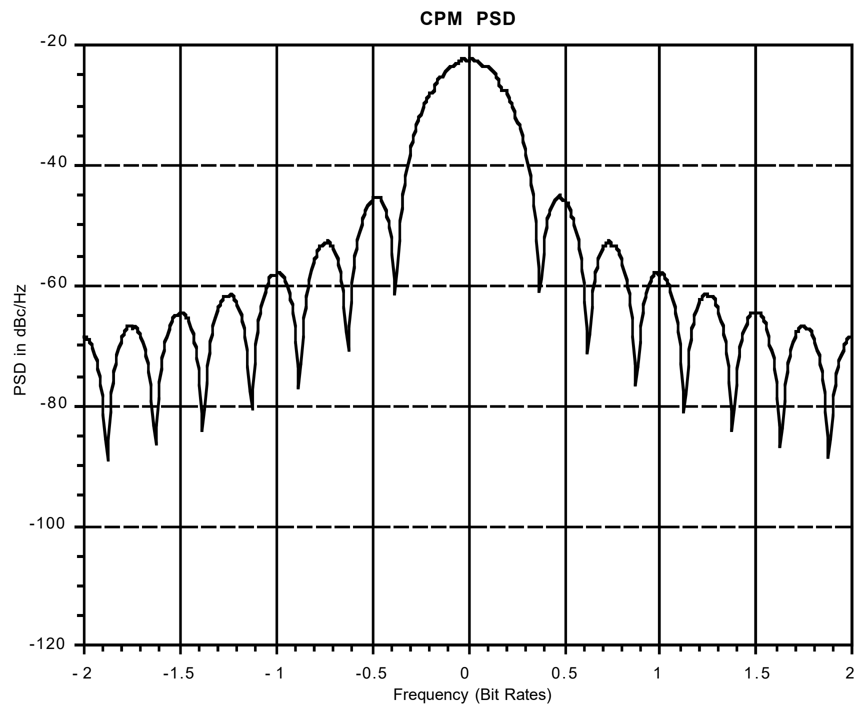
Phase Tree Representation



M=2, h=1/2, 1REC (MSK)

PSD vertical axis is dBc per FFT bin
1 FFT bin = 1/64 * symbol rate





M=4, h=1/4, 1REC

PSD vertical axis is dBc per FFT bin
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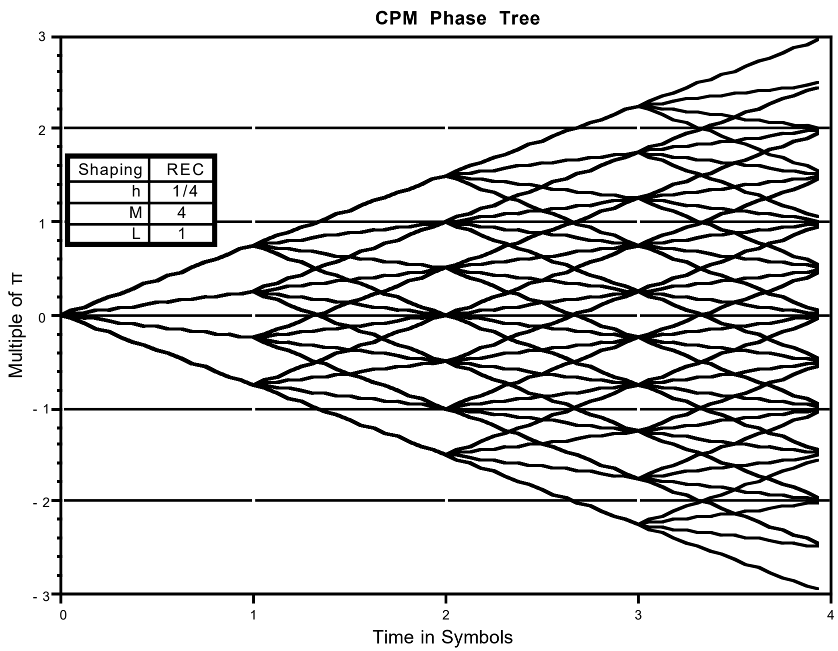
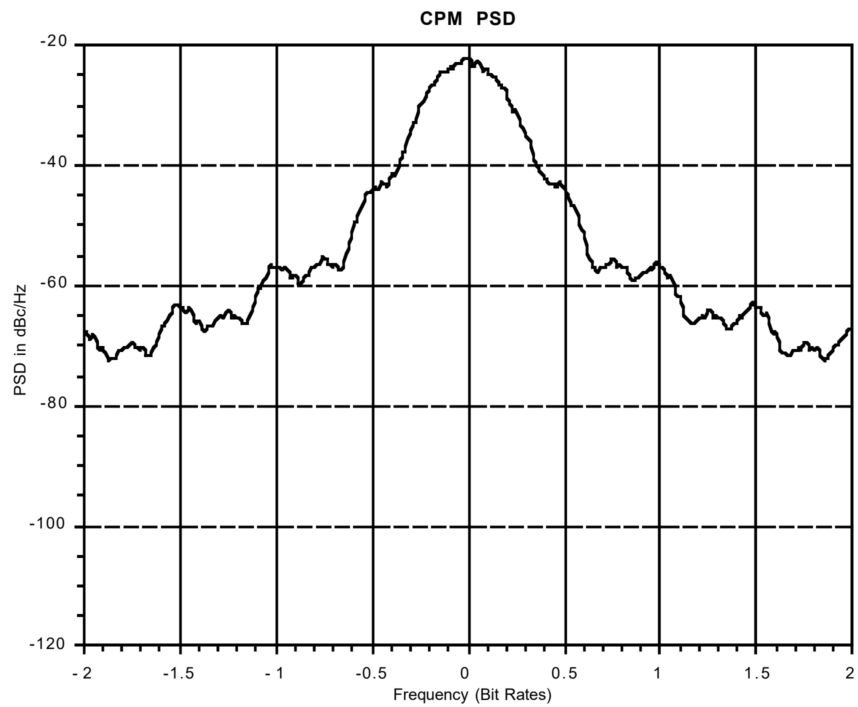
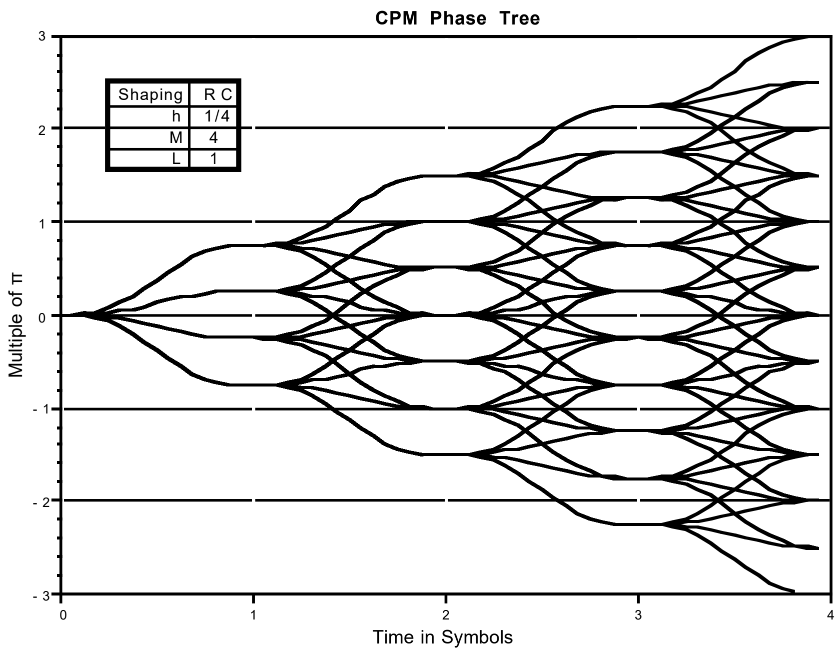
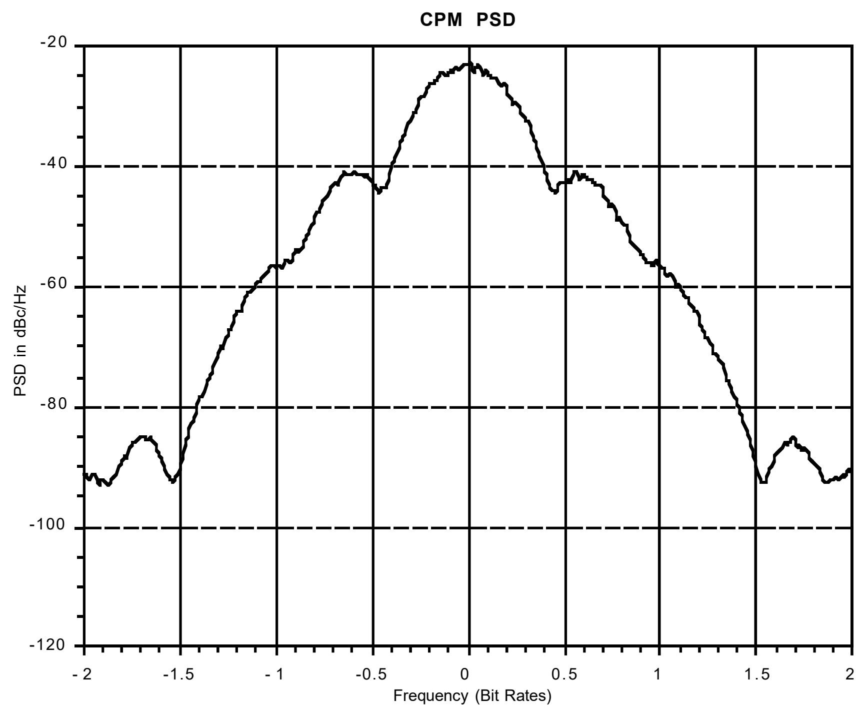




M=4, h=1/4, 1RC

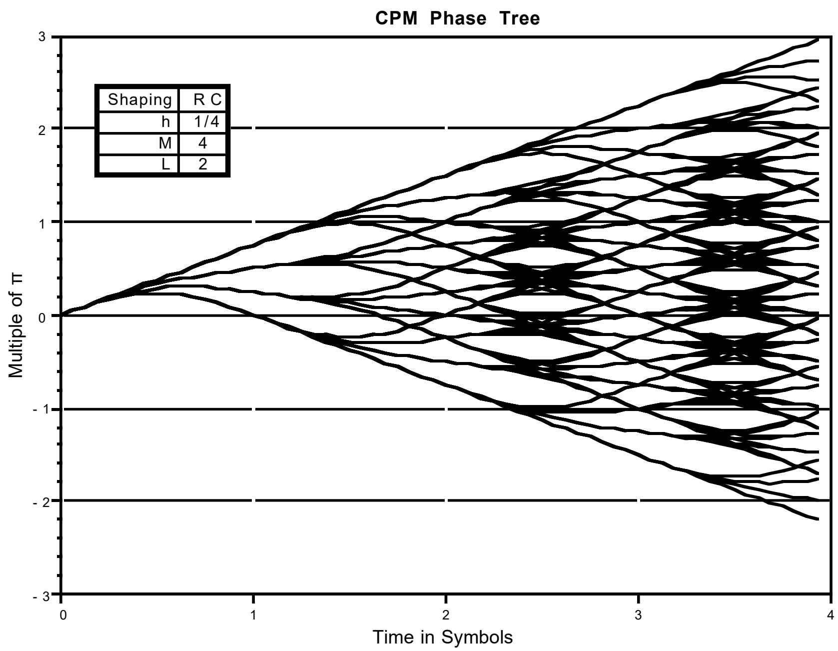
PSD vertical axis is dBc per FFT bin
1 FFT bin = 1/64 * symbol rate

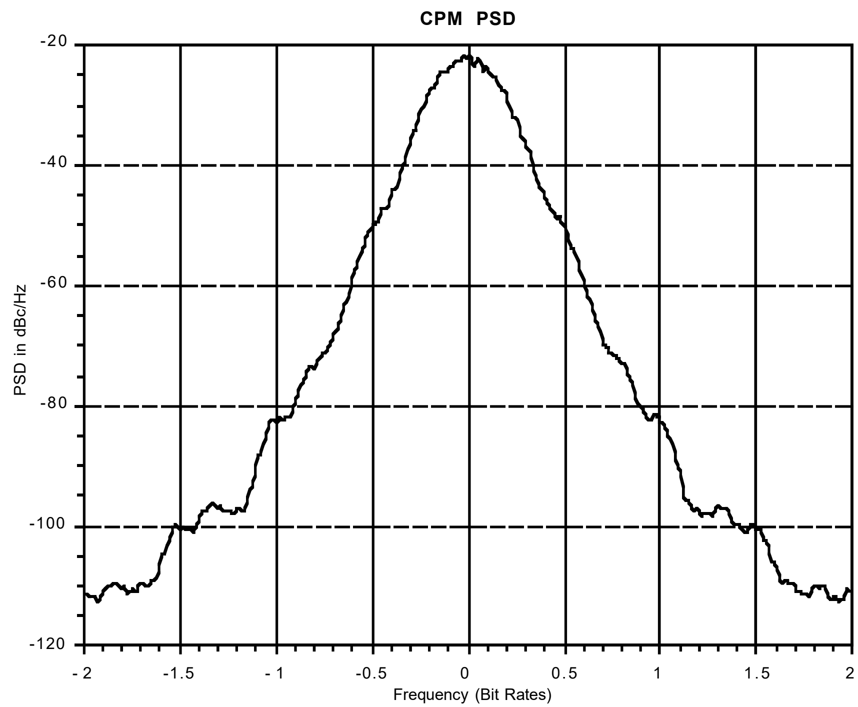




M=4, h=1/4, 2RC

PSD vertical axis is dBc per FFT bin
1 FFT bin = 1/64 * symbol rate





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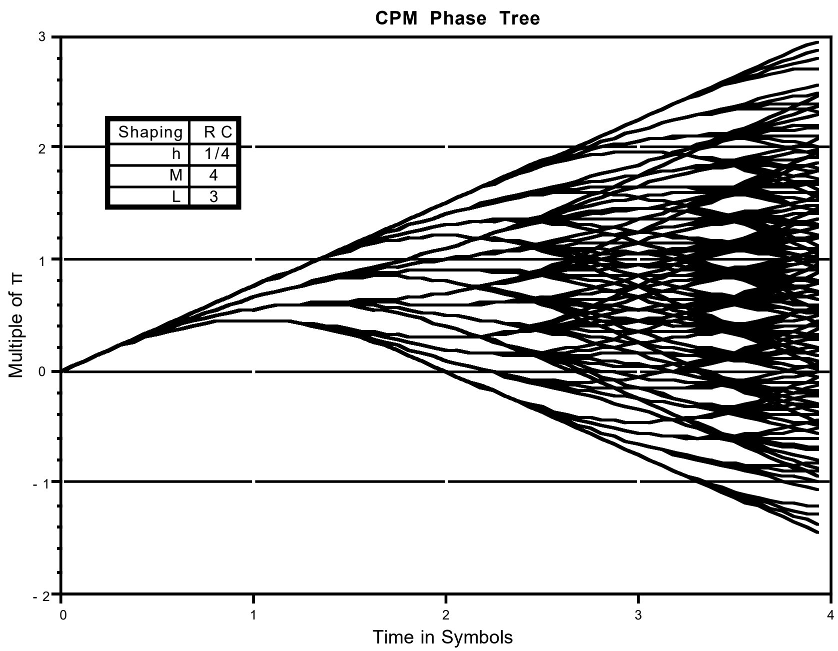
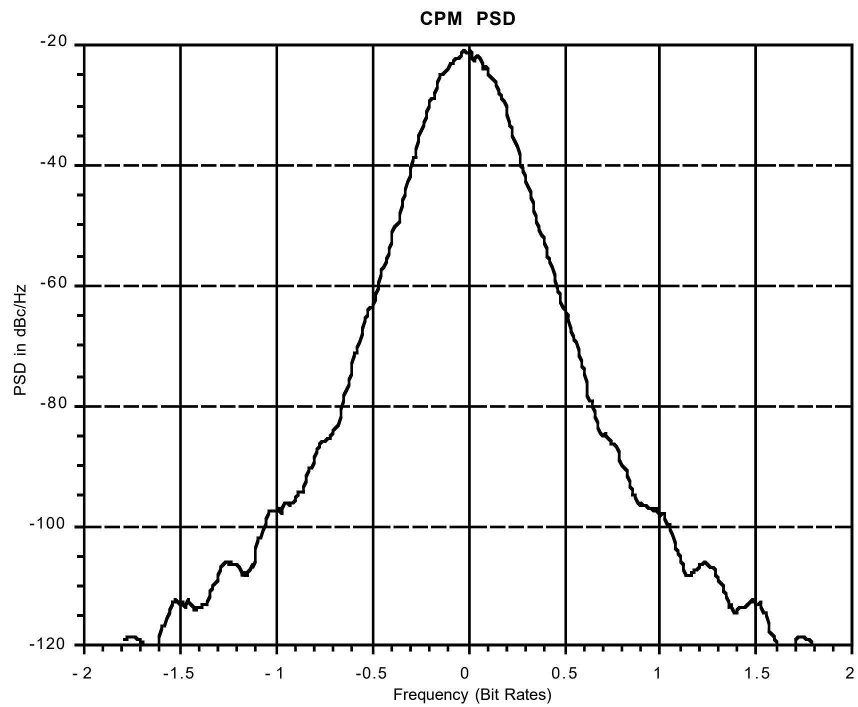
M=4, h=1/4, 3RC

PSD vertical axis is dBc per FFT bin
1 FFT bin = 1/64 * symbol rate



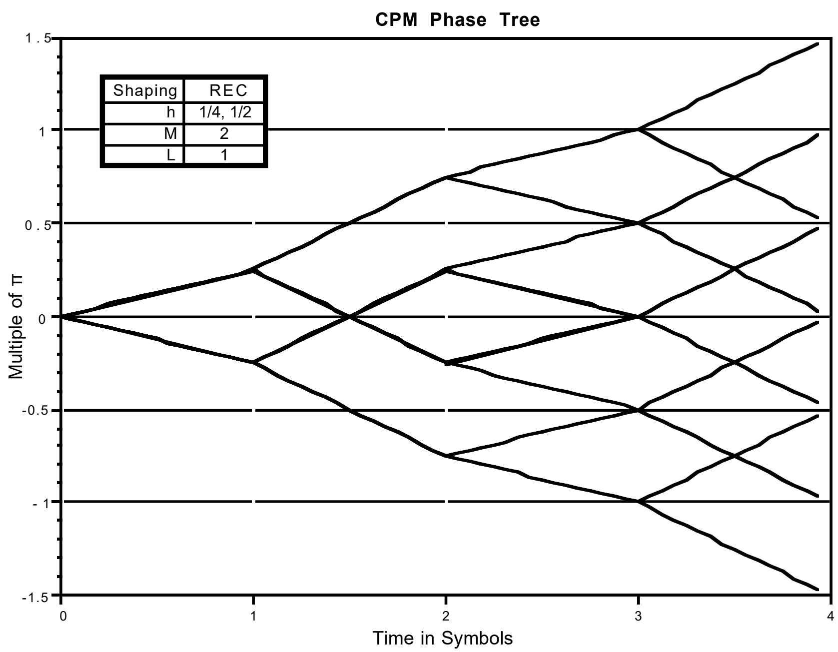


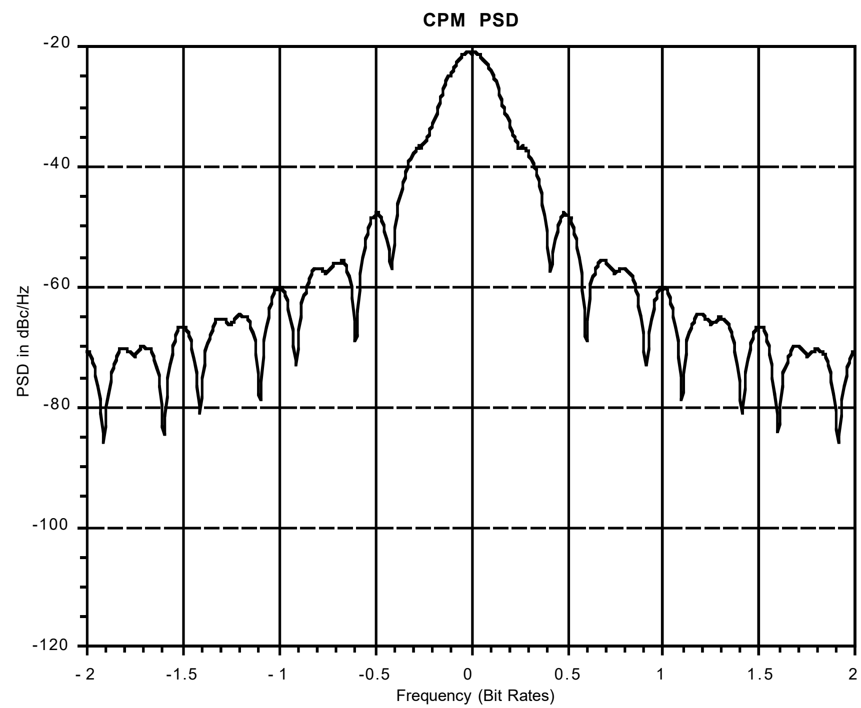
Multi-h CPM

- Cyclically rotates through multiple “sets” of FSK tones
- Increases minimum distance in trellis
  - Improves BER performance
- Widely proposed for high-performance nonlinear channels
  - MIL-STD-188-181B

M=2, h_1=1/4, h_2=1/2, 1REC

PSD vertical axis is dBc per FFT bin
1 FFT bin = 1/64 * symbol rate

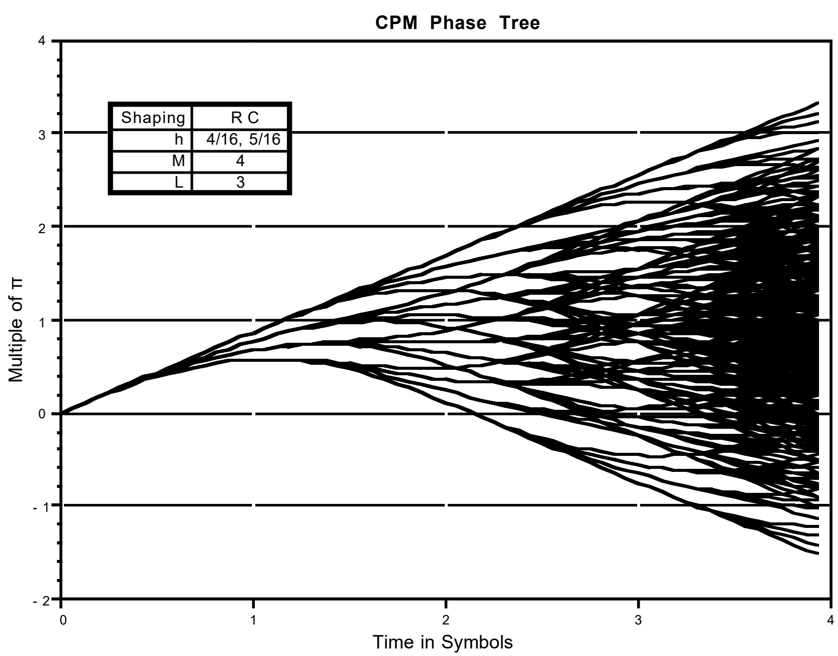


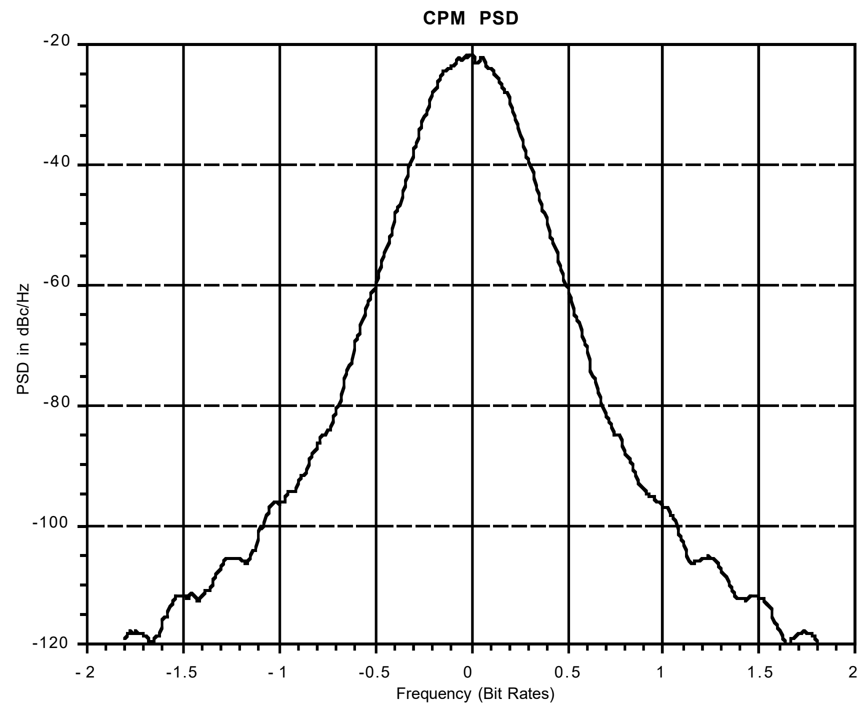


M=4, h_1=4/16, h_2=5/16, 3RC

ARTM Tier II Waveform

PSD vertical axis is dBc per FFT bin
1 FFT bin = 1/64 * symbol rate





CPM Summary

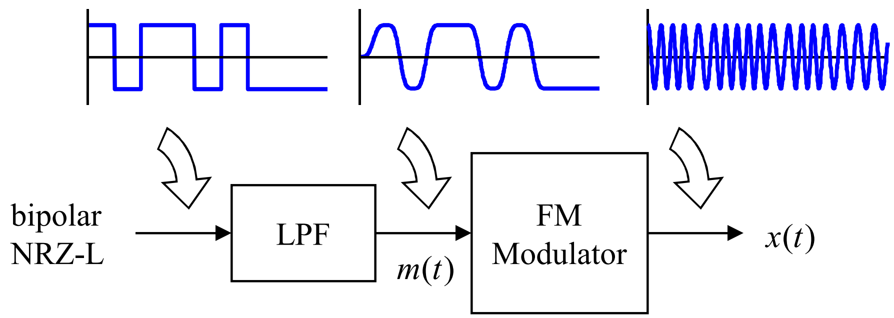
- To reduce bandwidth of a CPM signal, the phase transitions must be smoothed by:
  - Requiring phase to have more continuous derivatives
  - Spreading the phase change over more intervals (i.e., $L > 1$)
  - Reducing h
- The shape of $g(t)$ determines the smoothness of the information-carrying phase
- An endless variety of CPM schemes can be obtained by choosing different $g(t)$ pulse shapes and varying the parameters h and M.

Quasonix

ARTM Tier 0 (PCM/FM) (CPFSK)

The way things were

PCM/FM (Tier 0)



$$x(t) = A\cos\left(2\pi f_0 t + \phi(t)\right)$$

time-varying phase

$$\phi(t) = 2\pi f_d \int_{-\infty}^{t} m(\lambda)\,d\lambda$$

frequency is the time-derivative of the phase
since the phase is proportional to the integral of $m(t)$, the frequency is proportional to $m(t)$.

Figure from " Quadrature Modulation for Aeronautical Telemetry", by Michael Rice, BYU and Robert Jefferis, Tybrin Corp, ITC 2001. Reprinted by permission of the authors.

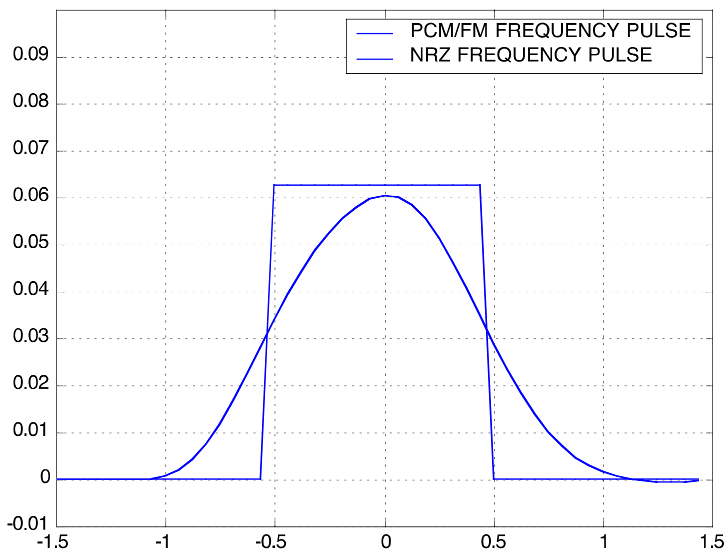
Tier 0 in CPM Notation

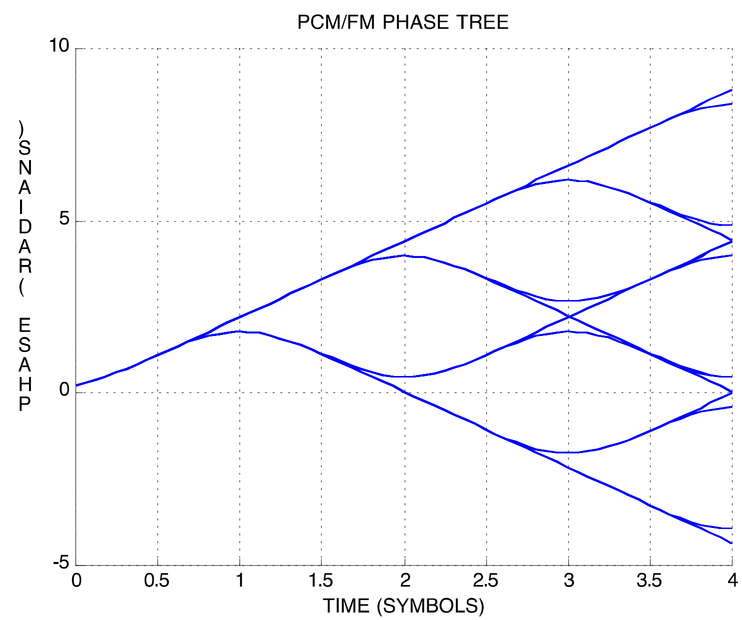
$$s(t) = \sqrt{2E/T}\cos[2\pi f_o t + \phi(t,\overline{\alpha}) + \phi_o]$$

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

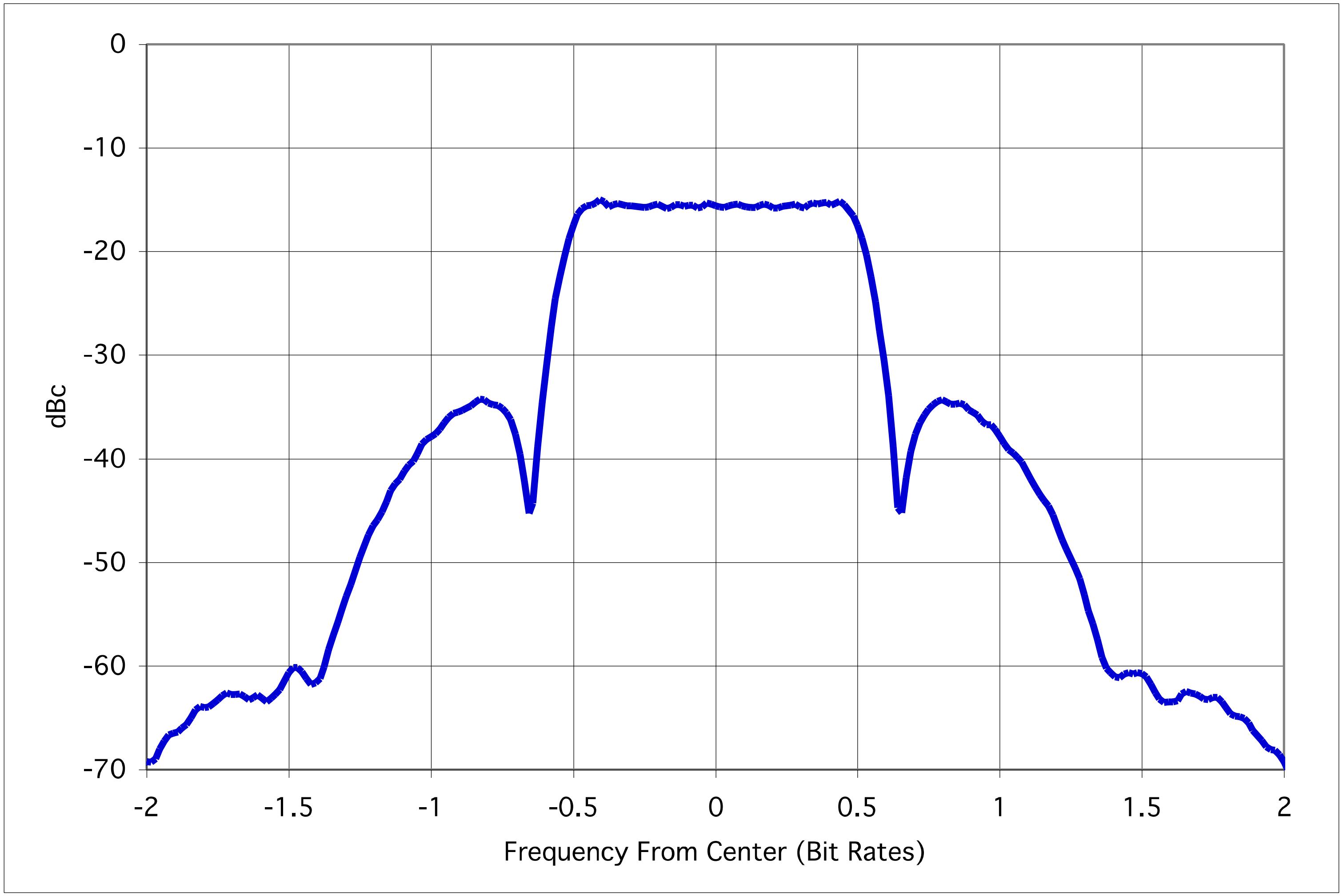
- M = 2 (binary)
- $\alpha_i = 2d_i - 1$
  - $d_i = \{0, 1\}$, $\alpha_i = \{-1, +1\}$
- h = 0.7
- g(t) is the normalized impulse response of a high order Bessel filter with 3 dB bandwidth = 0.7 * bit rate
  - Normalized such that the integral over all time = 1/2

PCM/FM as a Phase Modulation

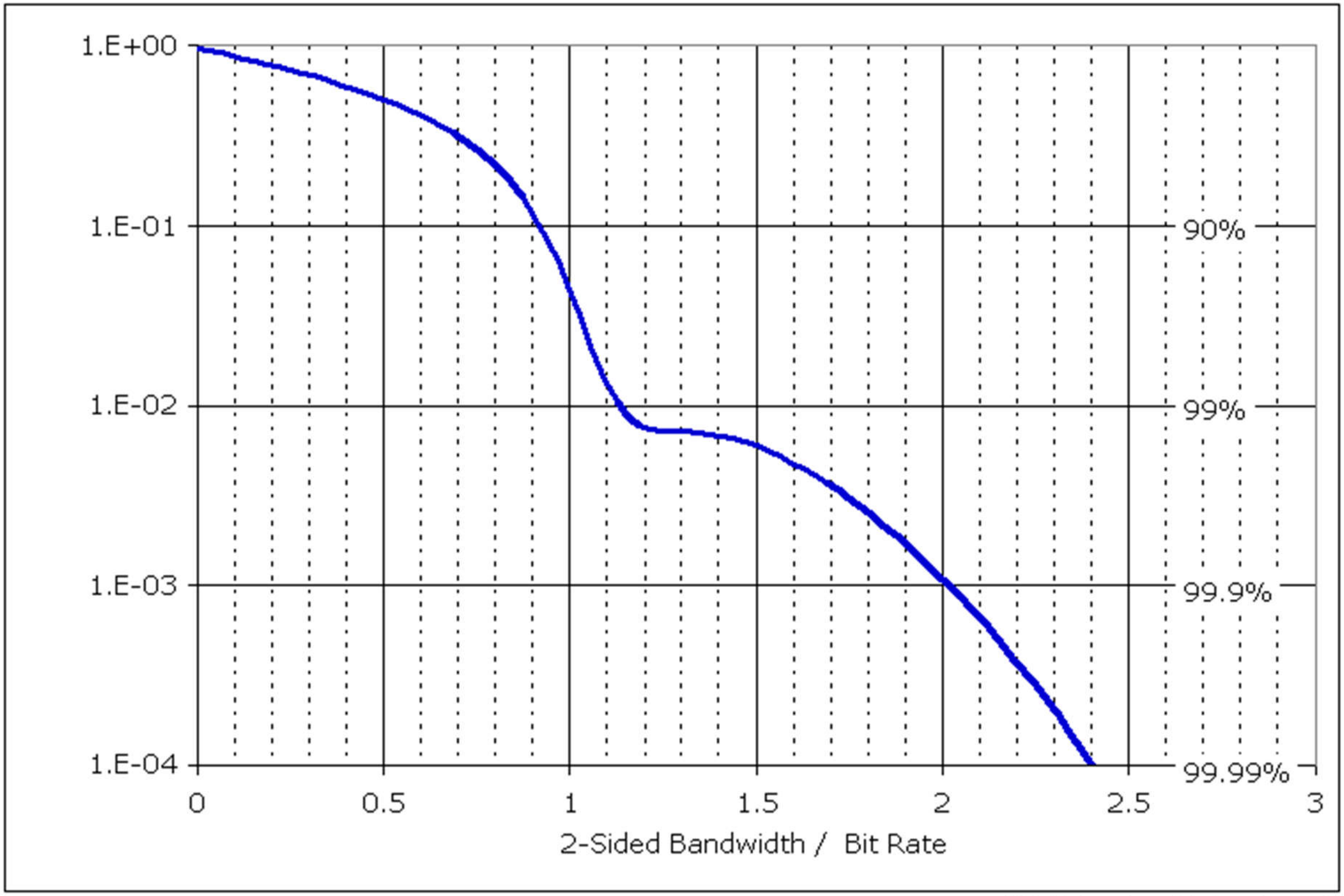




Power Spectral Density (PSD)



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

Tier I Overview

- Shaped OQPSK (SOQPSK)
  - Constant envelope modulation(s) introduced by Hill (ITC 2000)
  - Defined by 4 parameters (ρ, B, T_1, T_2)
  - Compatible with existing efficient non-linear class C power amplifier
  - Non-proprietary waveform
  - Comparable in performance and interoperable with FQPSK
- FQPSK
  - Patented by K. Feher
  - Defined by I and Q components
  - Non-constant envelope
  - Details are proprietary, contact Digcom

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

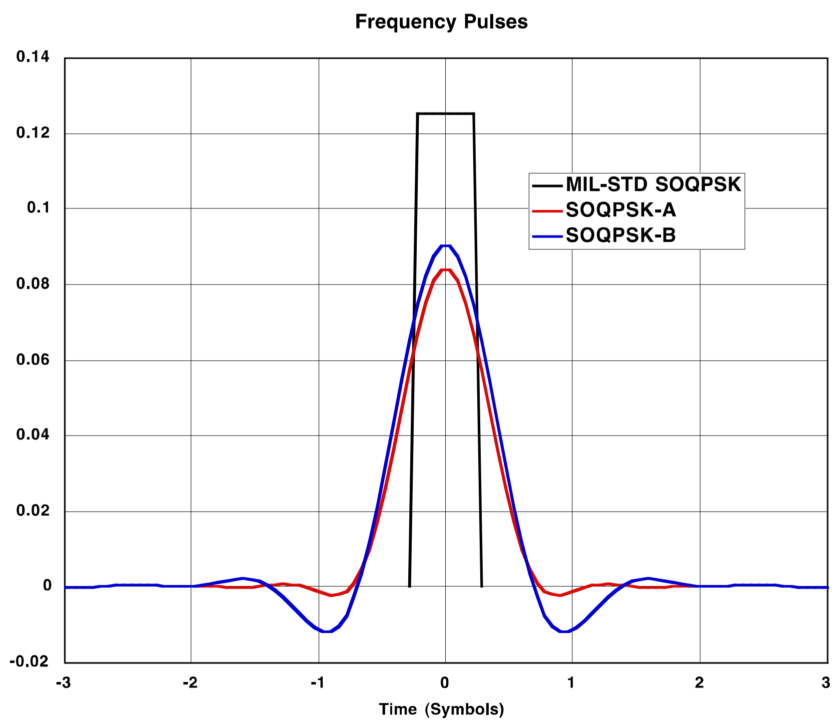
Definition of SOQPSK Pulse

g(t) = n(t) * w(t), where

$$n(t) = \frac{A\cos(\pi\rho Bt/T)}{1-4(\rho Bt/T)^2} * \frac{\sin(\pi Bt/T)}{(\pi Bt/T)}$$

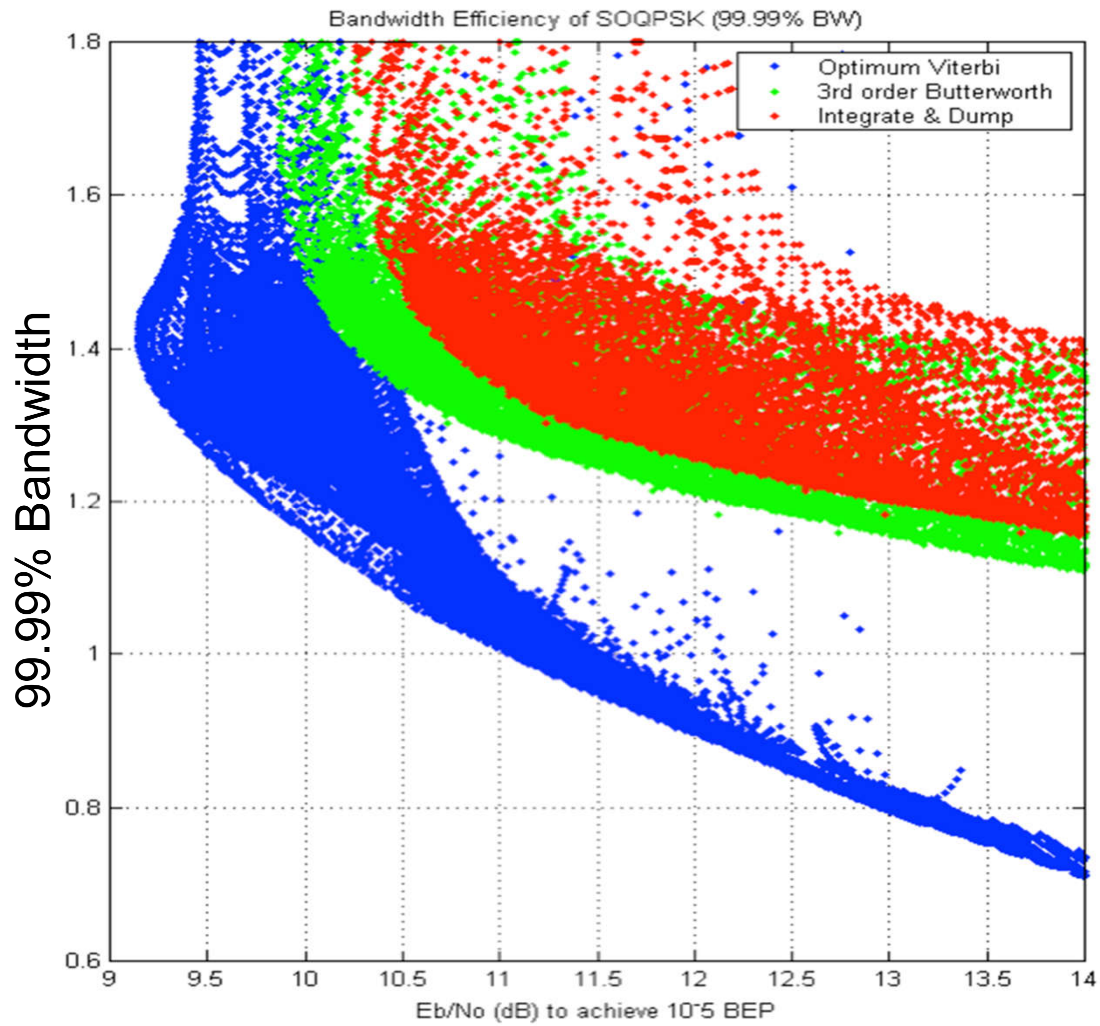
$$w(t) = \begin{cases} 1, & for \quad |t/T| < T_1 \\ \frac{1}{2} + \frac{1}{2}\cos\frac{\pi(|t/T| - T_1)}{T_2}, & for \quad T_1 < |t/T| < T_1 + T_2 \\ 0, & for \quad |t/T| > T_1 + T_2 \end{cases}$$

Frequency Pulse Shape, g(t)

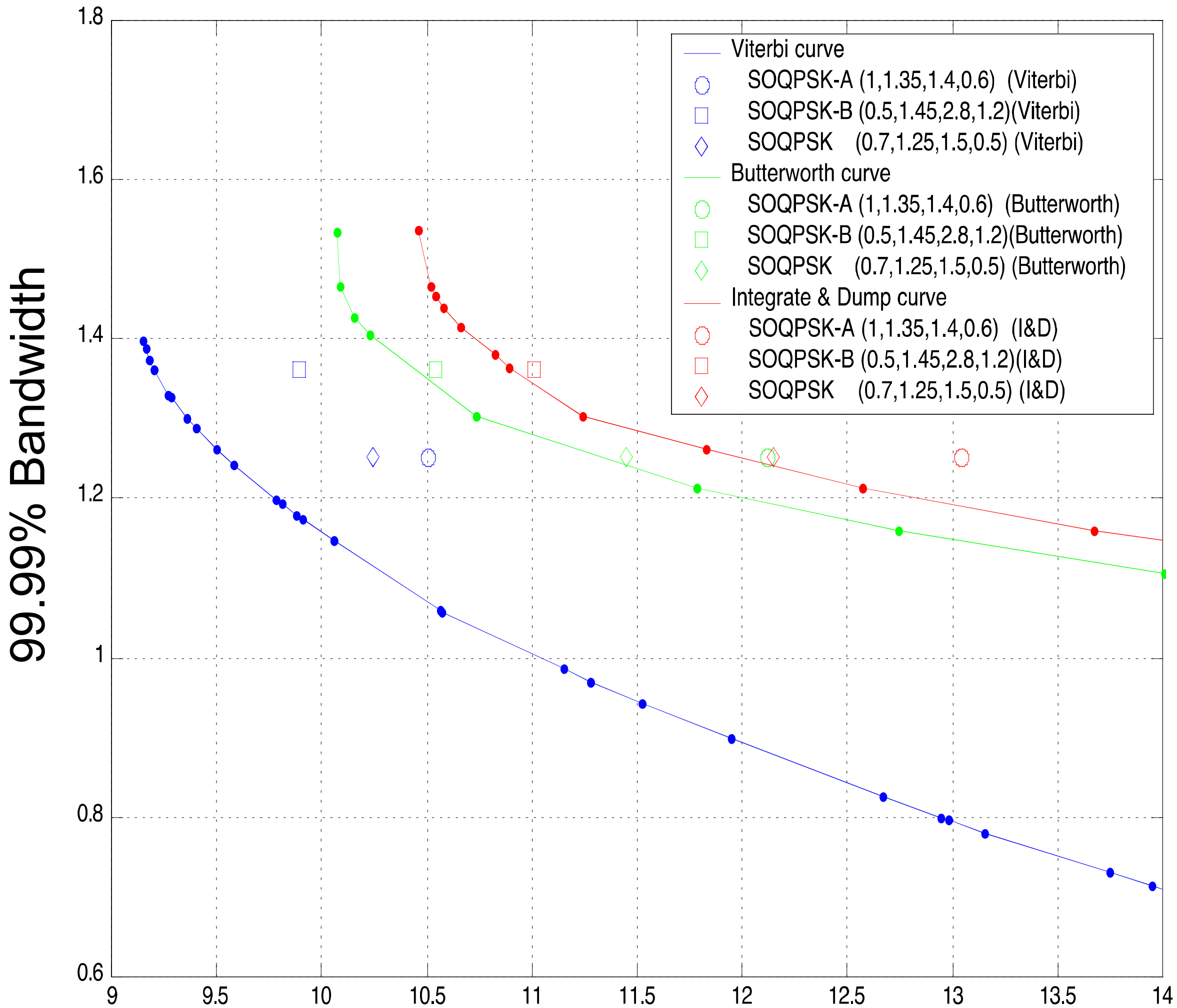


Parameter	SOQPSK-A	SOQPSK-B
ρ	1.0	0.5
B	1.35	1.45
T_1	1.4	2.8
T_2	0.6	1.2

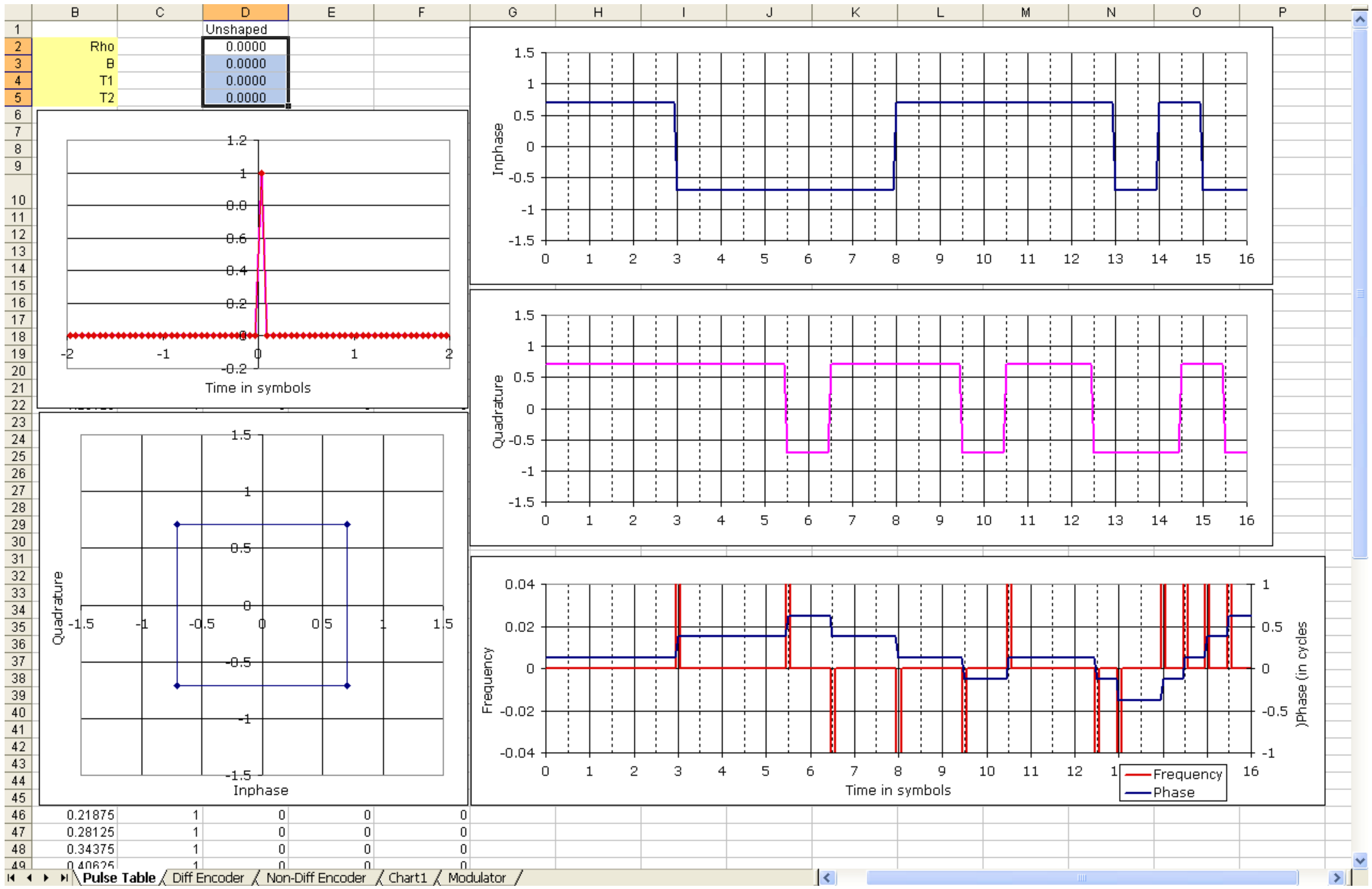
SOQPSK Variants



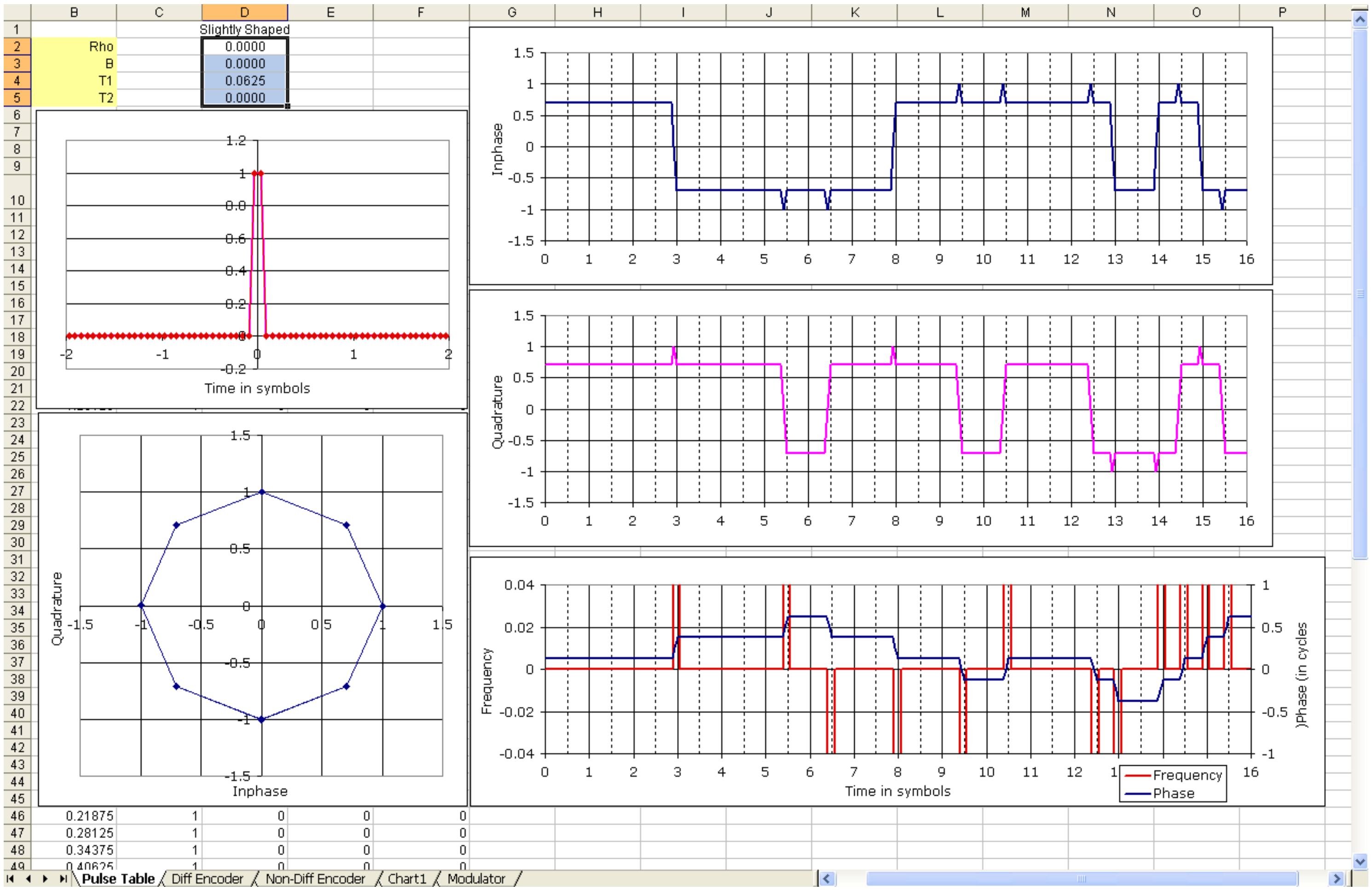
Optimal SOQPSK Variants



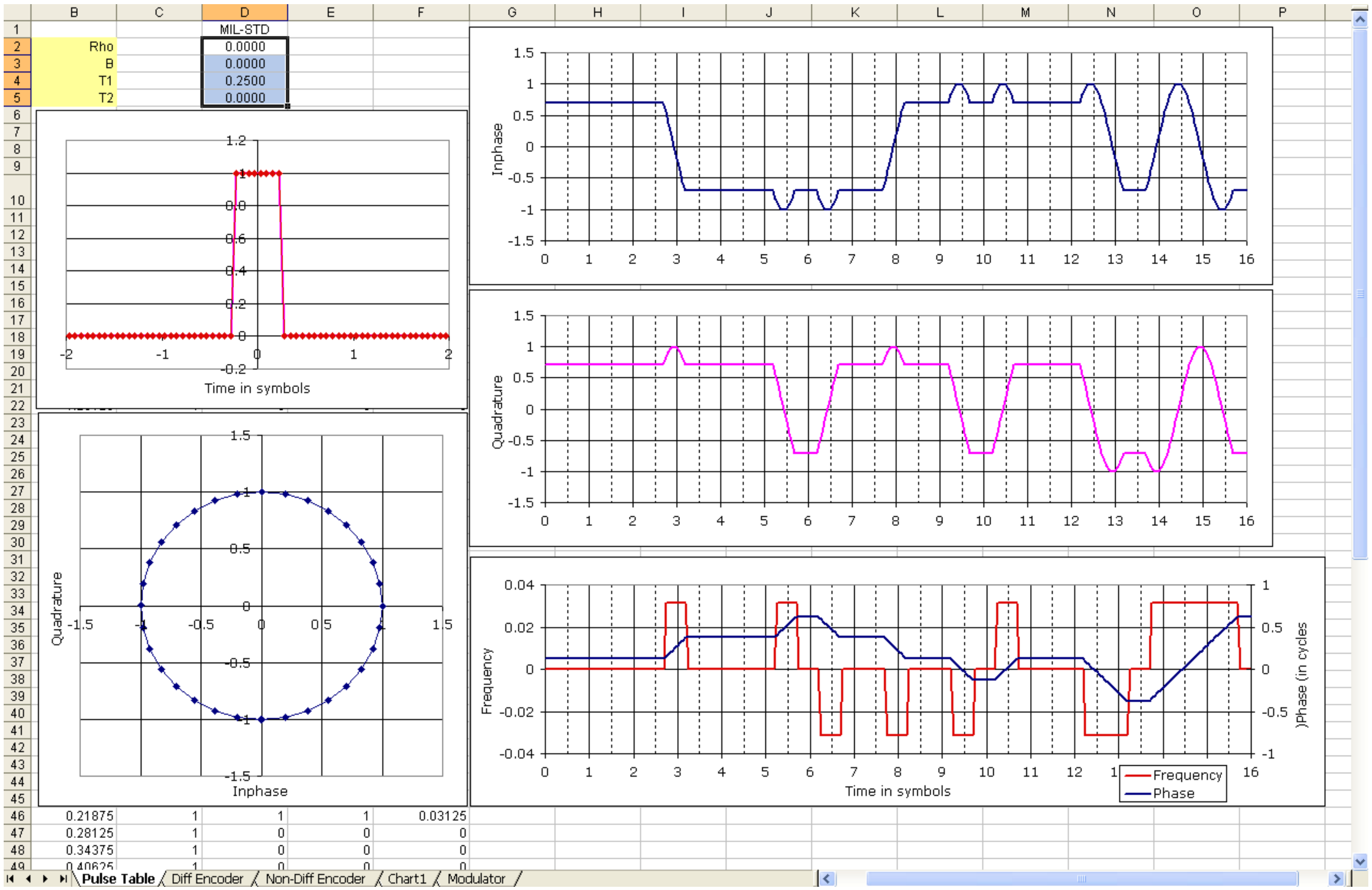
Unshaped Offset QPSK



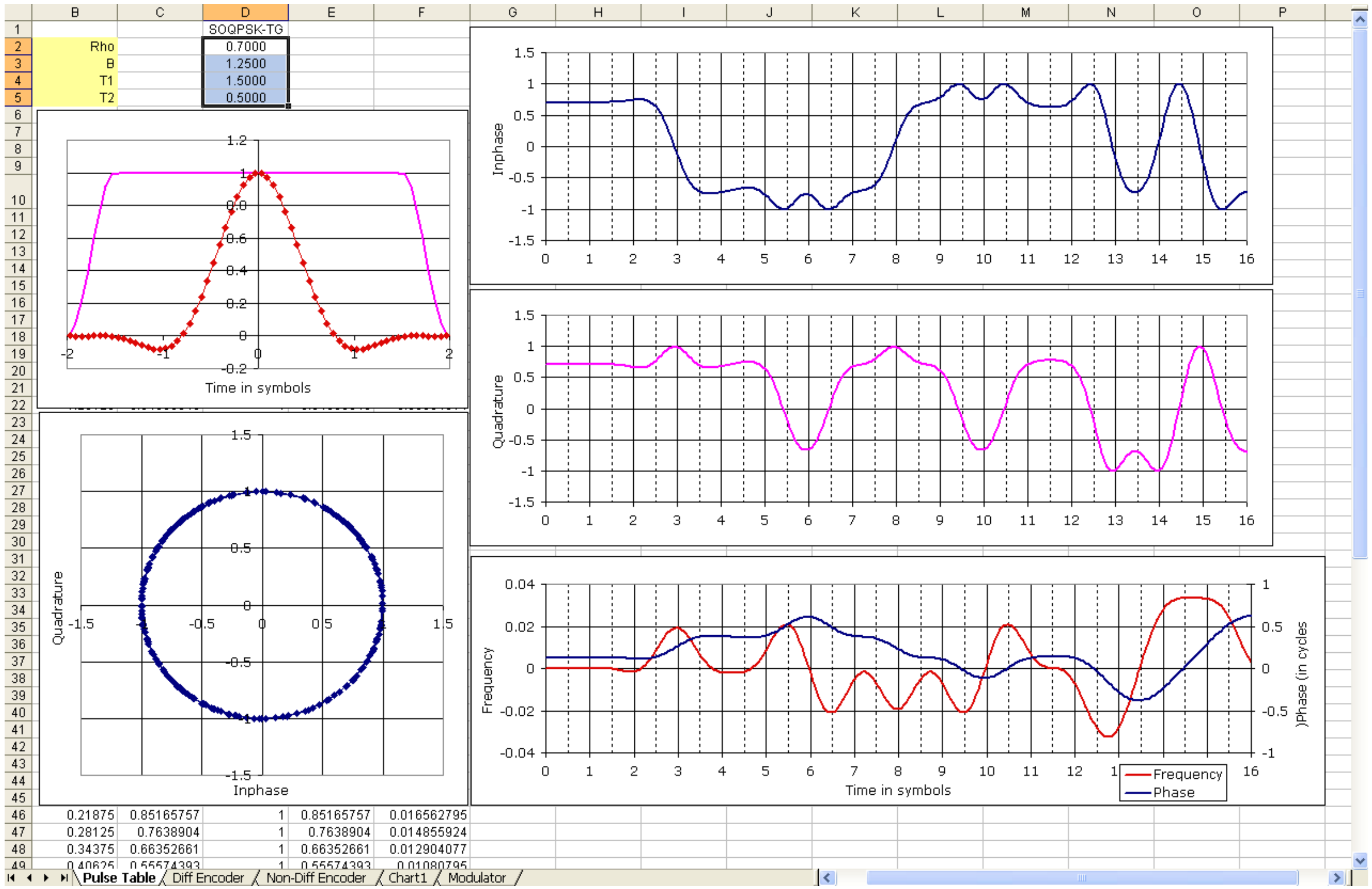
Slightly Shaped OQPSK



MIL-STD SOQSPK



SOQPSK-TG

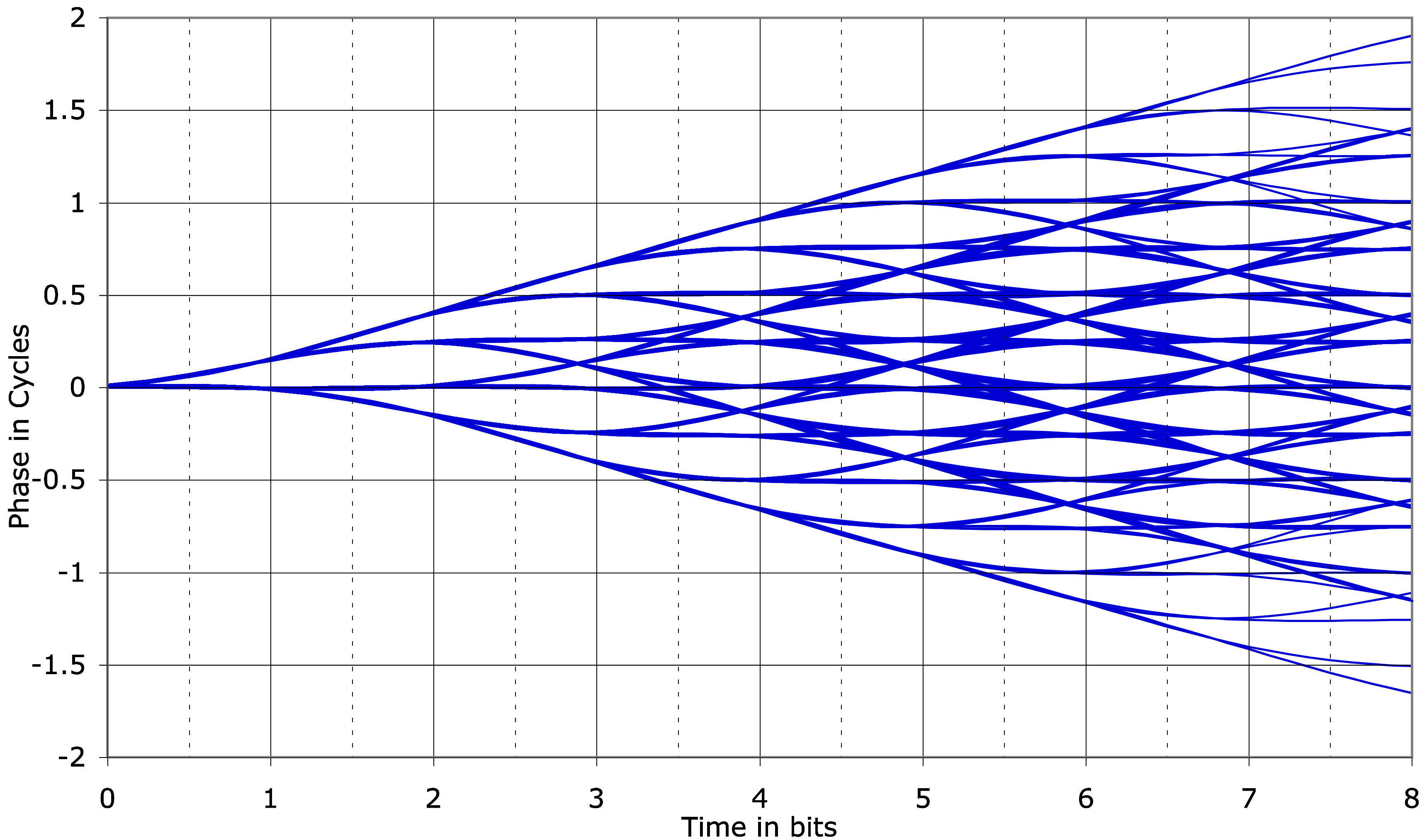


SOQPSK-TG
Rho 0.7000
B 1.2500
T1 1.5000
T2 0.5000
Time in symbols
Quadrature
Inphase
Frequency
Phase
)Phase (in cycles
0.21875 0.85165757 1 0.85165757 0.016562795
0.28125 0.7638904 1 0.7638904 0.014855924
0.34375 0.66352661 1 0.66352661 0.012904077
Pulse Table
Diff Encoder
Non-Diff Encoder
Chart1
Modulator

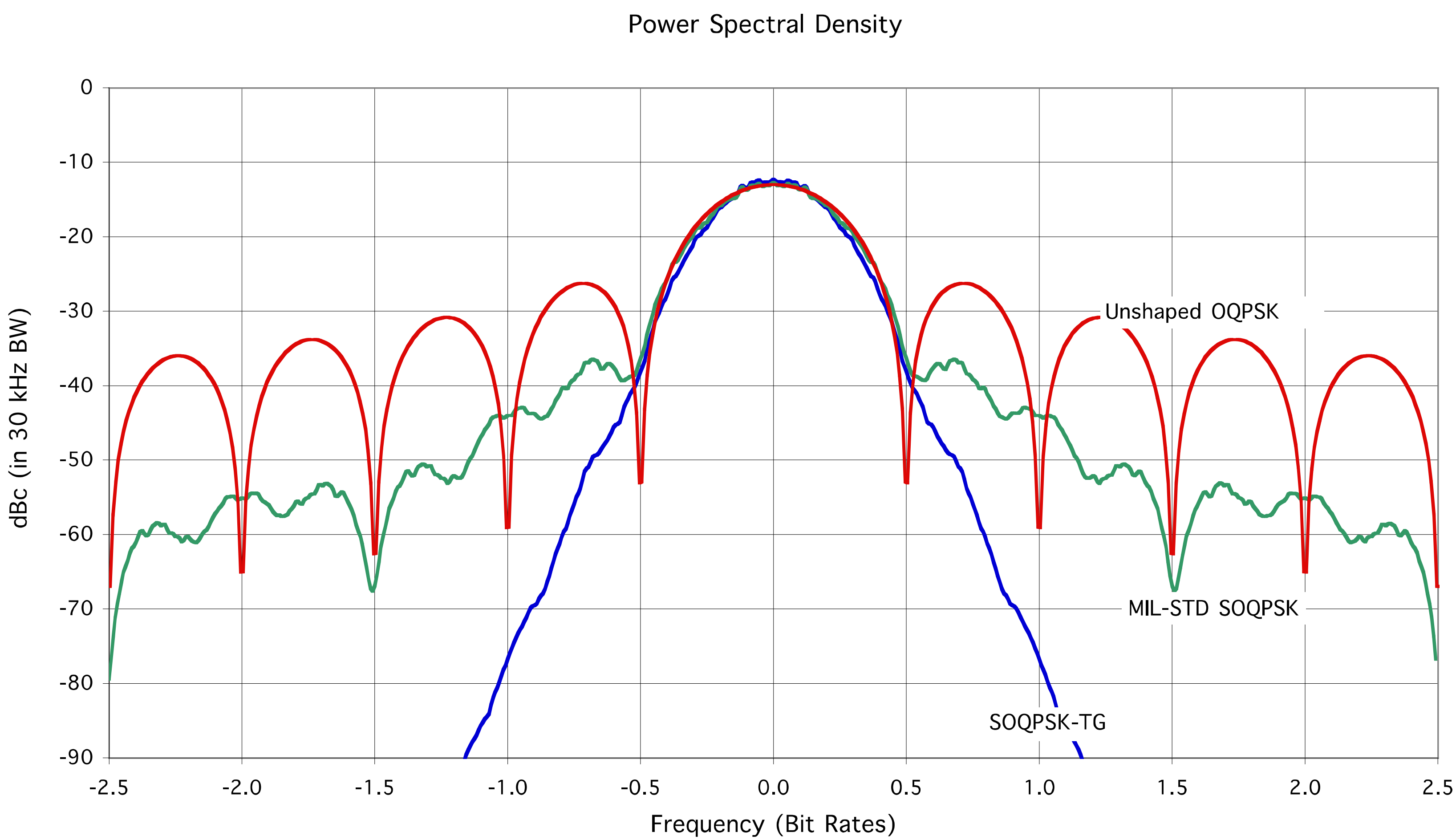
SOQPSK-TG

- Jump to file://localhost/Users/TerryHill/Documents/Quasonix/TIMTER/SOQPSK Modulator10.xls

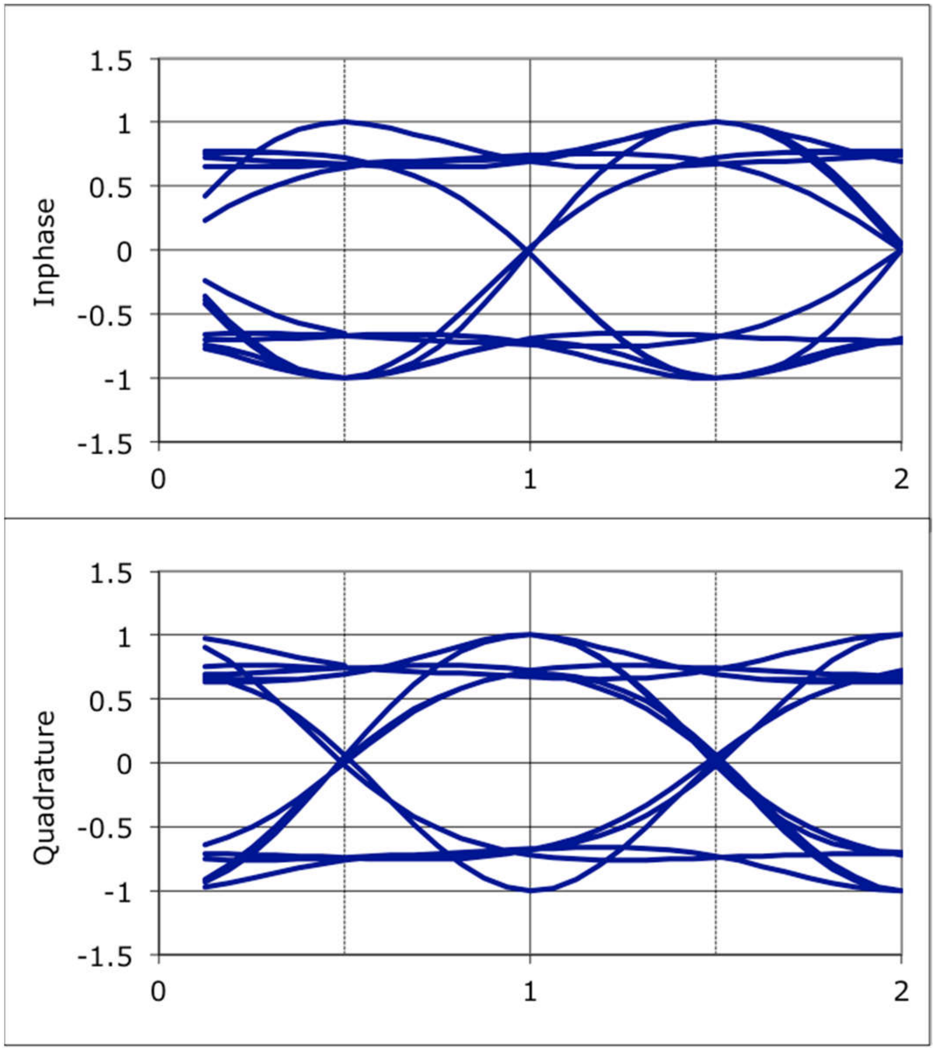
SOQPSK-TG Phase Tree



Power Spectral Density

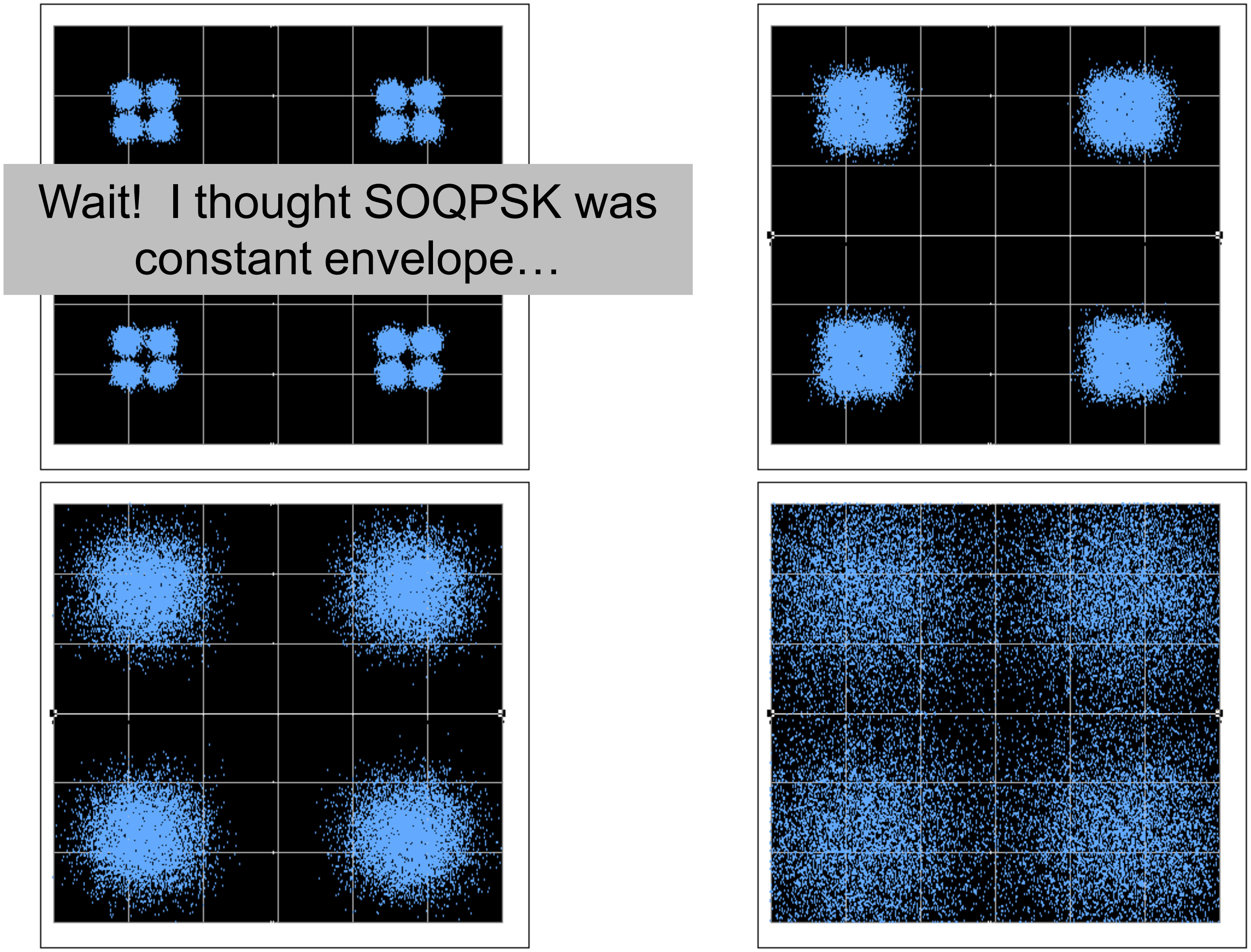


SOQPSK-TG Eye Patterns

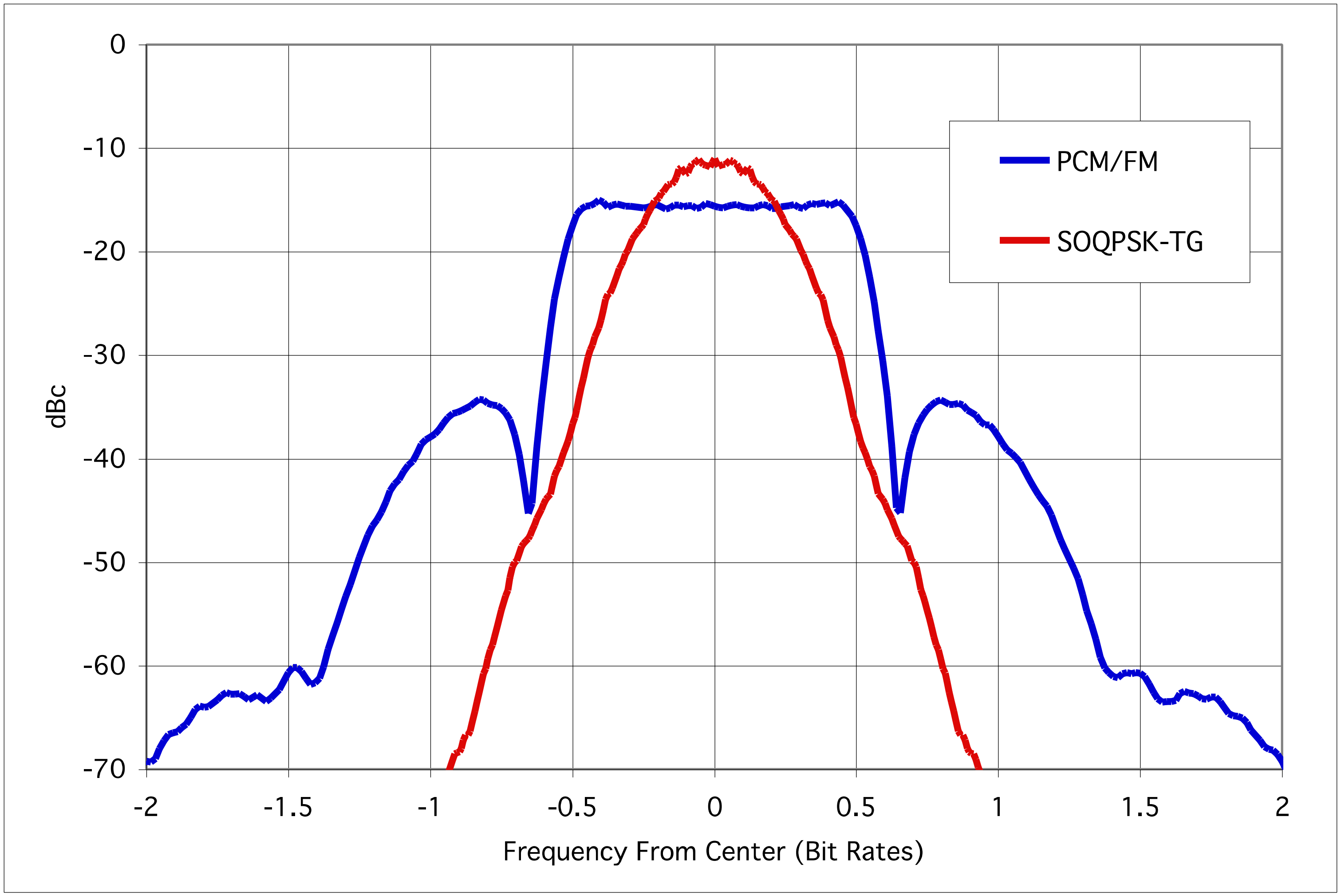


- Single-symbol detection is sub-optimal, but practical

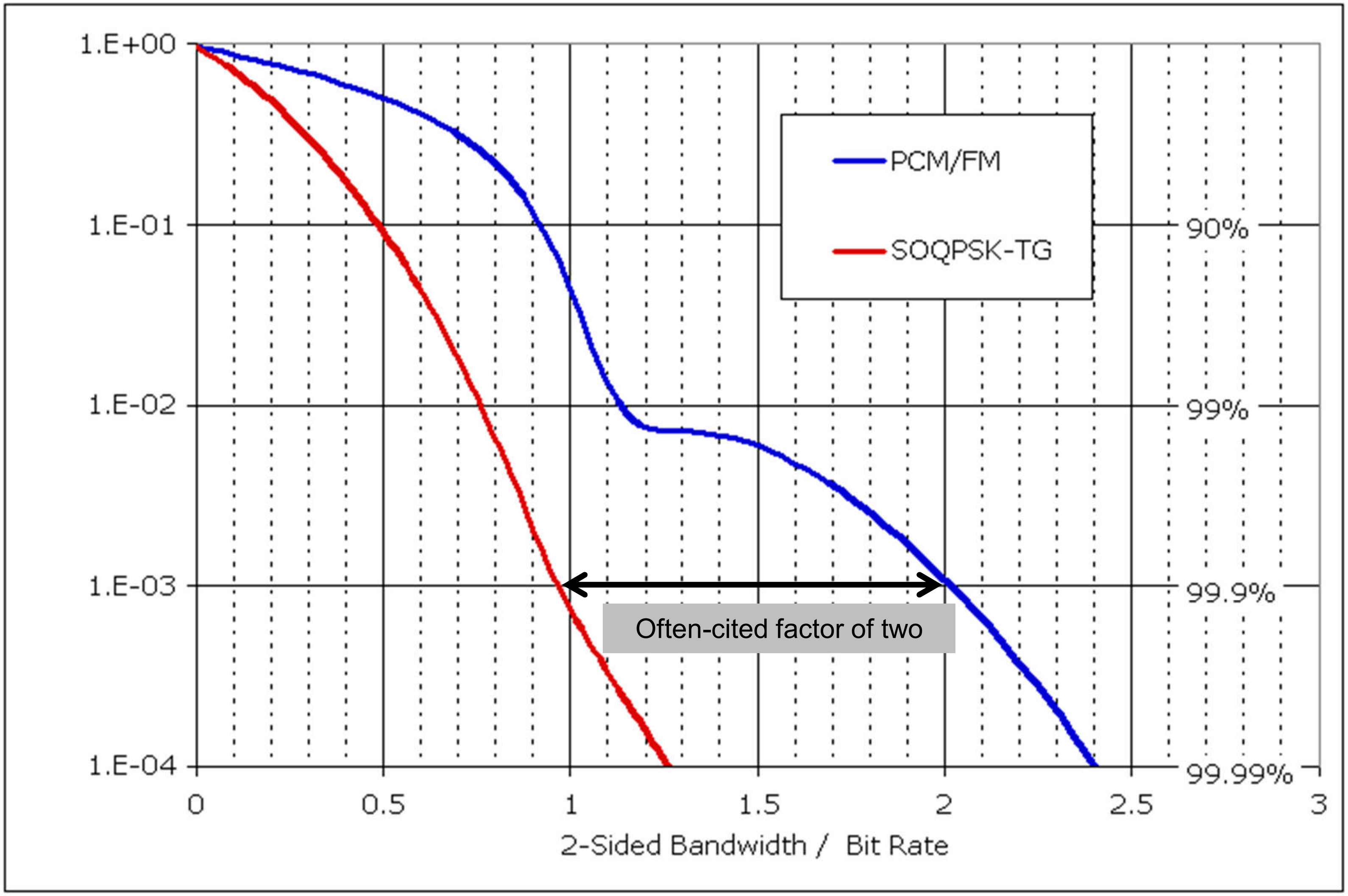
SOQPSK Constellations



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

Tier II Overview

- Multi-h CPM characteristics
  - Easy to trade off bandwidth and detection efficiency.
  - Constant envelope is ideal for high efficiency non-linear power amplifiers.
  - Detection efficiency is enhanced by periodically varying the modulation index (h).
    - Extends the point at which competing paths remerge thereby increasing the minimum distance and decreasing the probability of symbol error.
  - Nearly 2.5x improvement over PCM/FM in spectral efficiency with similar detection efficiency.

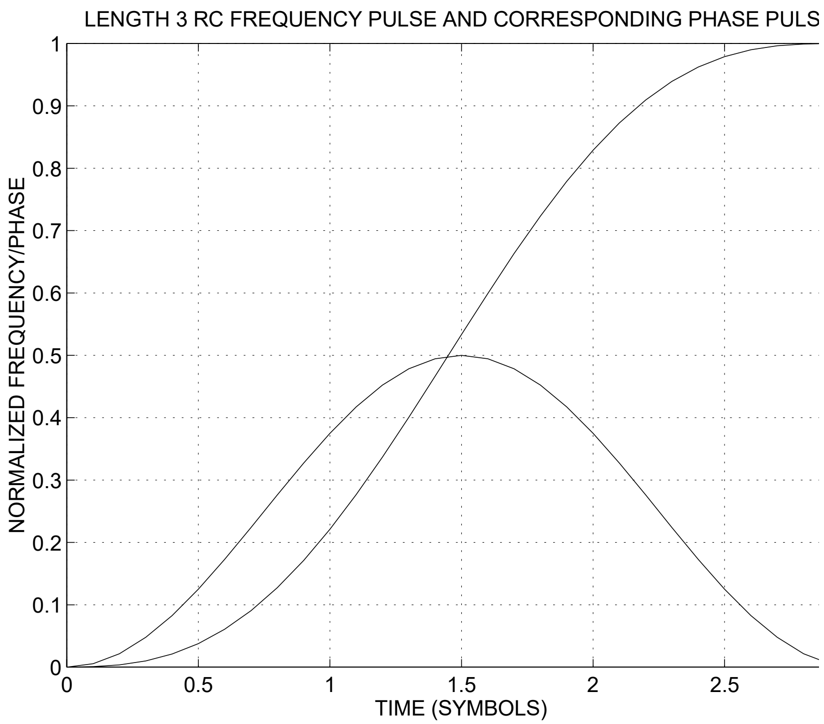
ARTM Tier II in CPM Notation

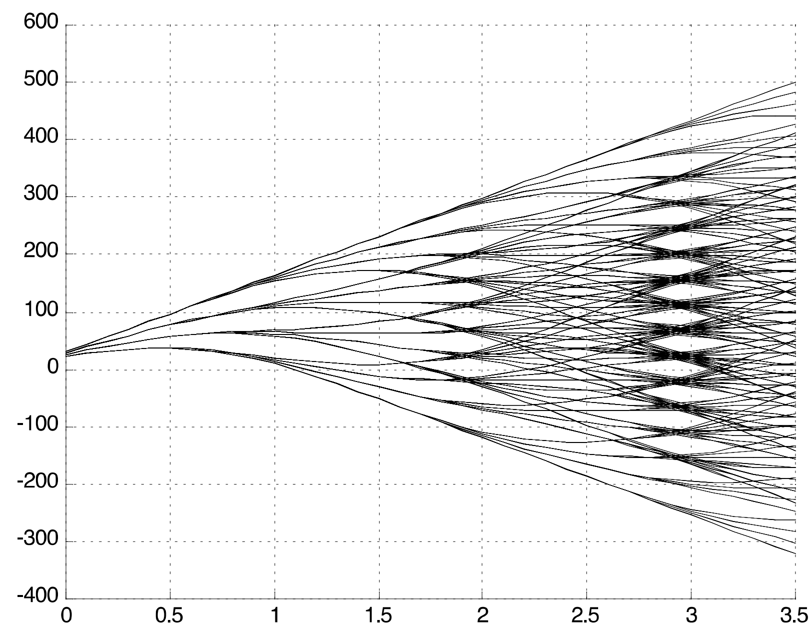
$$s(t) = \sqrt{2E/T}\cos[2\pi f_o t + \phi(t,\overline{\alpha}) + \phi_o]$$

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

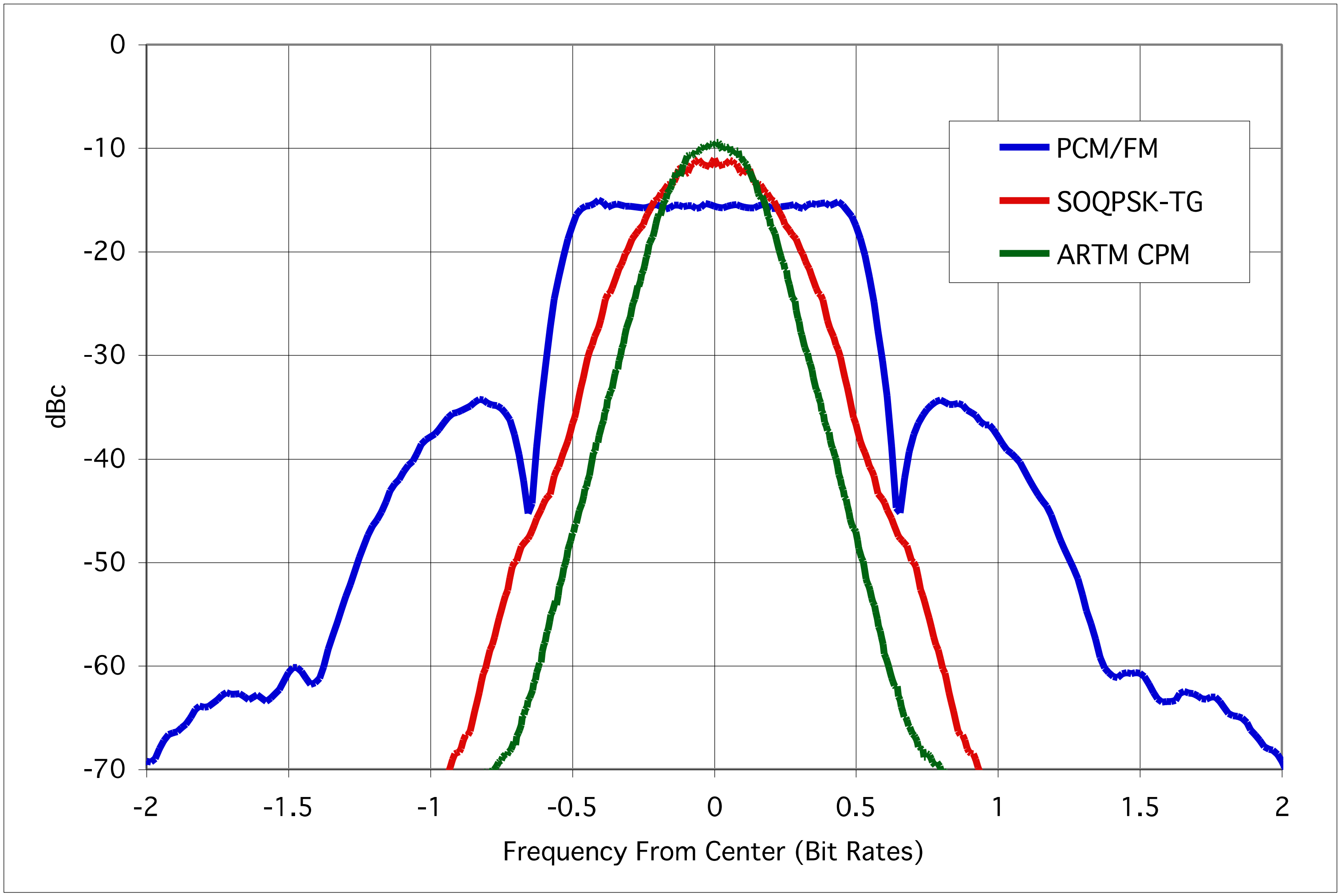
- M = 4 (quaternary)
- $\alpha_i = 2\,[2d_{1i} + d_{0i}] - 3$
  - $\alpha_i = \{-3, -1, +1, +3\}$
  - $d_i = \{0, 1\}$
- h = {4/16, 5/16}, alternating
- g(t) = raised cosine, 3 symbols (6 bits) in duration
  - Normalized such that the integral over all time = 1/2

Frequency Pulse & Phase Tree

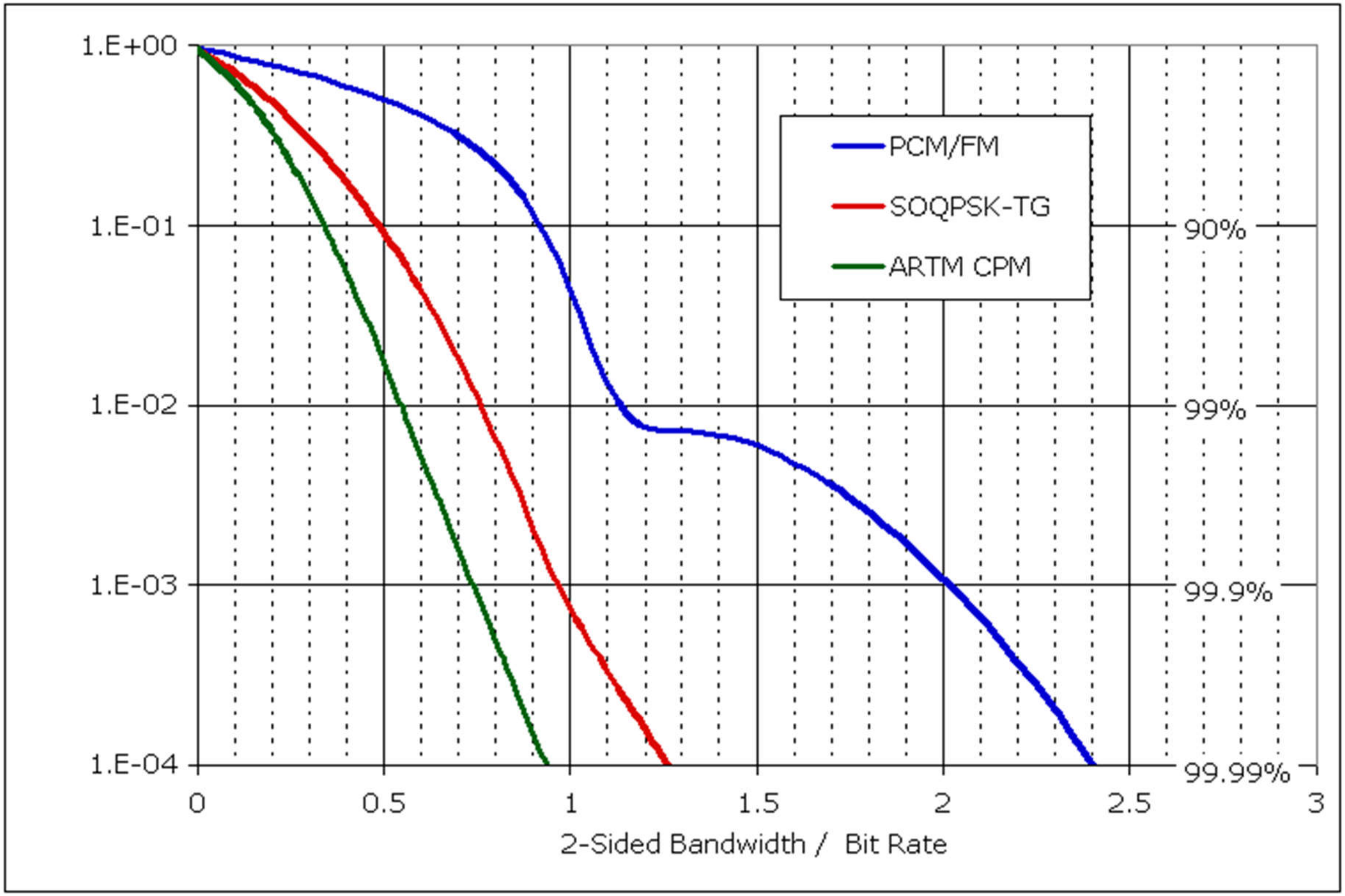




PSD (Tier 0, I, & II)



Fractional Out-of-band Power



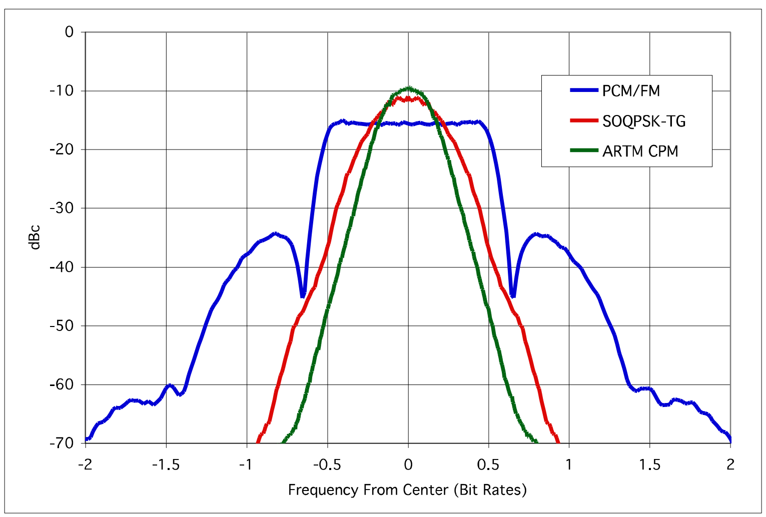
Tier II Multi-h CPM Summary

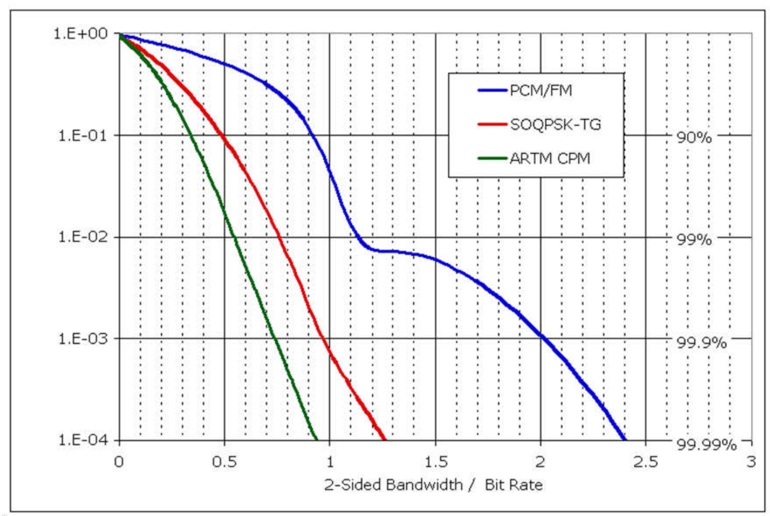
- Similar detection efficiency to PCM/FM.
- Constant envelope waveform is ideal for efficient non-linear PA's.
- Enhanced performance gained by increasing demodulator complexity.
- 99.9% bandwidth: 0.75 times bit rate

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

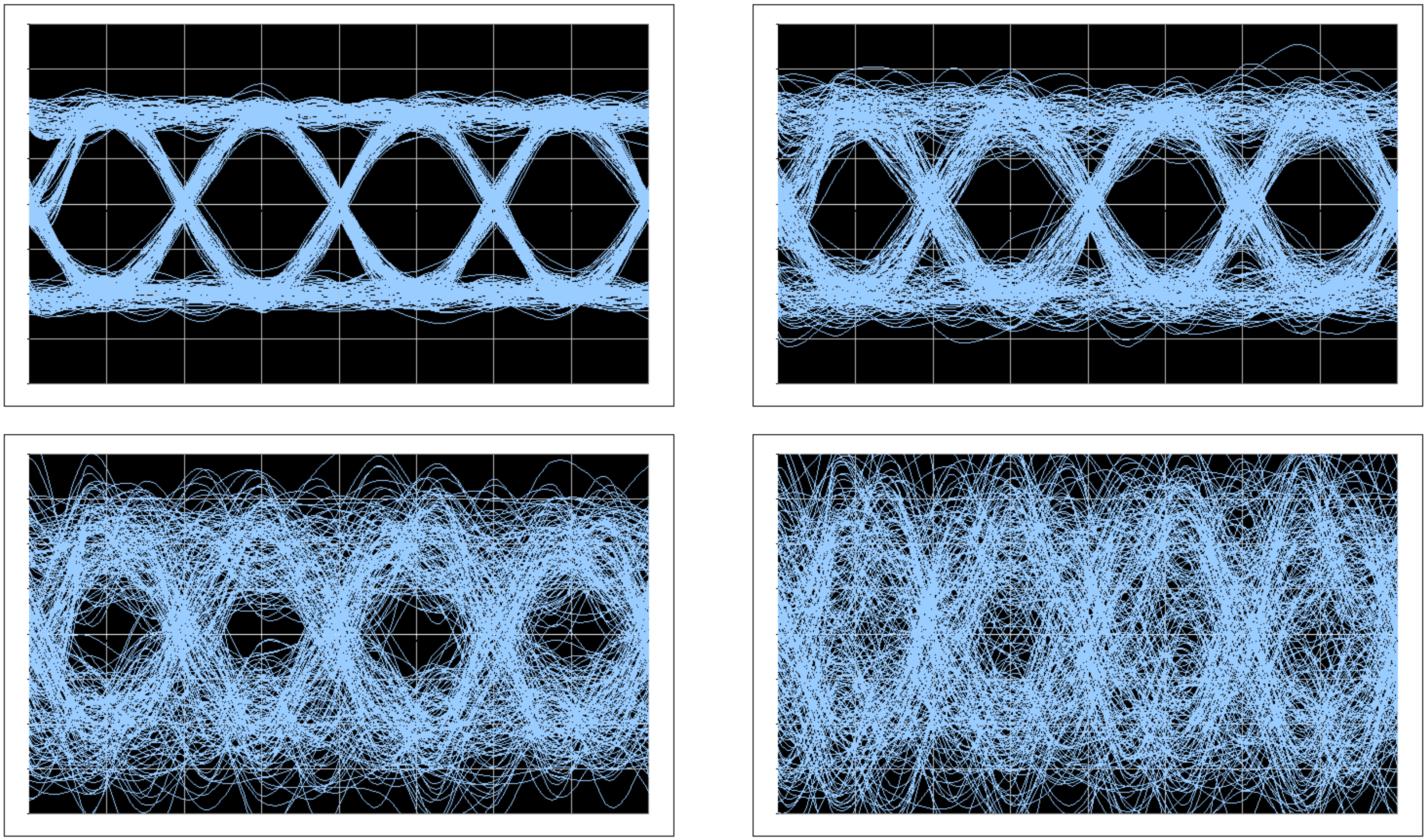
Tier 0 Single-Symbol Detection

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

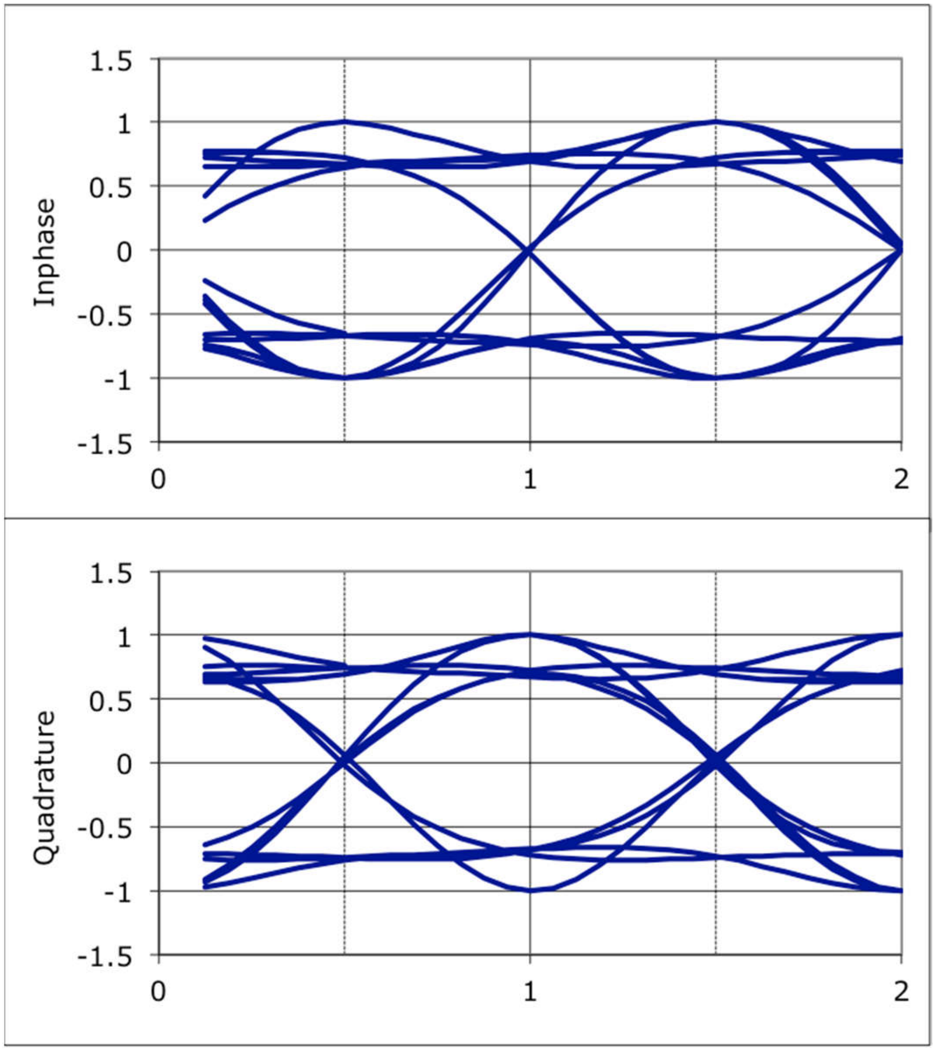
$$\phi(t,\overline{\alpha}) = 2\pi h \int_{-\infty}^{t} \sum_{i=-\infty}^{+\infty} \alpha_i g(\tau - iT)\,d\tau$$

- Differentiate the phase to get frequency
  - Limiter-discriminator
  - Phase locked loop
  - Digital processing
- If the frequency in this symbol > 0, data = 1
- If the frequency in this symbol < 0, data = 0

Tier 0 Frequency Detection

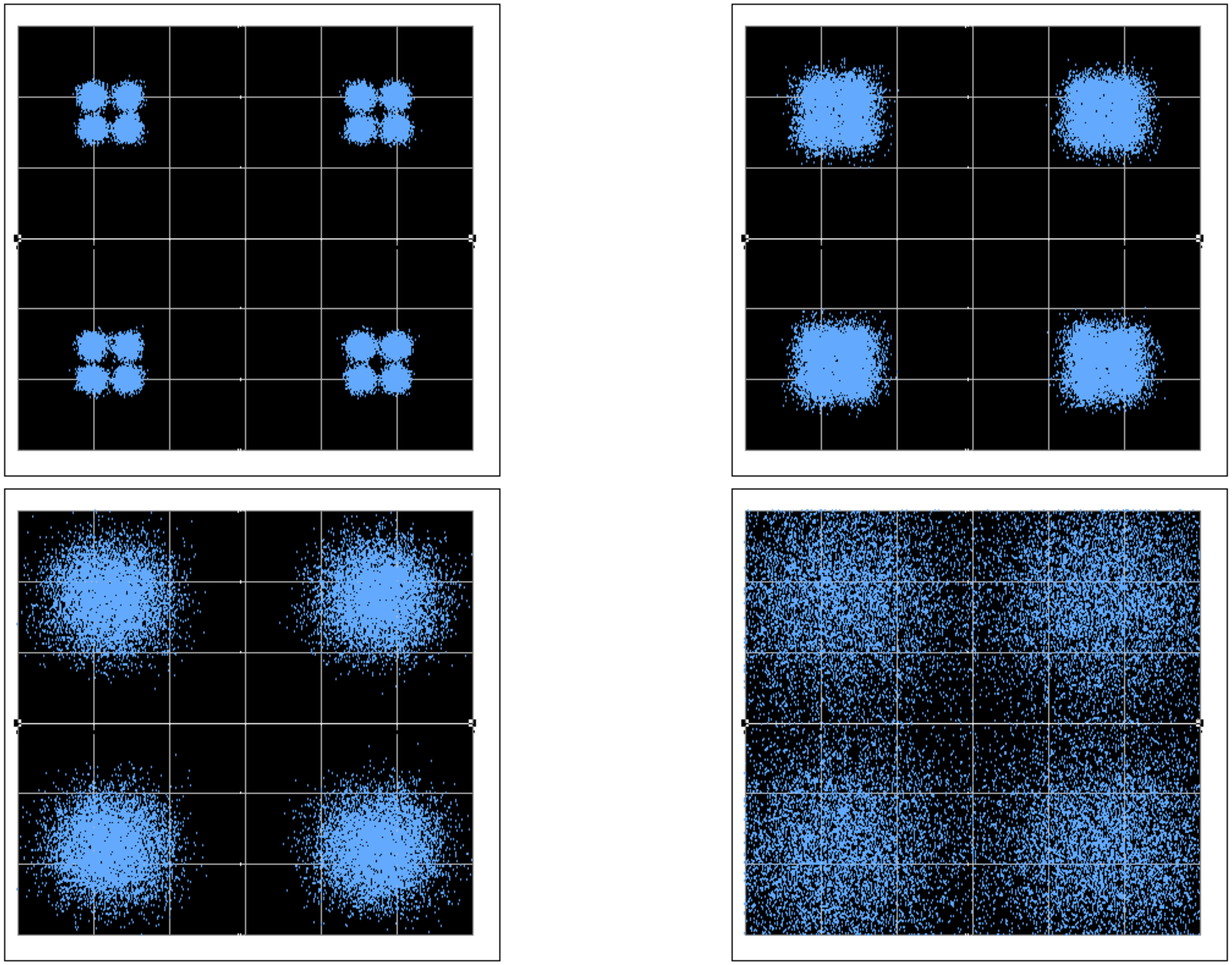


SOQPSK-TG Eye Patterns



- 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



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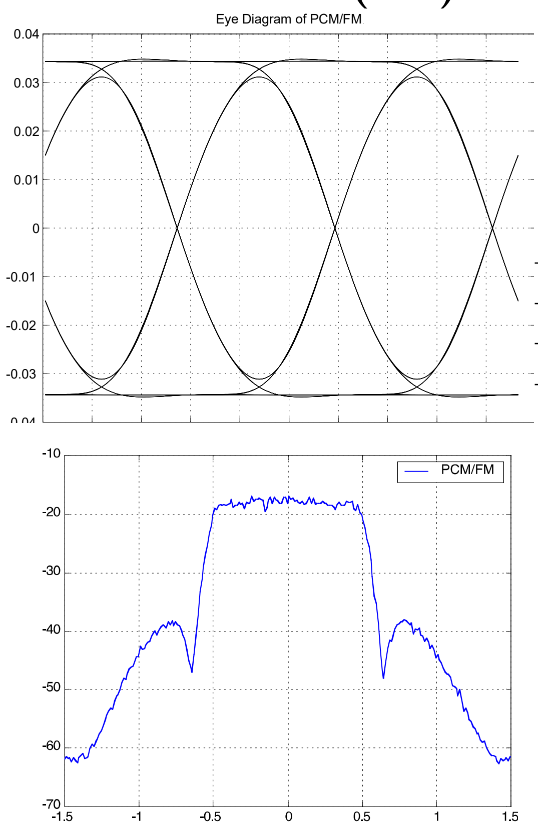
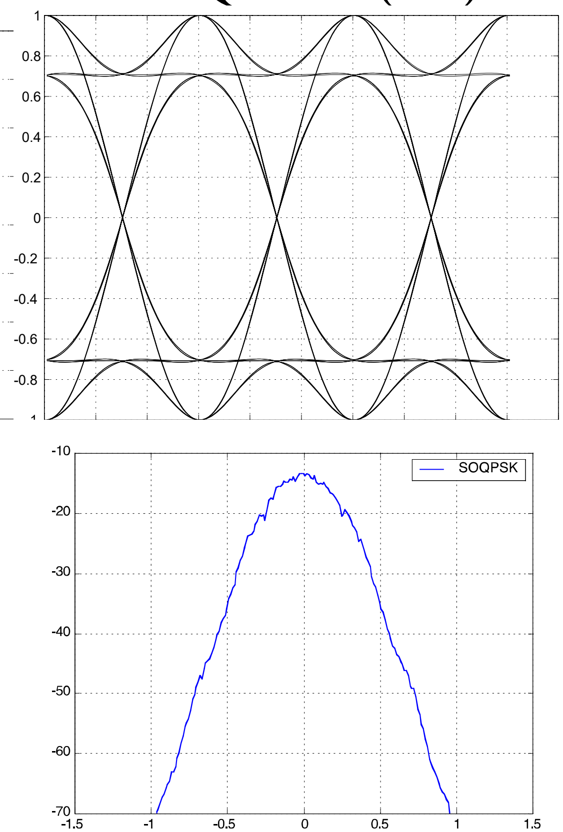
Waveform Comparison

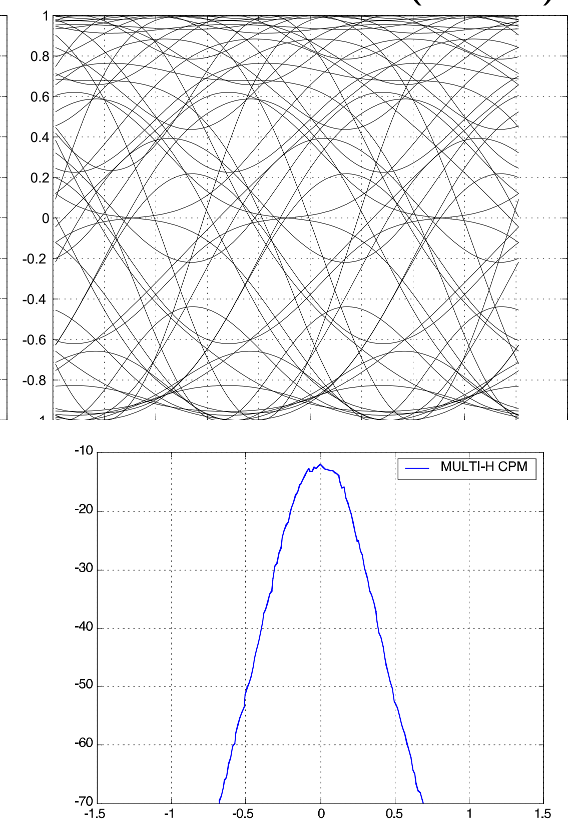
PCM/FM (1x)



SOQPSK (2x)



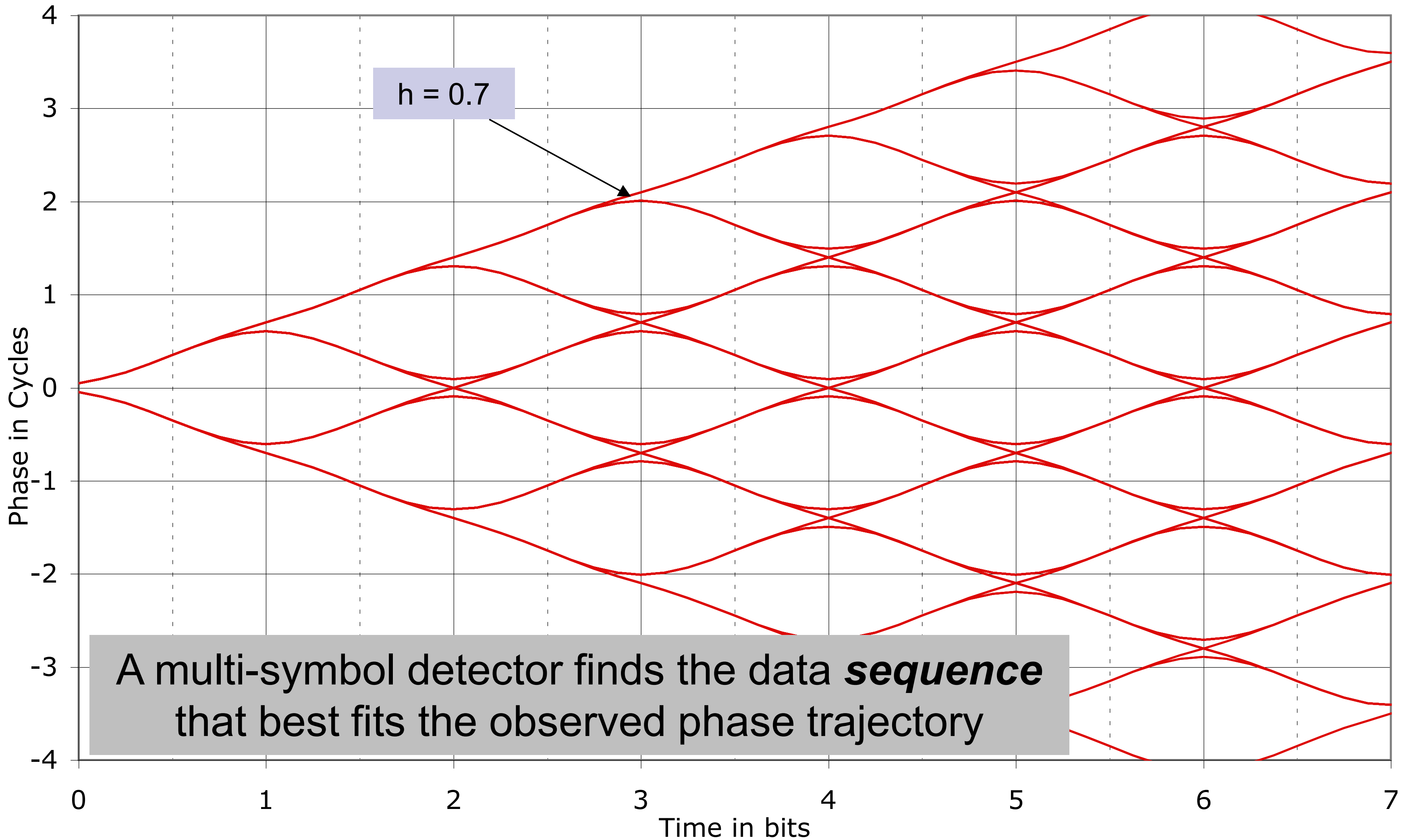
Multi-h CPM (2.5x)



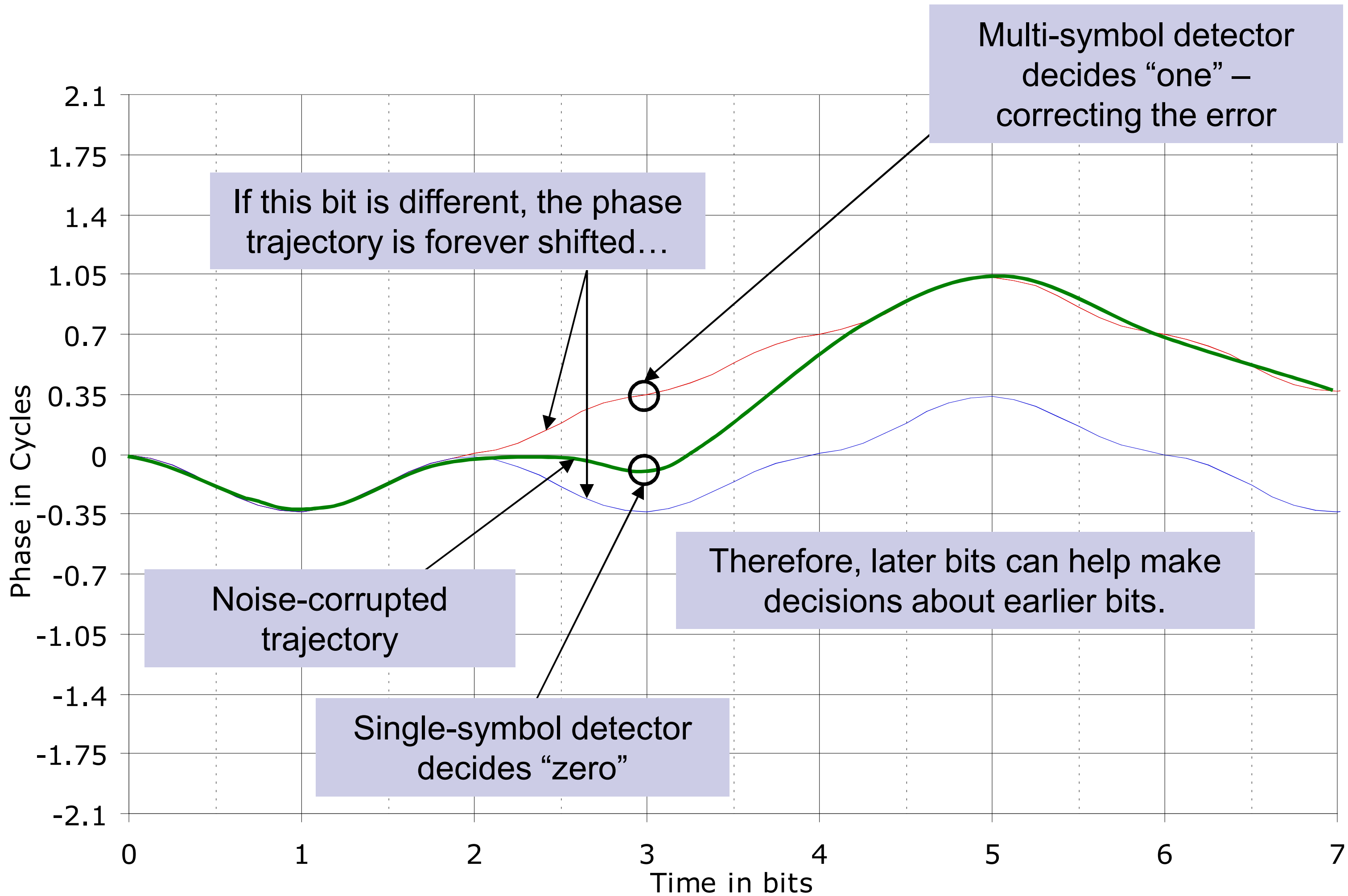
Trellis Demodulation Overview

- 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

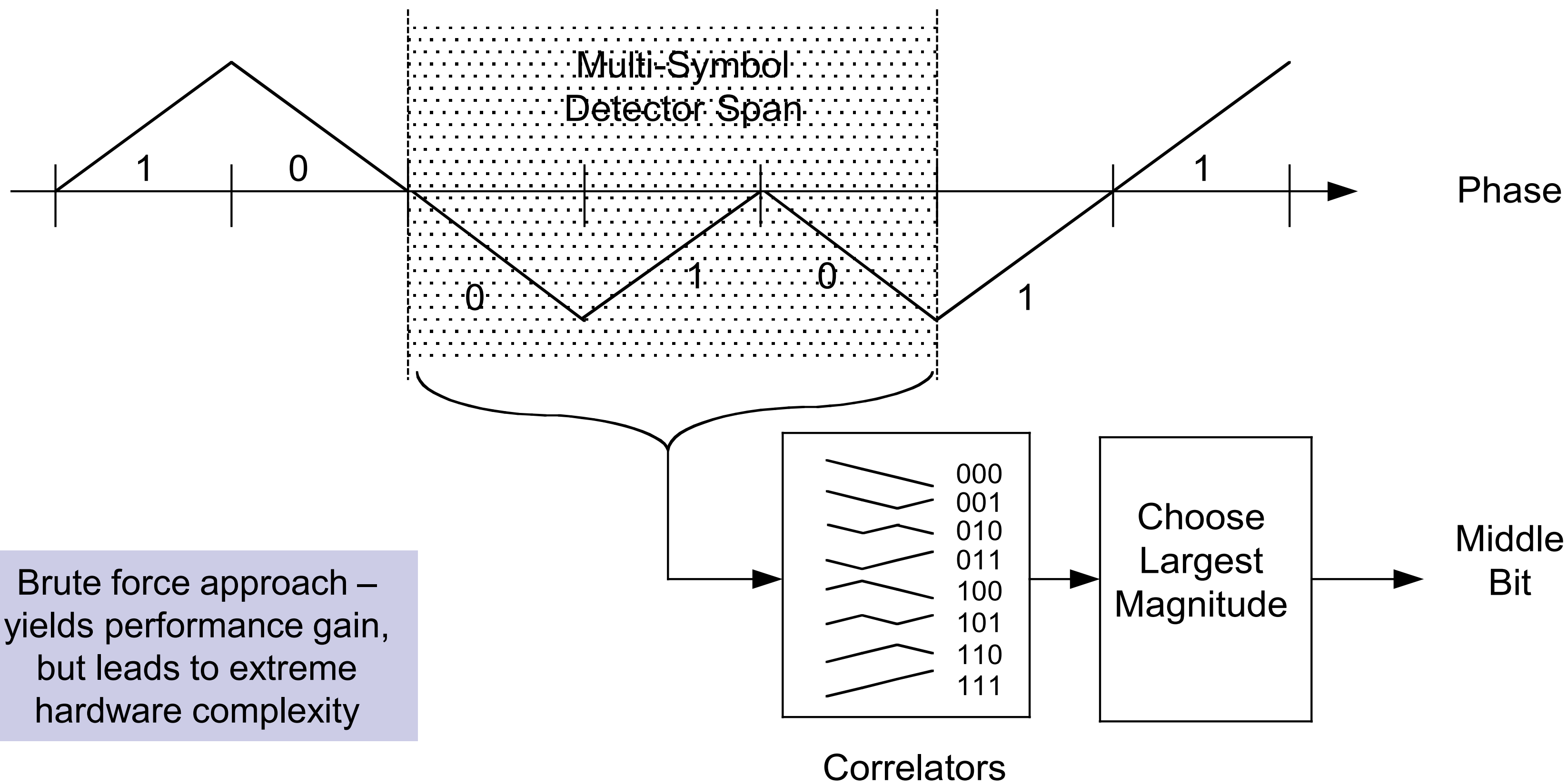
Tier 0 Phase Tree



Why Does It Matter?



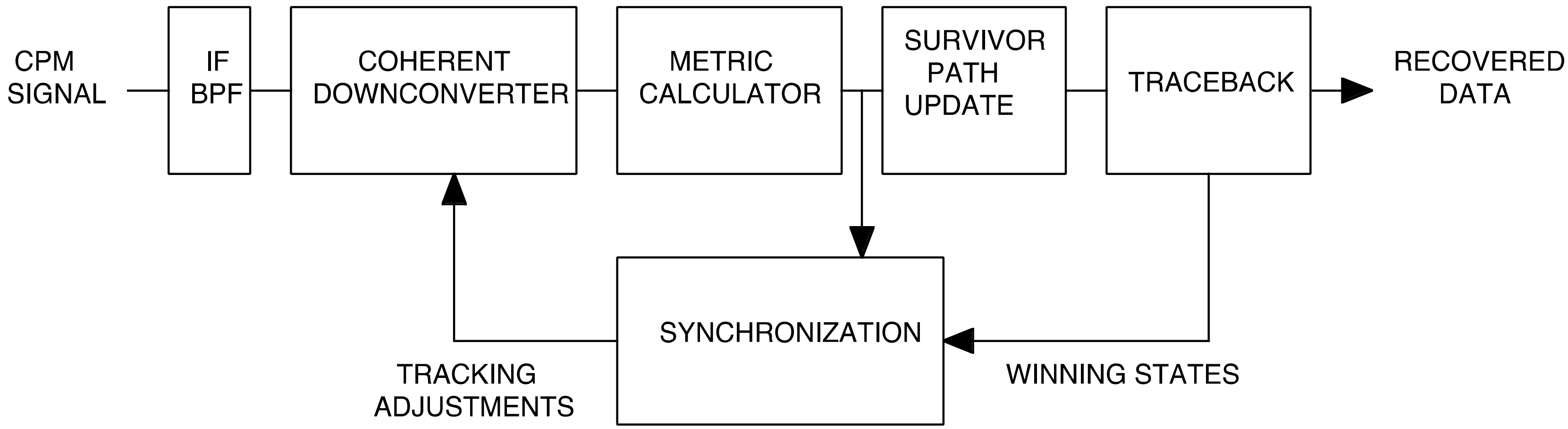
Multi-Symbol Detector Example



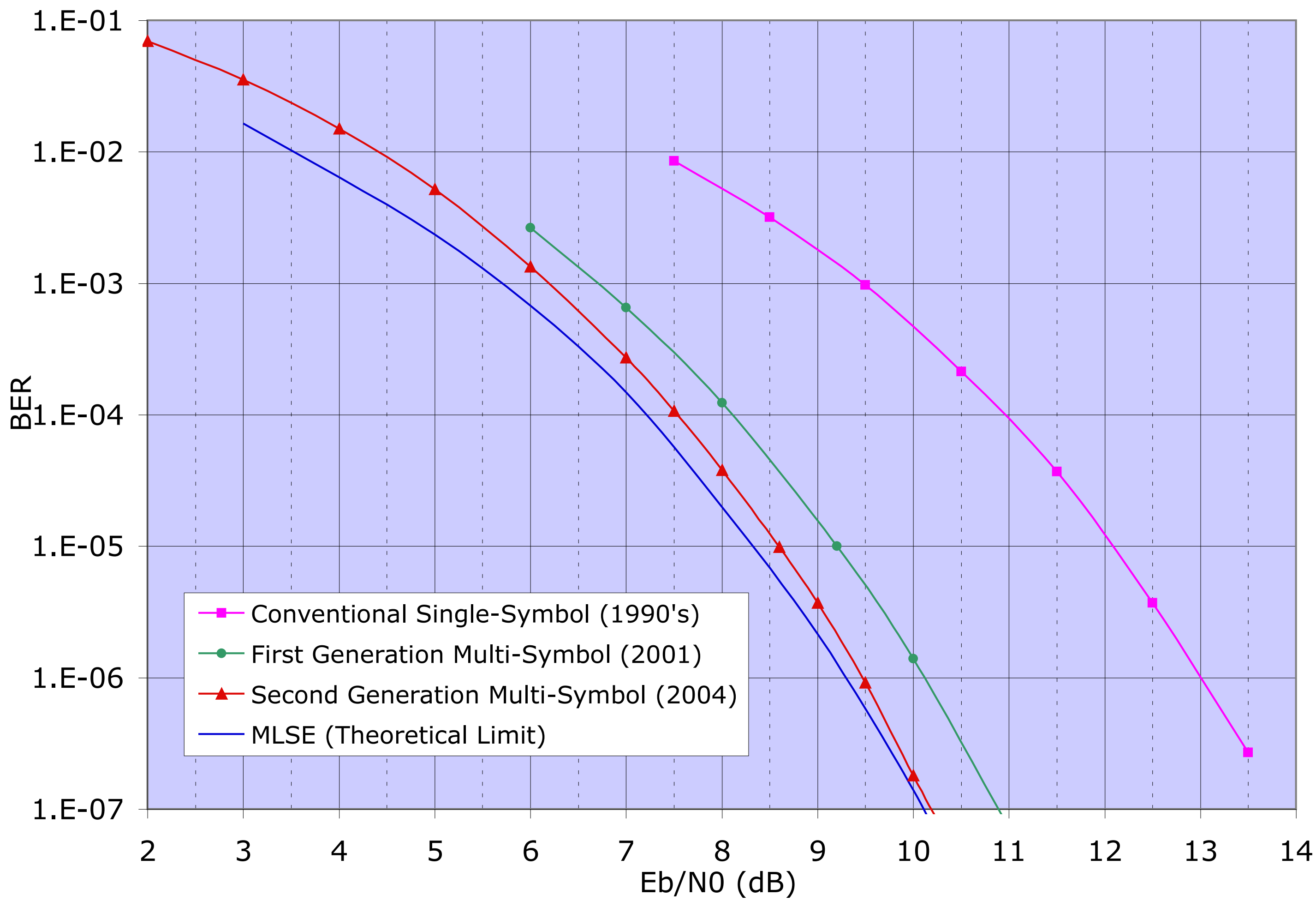
Brute force approach – yields performance gain, but leads to extreme hardware complexity

Generic Trellis Demodulator

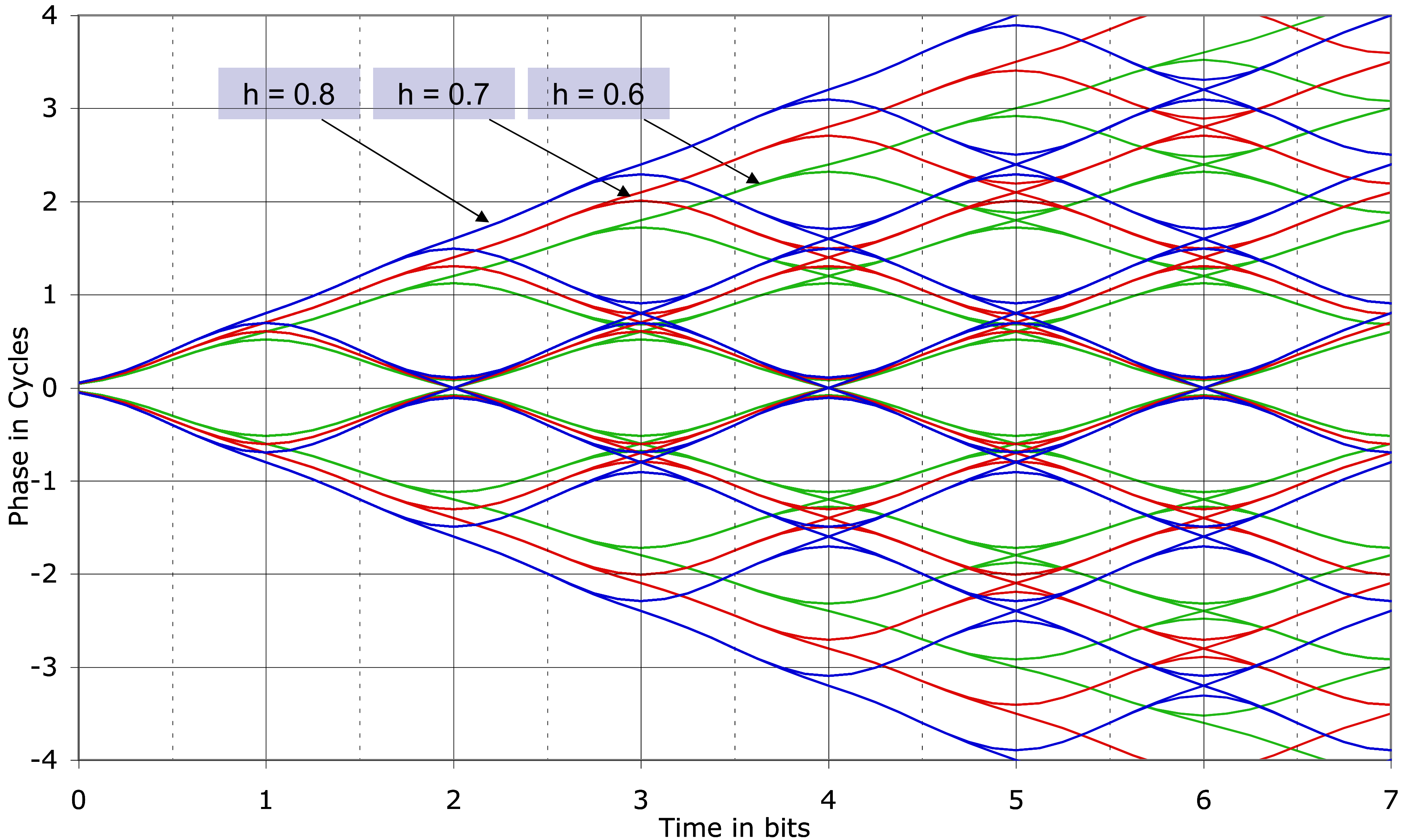
Brains over brawn – Efficient computation yields the same performance as the brute force approach, with far less hardware



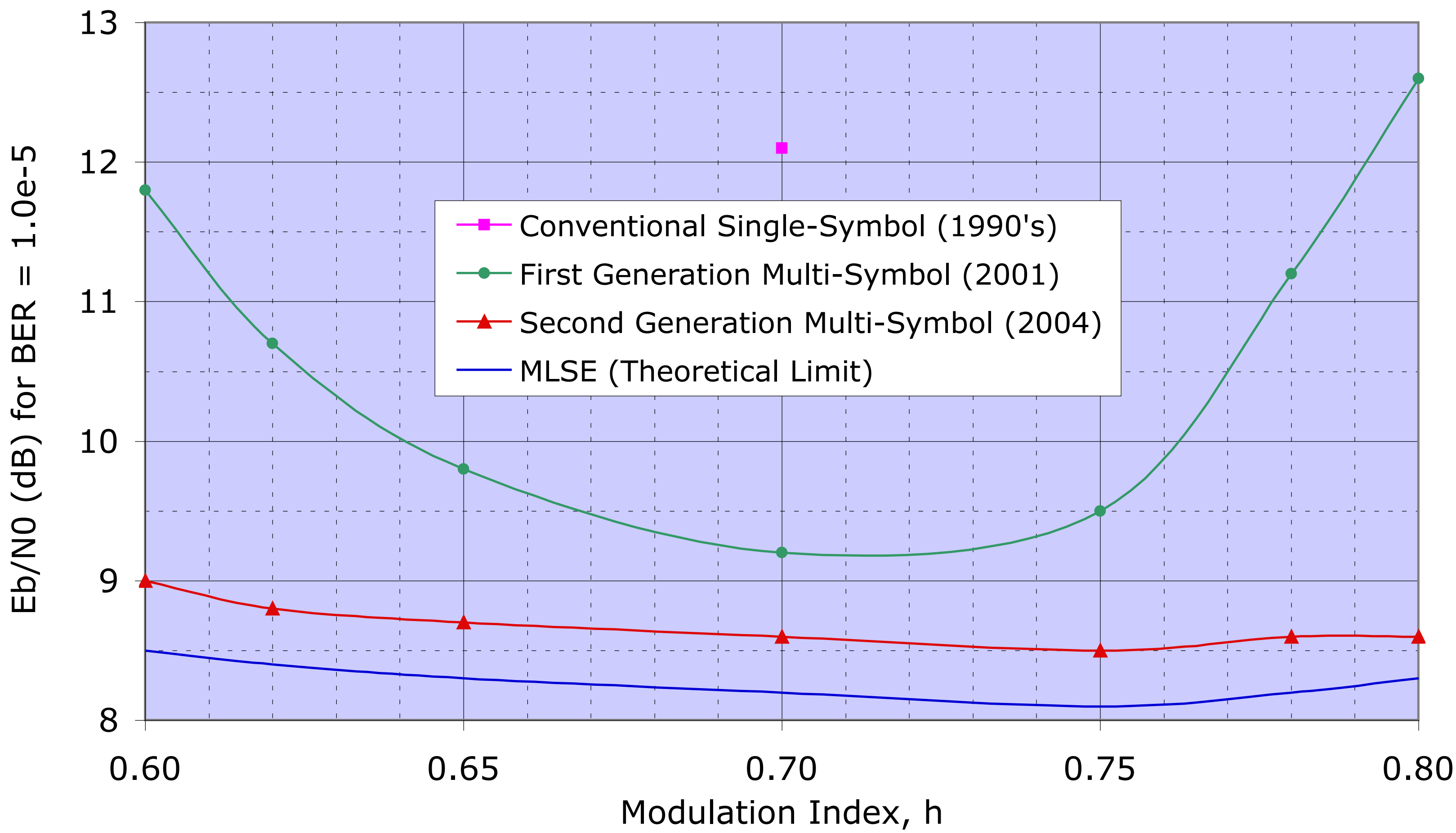
Tier 0 BER Performance



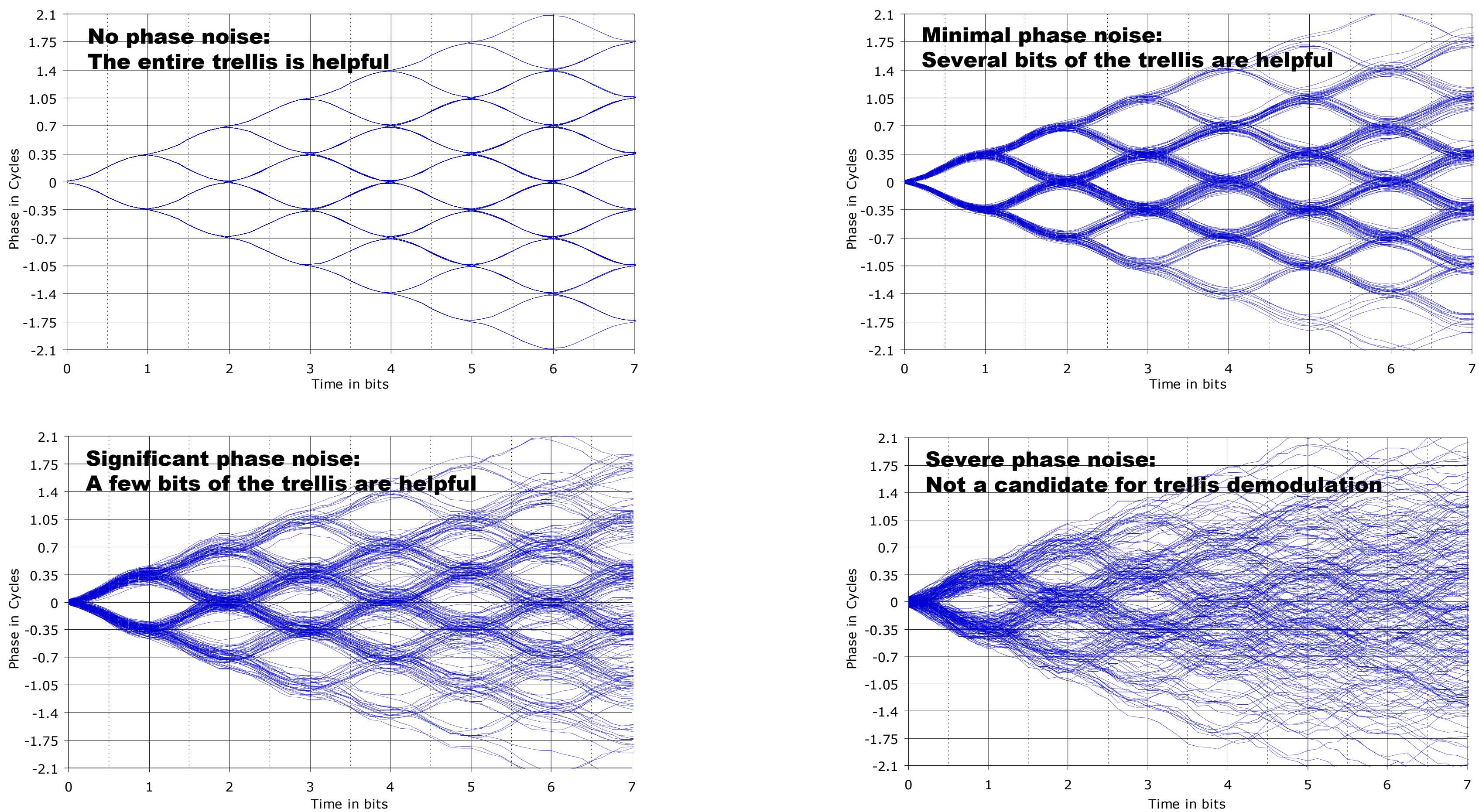
Legacy PCM/FM Transmitters



Effect of TX Deviation Error



What About Phase Noise?



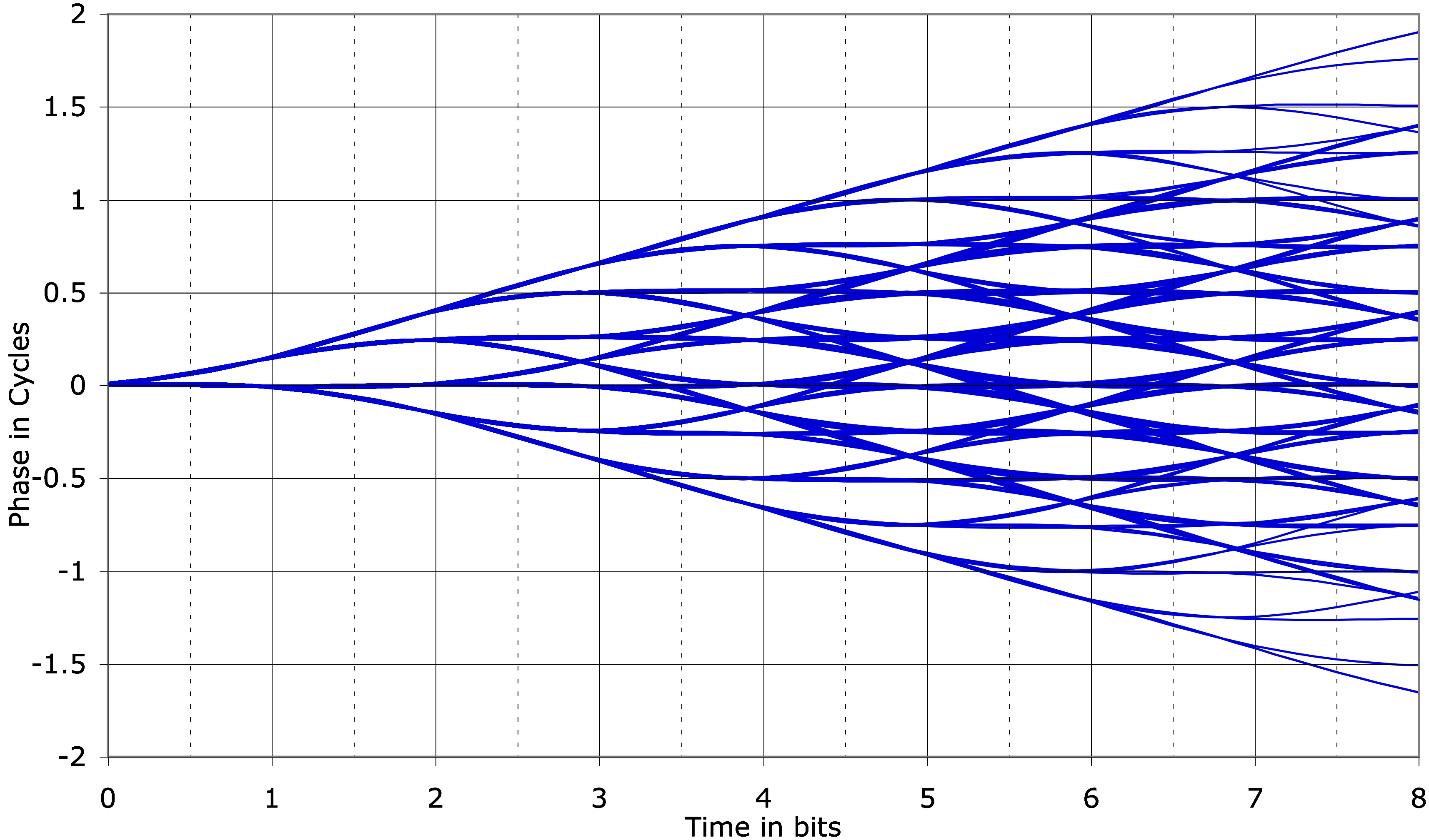
Phase Noise

- 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.

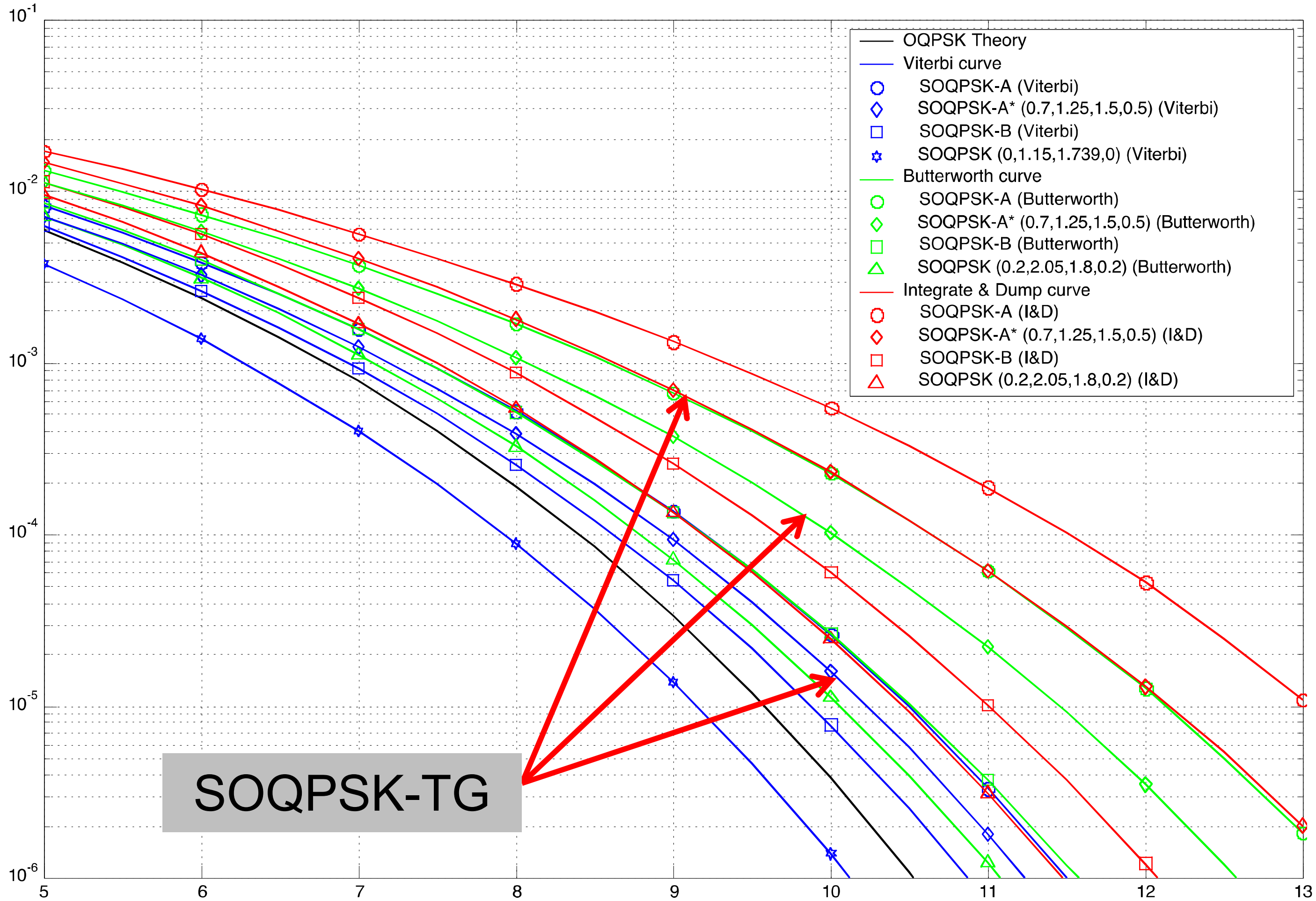
SOQPSK Detection

- 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

SOQPSK-TG Phase Tree



SOQPSK Detection Efficiency



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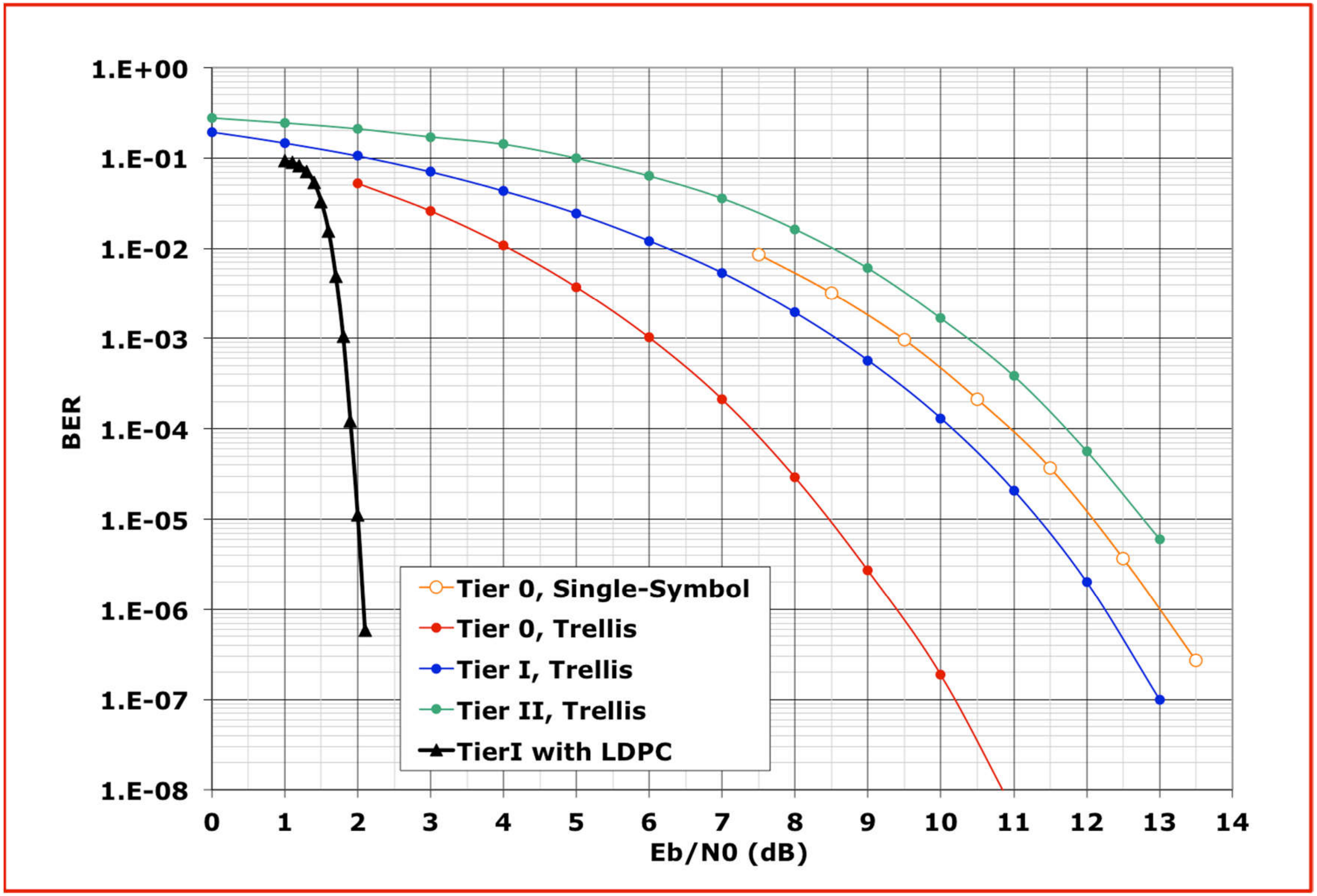
Multi-h CPM Detection

- 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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Synchronization

Telemetry Channels are Bursty

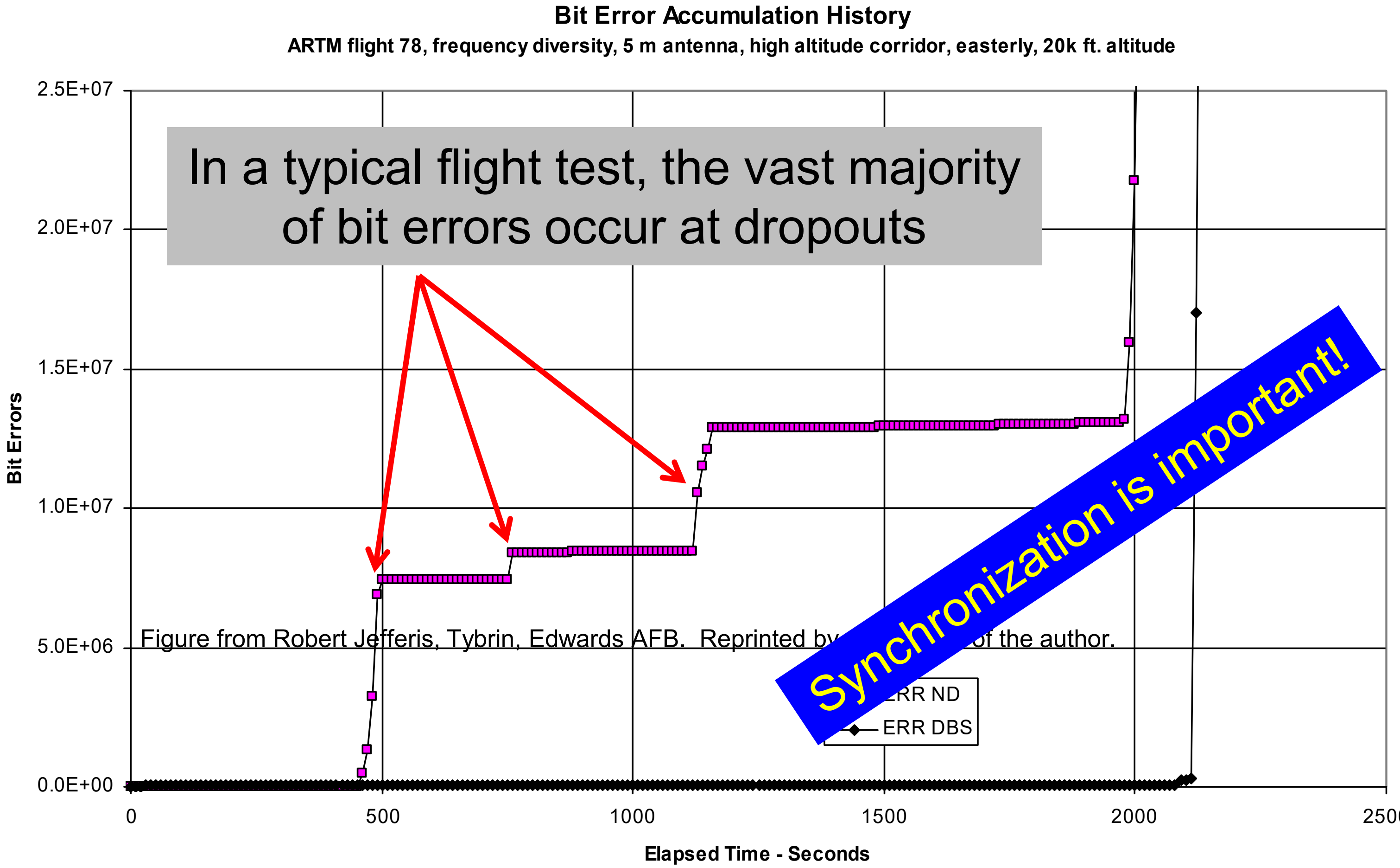
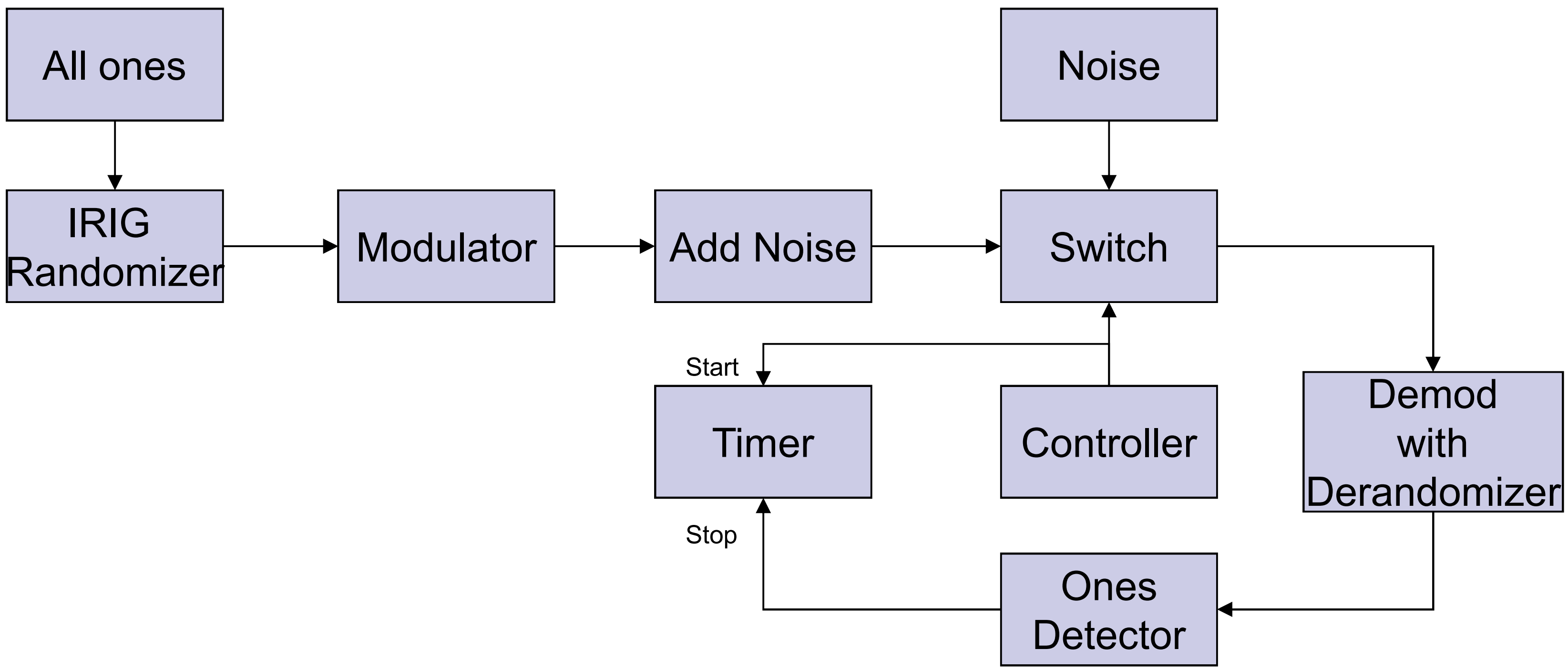


Figure from Robert Jefferis, Tybrin, Edwards AFB. Reprinted by … of the author.

Synchronization Test

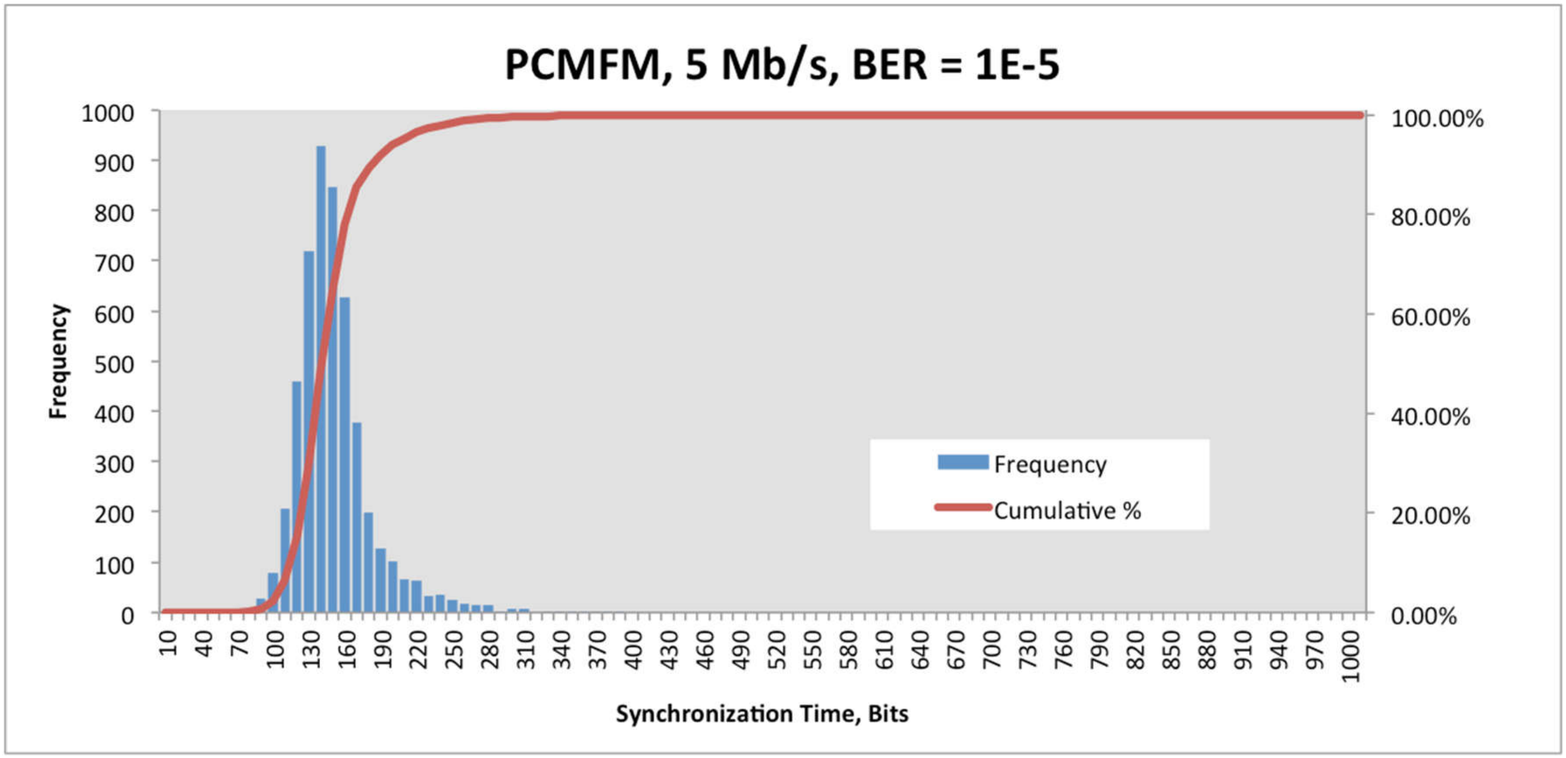
- IRIG 118-12, Procedure 7.4 (Flat Fade Recovery Test)
- Transmit randomized ones pattern
- Measure time at which output becomes “all (or mostly) ones”



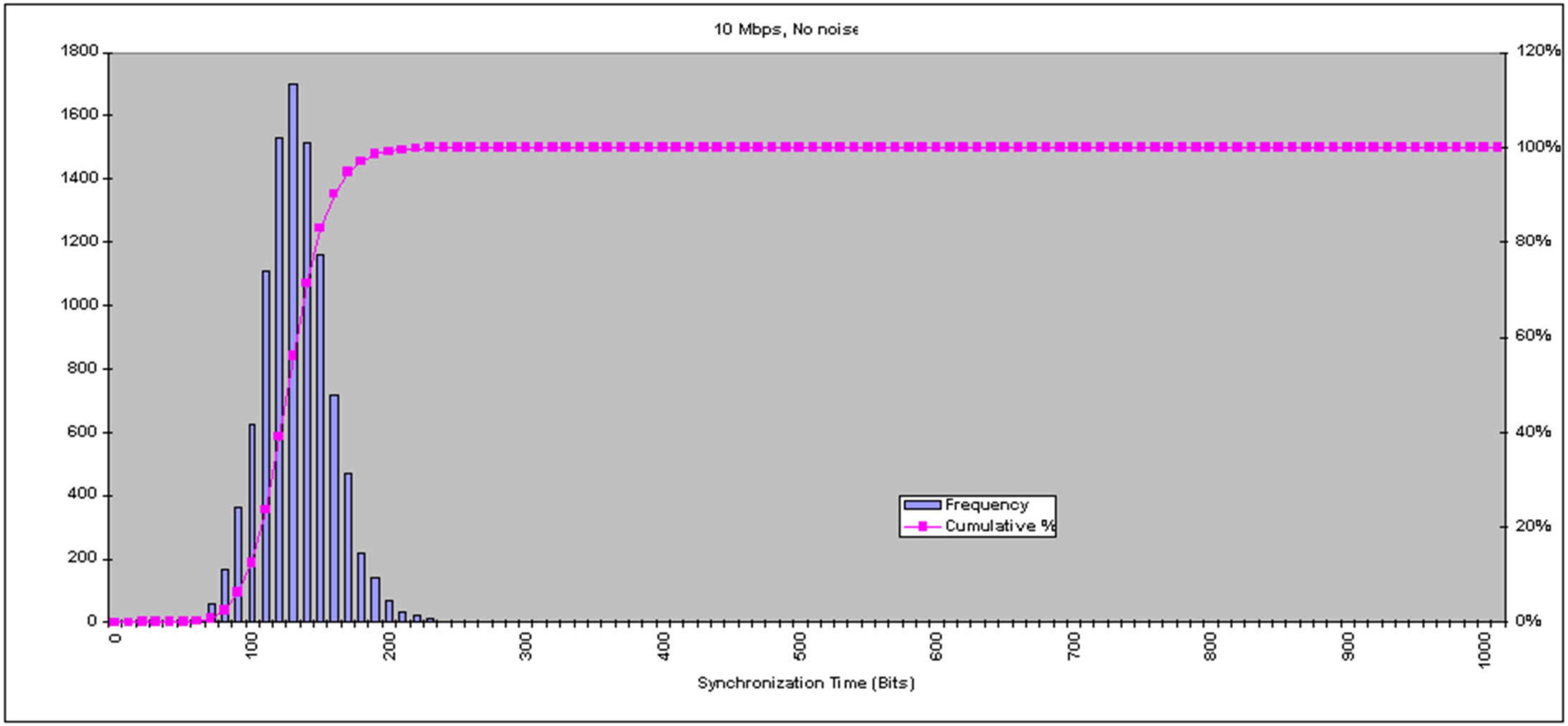
Synchronization Parameters

- Modulation technique
  - Tier 0 uses more bandwidth – easier to synchronize to
  - Tier I is spectrally compact, making it slippery – synchronization is more difficult
    - Trellis demodulation helps achieve sync
  - Tier II is even more compact – synchronization takes longer
- Bit rate
  - Fixed-duration tasks amount to more bits at high bit rates
- Signal to noise ratio
  - Sync times will be longer at low SNR
- Synchronization threshold
  - SNR at which the demodulator can *acquire* sync
- Sync loss threshold
  - SNR at which a synchronized demodulator will *drop* sync

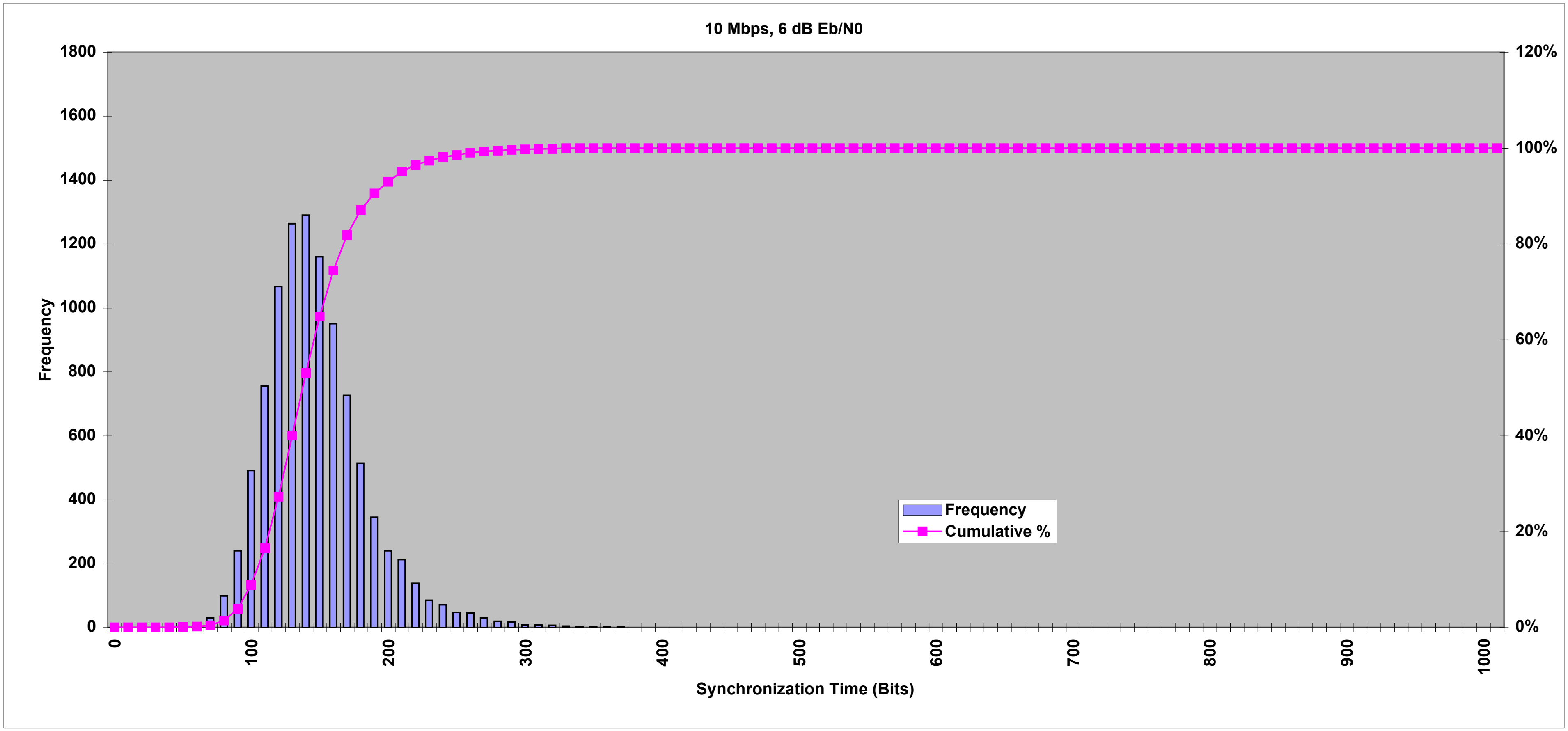
Tier 0 Synchronization, BER = 1e-5



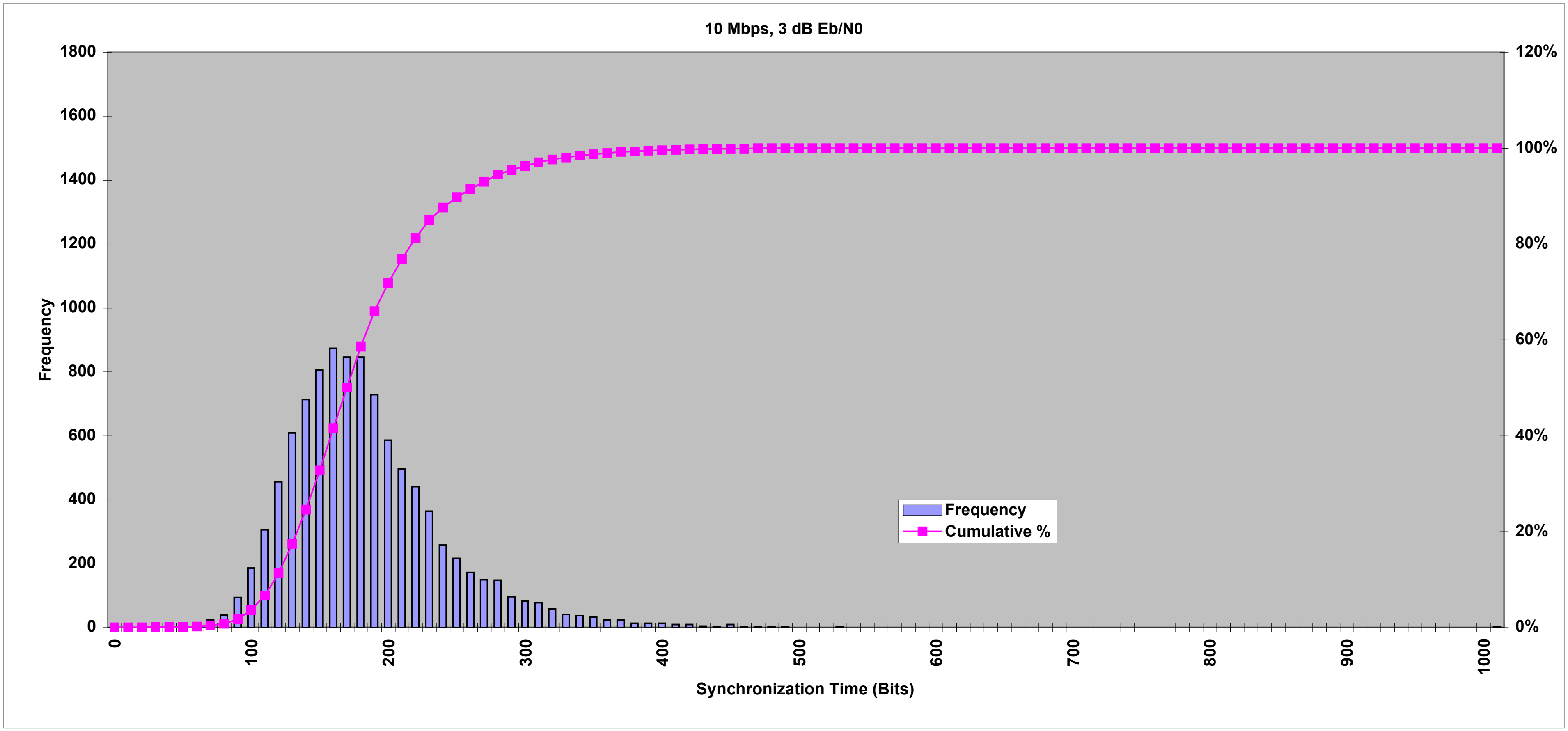
SOQPSK Synchronization, No Noise



SOQPSK Synchronization, 6 dB



SOQPSK Synchronization, 3 dB



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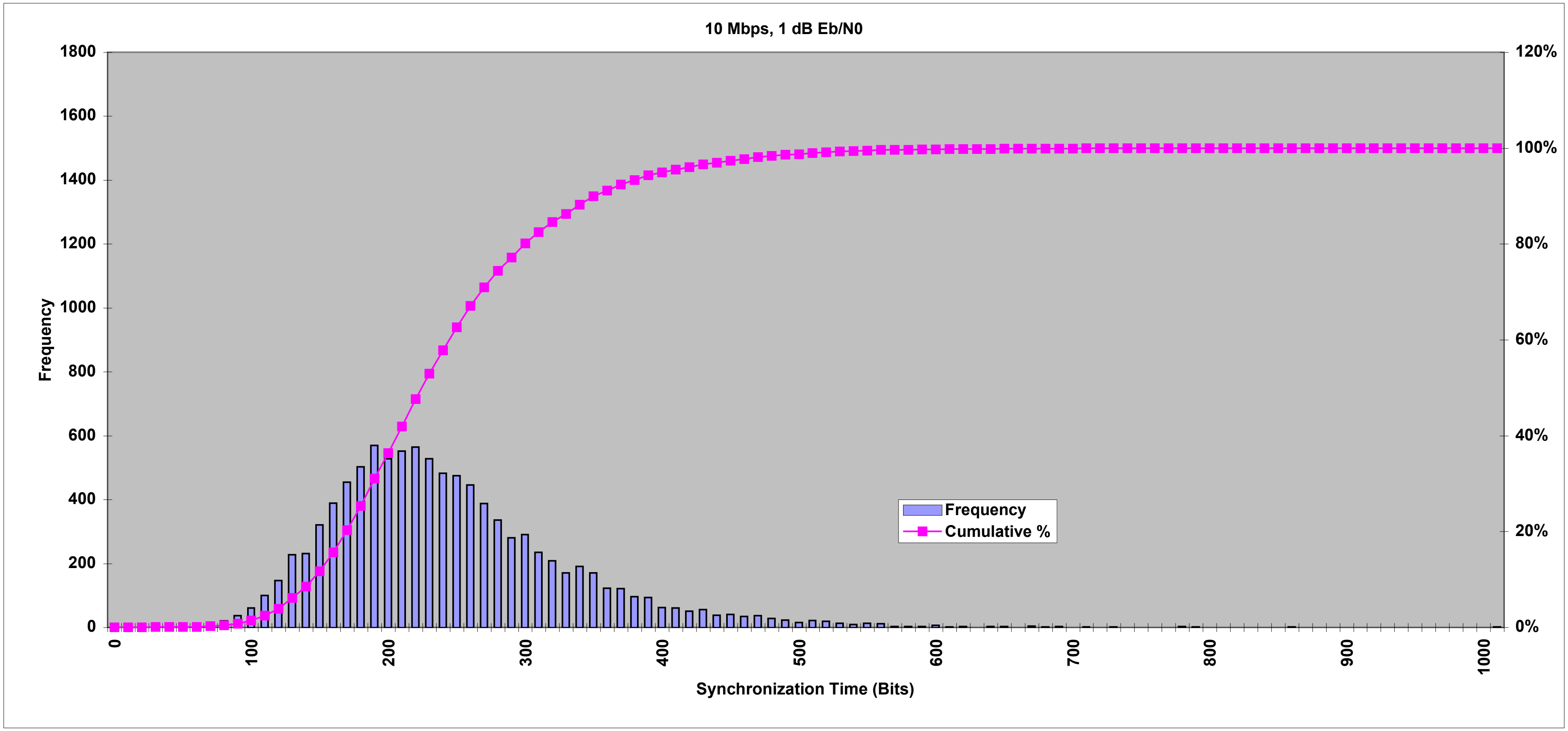
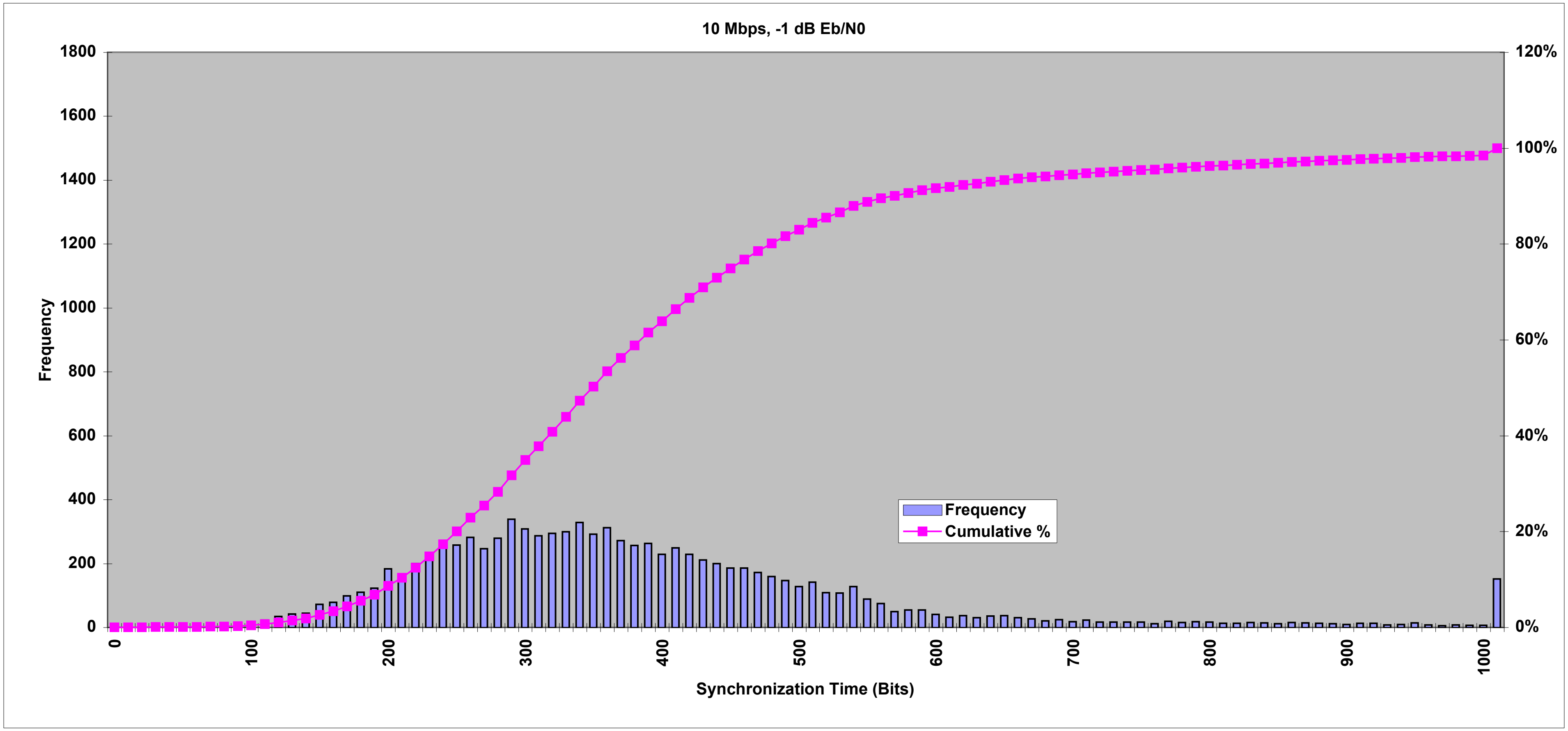
SOQPSK Synchronization, 1 dB



SOQPSK Synchronization, -1 dB



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Synchronization Summary

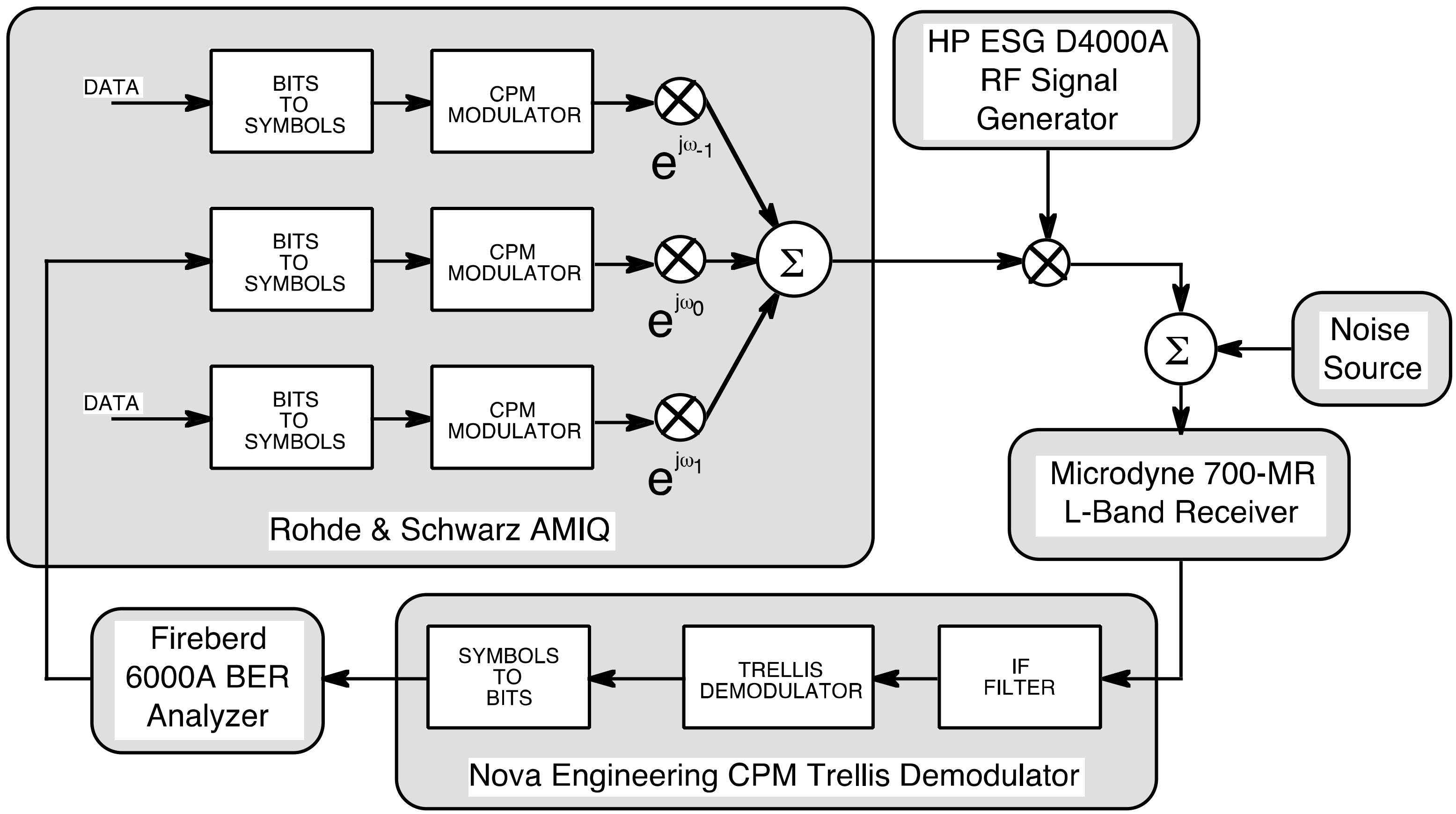
- The aeronautical telemetry channel is plagued with dropouts
- Rapid synchronization, and synchronization at low SNR, is the best means of minimizing the impact of these dropouts
- IRIG 118 defines test procedures for measuring sync time and sync thresholds
- Pay attention to synchronization performance!

Adjacent Channel Interference

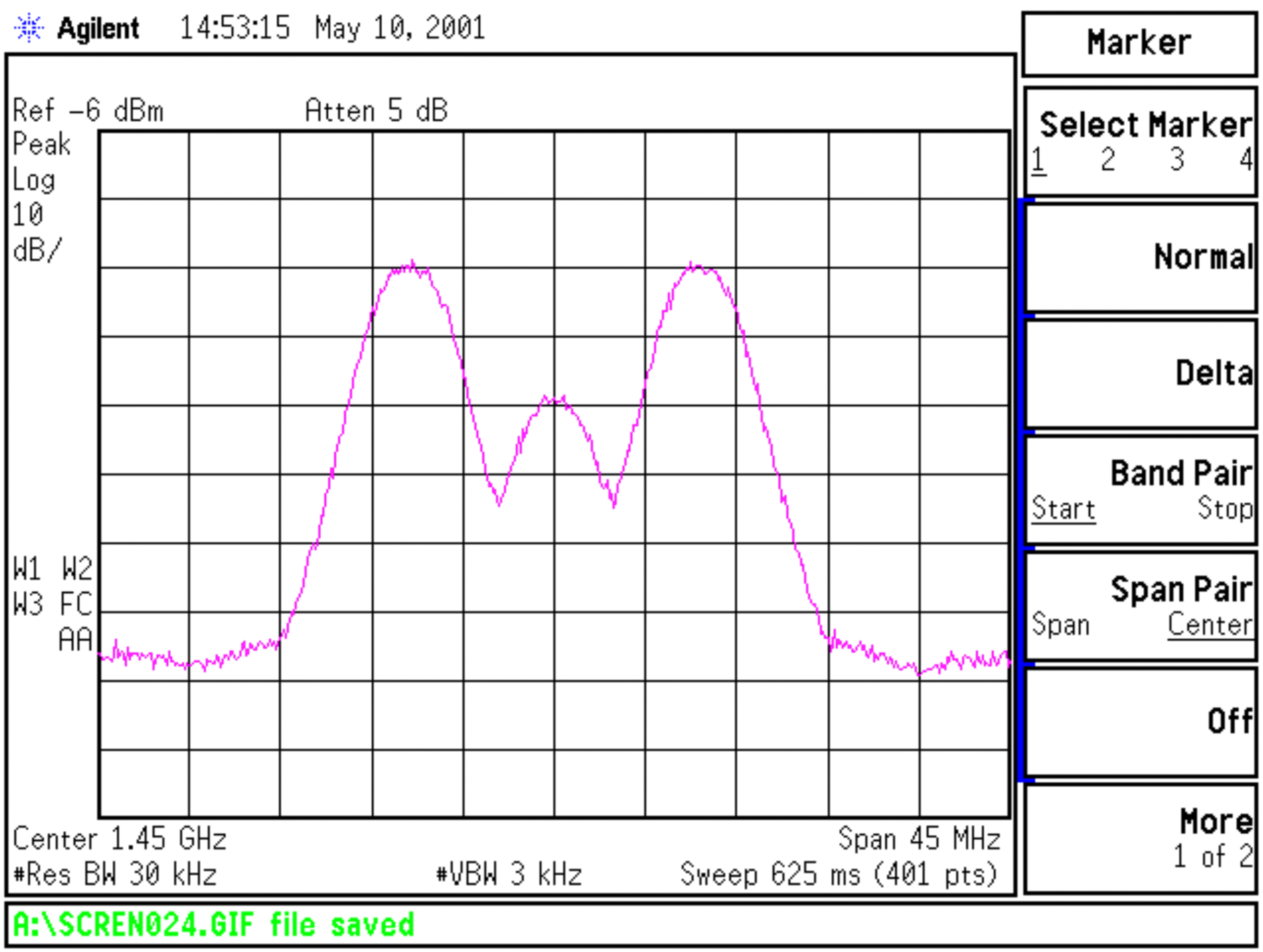
PSD is Half the Story

- Overall spectral efficiency is determined by spacing between channels
- Receiver selectivity affects channel spacing
- A valid comparison must account for both transmitted spectrum and “tolerable” receiver filtering
- Not all modulations are equally “tolerant” of IF filtering and interference
- **Multi-channel testing accounts for these factors**

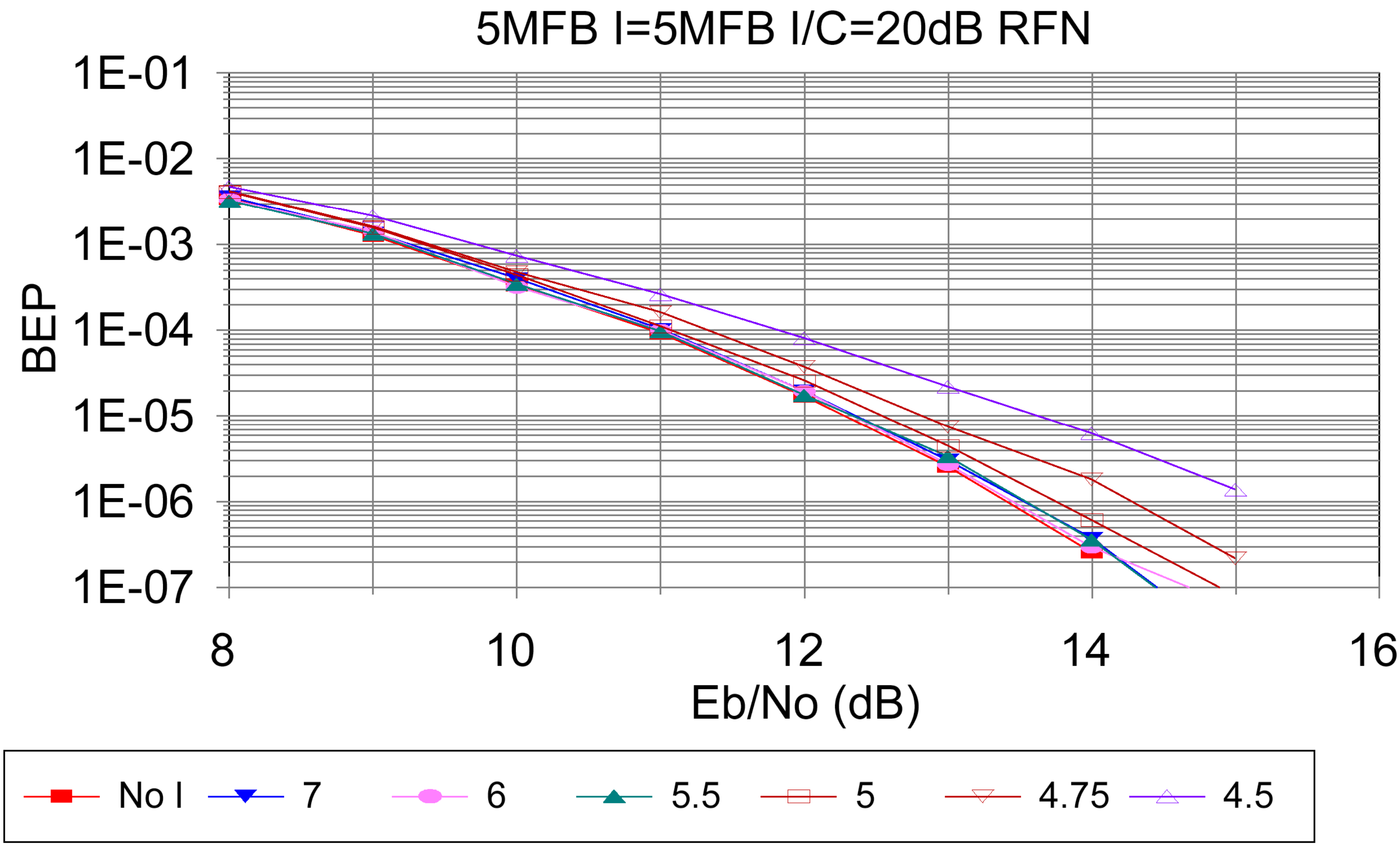
Multi-channel ACI Test Set



9 Mbps Multi-h CPM, Multichannel



BER as a Function of ΔF



From Gene Law, "Recommended Minimum Telemetry Frequency Spacing With CPFSK, CPM, SOQPSK, and FQPSK Signals", ITC 2003

Degradation as a Function of ΔF

From Gene Law, "Recommended Minimum Telemetry Frequency Spacing With CPFSK, CPM, SOQPSK, and FQPSK Signals", ITC 2003

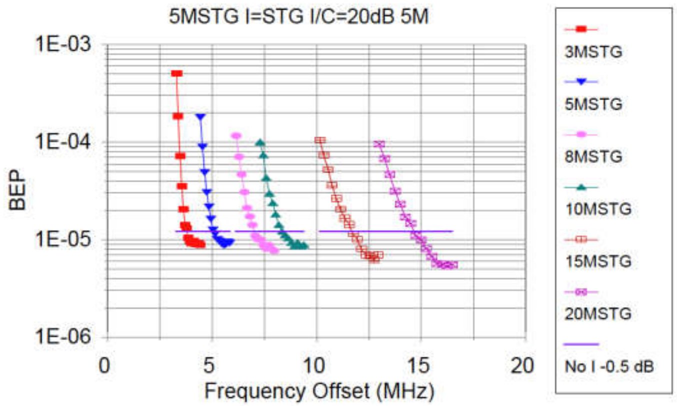


Figure 5. 5 Mbps SOQPSK-TG.

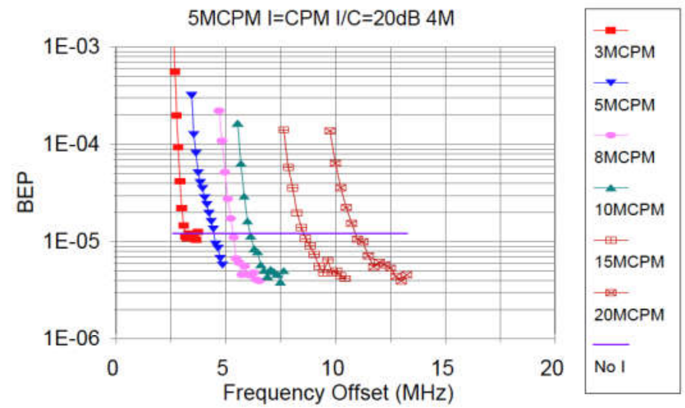


Figure 6. 5 Mbps multi-h CPM.

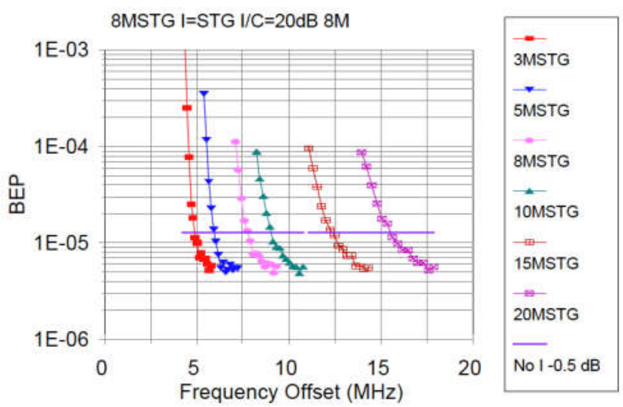


Figure 7. 8 Mbps SOQPSK-TG with 8 MHz IF BW.

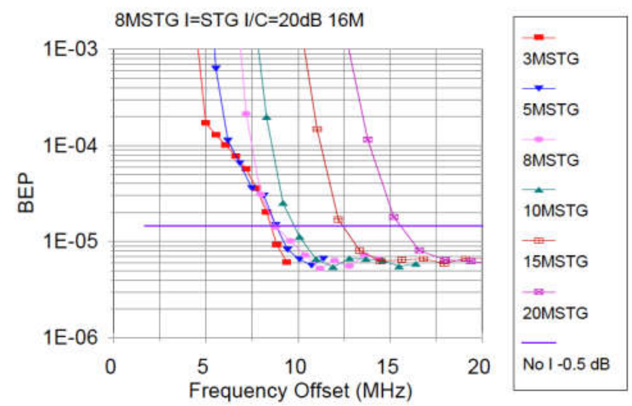
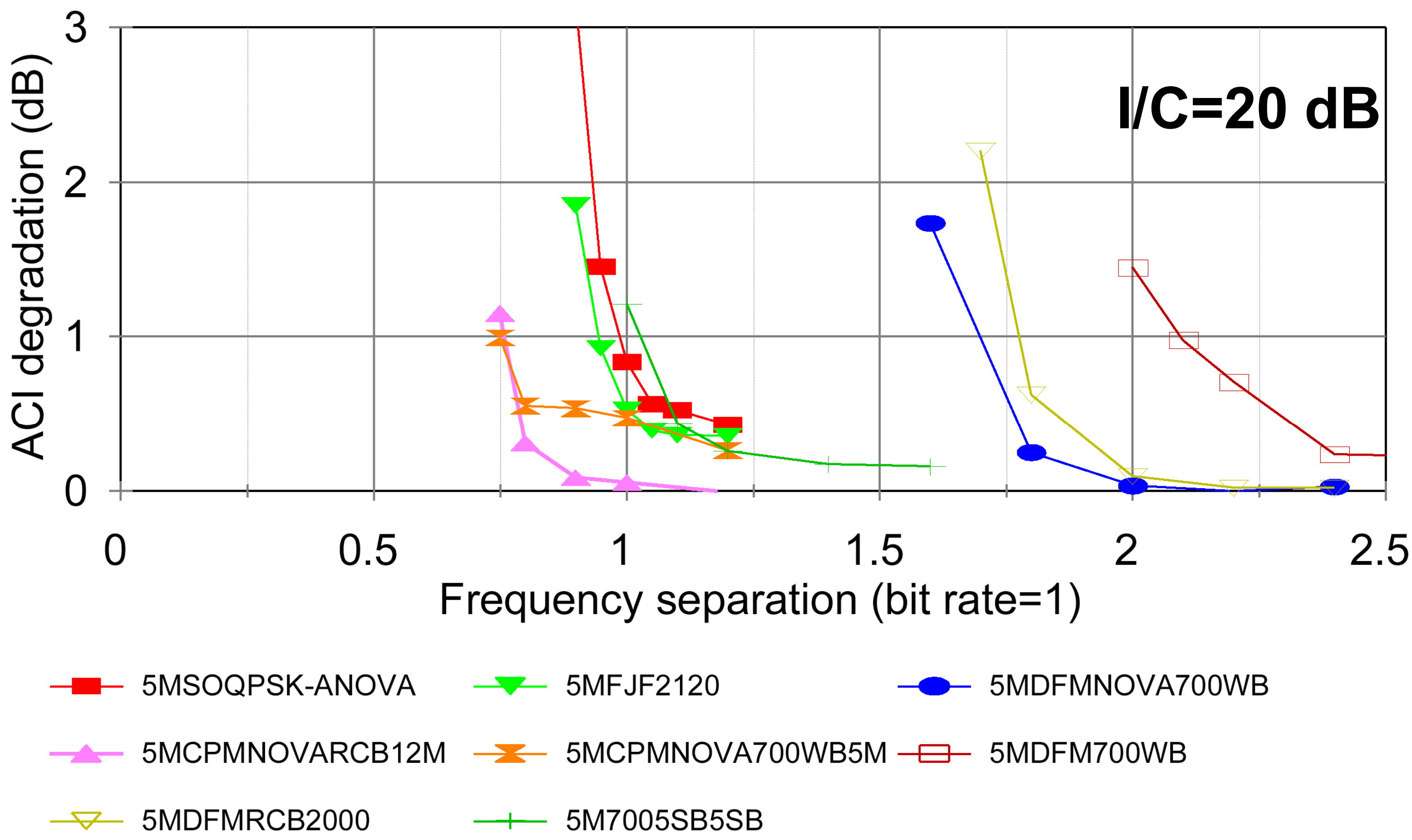


Figure 8. 8 Mbps SOQPSK-TG with 16 MHz IF BW.

ACI Summary

From Gene Law, "Recommended Minimum Telemetry Frequency Spacing With CPFSK, CPM, SOQPSK, and FQPSK Signals", ITC 2003



Frequency Separation Rule

$$\Delta F_0 = a_s{*}R_s + a_i{*}R_i$$

where:
- ΔF_0 = the minimum center frequency separation in MHz
- R_s = bit rate of desired signal in Mb/s
- R_i = bit rate of interfering signal in Mb/s

Modulation Type	a_s		a_i	Rs = Ri
NRZ PCM/FM	1	for receivers with RLC final Intermediate Frequency (IF) filters	1.2	2.2
	0.7	for receivers with Surface Acoustic Wave (SAW) or digital IF filters	1.2	1.9
	0.5	with multi-symbol detectors (or equivalent devices)	1.2	1.7
FQPSK-B, FQPSK-JR, SOQPSK-TG	0.45		0.65	1.1
ARTM CPM	0.35		0.5	0.85

- The NRZ PCM/FM signals are assumed to be premodulation filtered with a multi-pole filter with 3 dB point of 0.7 times the bit rate and the peak deviation is assumed to be approximately 0.35 times the bit rate.
- The receiver IF filter is assumed to be no wider than 1.5 times the bit rate and provides at least 6 dB of attenuation of the interfering signal.
- The interfering signal is assumed to be no more than 20 dB stronger than the desired signal.
- The receiver is assumed to be operating in linear mode; no significant intermodulation products or spurious responses are present.

~~Let’s Eat Students!~~

Let’s Eat, Students!

Commas Save Lives

See you back here at _______ PM

Multipath Propagation

Multipath Propagation

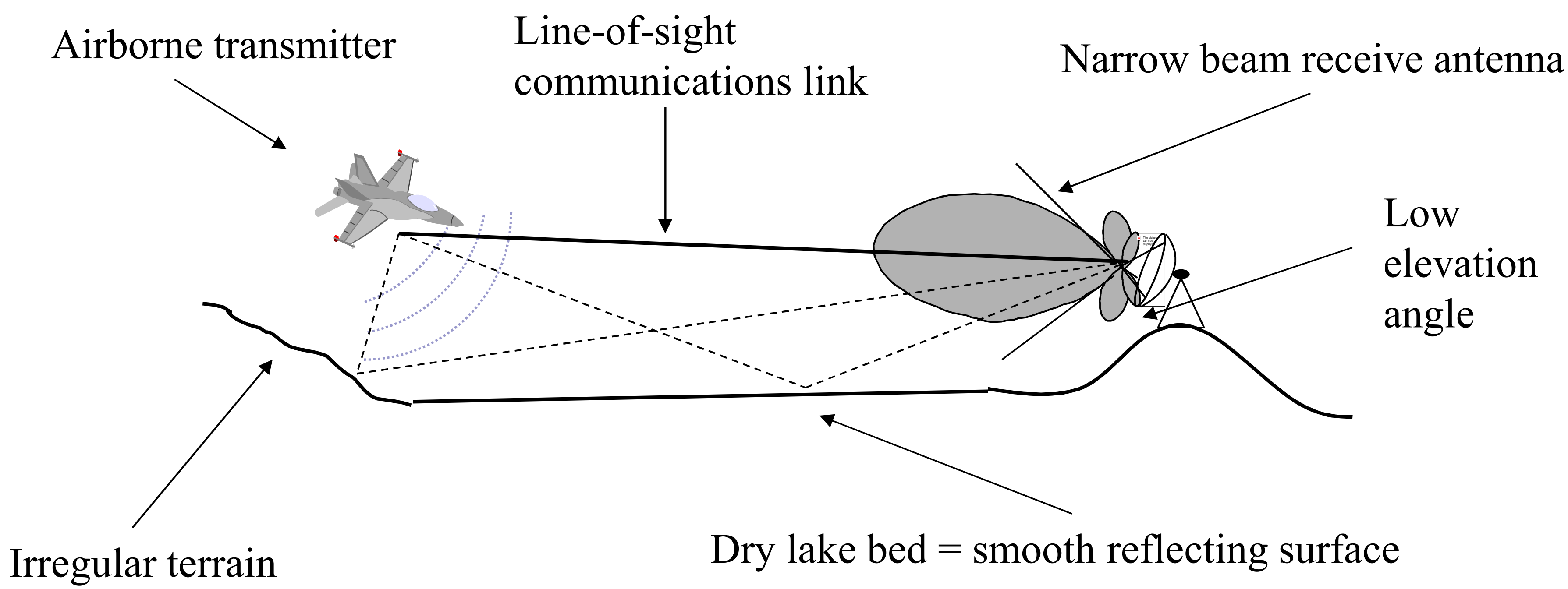
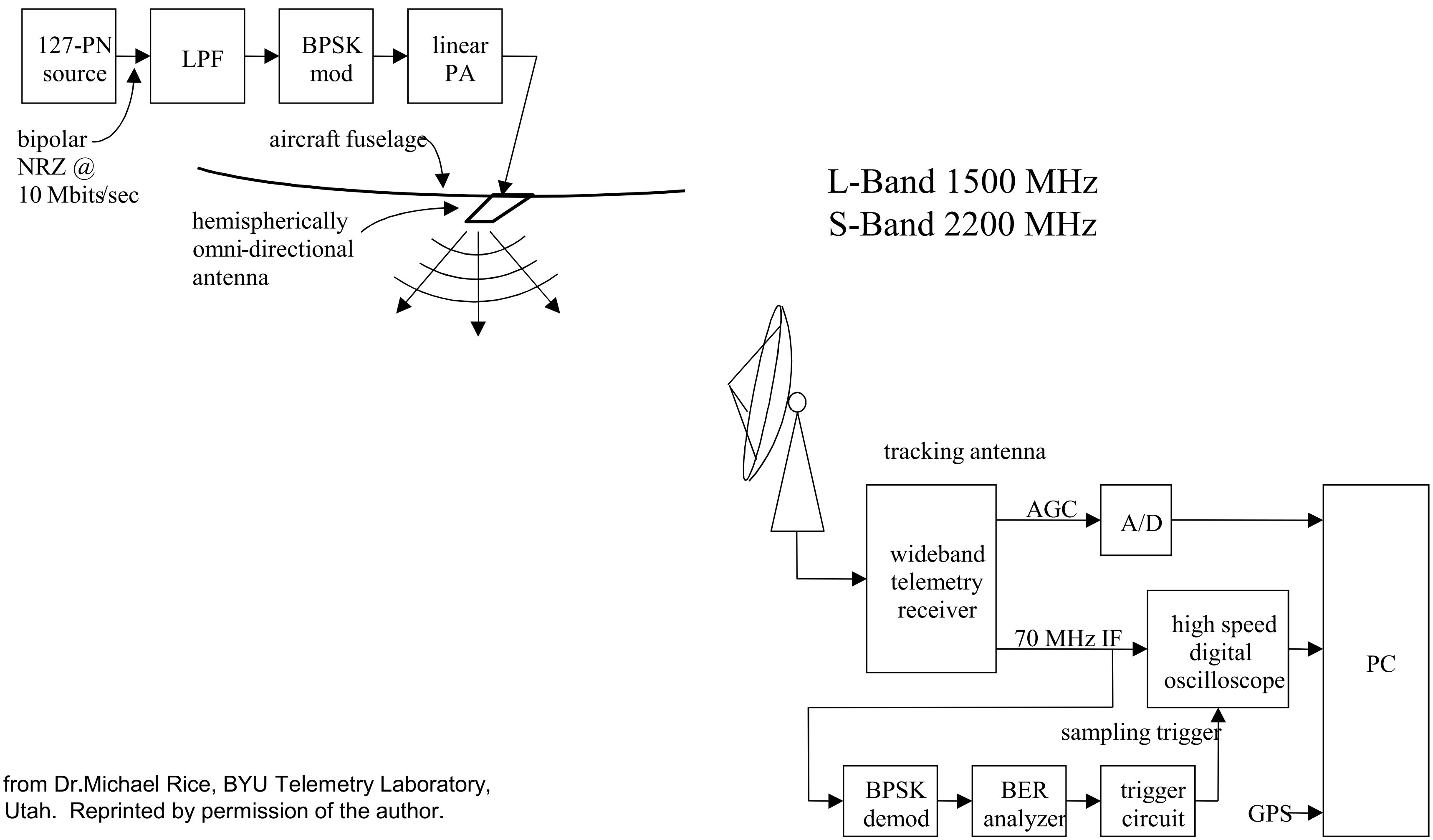


Figure from Dr.Michael Rice, BYU Telemetry Laboratory, Provo, Utah. Reprinted by permission of the author.

Multipath Experiments



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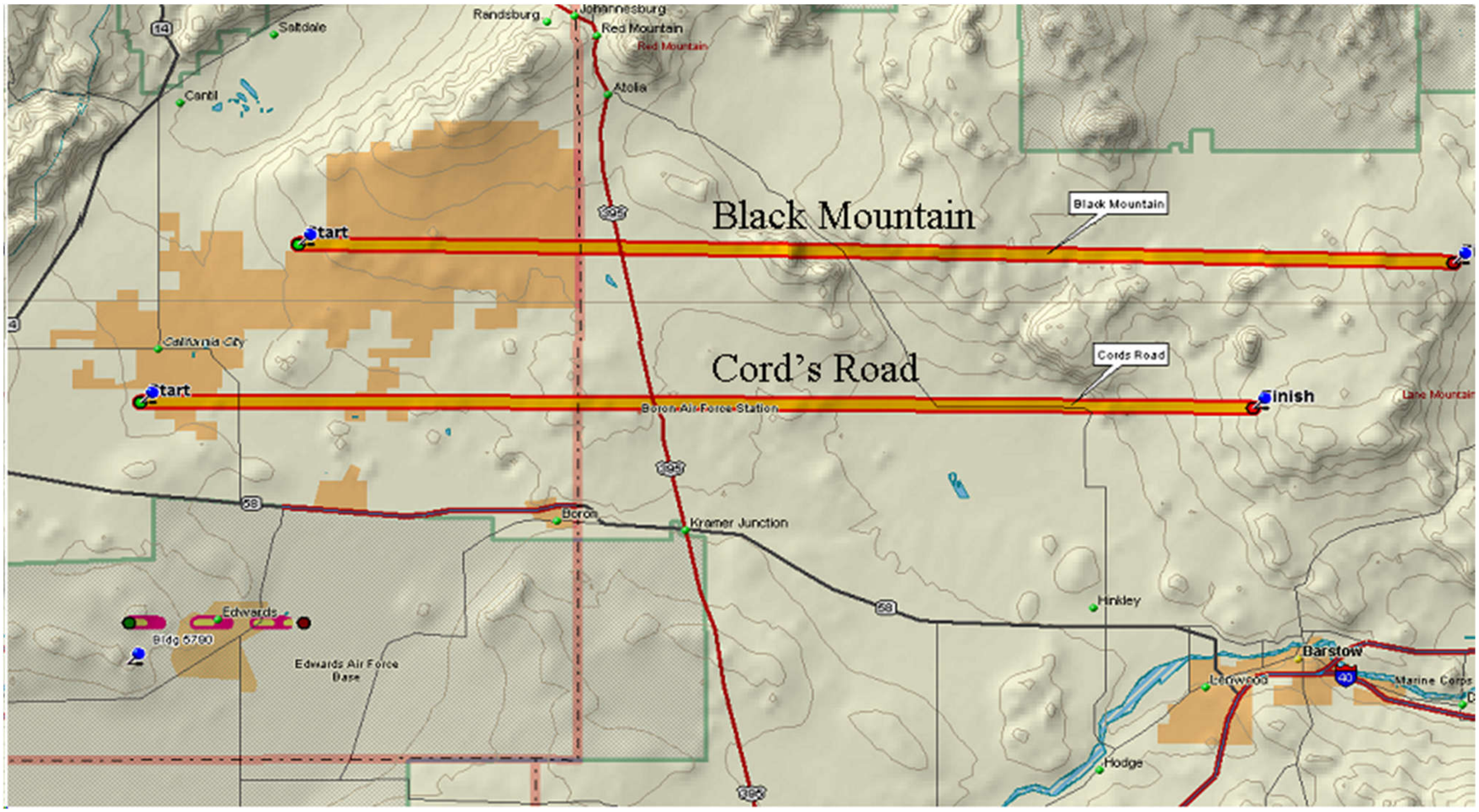
Edwards AFB Flight Paths



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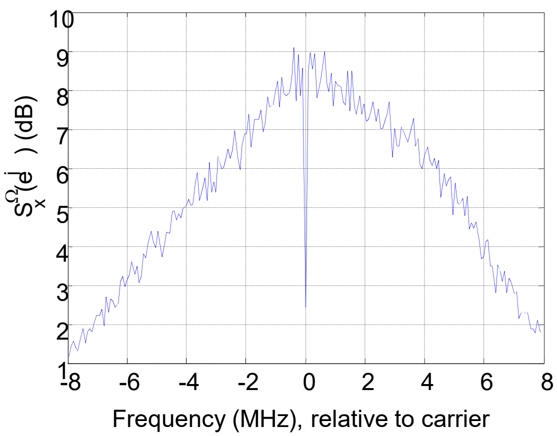
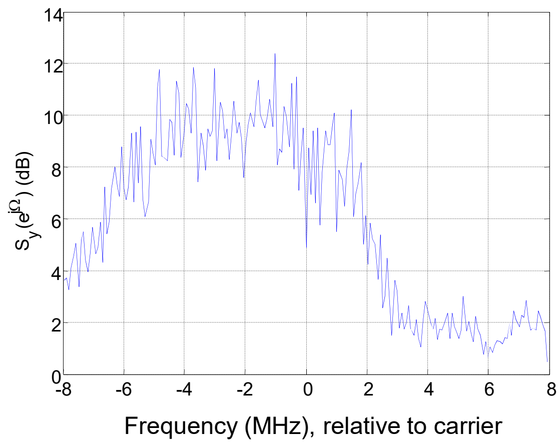
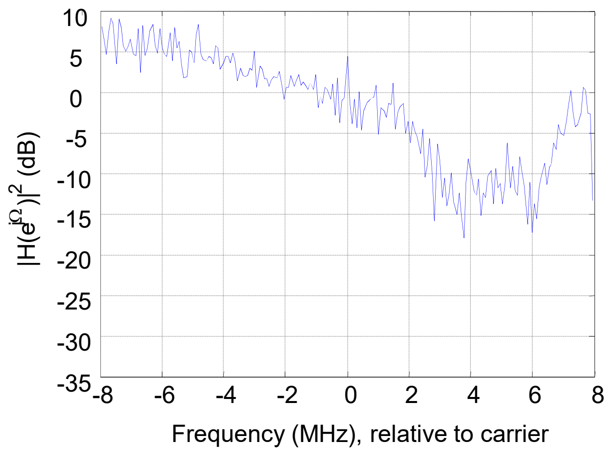
Signal Processing



Power spectral density of transmitted signal



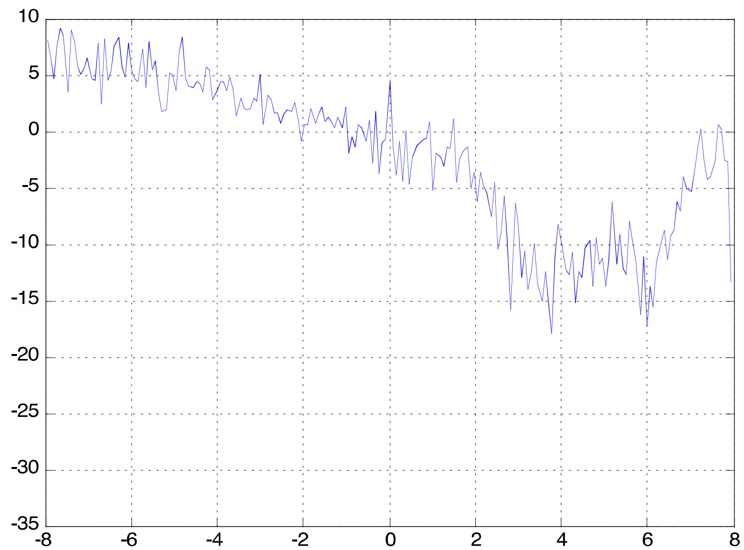
Power spectral density of received signal

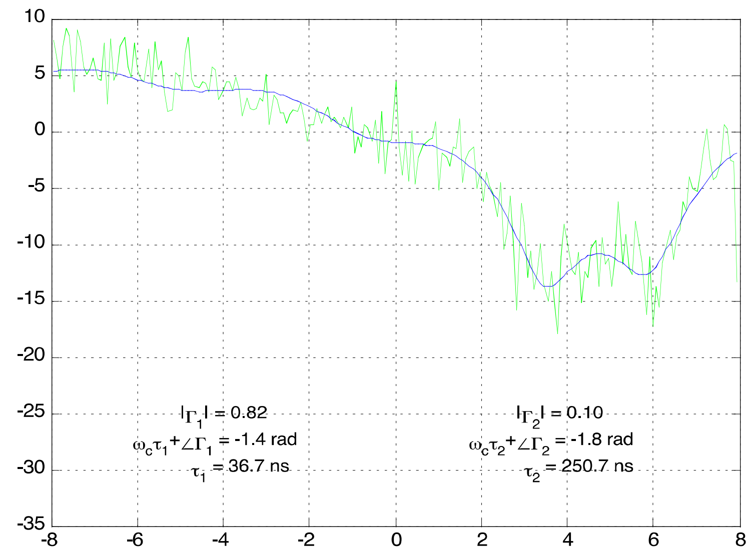


Estimate of channel transfer function

Figure from Dr.Michael Rice, BYU Telemetry Laboratory, Provo, Utah. Reprinted by permission of the author.

Modeling Procedure

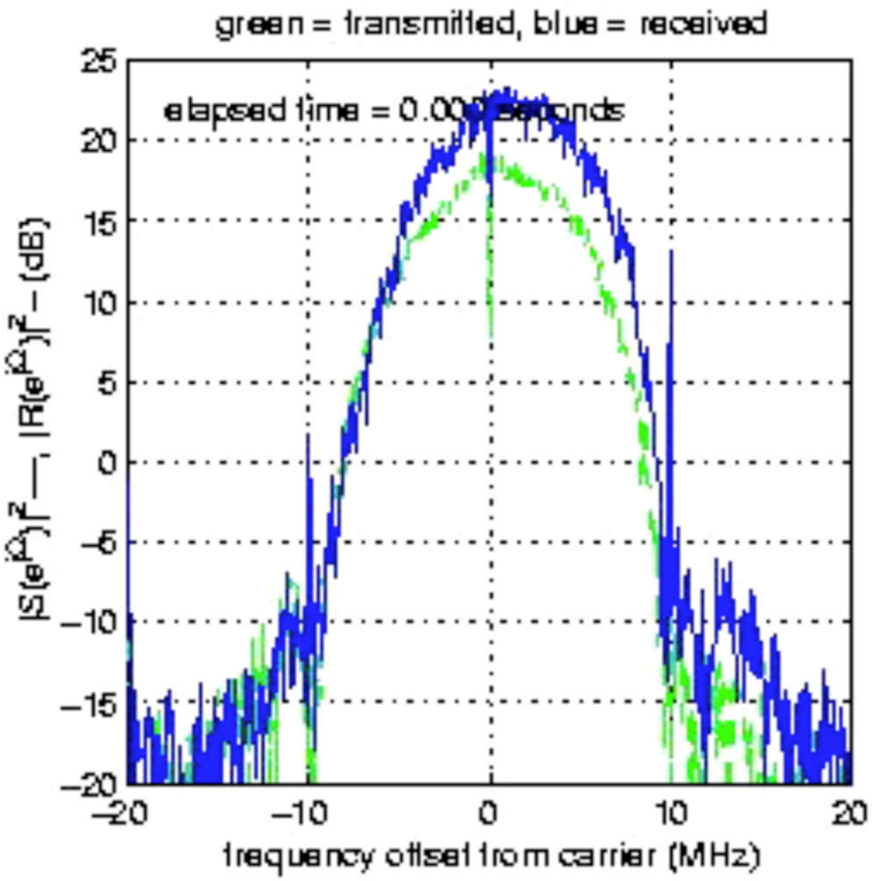




$$\hat{H}(\omega) = \frac{R(\omega)}{S(\omega)} \quad \begin{array}{l} \text{power spectral density of received signal} \\ \text{power spectral density of transmitted signal} \end{array}$$

Figure from Dr.Michael Rice, BYU Telemetry Laboratory, Provo, Utah. Reprinted by permission of the author.

Measurement and Modeling



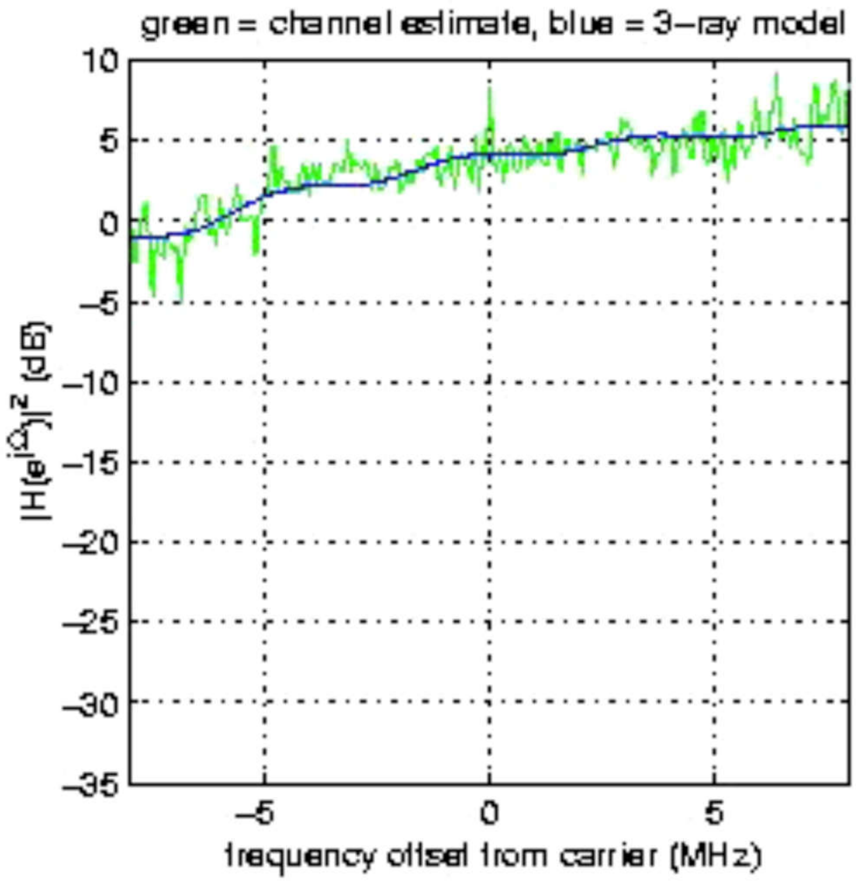
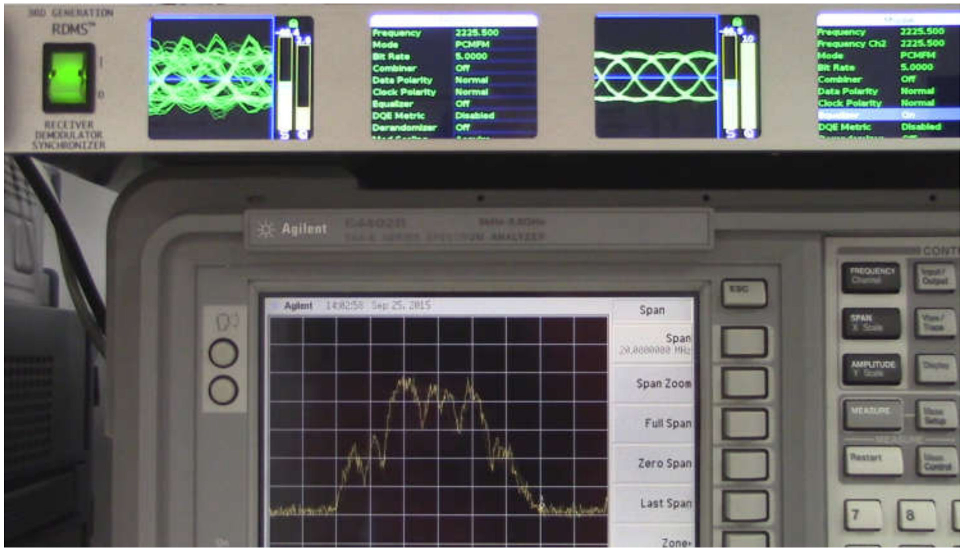


Figure from Dr.Michael Rice, BYU Telemetry Laboratory, Provo, Utah. Reprinted by permission of the author.

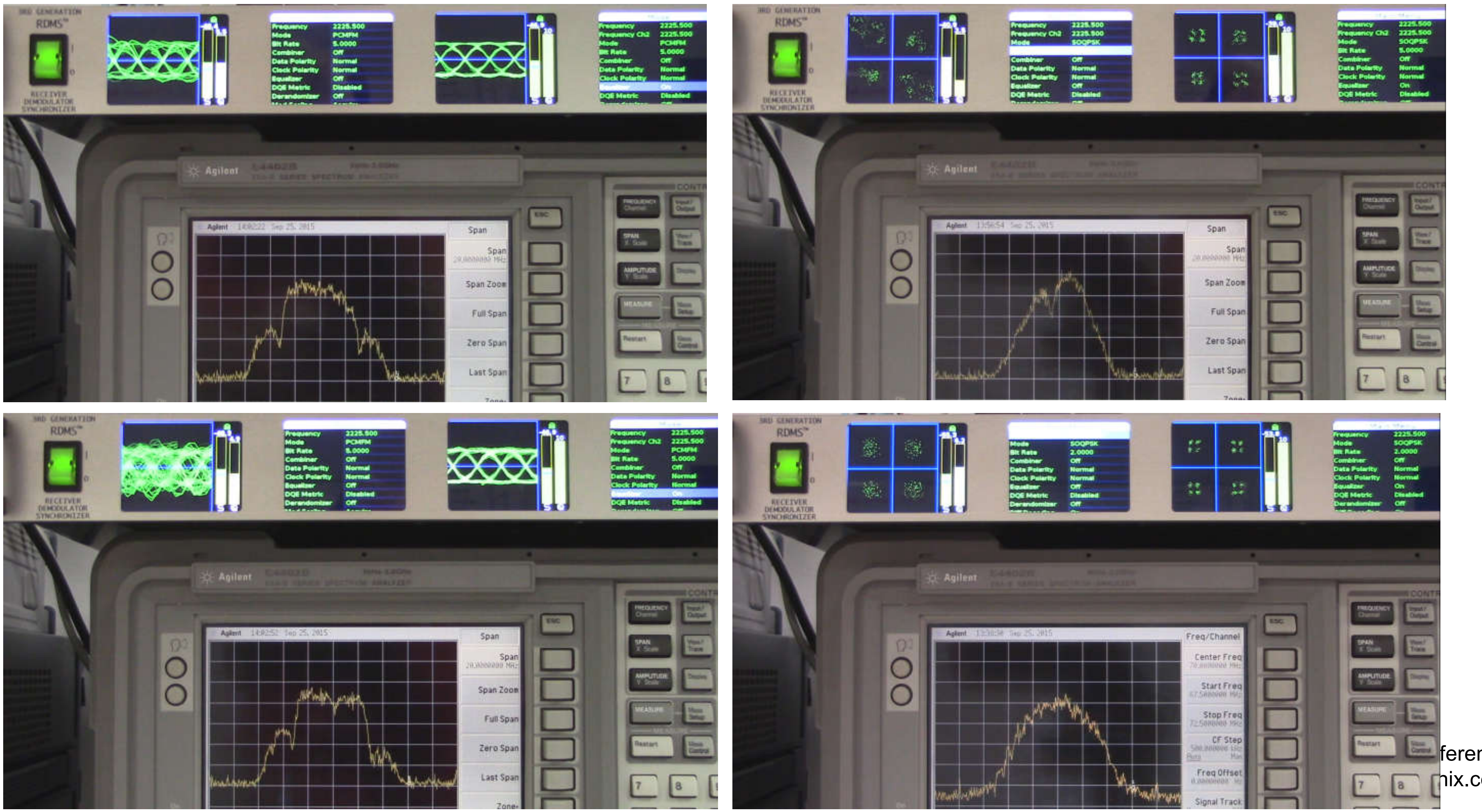
Multipath on the Tarmac

- Nearly static, frequency selective, long delays

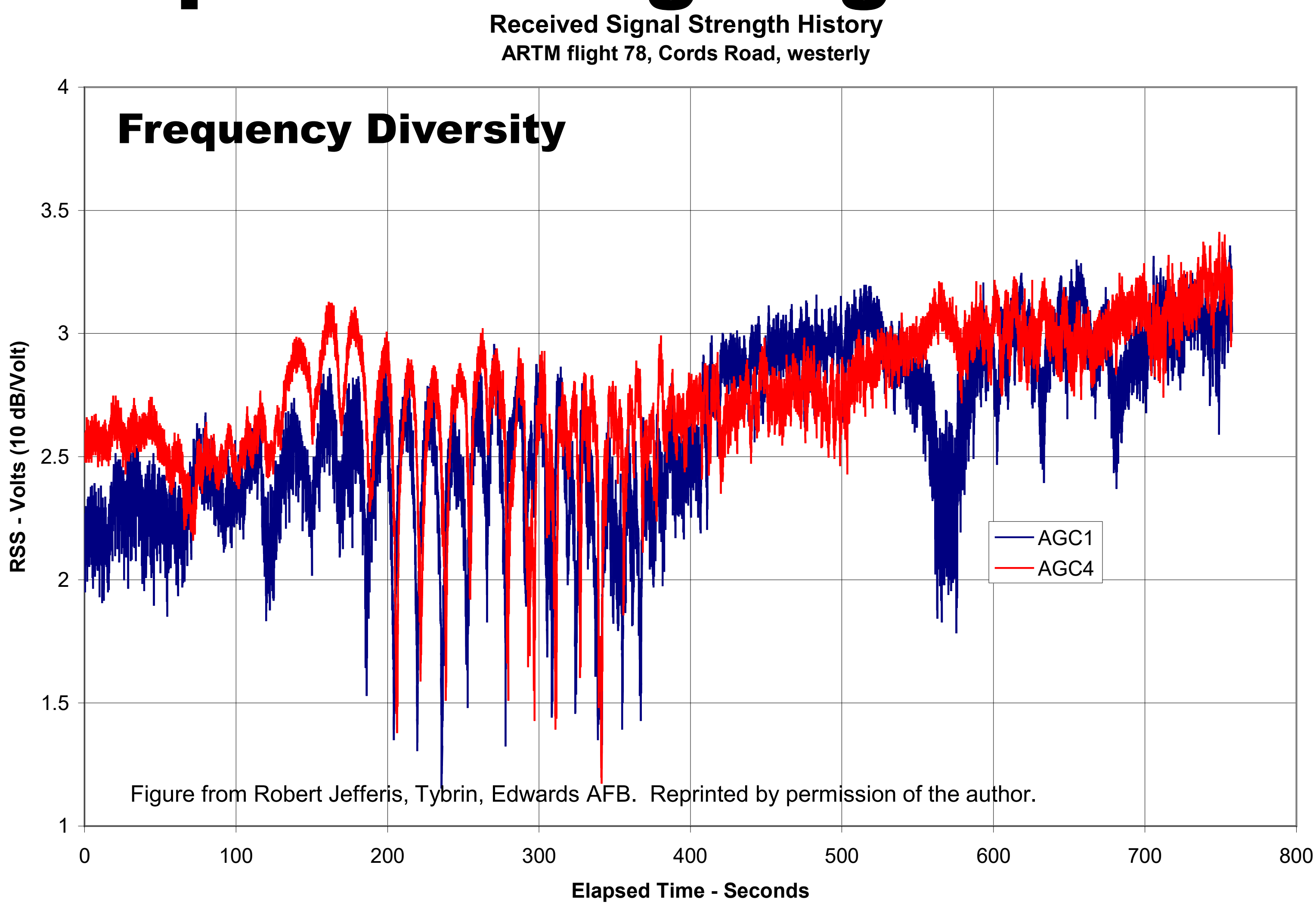


Multipath in Flight

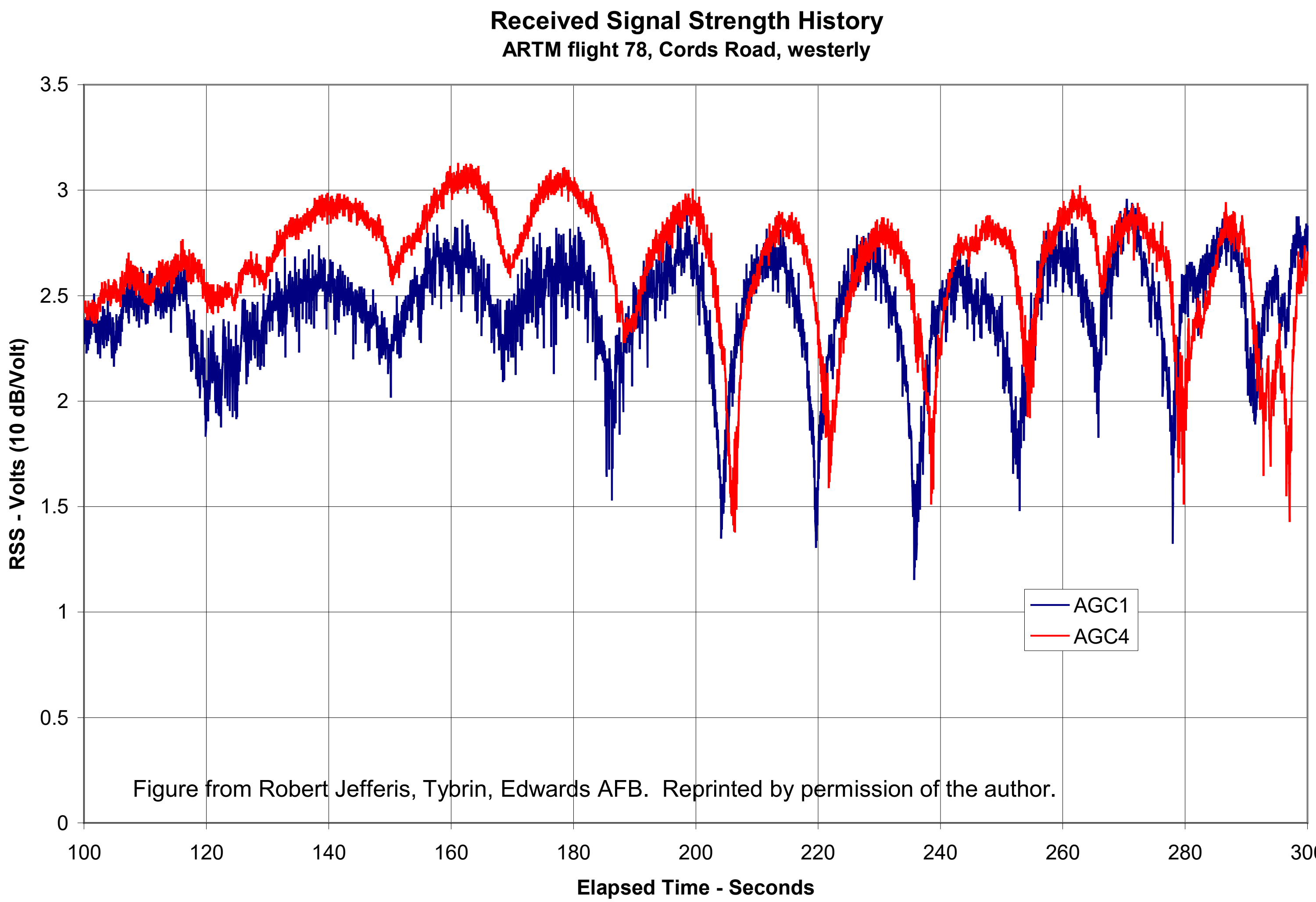
- Dynamic, frequency selective and flat fading, various delays



Multipath During Flight



Classic Two-Ray Multipath



Multipath Summary

- If your test article operates near the ground, you are quite likely experiencing multipath.
- If so, there will be intervals during which no useful data is recovered.
- Loss of bit count integrity is likely
  - Encrypted links will lose crypto sync
- What to do?
- Stay tuned for the “Mitigation” discussion

DSP Techniques for Telemetry

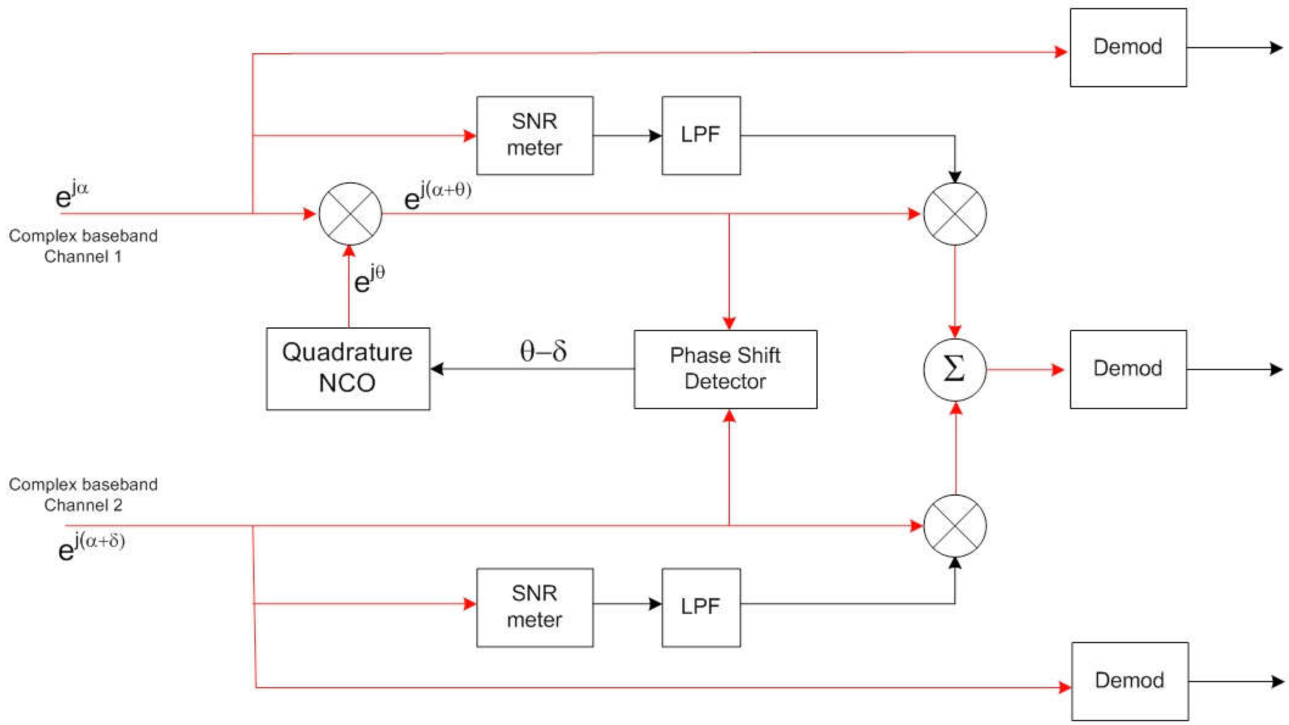
DSP Techniques for Telemetry

- Maximal ratio combining – optimal against AWGN
  - Polarization diversity
  - Frequency diversity
  - Receive-side processing, no transmitter impact
- Adaptive equalization
  - Powerful tool against multipath
  - Receive-side processing, no transmitter impact
- Best source selection
  - Combats all forms of signal impairment
  - Receive-side processing, no transmitter impact
- Space-time coding (STC)
  - Mitigates “built-in” multipath from dual TX antennas
  - Requires dual transmitters
- Forward error correction
  - Spending bandwidth to buy link margin
  - Requires encoder implemented in transmitter

Maximal Ratio Combining

- Many telemetry systems utilize diversity reception
  - Frequency separation using two transmitter
  - Orthogonal polarizations using cross-polarized antenna feeds
- Combining two (or more) copies of the same signal
  - Diversity combining
  - Creates a third signal to be demodulated
  - BER performance of third signal is better than either of the individual signals
- Special case – the leading use of diversity
  - Linearly polarized transmit antenna on test article – could be at any orientation
  - Left-hand and right-hand circularly polarized receive antennas
  - Each receive antenna loses half the transmit power
  - Diversity combiner puts it all back together, eliminating the polarization loss
  - Frequency diversity works the same way, but uses twice the bandwidth

Maximal Ratio Combining

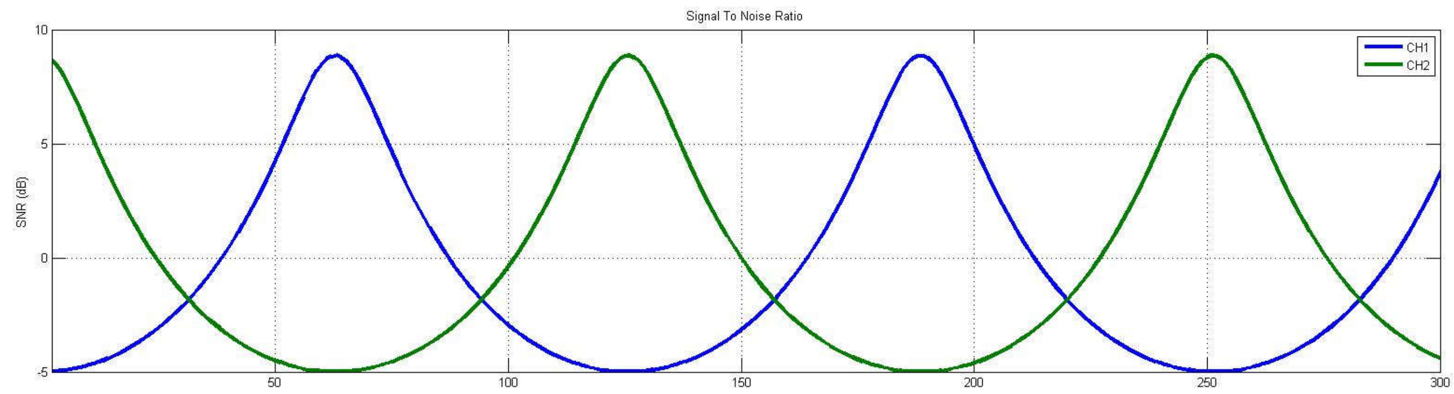


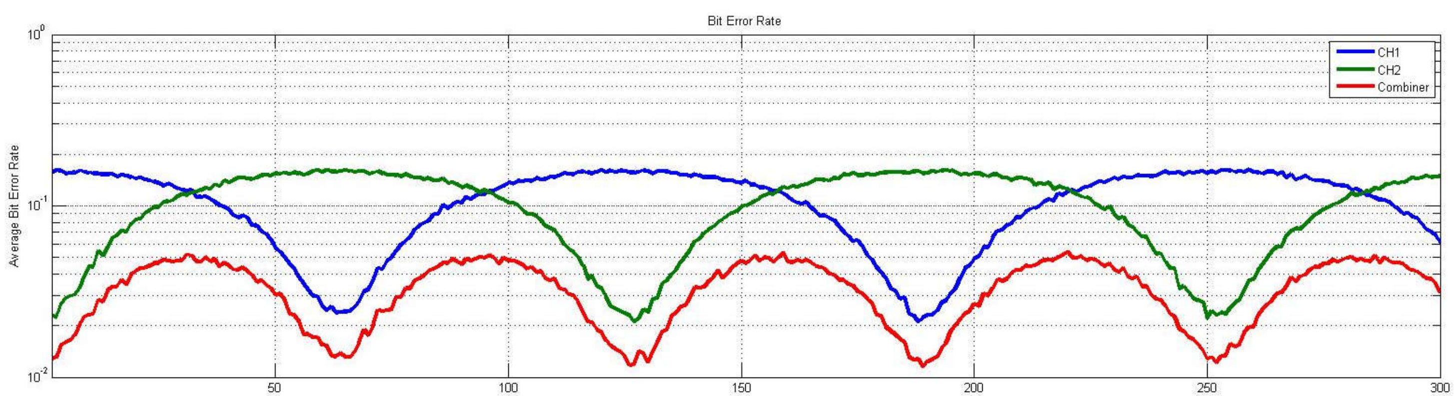
- Weight each signal in proportion to its SNR and add
- Yields optimum SNR on combined channel **in AWGN**
- $SNR_{combined} = SNR_a + SNR_b$

Maximal Ratio Combining

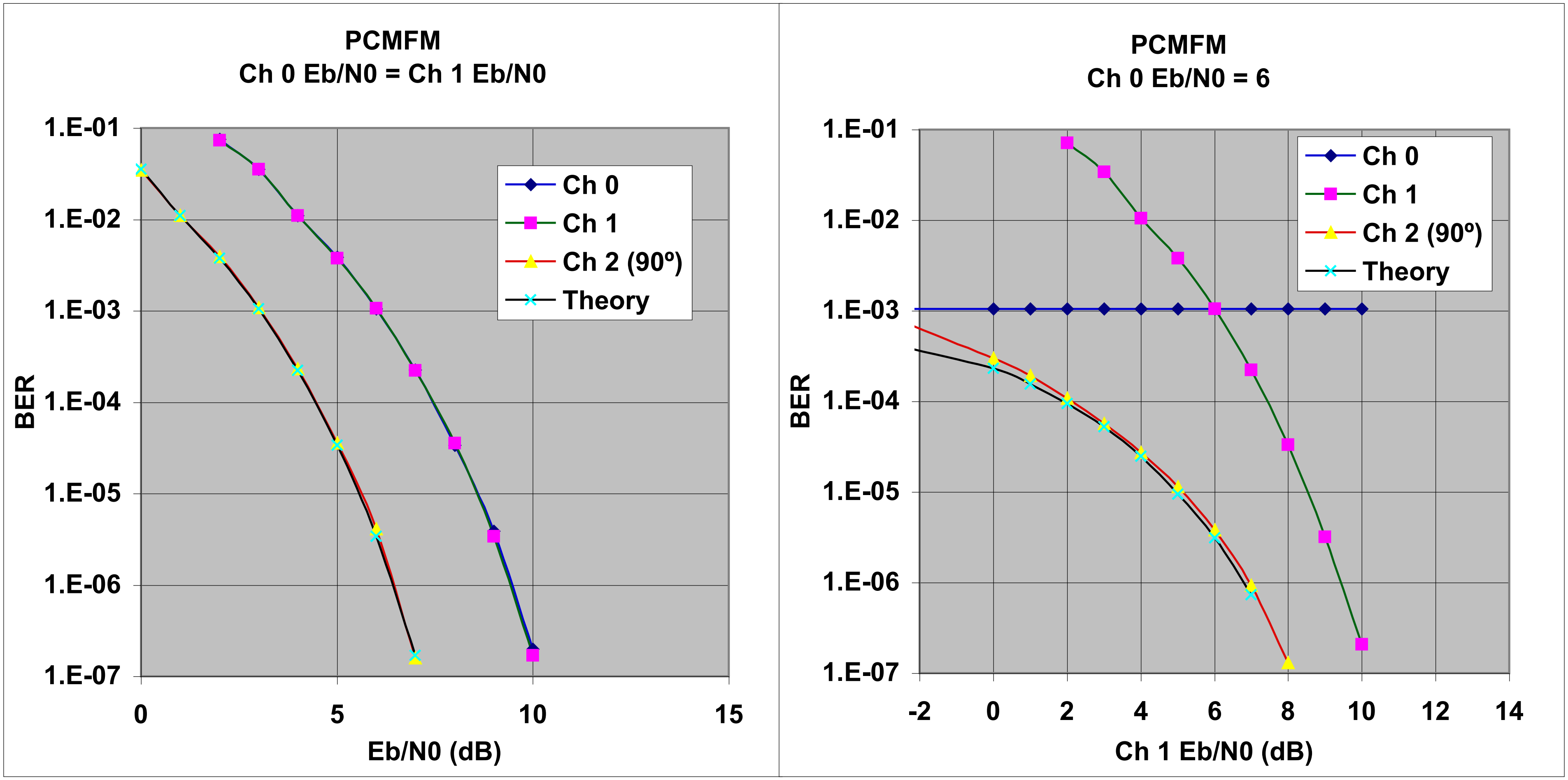
- Jump to file://localhost/Users/TerryHill/Documents/Quasonix/ITC 2015/Diversity Combiner.avi

BER Results - Fading Signals

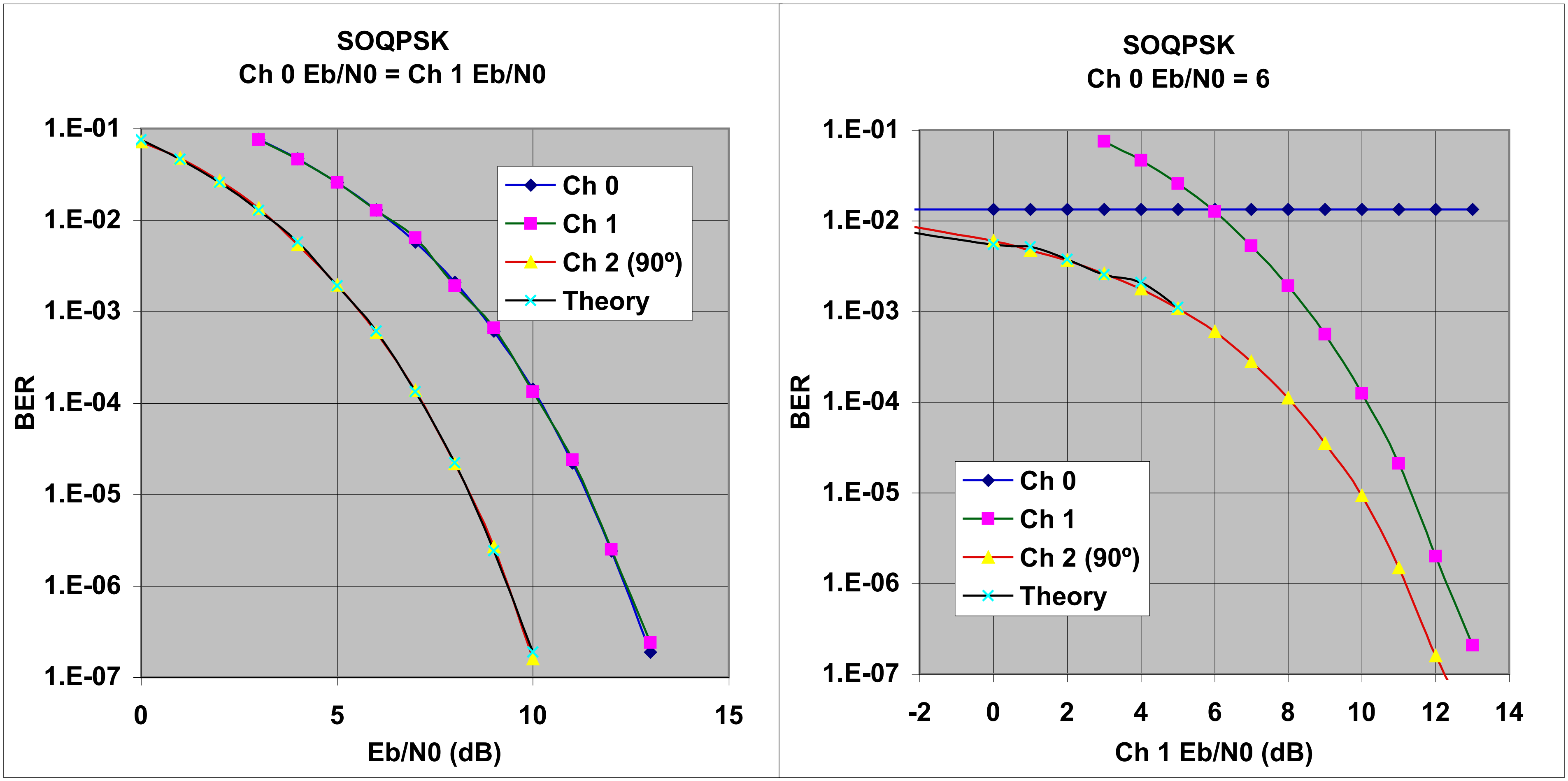




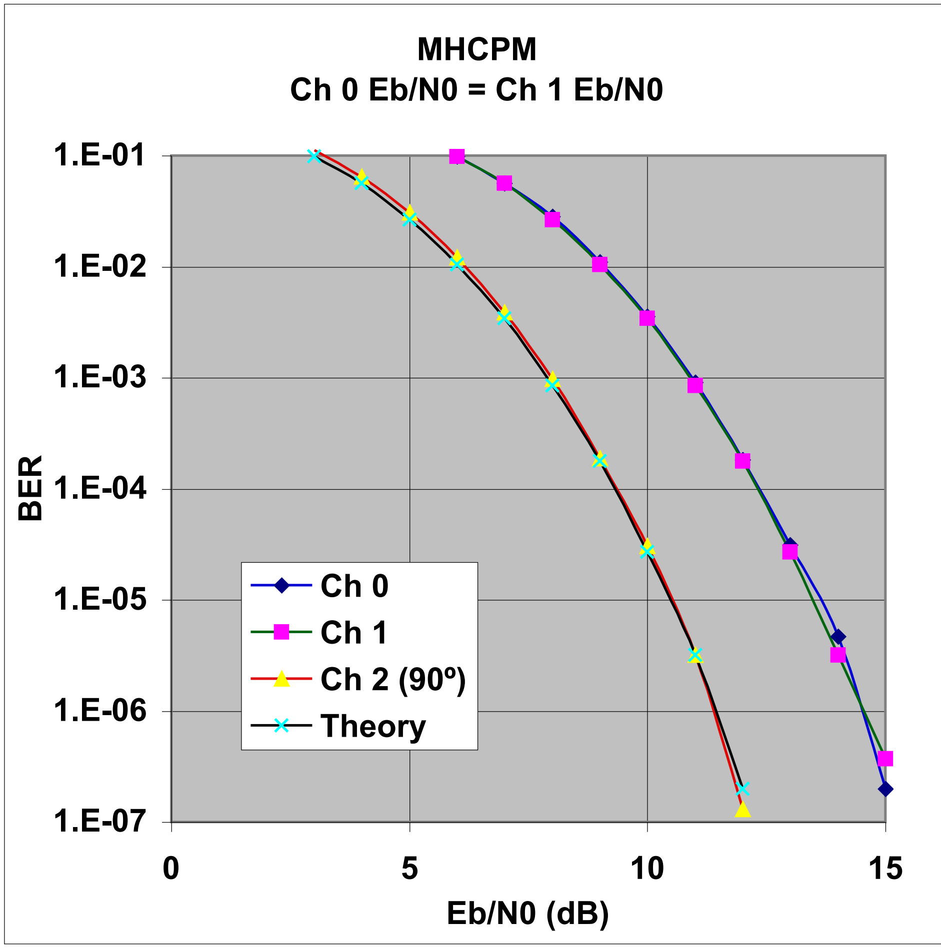
Measured Combiner BER - Tier 0

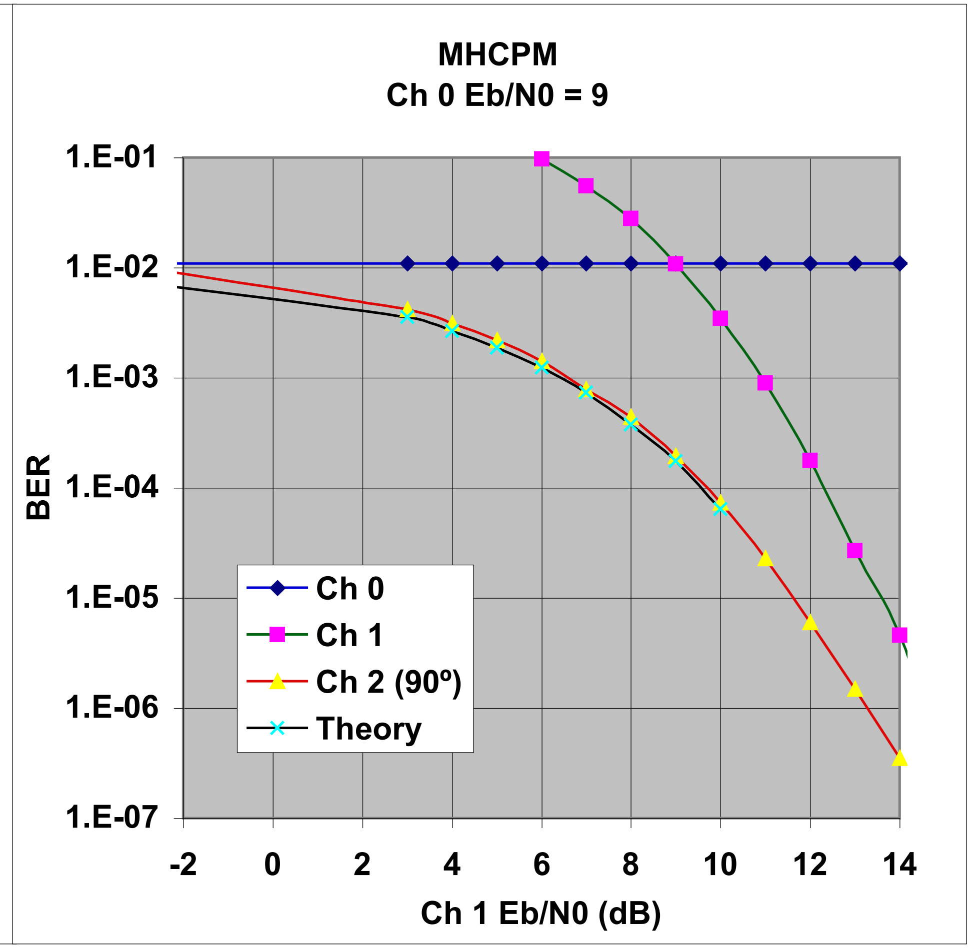


Measured Combiner BER - Tier I



Measured Combiner BER - Tier II





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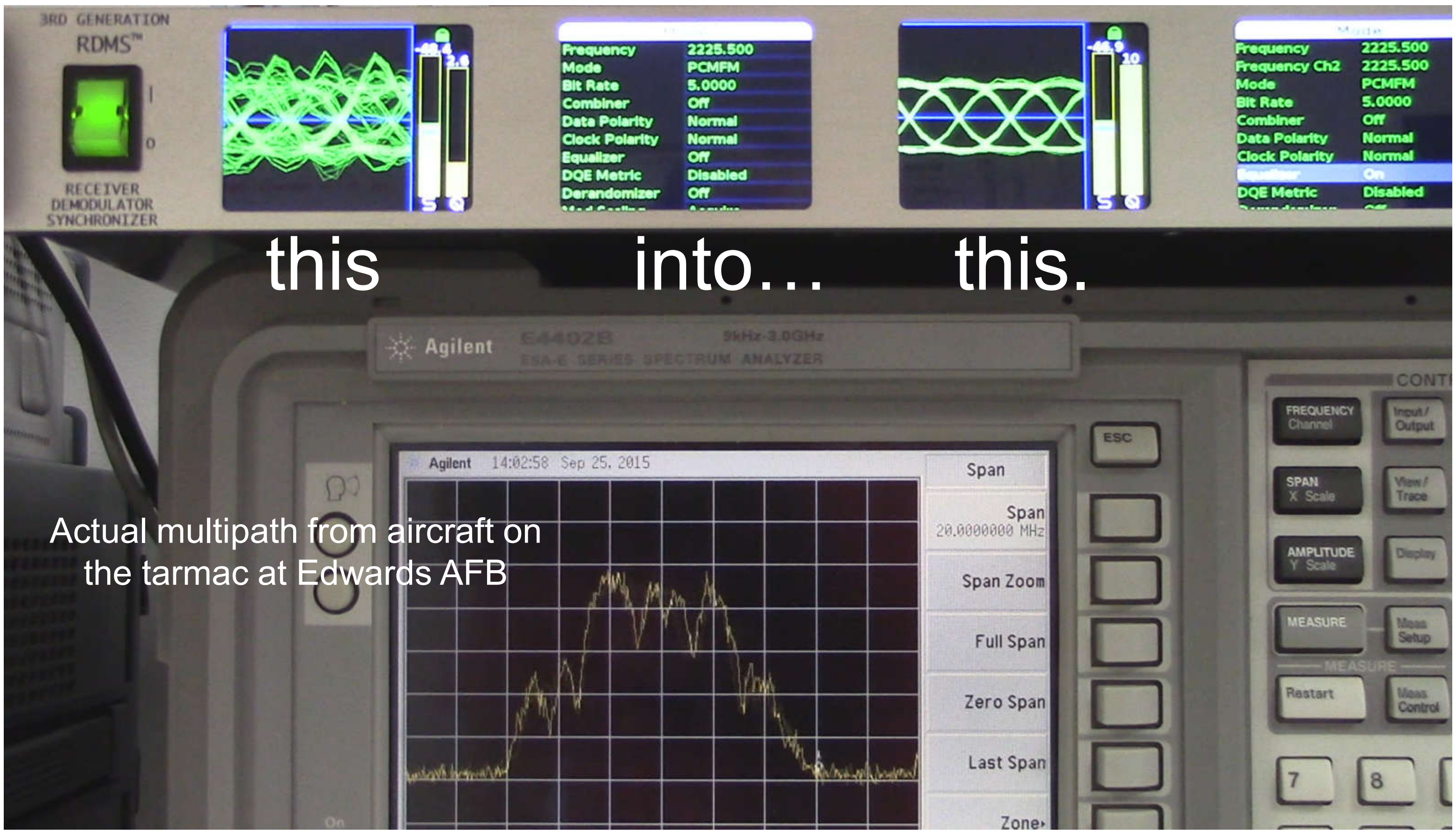
Combiner Summary

- Receive-side processing
  - No transmitter impact
- Phase aligns the signals
- Forms weighted sum of two inputs
- SNR of the weighted sum is at least as high as the better signal
- May be as much as 3 dB higher (equal input case)
- Conventional combiner design assumes signals are time-aligned
  - Performance falls off rapidly with increasing time skew
  - Combiner will probably fail altogether at ± ½ bit time skew
- Some combiners do both phase alignment *and* time alignment
  - Supports operation with spatially separated antennas
- If you have access to two copies of the signal, use them!

Adaptive Equalization

Multipath is Ugly

- Equalization can turn



- this into… this.

Actual multipath from aircraft on the tarmac at Edwards AFB

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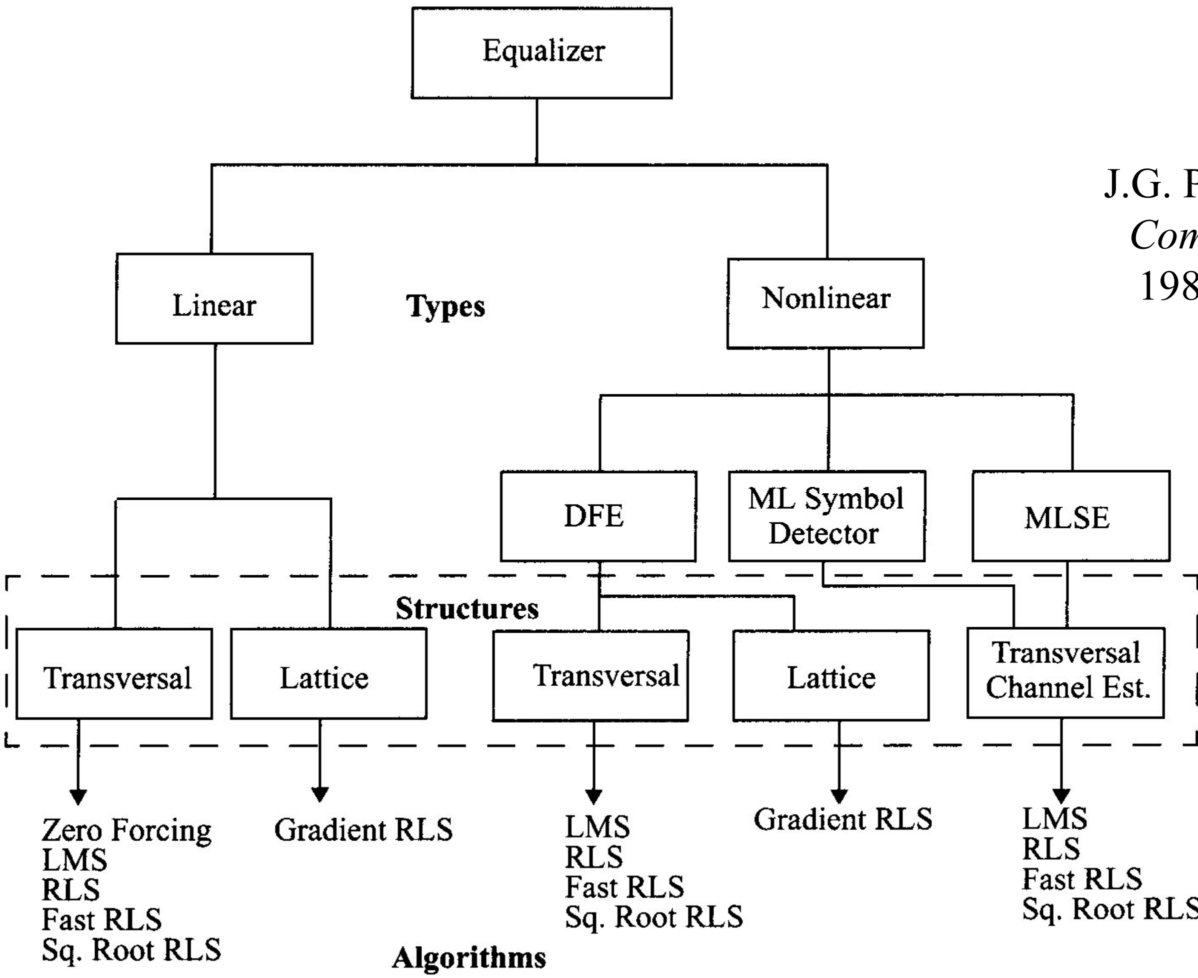
Adaptive Equalization

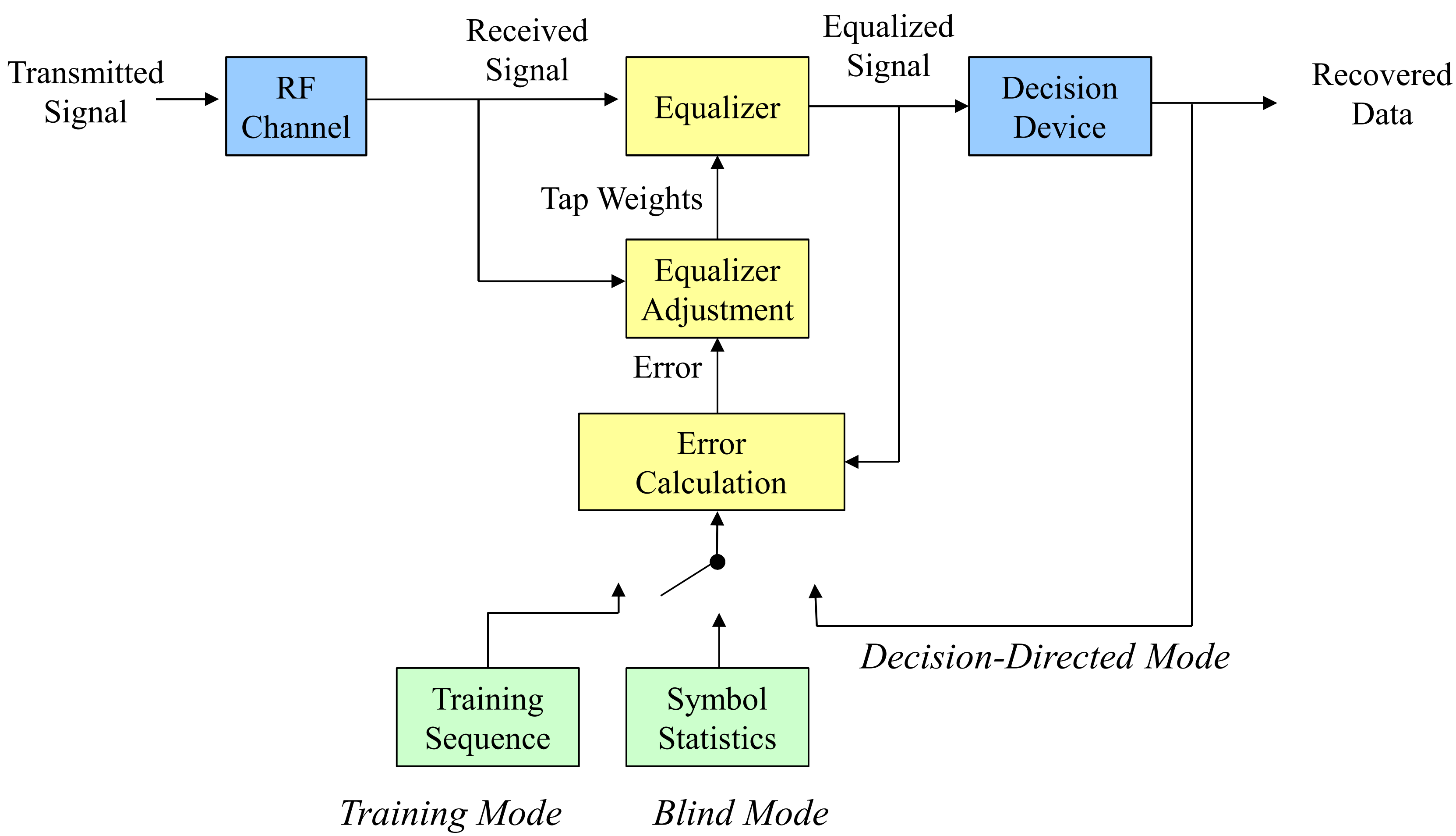
- Consider the multipath channel to be a filter
  - Varies over time
- Consider building a filter which "undoes" the filtering imposed by the channel
  - Let it keep track of the the channel and continuously adapt itself to the channel
- Presto! You have an adaptive equalizer
  - Can repair damage done by multipath
  - Works with a single receiver
  - Requires no bandwidth expansion
  - Requires no changes to the transmitter

Equalizer Techniques

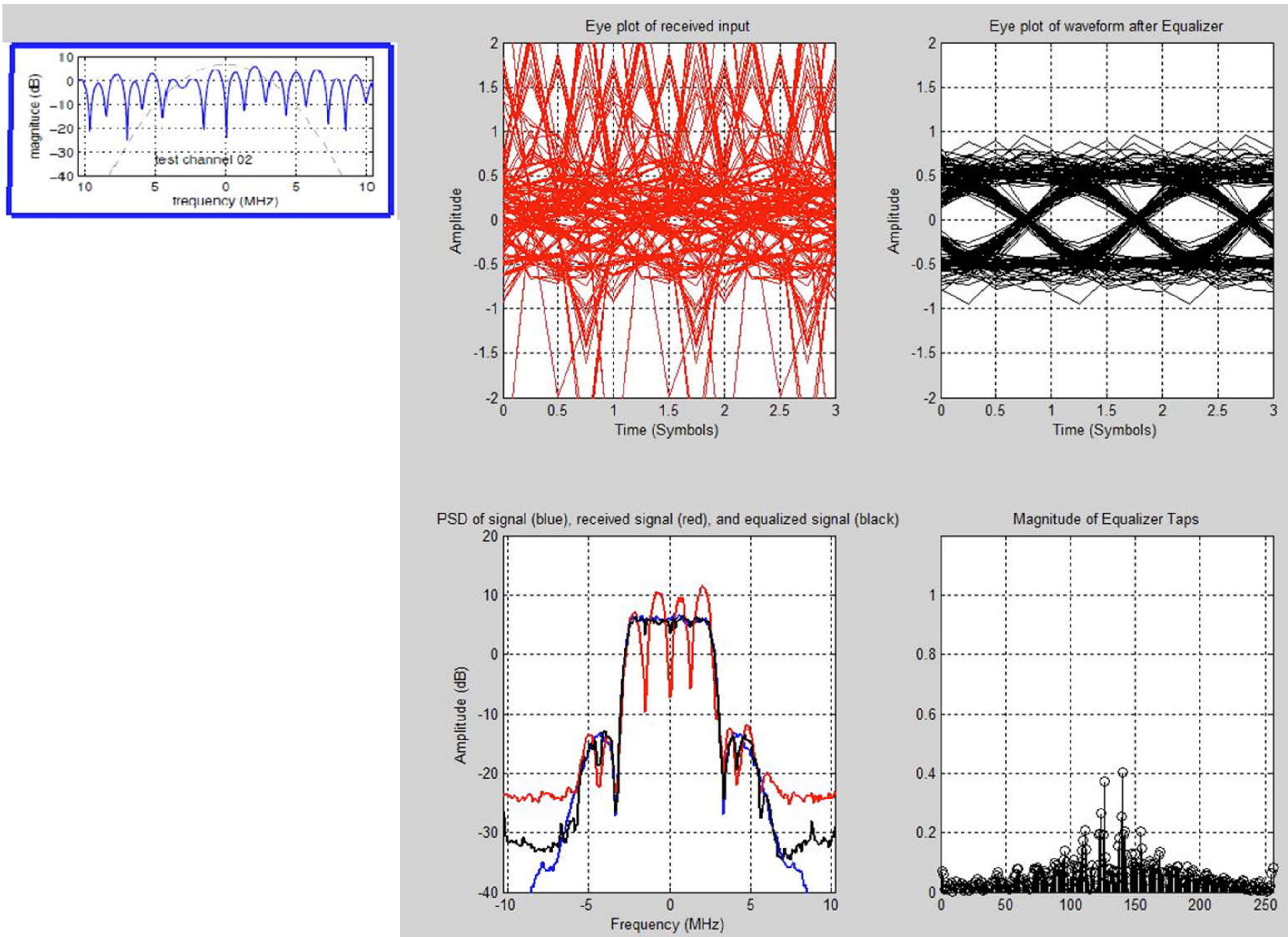


J.G. Proakis, *Digital Communications*. 1989 2nd Edition

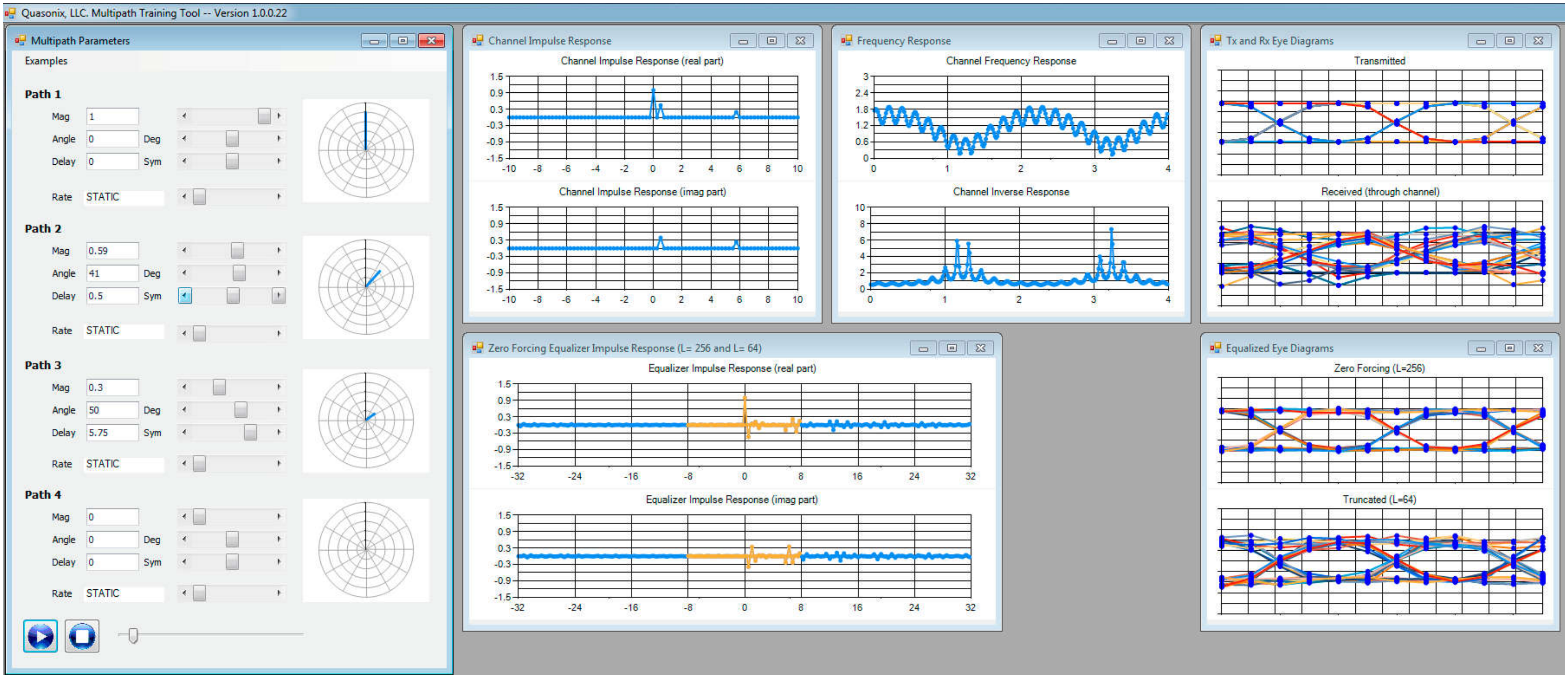
Generic Adaptive Equalizer



Equalizer AdaptationClick here



Dial-a-Channel



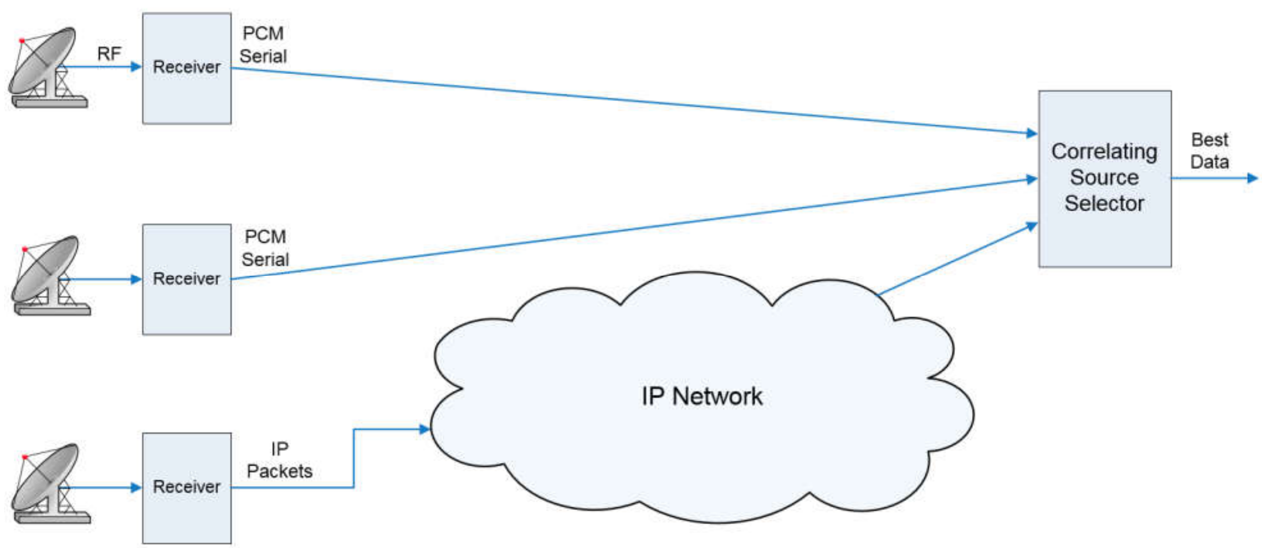
Adaptive Equalizer Summary

- Adaptive equalizer can "undo" multipath distortion
- Requires no changes at the transmit end
  - If available, a training sequence can be helpful
- Effectiveness of equalizer depends on the severity of the multipath
- Well-designed equalizers monitor their own performance, and disengage when they are doing badly.
  - This must be done without losing bit count integrity
- If you have multipath, use an equalizer!

Best Source Selection

Combining Multiple Sources

- Receive and demodulate the same signal at multiple receive sites
- Funnel all the demodulated data to one central location
- Time align the multiple data streams
- Build a better output stream from the multiple input streams



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Selection Algorithms

- Majority vote
  - Reasonably effective with three or more sources
  - Reduces to guesswork with only two sources
  - Sub-optimal for any number of sources
- PCM frame header accuracy
  - Uses only a small fraction of the bits to make an estimate
  - Poor resolution (BER is typically measured as Num_errors ÷ 32)
  - Useless with encrypted data
- Log-likelihood ratio
  - Uses all the bits
  - Works with encrypted data
  - Max-likelihood (optimal) combining scheme
    - Rice, Michael and Perrins, Erik. *"Maximum Likelihood Detection From Multiple Bit Sources"*, Proceedings of the International Telemetering Conference, Las Vegas, NV, USA, 2015.

Why Measure Data Quality?

- Telemetry links suffer from a wide range of impairments
  - Noise
  - Interference
  - Multipath
  - Shadowing
  - Loss of antenna track
- We need a way to asses the impact of *all* these impairments
- We need to compute p_n
  - Quickly
  - Accurately

$$
\begin{aligned}
\hat{x} = 0 \iff & \prod_{n \in \mathcal{N}_0} p(y_n|x=0) \prod_{n \in \mathcal{N}_1} p(y_n|x=0) > \prod_{n \in \mathcal{N}_0} p(y_n|x=1) \prod_{n \in \mathcal{N}_1} p(y_n|x=1) \\
\iff & \prod_{n \in \mathcal{N}_0} (1-p_n) \prod_{n \in \mathcal{N}_1} p_n > \prod_{n \in \mathcal{N}_0} p_n \prod_{n \in \mathcal{N}_1} (1-p_n) \\
\iff & \log\left(\prod_{n \in \mathcal{N}_0} (1-p_n) \prod_{n \in \mathcal{N}_1} p_n \right) > \log\left(\prod_{n \in \mathcal{N}_0} p_n \prod_{n \in \mathcal{N}_1} (1-p_n) \right) \\
\iff & \sum_{n \in \mathcal{N}_0} \log(1-p_n) + \sum_{n \in \mathcal{N}_1} \log(p_n) > \sum_{n \in \mathcal{N}_0} \log(p_n) + \sum_{n \in \mathcal{N}_1} \log(1-p_n) \\
\iff & \sum_{n \in \mathcal{N}_0} \log(1-p_n) - \sum_{n \in \mathcal{N}_0} \log(p_n) > \sum_{n \in \mathcal{N}_1} \log(1-p_n) - \sum_{n \in \mathcal{N}_1} \log(p_n) \\
\iff & \sum_{n \in \mathcal{N}_0} \log\left(\frac{1-p_n}{p_n}\right) > \sum_{n \in \mathcal{N}_1} \log\left(\frac{1-p_n}{p_n}\right).
\end{aligned}
$$

Rice, Michael and Perrins, Erik. "Maximum Likelihood Detection From Multiple Bit Sources", Proceedings of the International Telemetering Conference, Las Vegas, NV, USA, 2015.

Terminology

- BER (Bit Error Rate)
  - *Measured* as (number of errors / number of bits)
  - Assumes you know the data in advance
  - Measuring very low BER requires a long time
  - Converges to BEP if test runs long enough, *and channel is static*
- BEP (Bit Error Probability)
  - *Calculated* likelihood that a bit is in error
  - Even very low BEP can be determined from only a few bits
- DQM (Data Quality Metric)
  - Derived directly from BEP
  - Expressed as a 16-bit integer
- DQE (Data Quality Encapsulation)
  - Process of “bundling” DQM words and payload data
  - Includes a sync word to aid BSS time alignment

Data Quality Encapsulation

- Payload data is bundled with its DQM, to give Best Source Selectors a valid basis for “best”
- Interoperability among vendors requires standards
  - DQM calibration against multiple signal impairments
  - DQE packet structure
- Quasonix has developed and shared an open DQM/DQE format
  - Published at ITC 2015
  - License-free, royalty-free
  - Proposed for adoption as an RCC standard
- Includes test procedures to evaluate DQM accuracy

How to Assess Data Quality

- *Measured* BER is not practical
  - Requires known data in the stream – not possible with encryption
  - Takes a long time to measure low BERs
- Bit error *probability* (BEP), however…
  - Does not require any known data
  - Can be determined quickly and accurately from demodulator statistics
  - Is an *unbiased* quality metric, regardless of channel impairments
  - When calibrated per a standardized procedure, DQM based on BEP allows DQE from multiple vendors to interoperate
- Each vendor can use their own algorithm for developing BEP
- DQM is calculated directly from BEP
  - Use of Likelihood Ratio leads to maximum likelihood BSS algorithms
  - Converted to 16-bit integer on log scale

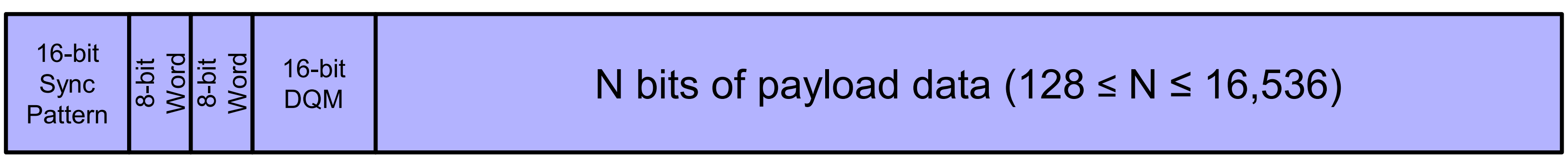
Definition of DQM

- Start with BEP, derived within demod
- Likelihood Ratio (LR) = (1 - BEP) / BEP
- DQM = min (round (log10 (LR) / 12 * (2^16)), 2^16 -1)
  - 16-bit unsigned integer, ranges from 0 to 65,535
- Easily reversed:
  - LR = 10^(-12 * DQM / 2^16)
  - BEP = 1 / (1 + LR)
- Define "Q" as the "User's DQM"
  - Q = 12 * DQM / 65535
  - Represents the exponent of 10 in the BEP
  - Examples:
    - Q = 3 → BEP = 1e-3
    - Q = 7 → BEP = 1e-7
  - Arbitrarily cap Q at "a perfect 10".

BEP	LR	DQM	Q
0.5	1.00	0	0.00
1E-01	1.11111E-01	5211	0.95
1E-02	1.01010E-02	10899	2.00
1E-03	1.00100E-03	16382	3.00
1E-04	1.00010E-04	21845	4.00
1E-05	1.00001E-05	27307	5.00
1E-06	1.00000E-06	32768	6.00
1E-07	1.00000E-07	38229	7.00
1E-08	1.00000E-08	43691	8.00
1E-09	1.00000E-09	49152	9.00
1E-10	1.00000E-10	54613	10.00
1E-11	1.00000E-11	60075	10.00
1E-12	1.00000E-12	65535	10.00

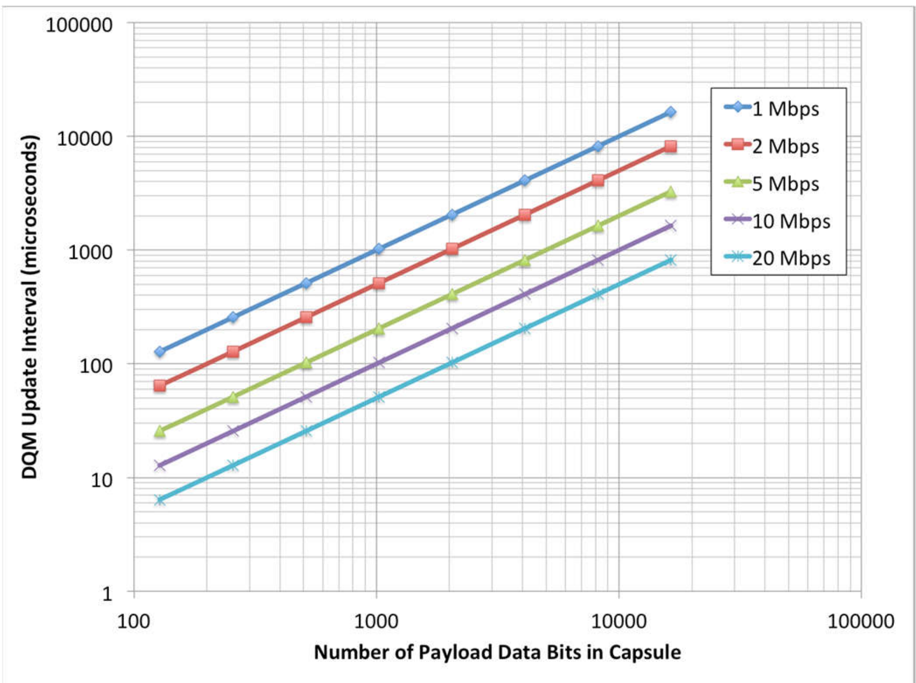
DQE Format

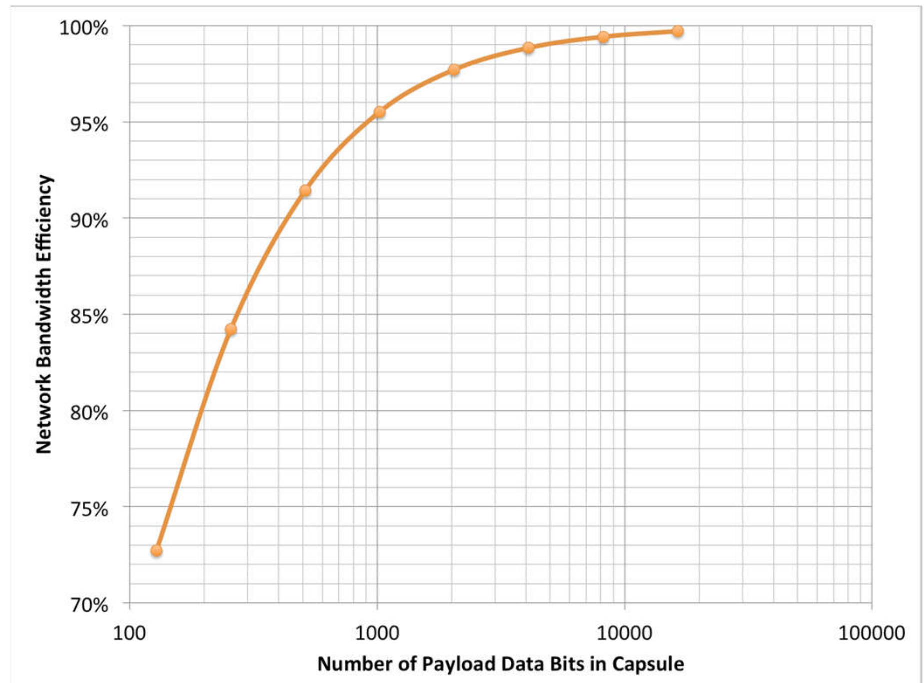
- Header
  - 16-bit sync pattern (0xFAC4)
    - MSB first: 1111101011000100
  - 8-bit reserved word, potentially for packet header version number (currently 0)
  - 8-bit reserved word, potentially for source ID tag (currently 0)
  - 16-bit DQM
- Payload data
  - User selectable length, (128 ≤ N ≤ 16,536)
  - Defaults to 4096



DQM Parameter Trades

- Choice of N impacts both DQM update rate and network efficiency





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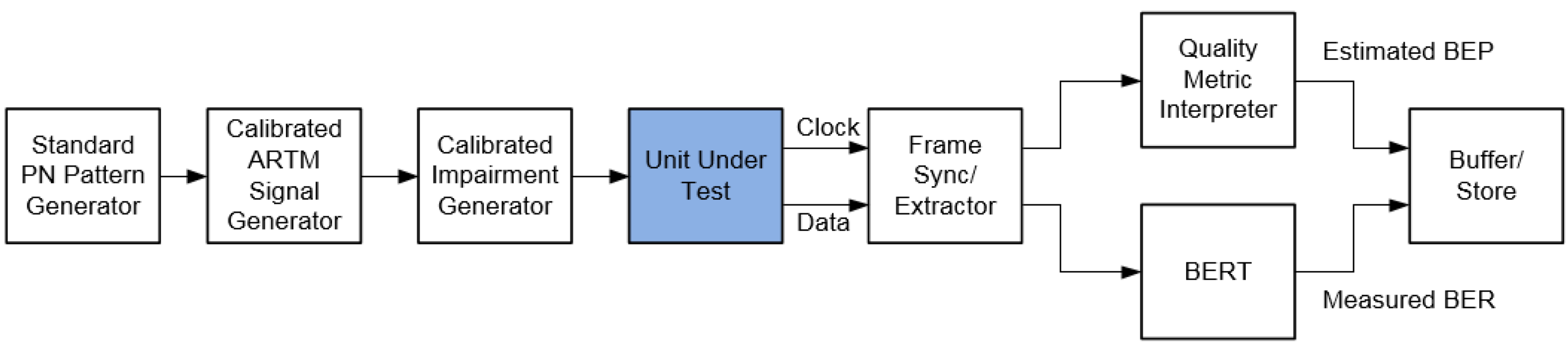
Calibration of DQM

- Calibrate DQM under various channel impairments:
  - AWGN – static level
  - AWGN – dynamic level (step response)
  - Dropouts
  - In-band and adjacent channel interference
  - Phase noise
  - Timing jitter
  - Static multipath
- Test procedures are being developed to evaluate accuracy of DQM
  - Targeted for inclusion in IRIG 118

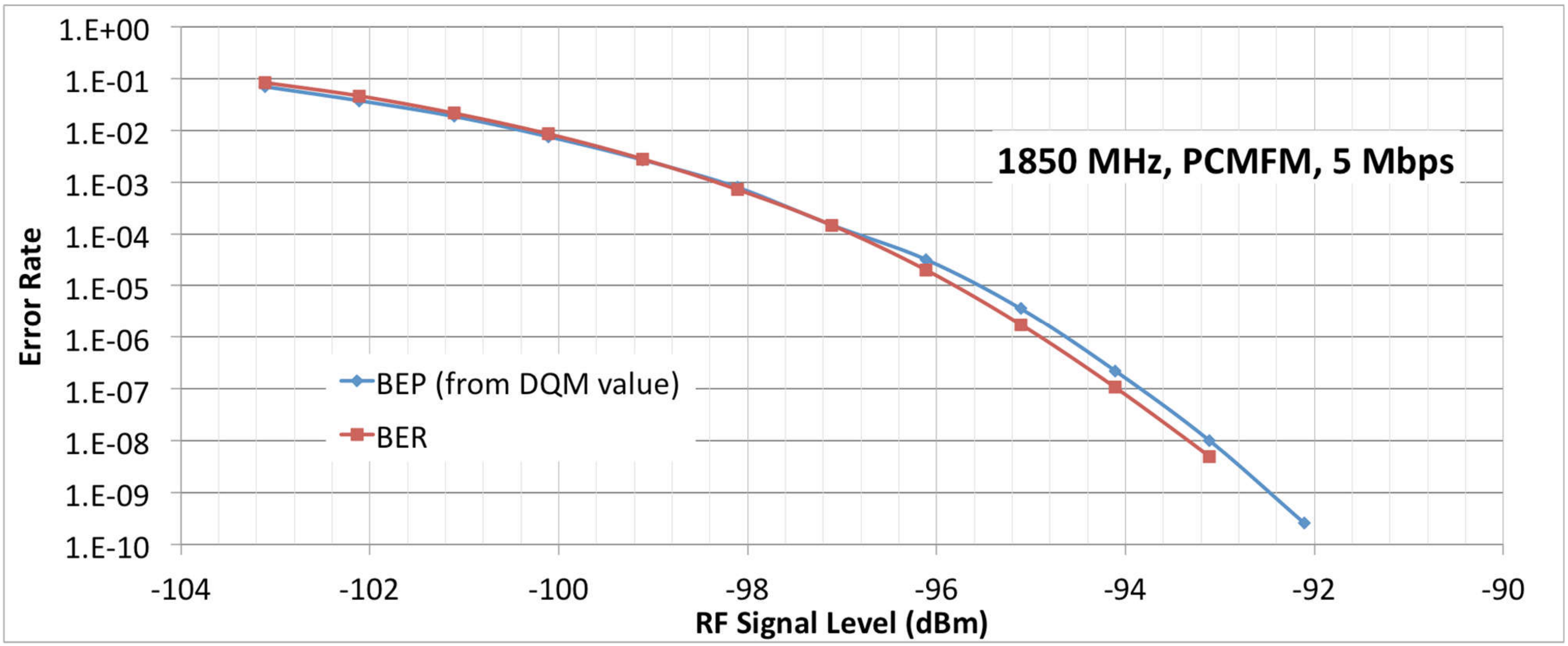
DQM Calibration Fixture

- Synthesize "impaired" RF signal
- Recover the "corrupted" data (with clock)
- Extract the frame sync word, including DQM
- Measure BER of payload data
- Compare DQM (converted to BEP) to measured BER
  - Recorded and stored on a packet-by-packet basis



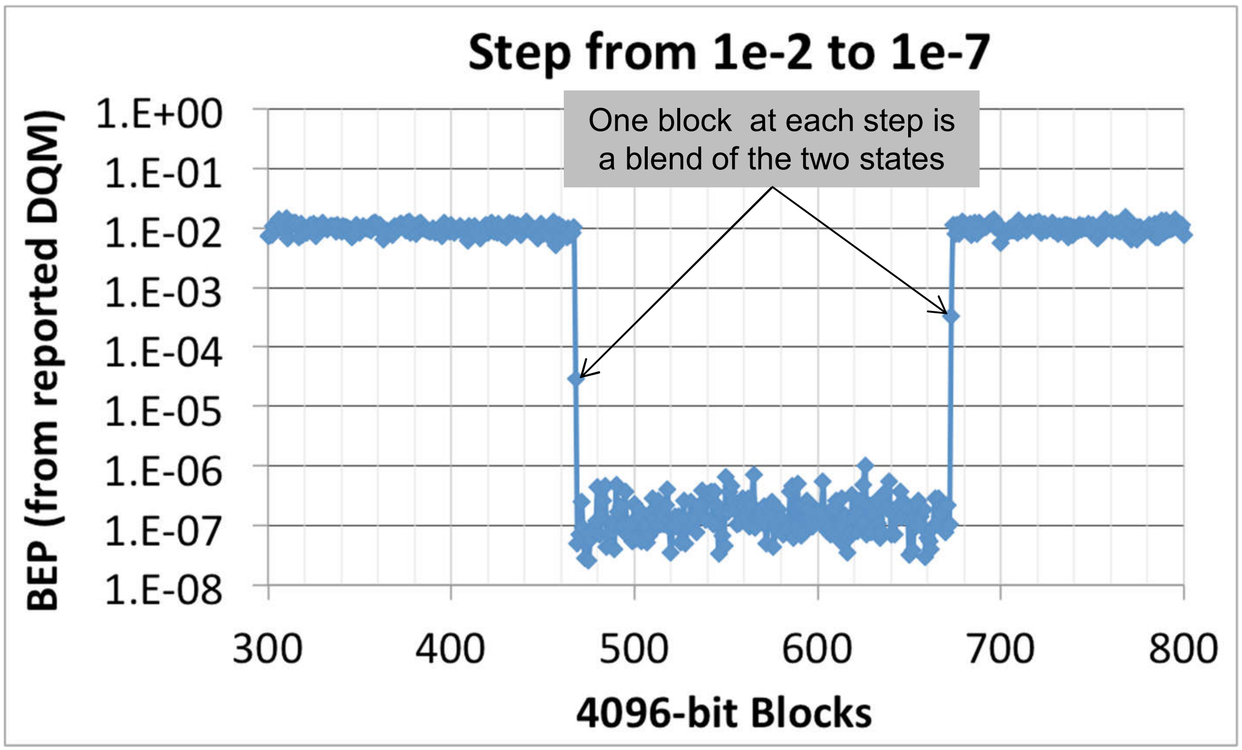
DQM Calibration in AWGN

- Required as a baseline for all other tests



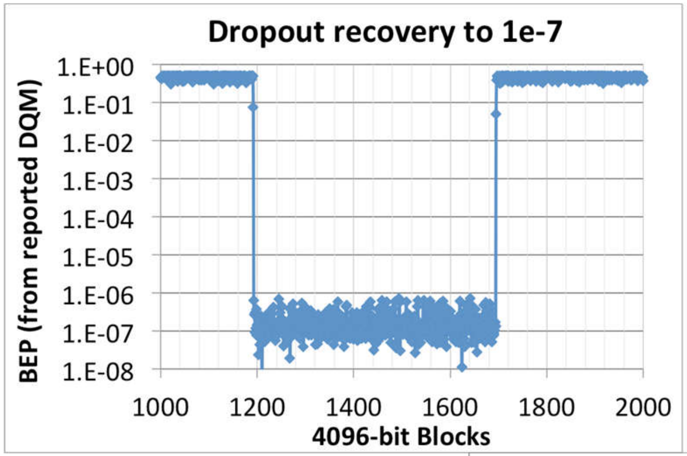
DQM Step Response

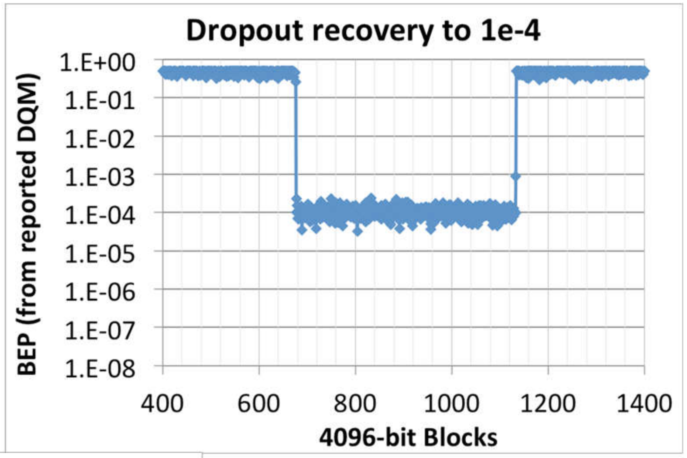
- Assesses timeliness of DQM values
- UUT stays synchronized during test

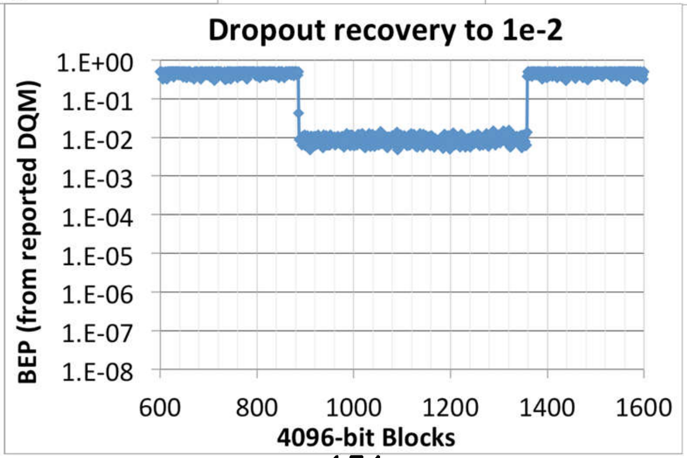


DQM Fade Recovery

- Includes UUT synchronization time

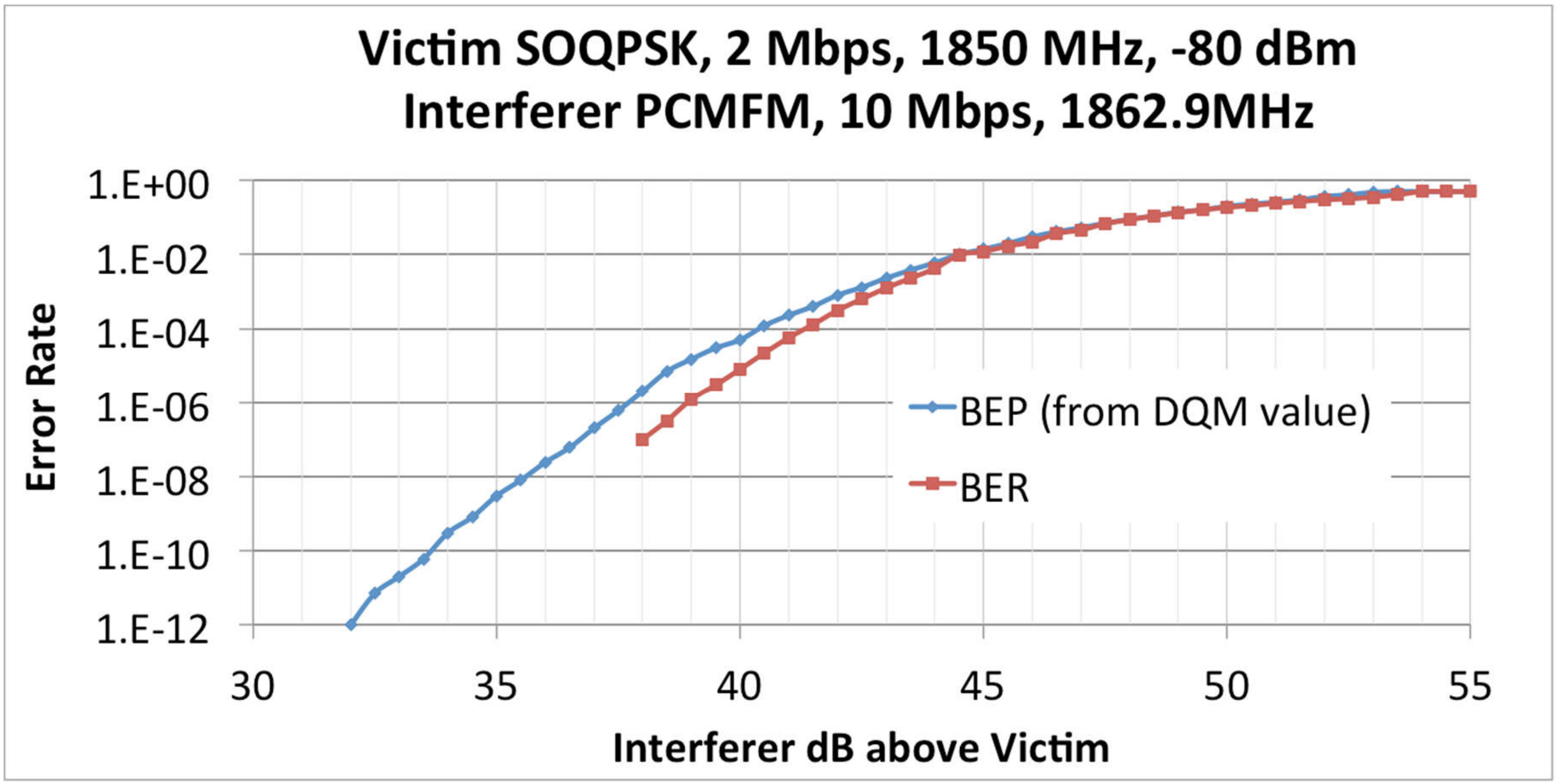






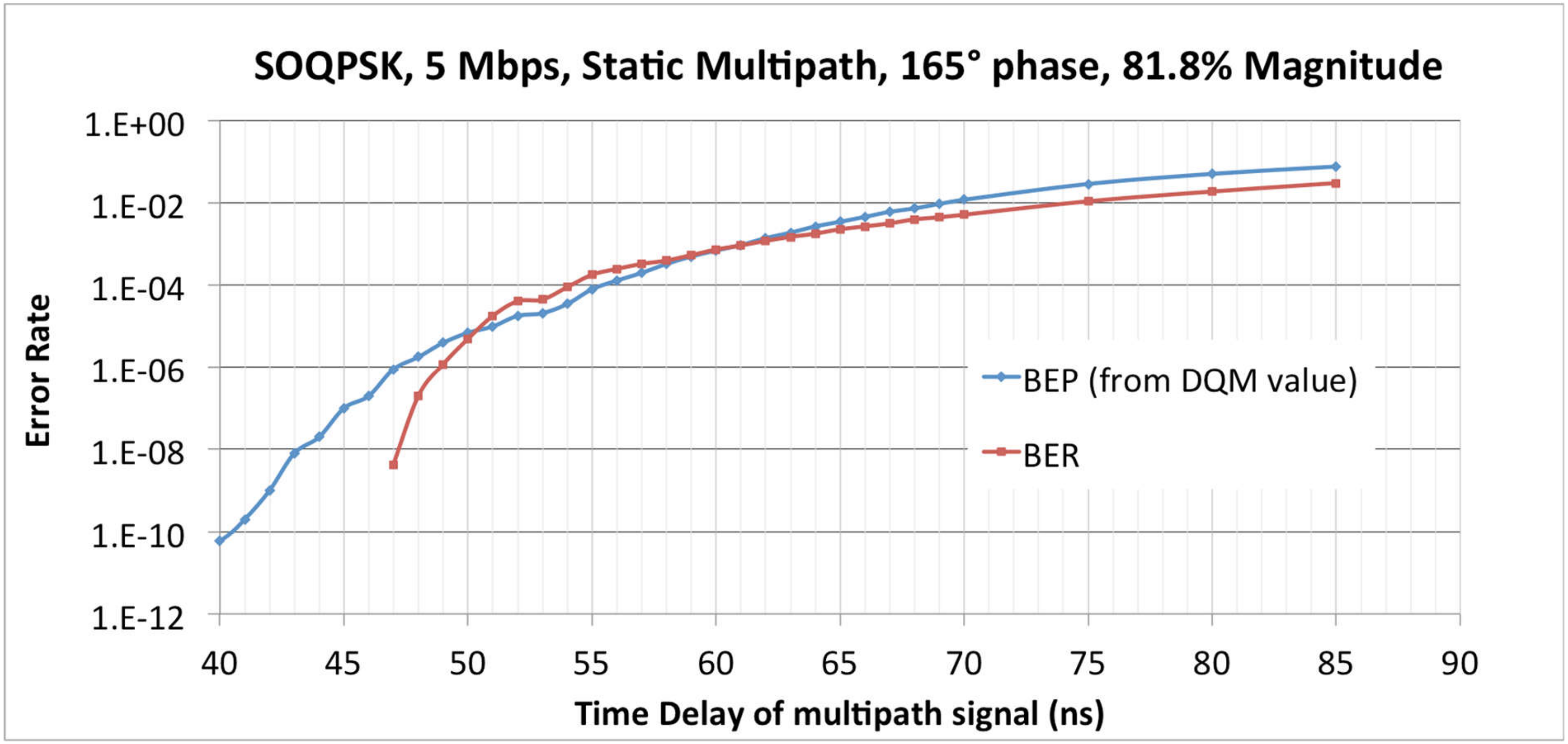
DQM Interference Test

- Interference is not AWGN, but it causes bit errors



DQM in Multipath

- Test run at high signal level – essentially no noise



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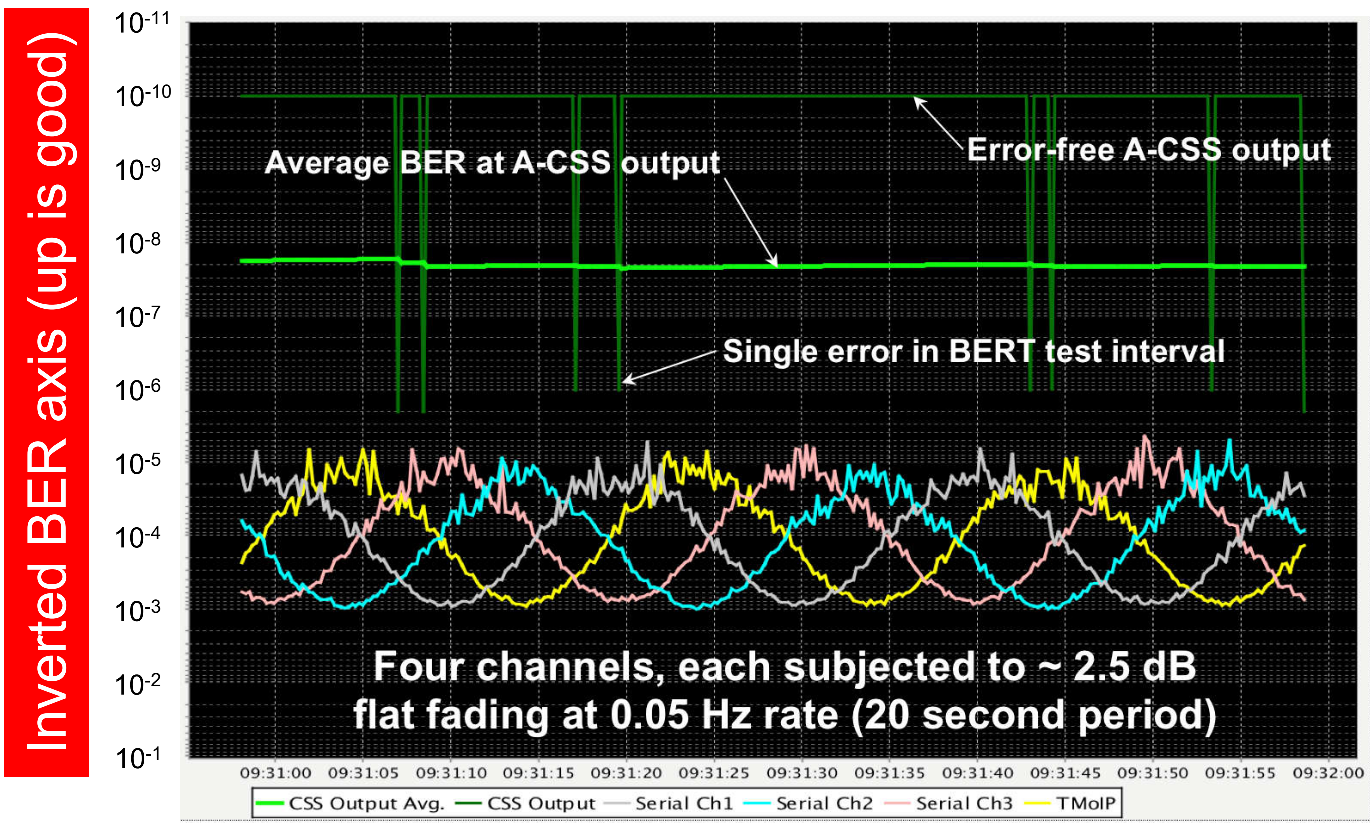
Does it work?

- Four “poor” channels for input to BSS
- One nearly error-free output from BSS

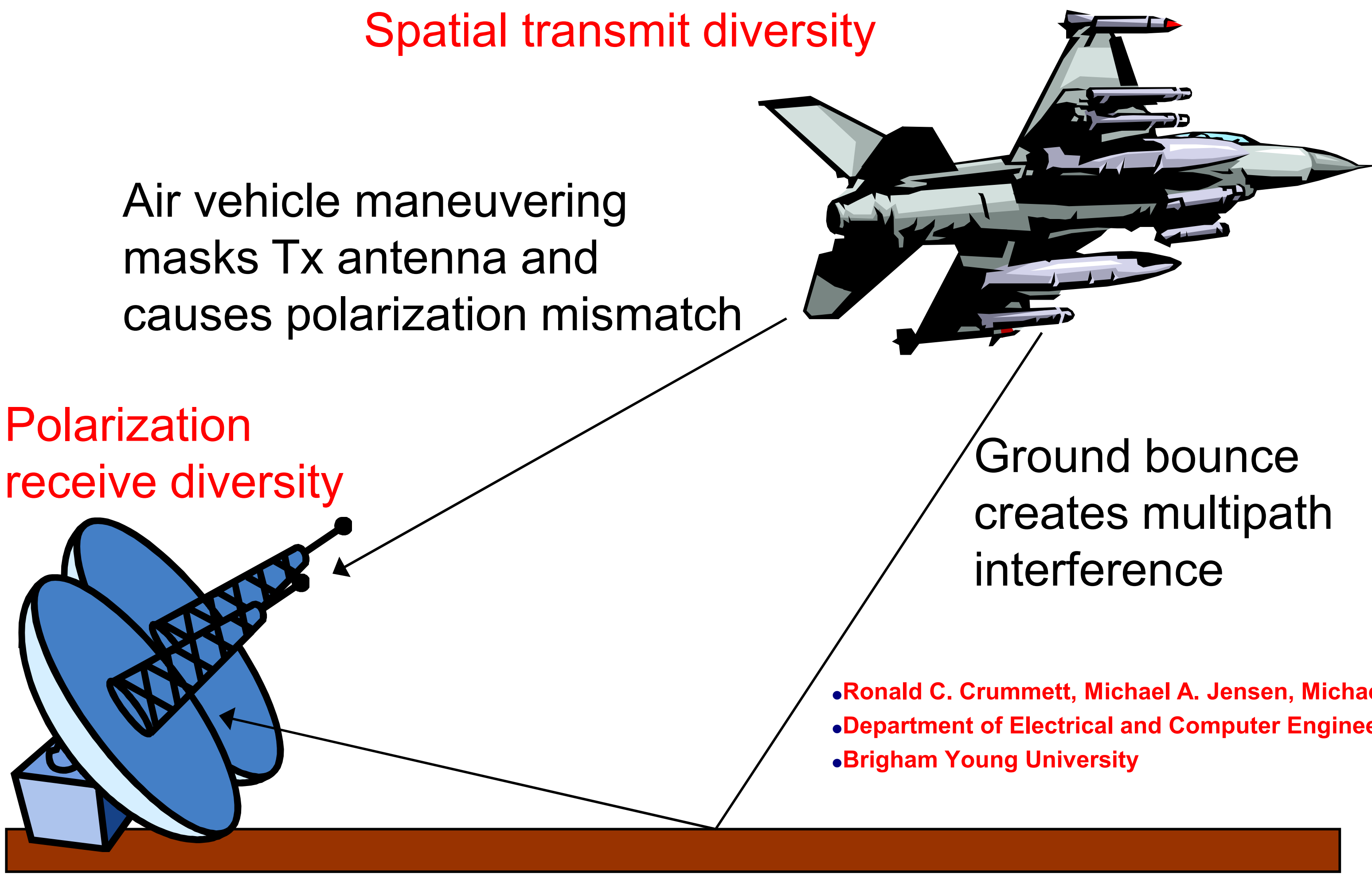


BSS Summary

- Correlating (time-aligning) source selectors deliver output data that is better than any single input stream
- Combats *all* forms of signal impairment
  - Noise
  - Multipath
  - Interference
  - Shadowing
  - Loss of antenna track
- Diversity can be in any form
  - Polarization
  - Frequency
  - Spatial
- DQE / DQM equip the BSS to make optimal decisions

Space-Time Coding

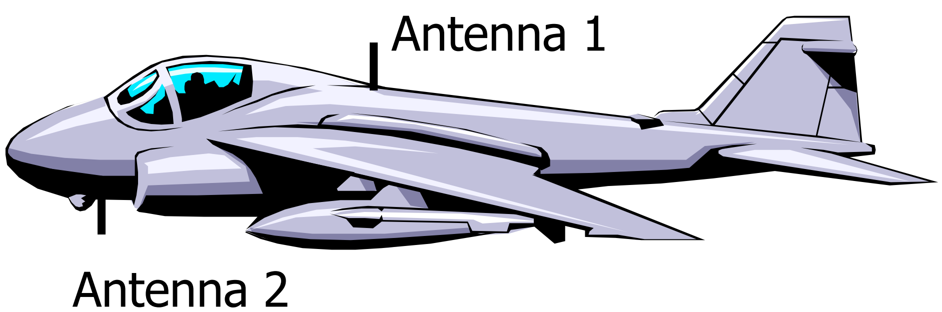
Space-Time Coding

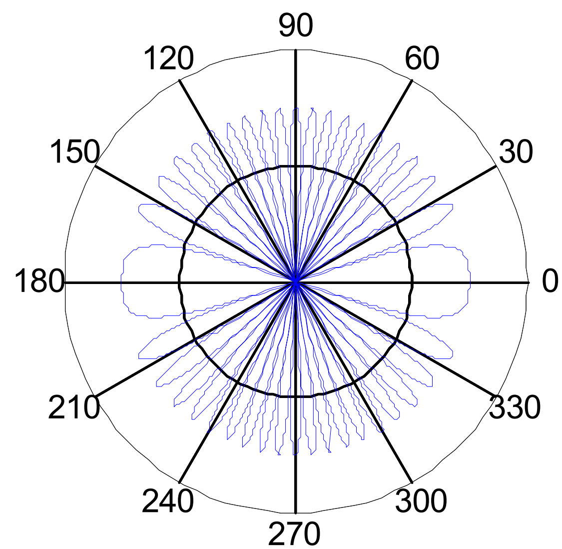


- Ronald C. Crummett, Michael A. Jensen, Michael D. Rice
- Department of Electrical and Computer Engineering
- Brigham Young University

Difficulties with TX Diversity

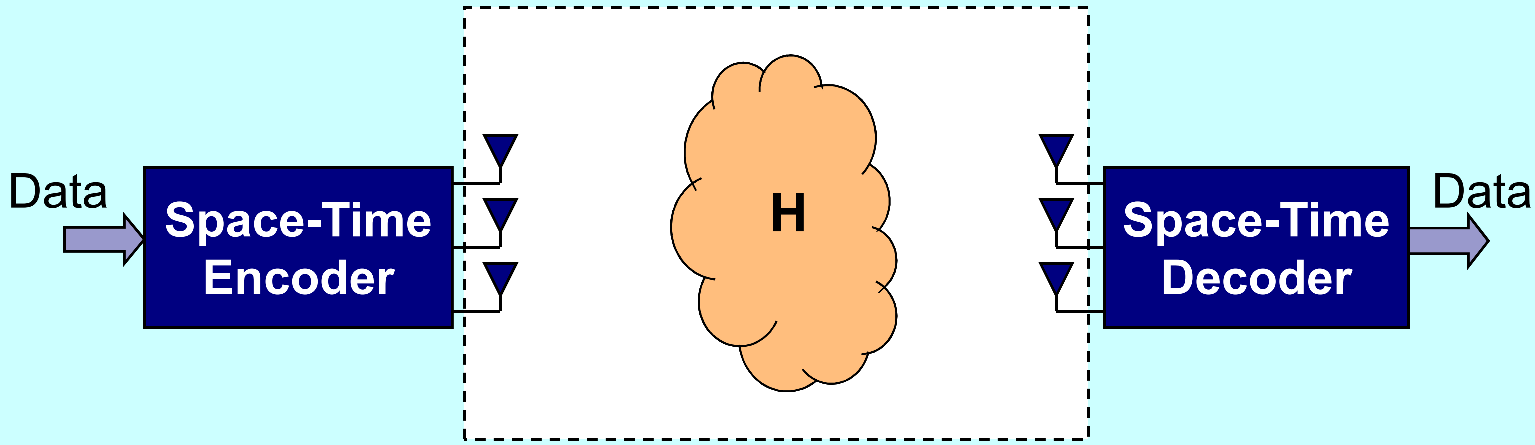
Spatially Separated Antennas Create Interference Pattern





MIMO Communications

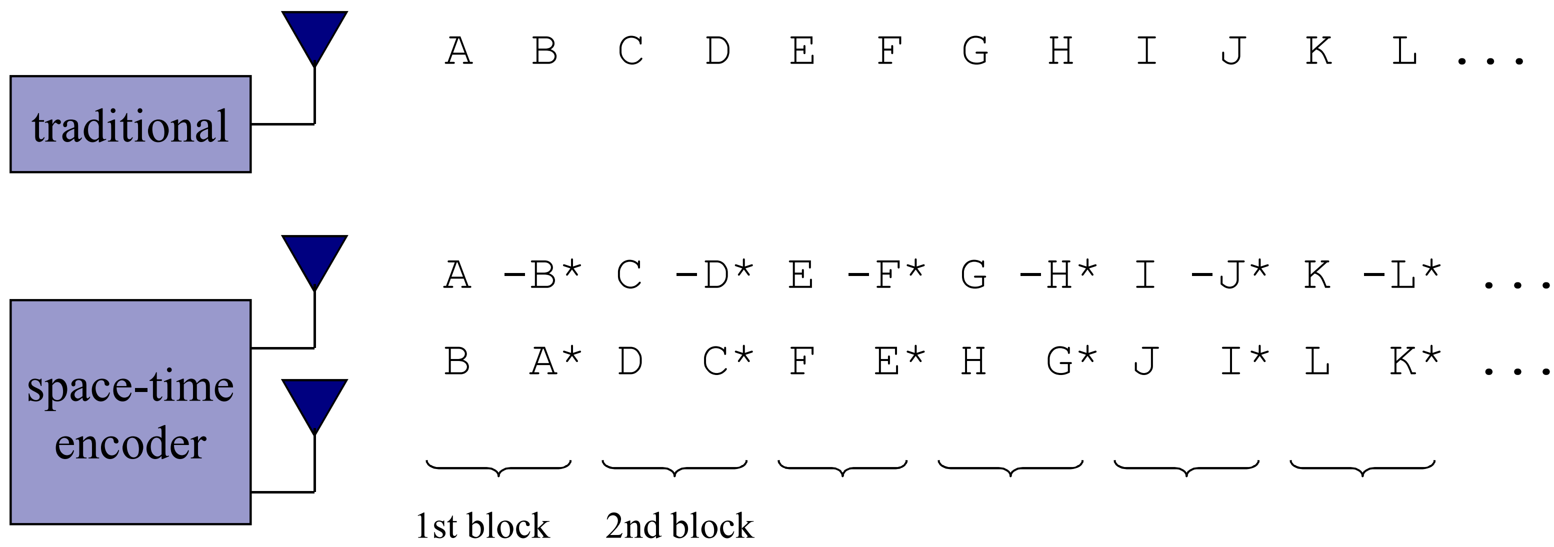
MIMO: Multiple-Input Multiple-Output
Exploit multiple communication ***modes***



Potential Benefits:

- Diversity (robust communications)
- Increased data throughput

Alamouti Space-Time Coding



- 2 transmit antennas + 1 receive antenna version
- 2 transmit antennas + 2 receive antennas version
- Calderbank showed that the Alamouti schemes are special cases of more general "orthogonal designs"

Traditional Transmission

Each symbol is simultaneously sent from both antennas

$$r = \frac{1}{\sqrt{2}}(h_1 + h_2)s + \eta$$

Power equally divided between antennas

Received signal energy

$$E_T = \mathrm{E}\left\{\frac{1}{2}\left[(h_1 + h_2)s\right]^*(h_1 + h_2)s\right\} = \frac{1}{2}\left|h_1 + h_2\right|^2 \mathrm{E}\left\{\left|s^2\right|\right\} = \frac{1}{2}\left|h_1 + h_2\right|^2 E_s$$

With the noise energy as N_o, the received SNR is

$$SNR_T = \frac{1}{2}\left|h_1 + h_2\right|^2 \frac{E_s}{N_o}$$

Alamouti Space-Time Coding

Signal energy over one symbol time:

$$E_{A,1} = \mathrm{E}\left\{\left[\frac{1}{2}\left(|h_1|^2 + |h_2|^2\right)\right]^2 s_1^* s_1\right\} = \left[\frac{1}{2}\left(|h_1|^2 + |h_2|^2\right)\right]^2 E_s$$

Received noise energy:

$$N_{A,1} = \mathrm{E}\left\{\frac{1}{2}\left(h_1^*\eta_1 + h_2\eta_2^*\right)^*\left(h_1^*\eta_1 + h_2\eta_2^*\right)\right\} = \frac{1}{2}|h_1|^2\mathrm{E}\left\{|\eta_1|^2\right\} + \frac{1}{2}|h_2|^2\mathrm{E}\left\{|\eta_2|^2\right\} = \frac{1}{2}\left(|h_1|^2 + |h_2|^2\right)N_o$$

Signal-to-Noise Ratio:

$$SNR_A = \frac{1}{2}\left(|h_1|^2 + |h_2|^2\right)\frac{E_s}{N_o}$$

Symbol Error Rate - QPSK

SER for QPSK in AWGN

$$P(E) = 2Q\left(\sqrt{\frac{E_s}{N_o}}\right)$$

Using two transmit antennas (traditional signaling)

$$P(E \mid \theta, \phi) = 2Q\left(\sqrt{\frac{E_s}{N_o}\frac{\left|h_1(\theta,\phi) + h_2(\theta,\phi)\right|^2}{2}}\right)$$

If the aircraft is rotated 360° in the horizontal plane

$$P(E \mid \theta) = \frac{1}{2\pi}\int_0^{2\pi} 2Q\left(\sqrt{\frac{E_s}{N_o}\frac{\left|h_1(\theta,\phi) + h_2(\theta,\phi)\right|^2}{2}}\right) d\phi$$

Symbol Error Rate - QPSK

Traditional signaling

$$P(E \mid \theta) = \frac{1}{2\pi}\int_0^{2\pi} 2Q\left(\sqrt{\frac{E_s}{N_o}\frac{\left|h_1(\theta,\phi)+h_2(\theta,\phi)\right|^2}{2}}\right)d\phi$$

Addition of transfer functions leads to reduction in effective SNR

For Alamouti signaling

$$P(E \mid \theta) = \frac{1}{2\pi}\int_0^{2\pi} 2Q\left(\sqrt{\frac{E_s}{N_o}\frac{\left|h_1(\theta,\phi)\right|^2+\left|h_2(\theta,\phi)\right|^2}{2}}\right)d\phi$$

Only magnitudes of transfer functions used in sum

Alamouti Scheme

Consider BPSK Signaling and Assume $s_1 = s_2 = 1$

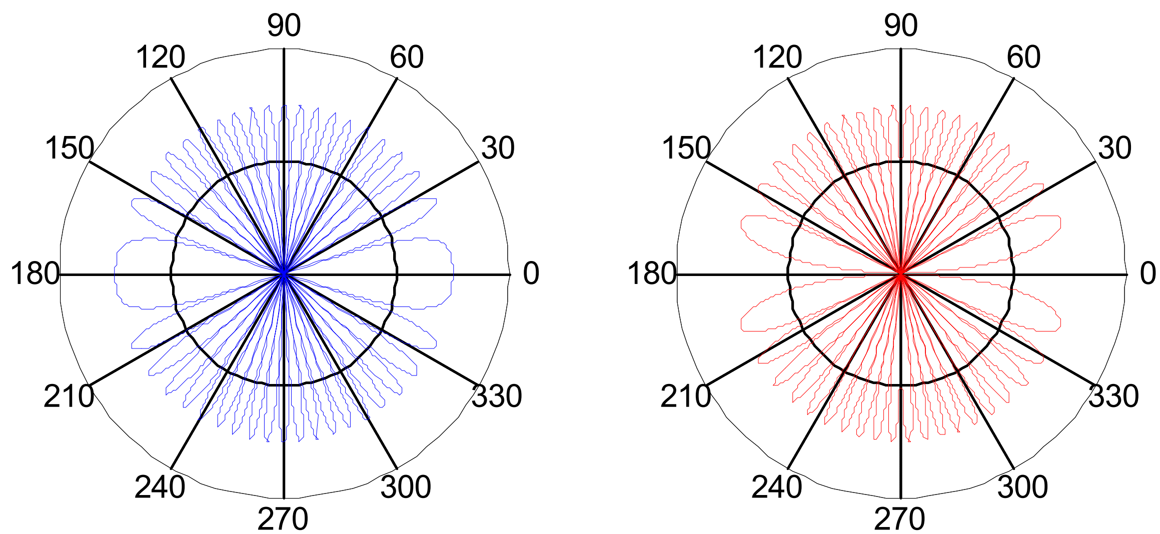
Time Slot 1:

Gain Pattern: $G_{t1}(\phi) = 2\cos^2\left[\frac{kd}{2}\cos\phi\right]$

Time Slot 2:

Gain Pattern: $G_{t2}(\phi) = 2\sin^2\left[\frac{kd}{2}\cos\phi\right]$

Antenna Pattern Interpretation



Symbol Error Rate

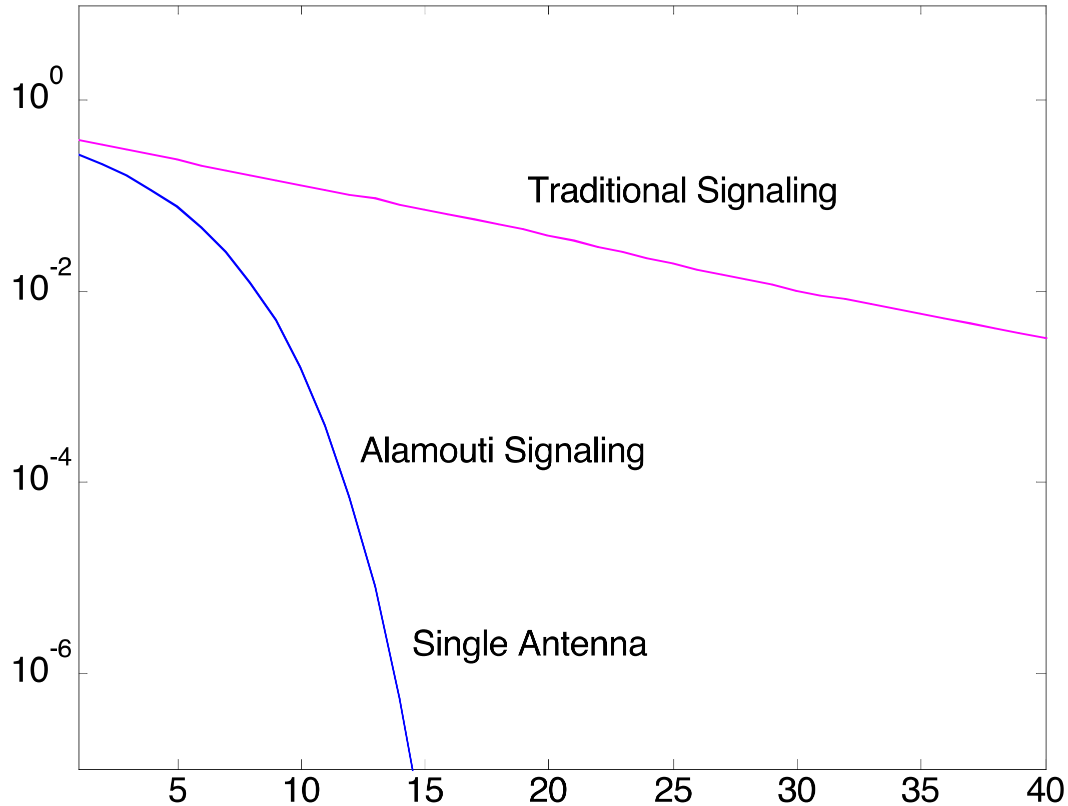
Similar expressions have been derived for:

- Polarization diversity at receiver (Maximal Ratio combining)
- One multipath (ground) bounce
- BPSK and 16-QAM signal constellations

for both Traditional Signaling and Alamouti Signaling

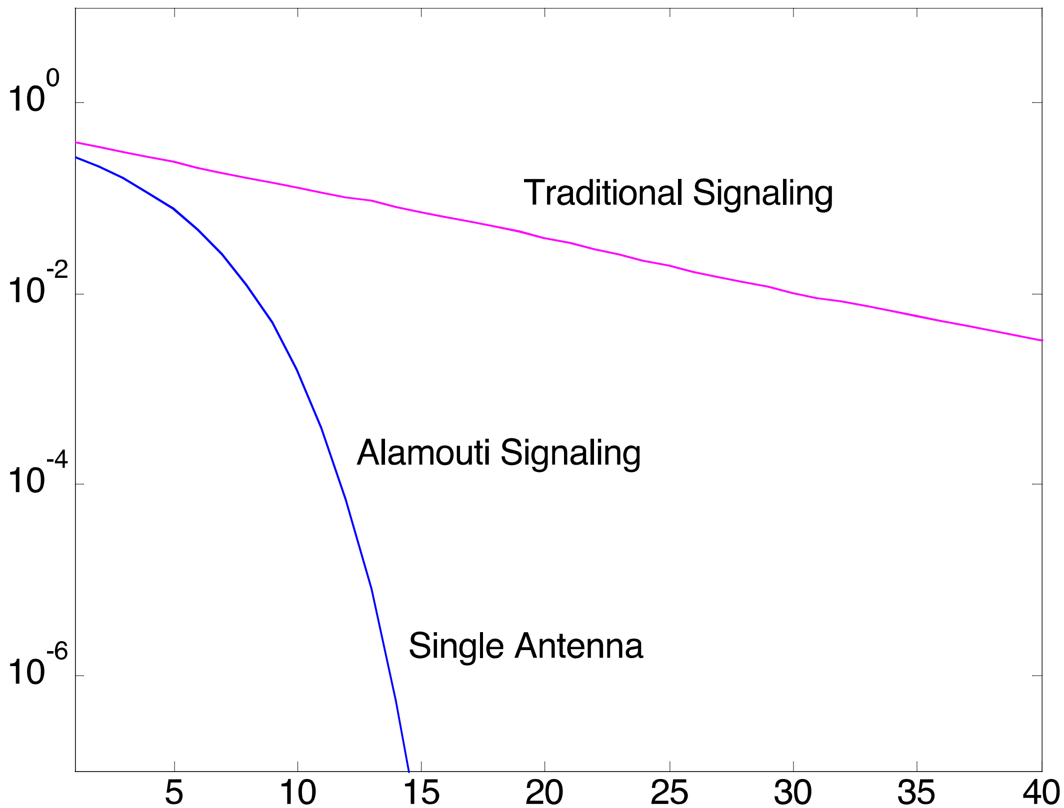
SER Simulations

Antenna Separation: 20' Horizontal, 8' Vertical
Antenna Patterns: Isotropic



Simple AWGN Channel

SER Simulations

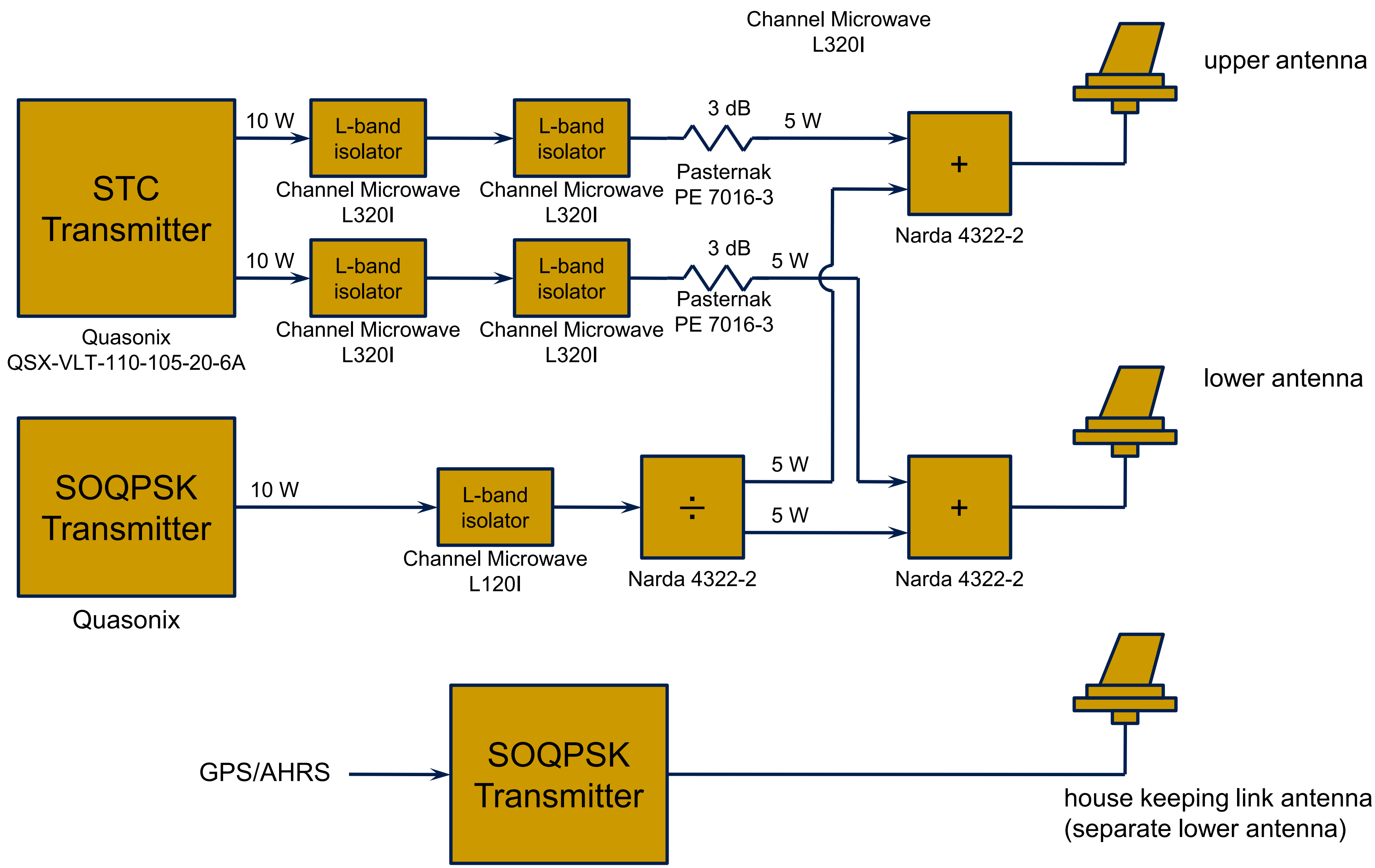


Circular Polarization Diversity Reception

Results Identical to Single Receive Antenna System

Flight Tests: Airborne Configuration

BYU

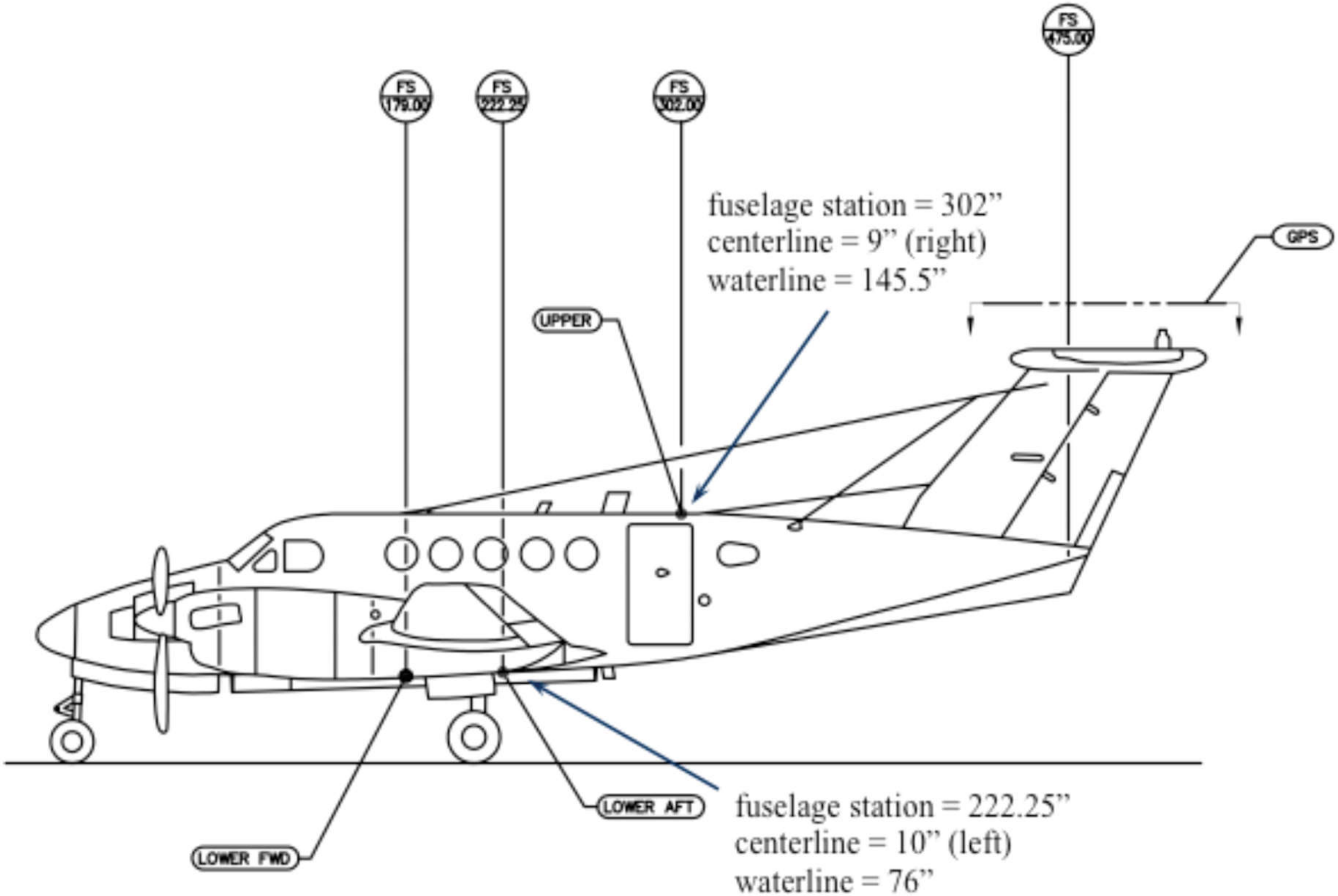


C-12 Beechcraft: Airborne Platform

BYU

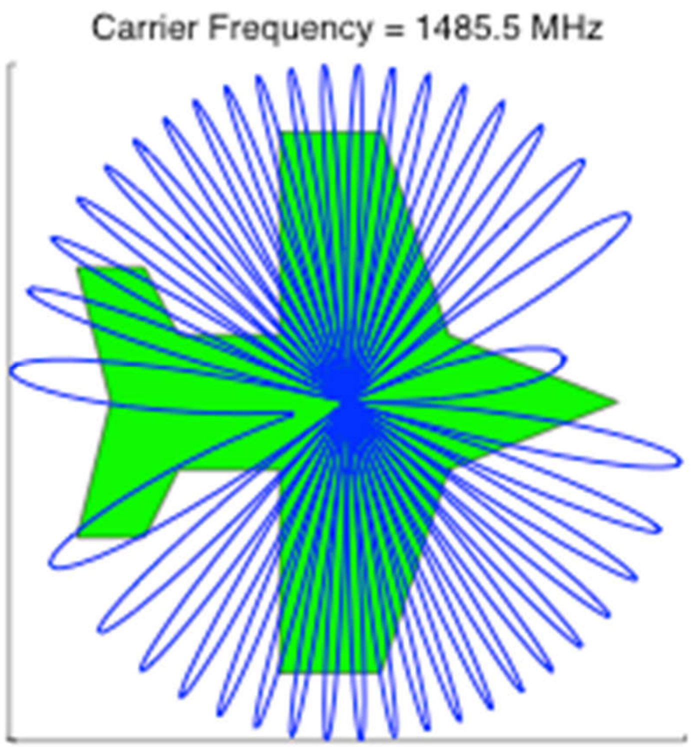
Antenna Locations

BYU

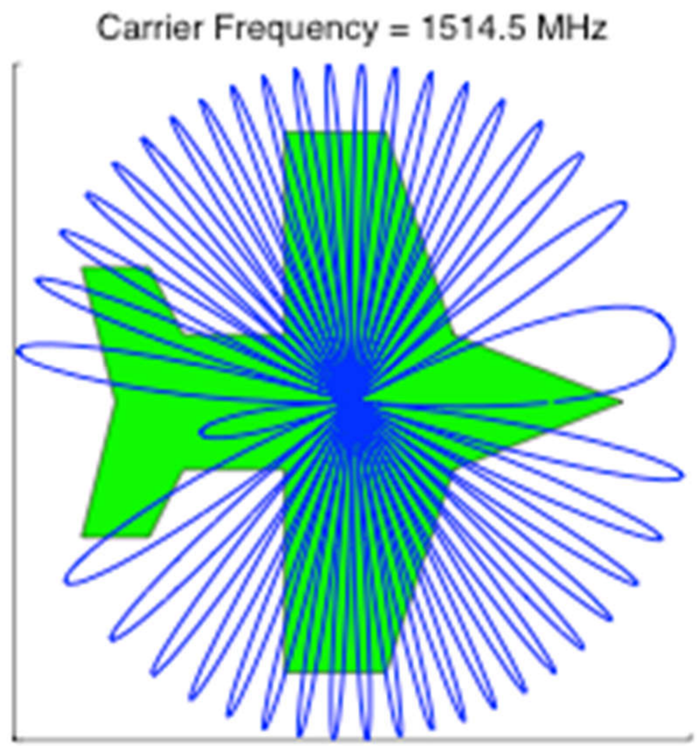


Flight Tests: Idealized Gain Patterns

STC Frequency

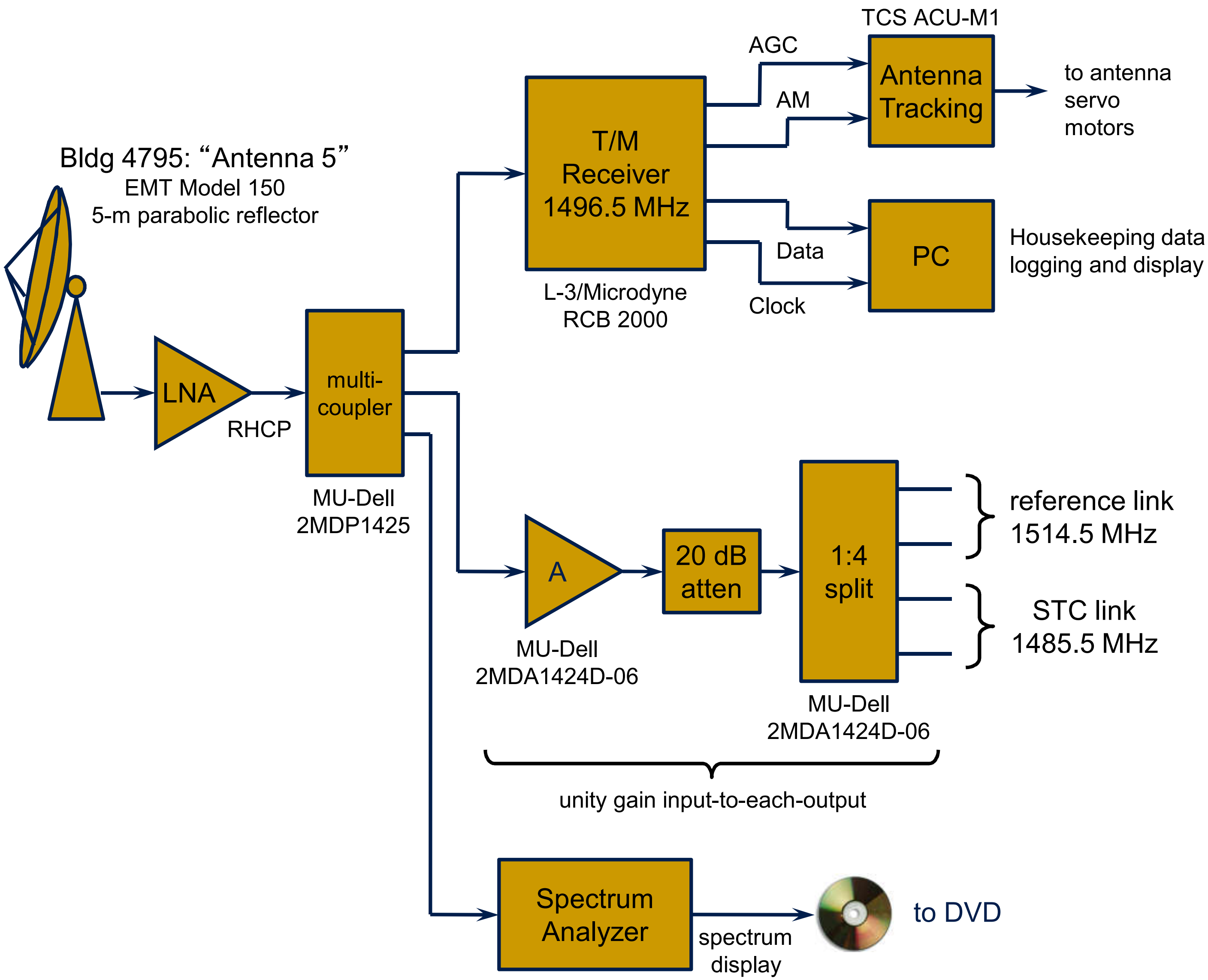


Reference Link Frequency



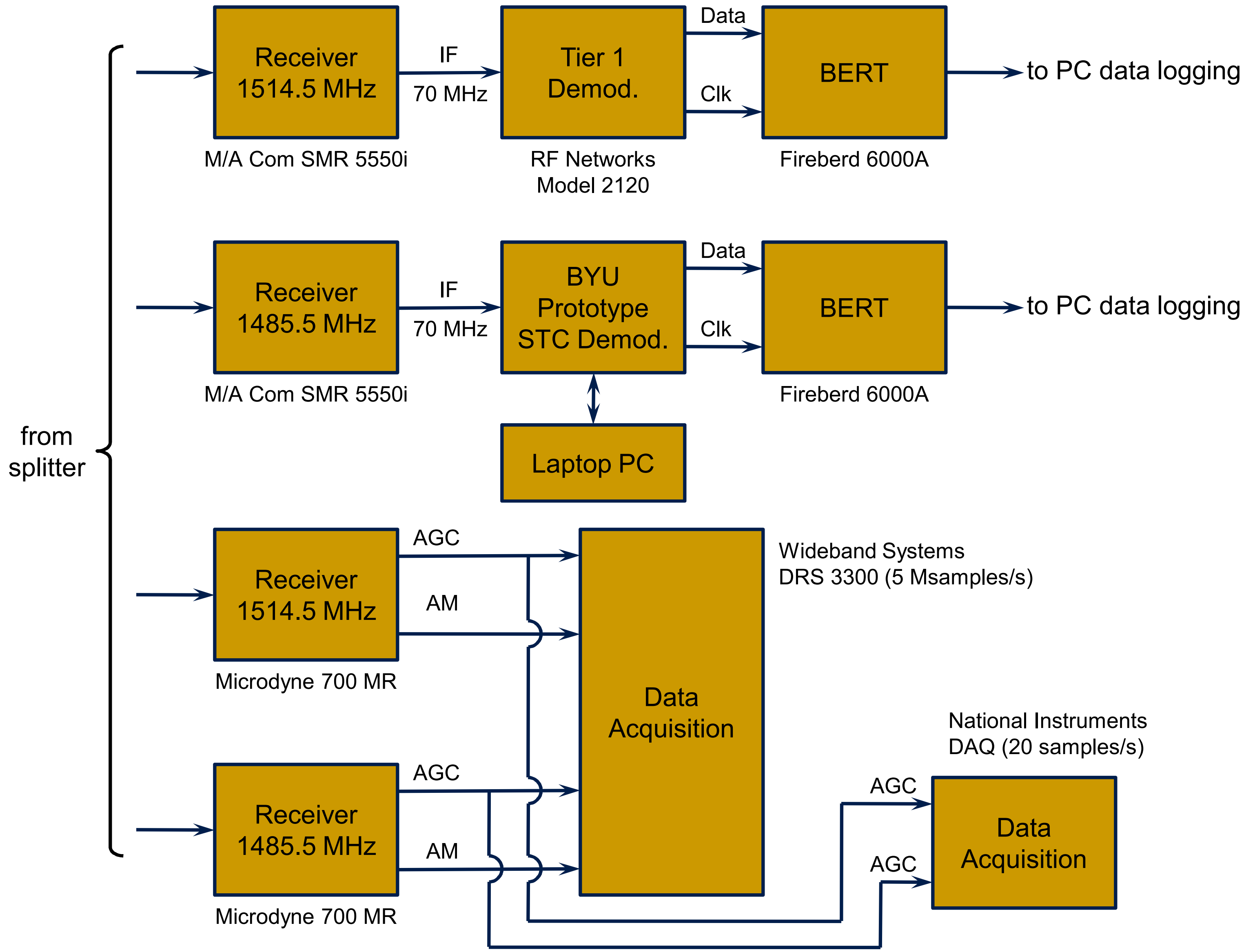
Flight Tests: Ground Station Configuration

BYU



Test Flights: Ground Station Configuration

BYU

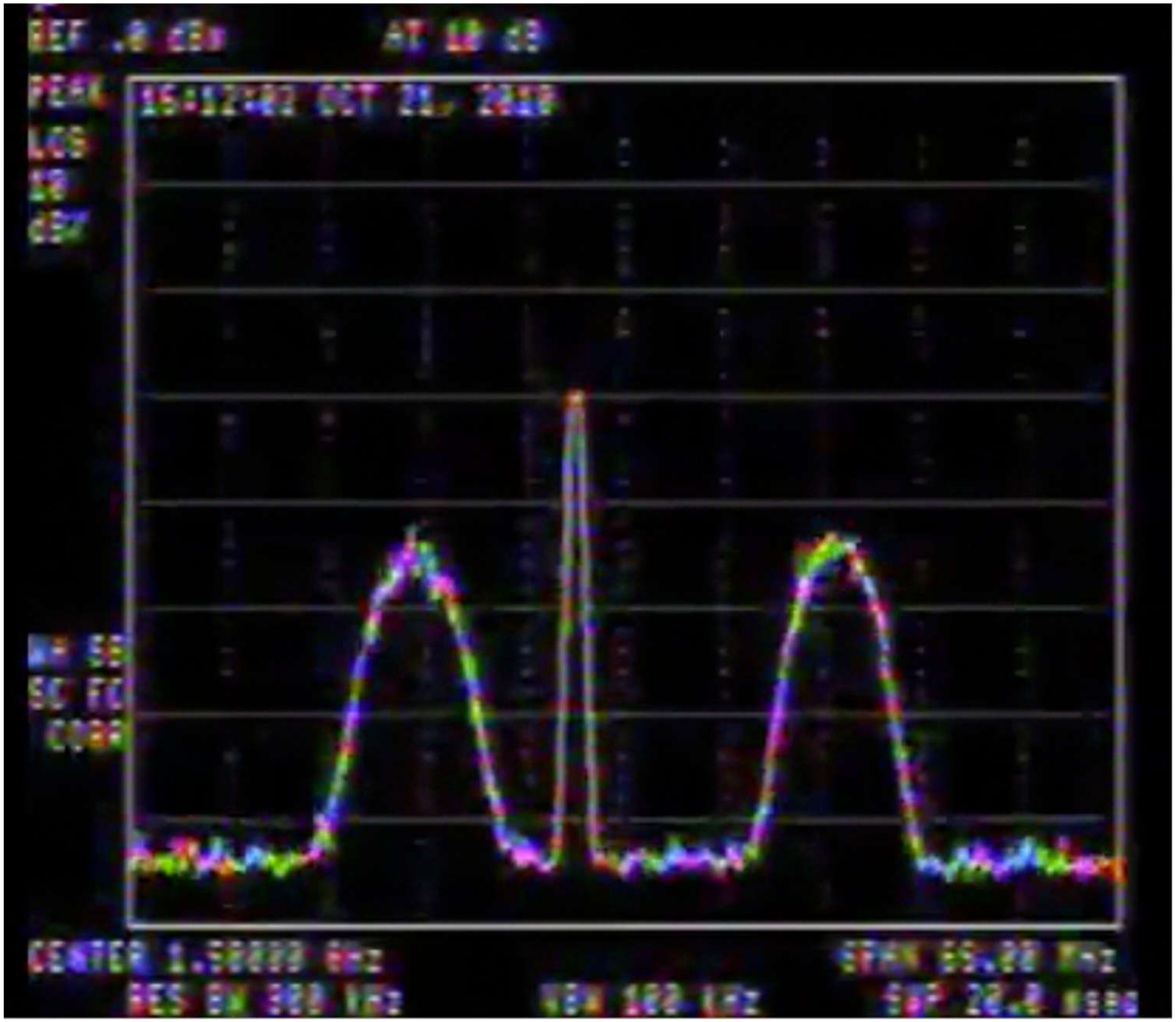


Test Flights: Ground Station Configuration

BYU

Test Flights: Ground Station Configuration

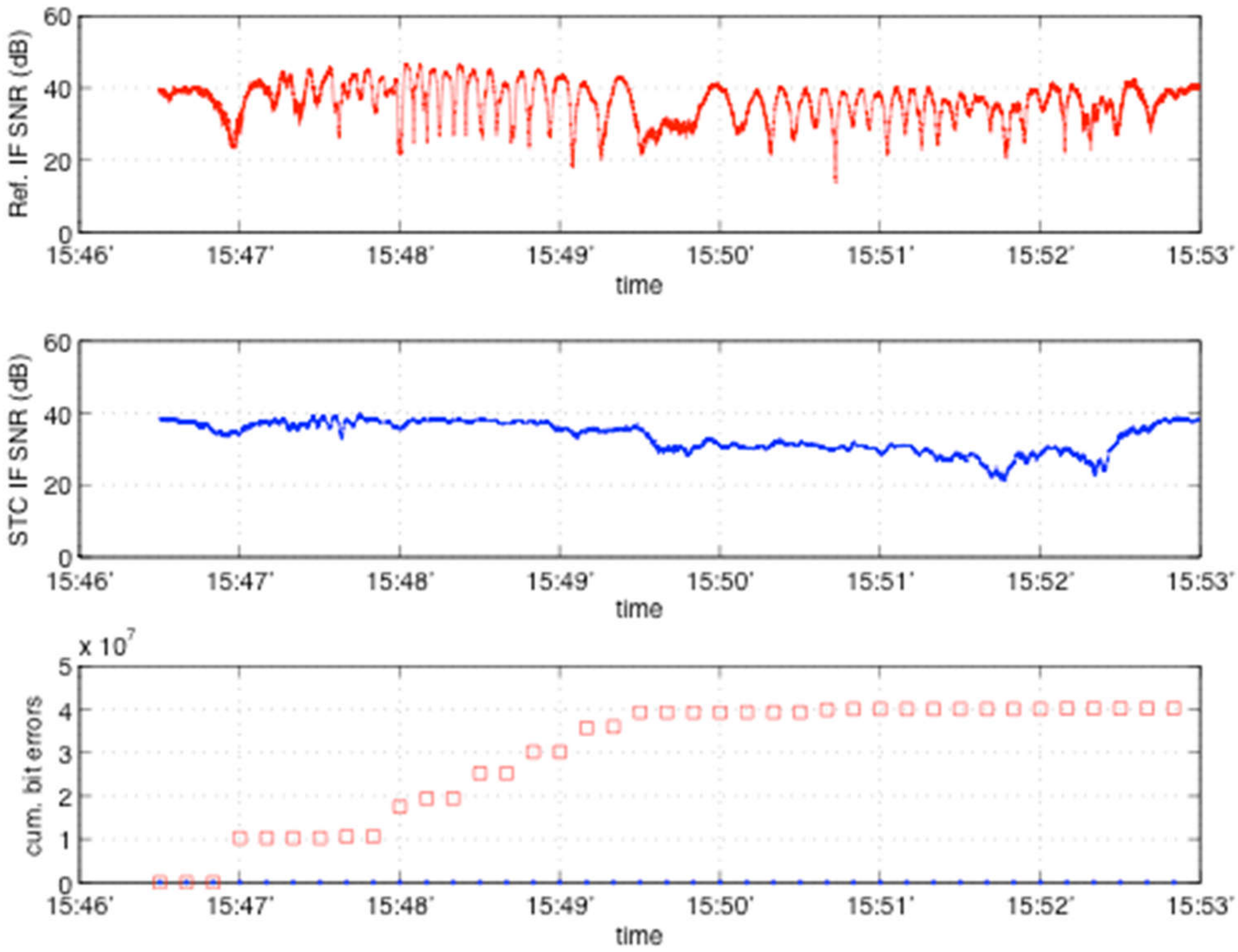
STC Video Clip



M1: Left-Hand Turn @ 10° bank

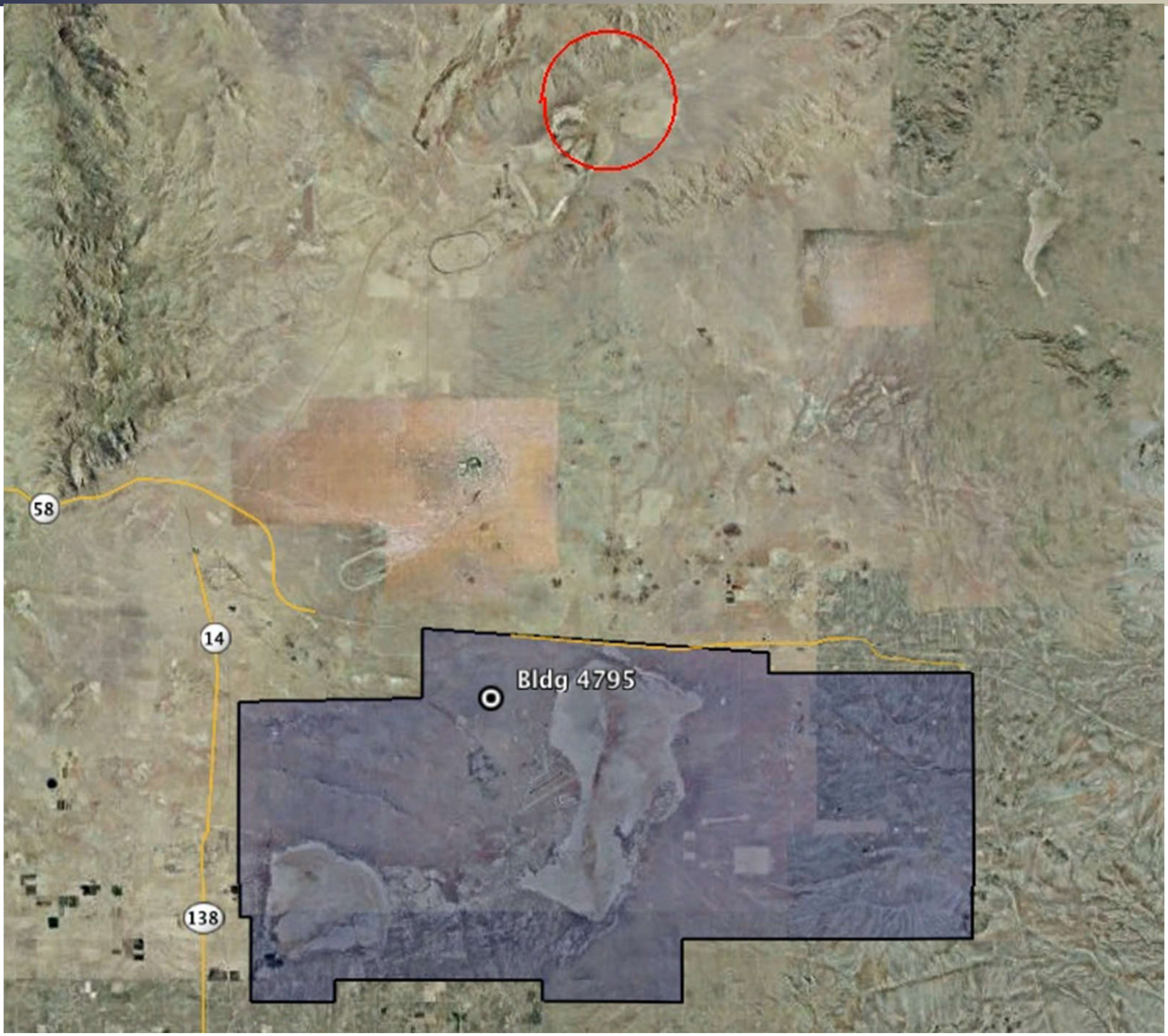
BYU

M1: Test Results



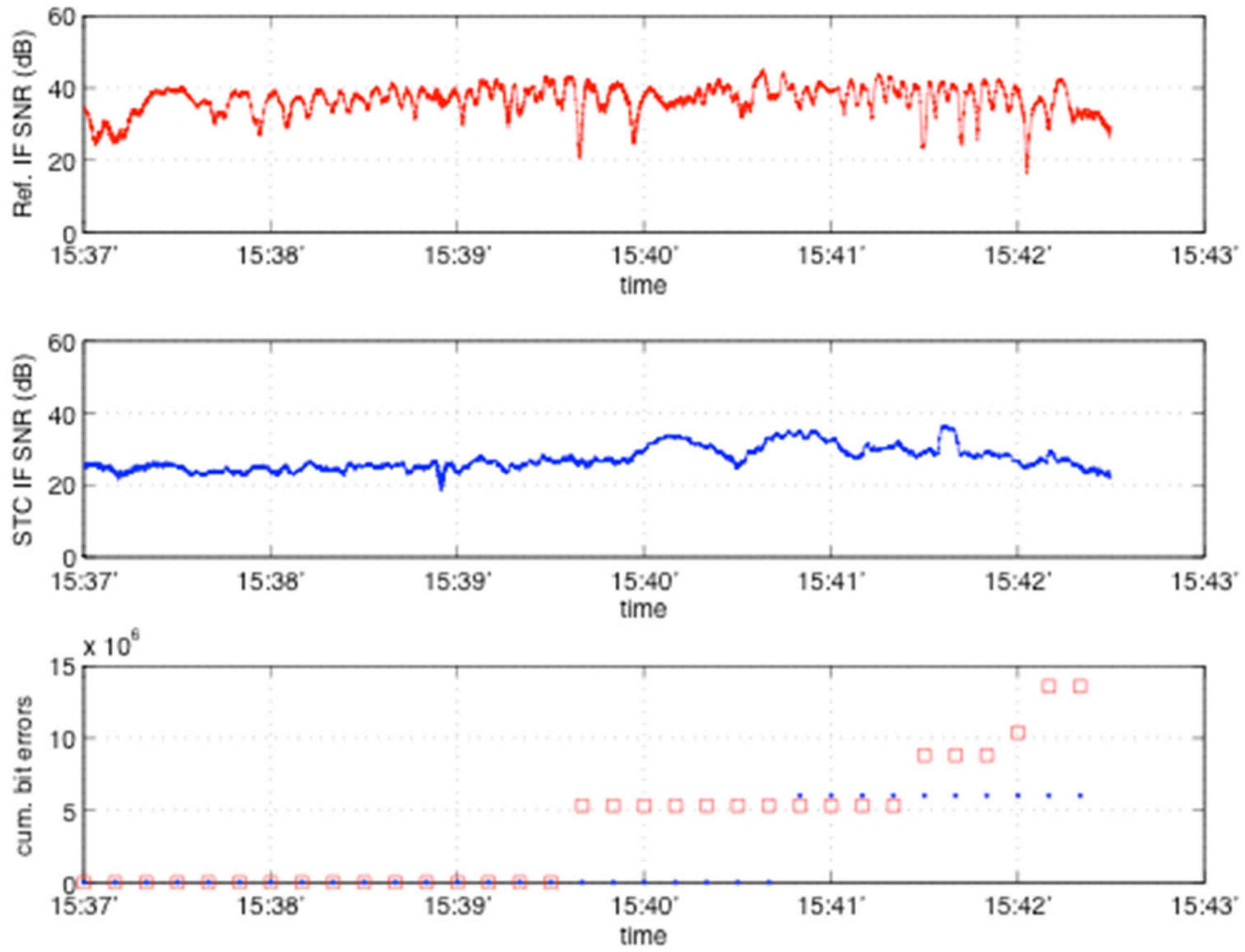
M2: Right-Hand Turn @ 10° bank

BYU

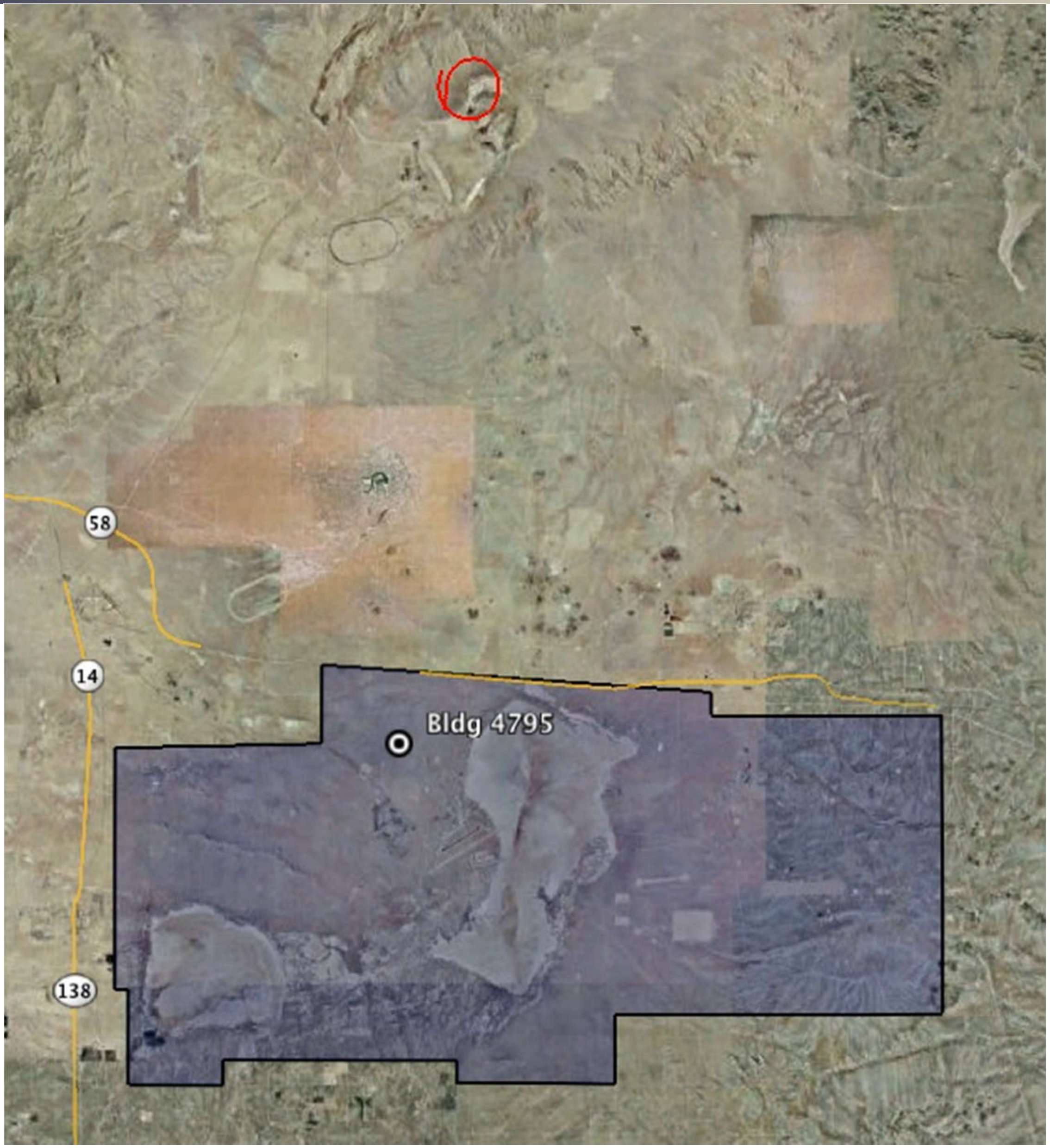


M2: Test Results

BYU

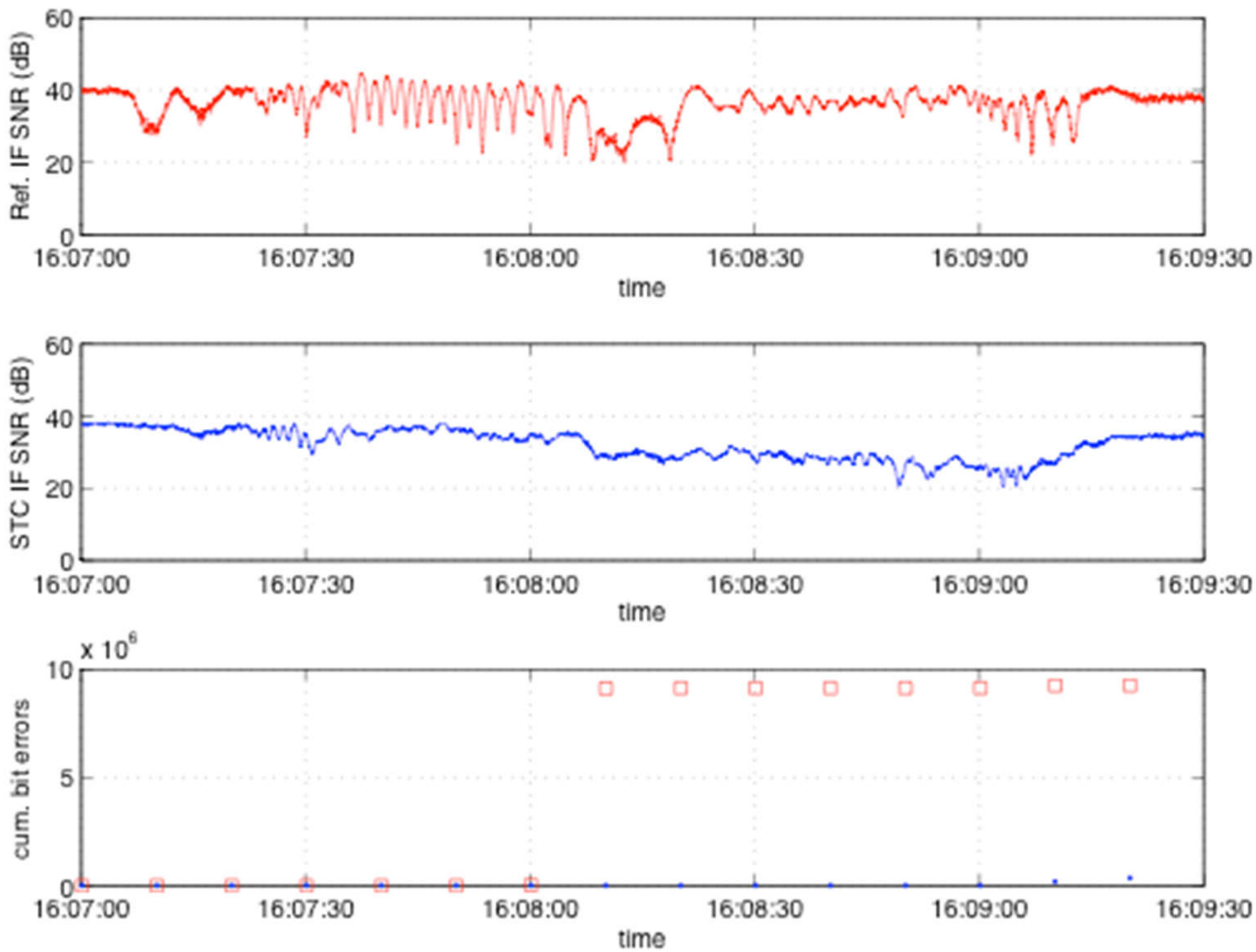


M3: Left-Hand Turn @ 30° bank



M3: Test Results

BYU

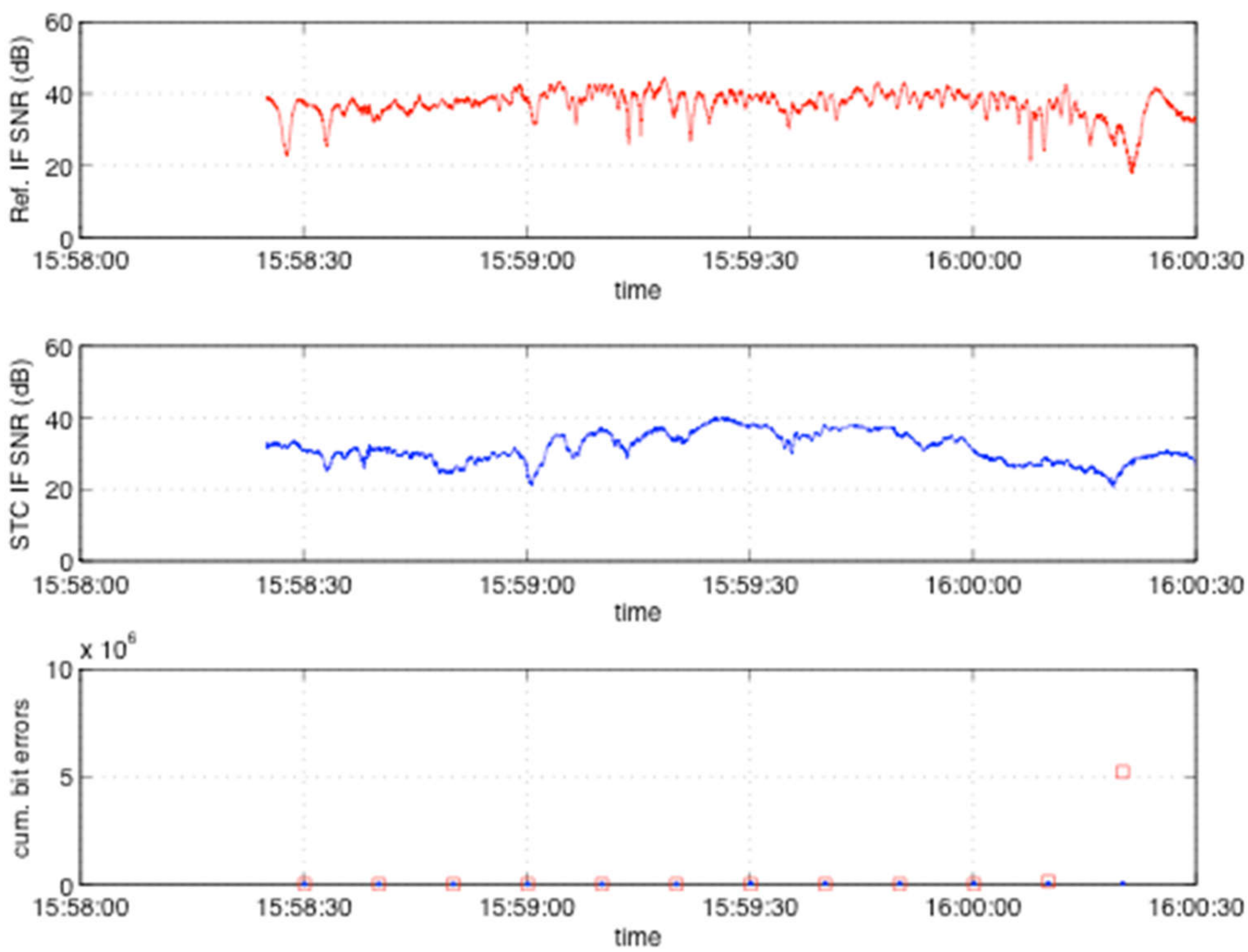


M4: Right-Hand Turn @ 30° bank

BYU

M4: Test Results

BYU

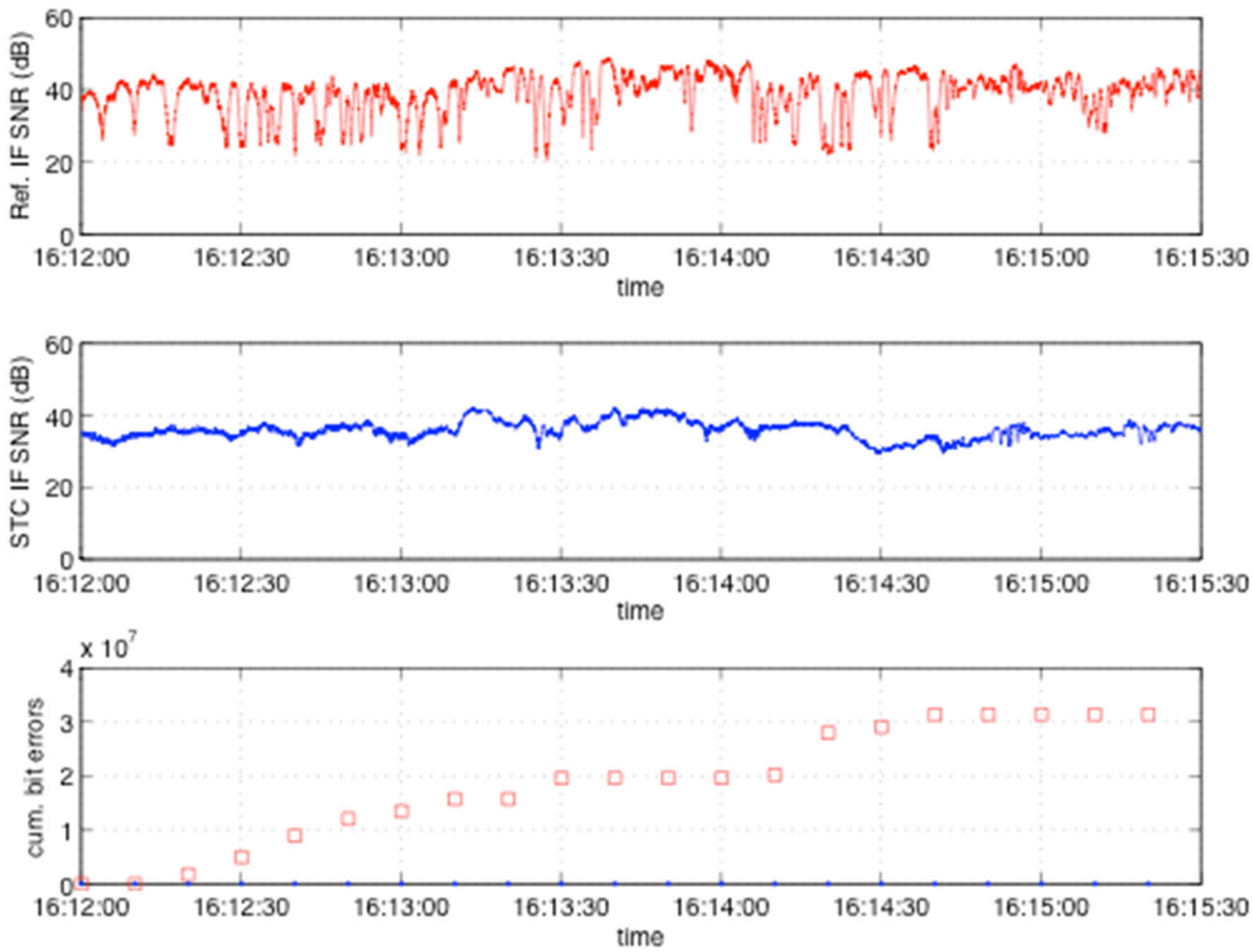


M3 to C2 Transition

BYU

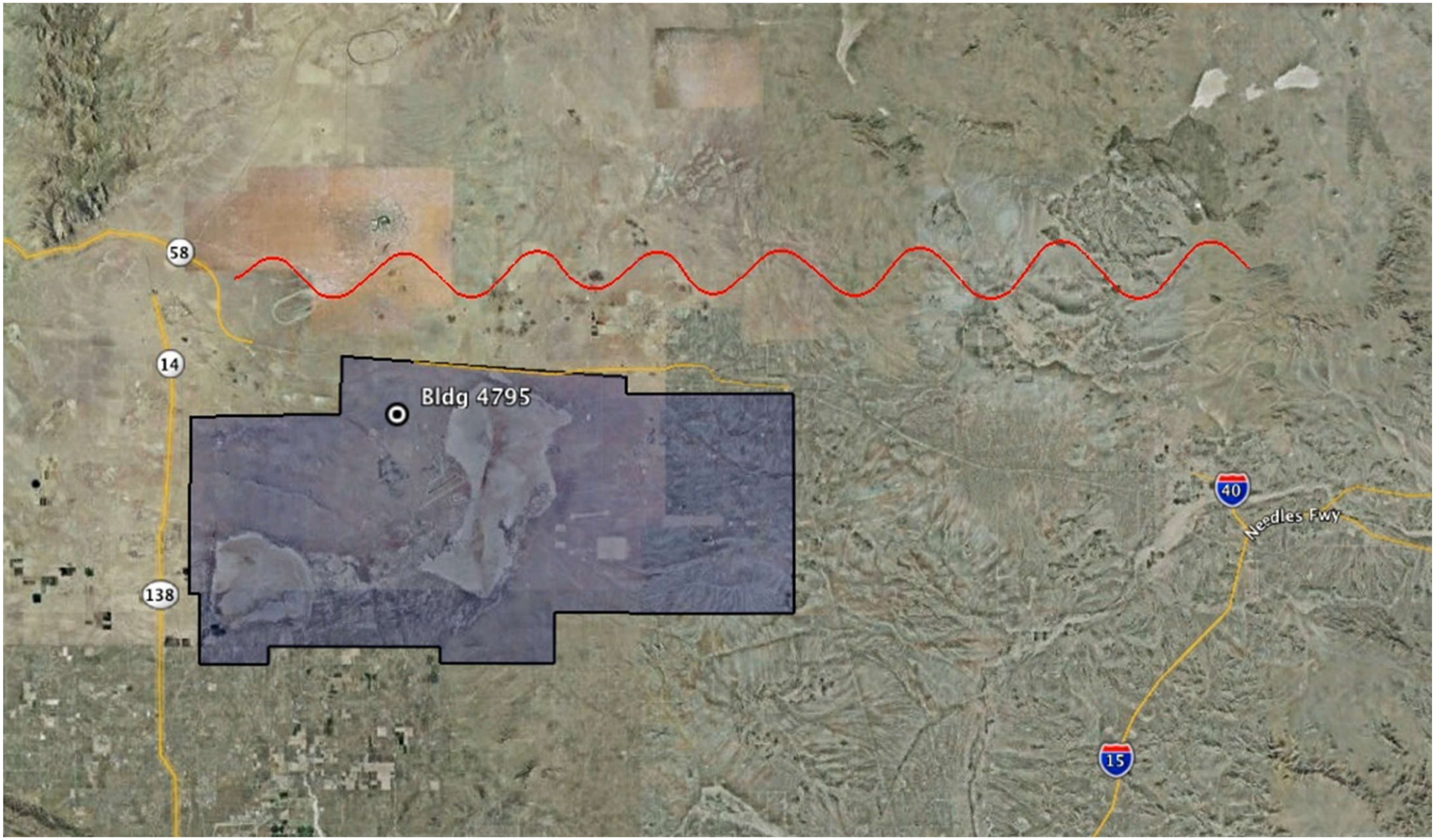
M3 to C2 Transition Test Results

BYU



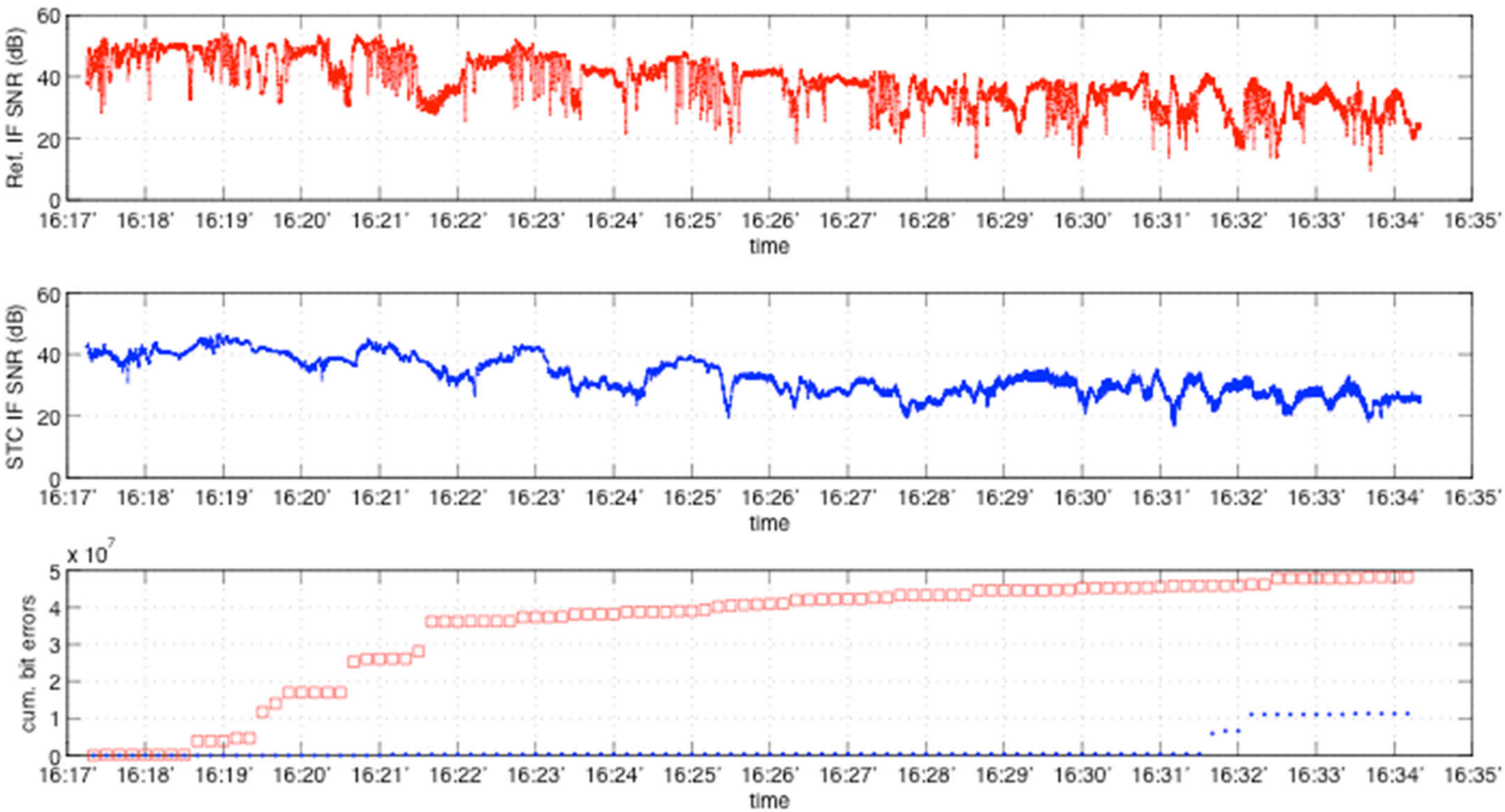
C2: Cords Road West-to-East

BYU



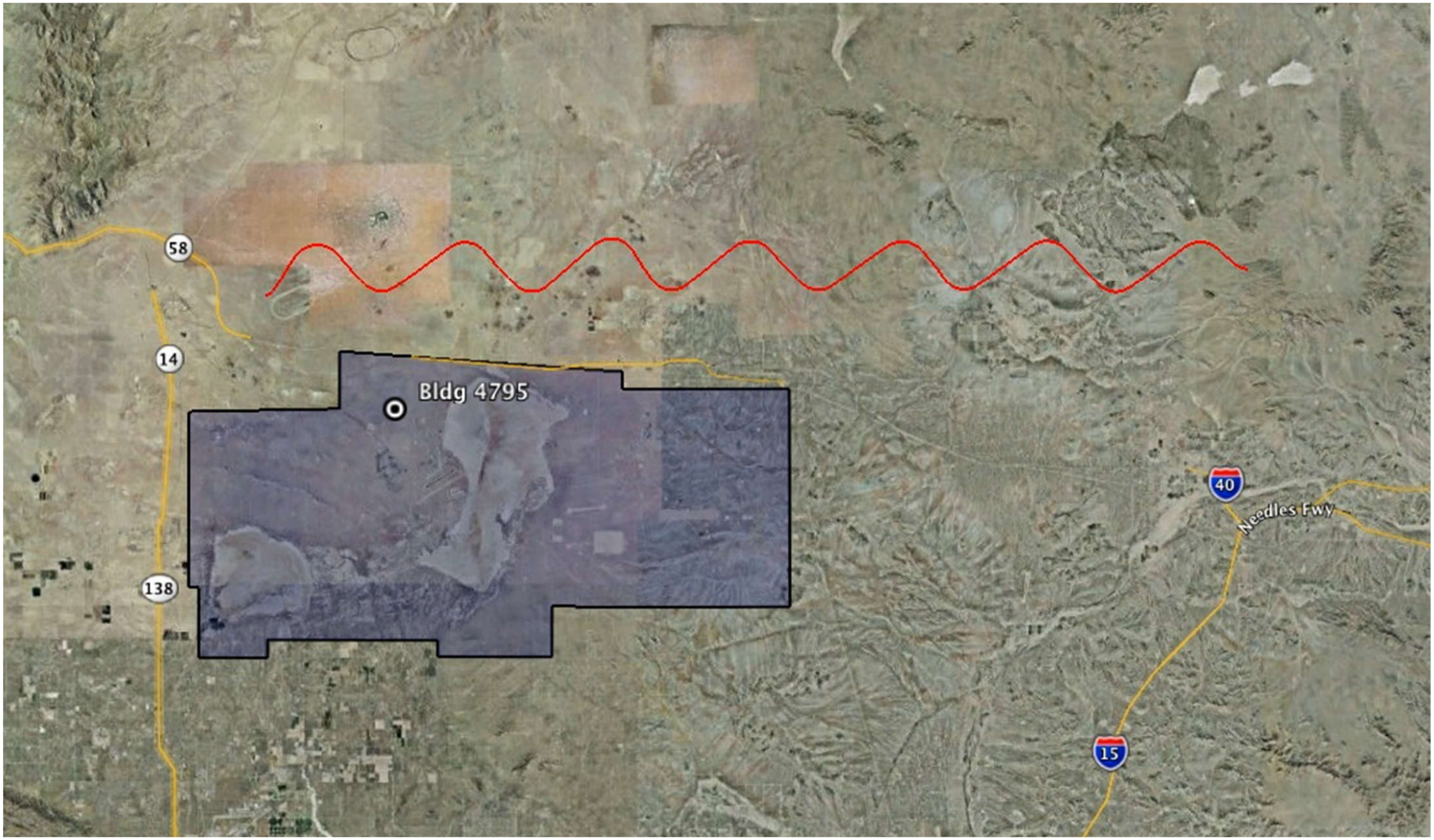
C2: Test Results

BYU

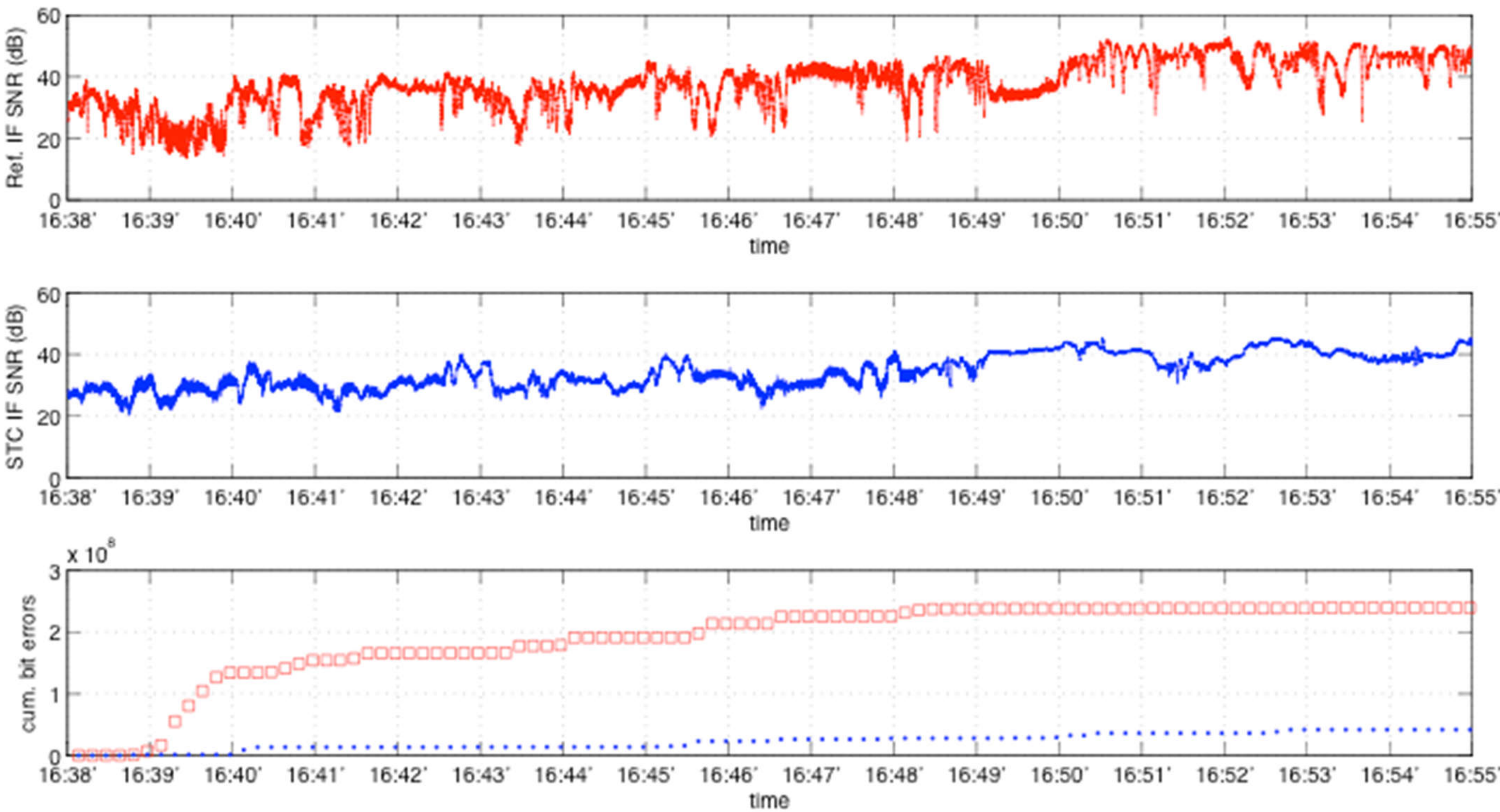


D2: Cords Road East-to-West

BYU



D2: Test Results



STC Summary

Dual-Antenna Diversity Scheme

- Removes interference created by multiple transmit antennas
  - SNR equivalent to single antenna transmission
  - Multi-antenna scheme alleviates masking during maneuvering
  - Can be used with diversity reception
- Realtime hardware flight tested at Edwards AFB and showed substantial performance benefit

Forward Error Correction

Forward Error Correction

- Basic premise
  - Insert redundant bits into transmitted stream
  - Use known relationships between bits to correct errors
- Countless schemes have been developed
  - Convolutional code / Viterbi decoder
  - Block codes
    - BCH
    - Reed-Solomon
  - Concatenated codes
    - RS / Viterbi
    - Turbo product codes (TPC)
  - Low Density Parity Check (LDPC)

LDPC Codes - History

- LDPC: Low Density Parity Check
- Linear block codes
  - Some are systematic
- Developed by Robert G. Gallager at M.I.T. in 1960
  - Published by the M.I.T Press as a monograph in 1963
- No practical implementations at that time
- Re-discovered by David J.C. MacKay in 1996
  - Began displacing turbo codes in the late 1990s
- Recent history
  - 2003: LDPC code selected for the new DVB-S2 standard for the satellite digital TV
  - 2006: LDPC code selected for 10GBase-T Ethernet (10 Gbps over twisted-pair cables)
  - 2007: LDPC codes published by CCSDS as an “Orange Book”
  - 2008: LDPC code selected for the ITU-T G.hn standard
  - 2009: LDPC codes adopted for Wi-Fi 802.11 High Throughput (HT) PHY specification
  - 2012: LDPC code selected for integrated Network Enhanced Telemetry (iNET)

LDPC AR4JA Codes

- AR4JA: Accumulate-Repeat-4-Jagged-Accumulate
- Published by CCSDS as an “Orange Book”
  - Low Density Parity Check Codes For Use in Near-Earth and Deep Space Applications
- Defines a family of systematic LDPC codes

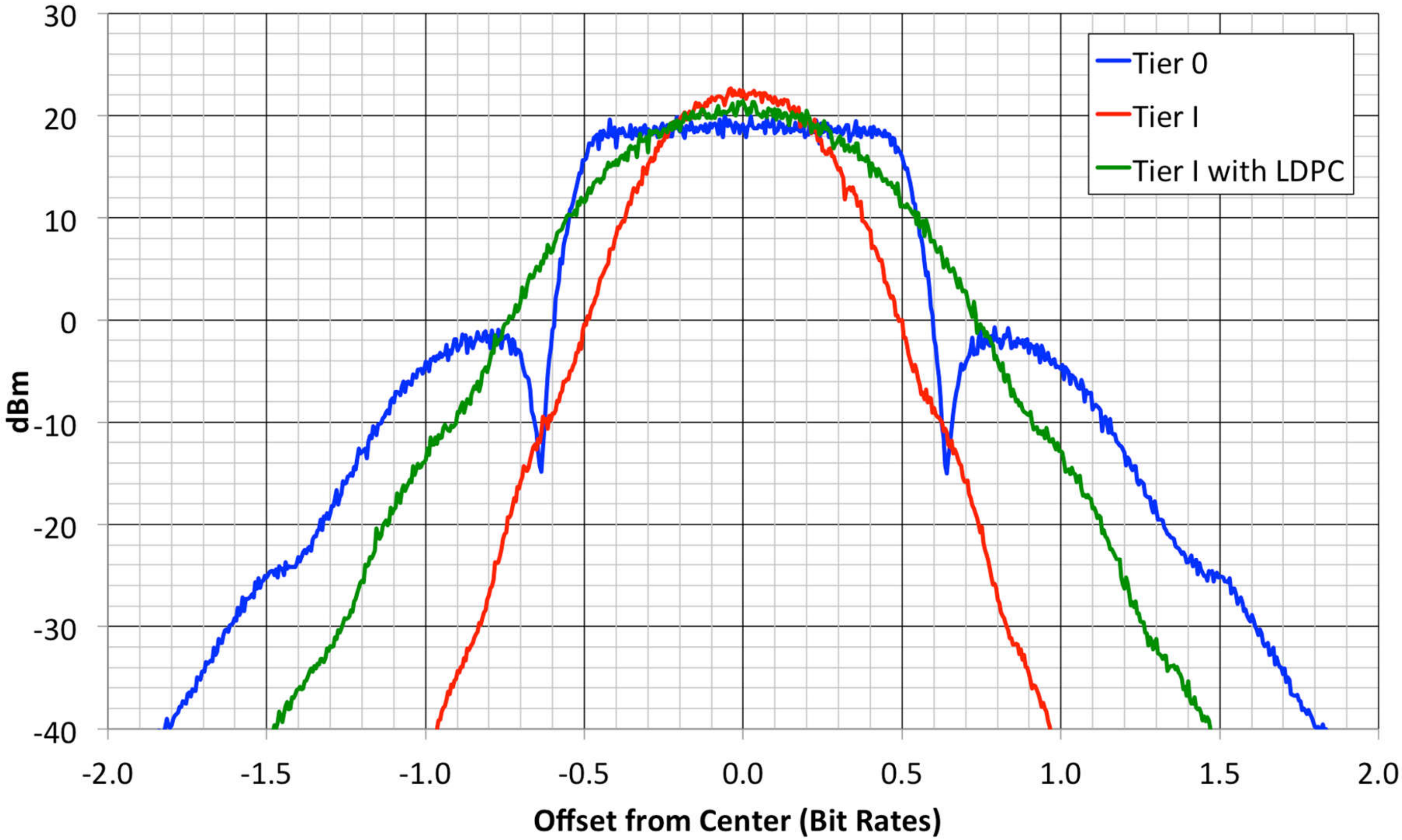
Information block length *k*	Code block length *n*		
	rate 1/2	rate 2/3	rate 4/5
1024	2048	1536	1280
4096	8192	6144	5120
16384	32768	24576	20480

- Defines attached sync markers (ASM)
  - Specified in section 6 of CCSDS Recommended Standard CCSDS 131.0-B-1
- Present work based on the (6144, 4096) code

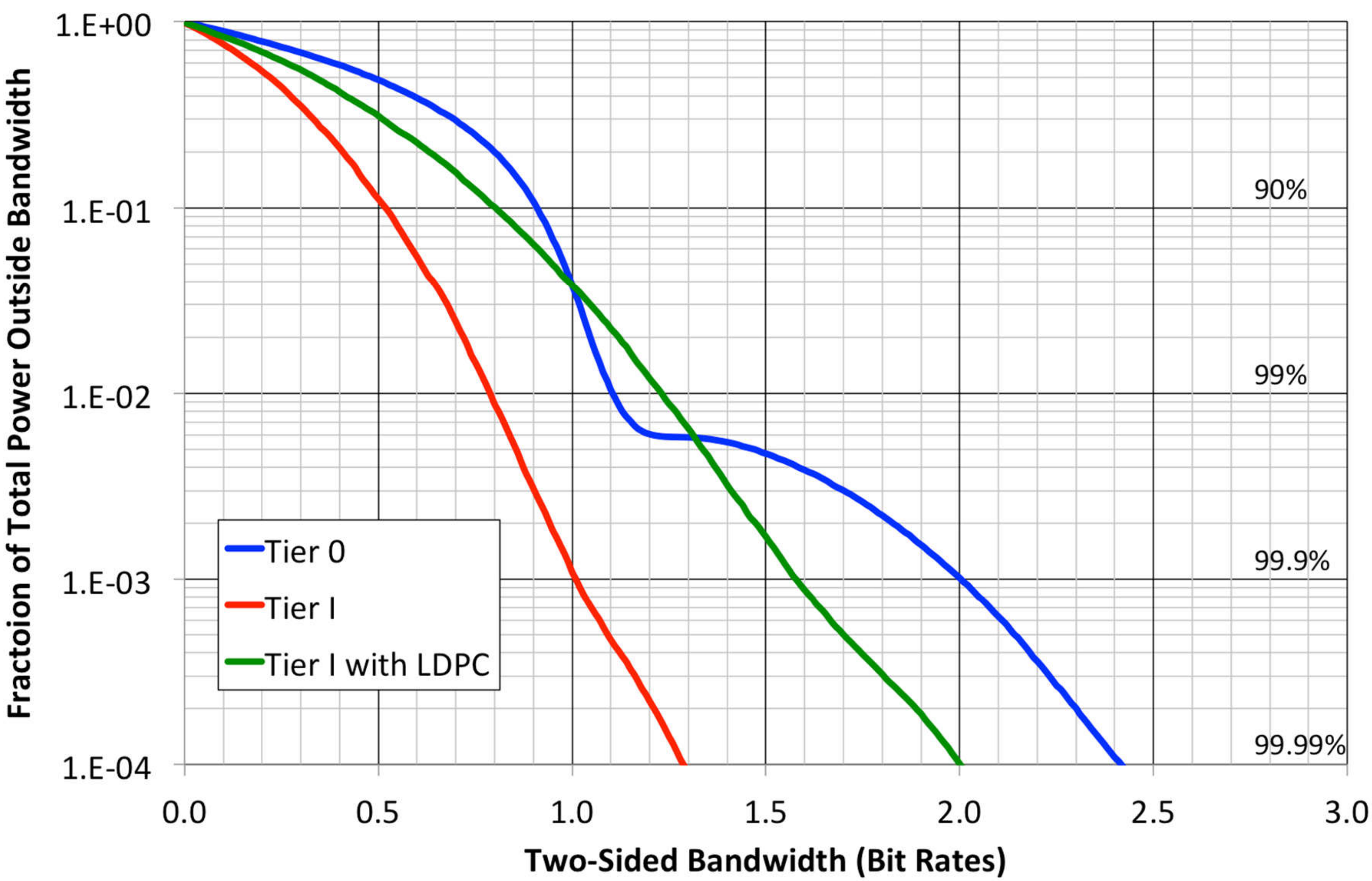
Packet Assembly

- Input 4096 data bits
  - Randomize prior to encoding, if necessary
- Compute and append 2048 parity bits
- Prepend 256-bit attached sync marker (ASM)
  - Yields a 6400-bit packet
  - Each and every code word carries the ASM: A, A, Ā, A
    - A = FCB88938D8D76A4F
    - Ā = 034776C7272895B0
  - Synchronization requires at most one code word

Spectral Characterization



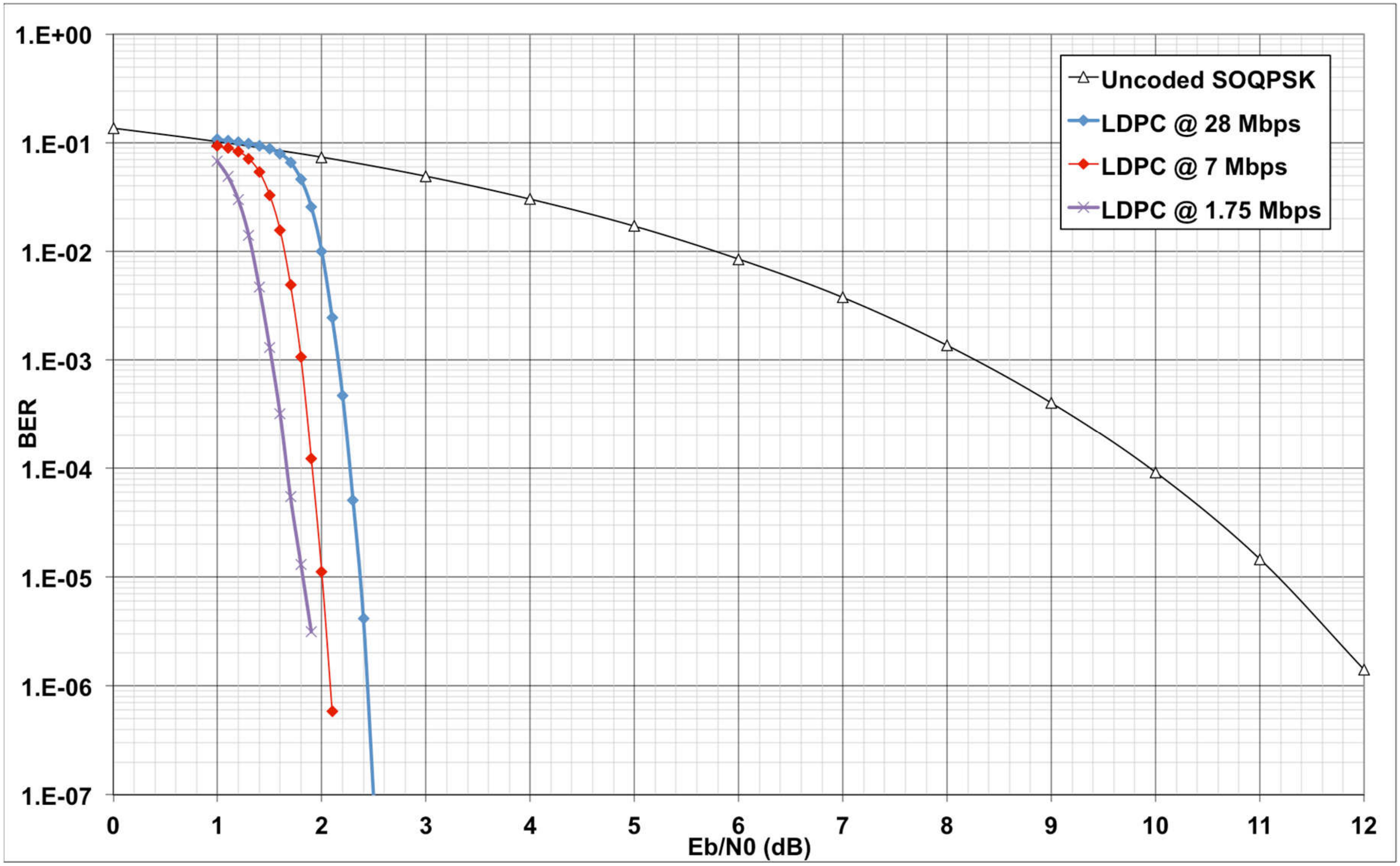
Fractional Out-of-Band Power



Decoder

- Demodulate SOQPSK with soft decisions
  - Implemented 8-bit decisions
    - Iterative decoders work best with high resolution soft decisions
  - Estimate E_b/N_0 for soft decision scaling
- Correlate for ASM with hard decisions
  - Resolves the 4-ary phase ambiguity in SOQPSK
  - Virtually certain sync at E_b/N_0 = 0 dB
- Initialize decoder
- Execute decode iterations until next code word
  - Coding gain varies with bit rate

Measured BER Results



LDPC from Appendix 2-D

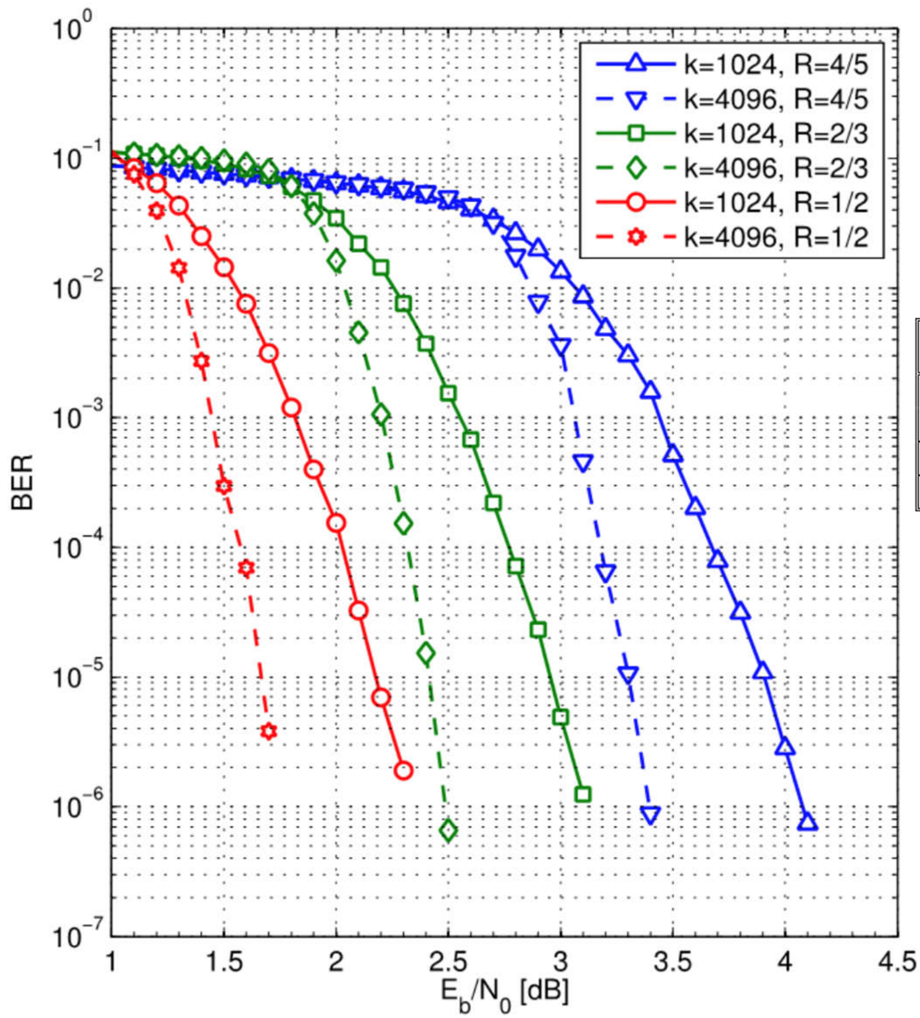
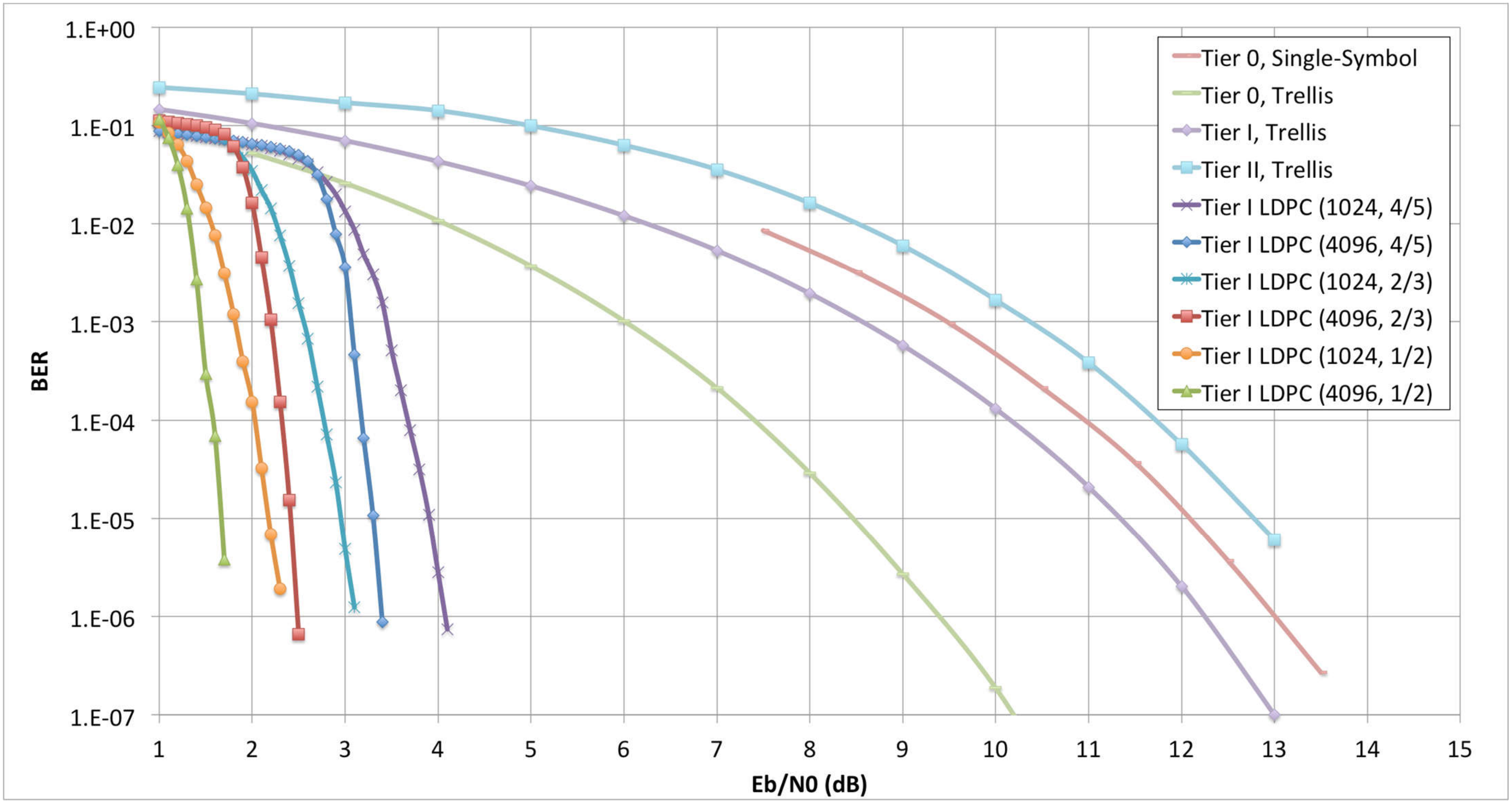


Table D-11. Bandwidth Expansion Factor			
Information Block Length, *k*	Bandwidth Expansion Factor		
	Rate 1/2	Rate 2/3	Rate 4/5
1024	33/16	25/16	21/16
4096	33/16	25/16	21/16

BER – All Modes



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Conclusions

- Rate 2/3 LDPC code yields ≈9 dB coding gain relative to uncoded SOQPSK
  - ±0.5 dB, depending on data rate
- 256-bit ASM provides reliable, fast synchronization at Eb/N0 < 0 dB
  - Synchronization is consistently achieved in < 4096 data bits
- Bandwidth expansion of 25/16
  - Still 22% less bandwidth than legacy PCM/FM
- SOQPSK with LDPC offers a reasonable trade of spectral efficiency for a significant gain in detection efficiency
- 5 other LDPC codes offer similar trade of bandwidth for BER performance

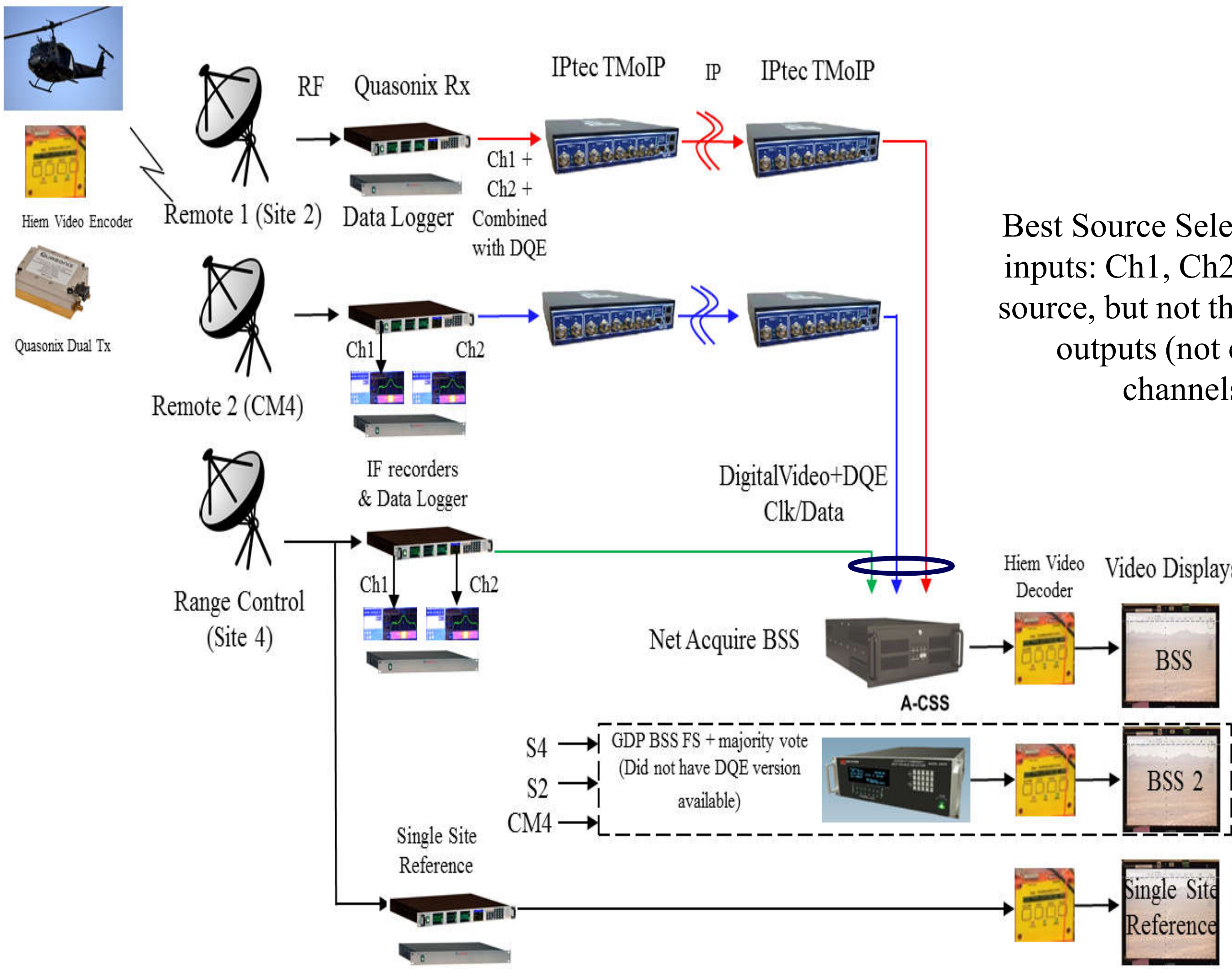
How Well Does It All Work Together?

Yuma Proving Grounds, AZ
Feb 8-11, 2016

Recipe for Delivering Every Bit

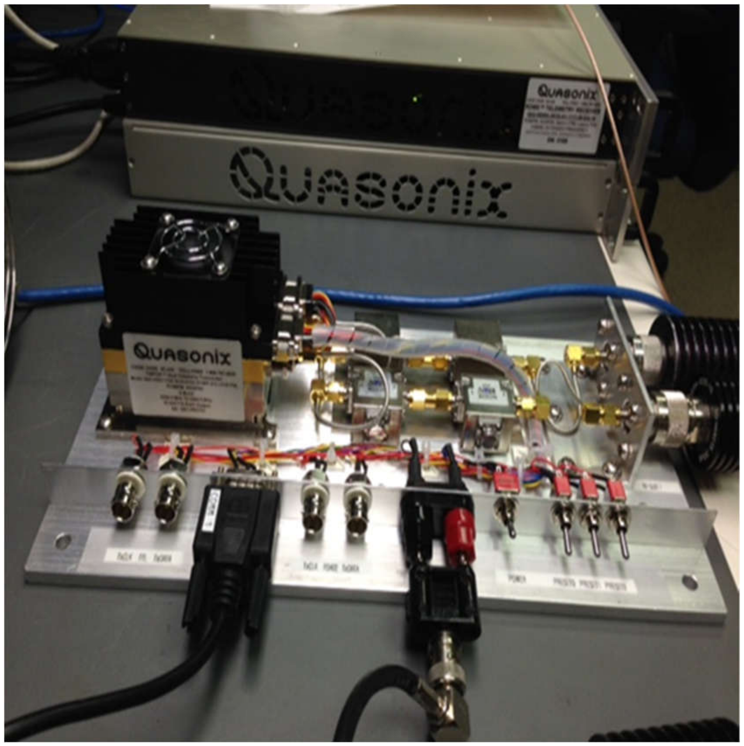
- Space Time Coding (STC)
  - Eliminates aircraft pattern nulls
- Low Density Parity Check (LDPC) coding
  - Improves margin, stops “dribbling errors”
- Adaptive Equalization (for non-STC signals)
  - Mitigates multipath
- Spatial diversity with correlating source selection
  - Eliminate coverage-based dropouts
  - Requires DQE/DQM for optimal operation
  - TMoIP makes delivery easy

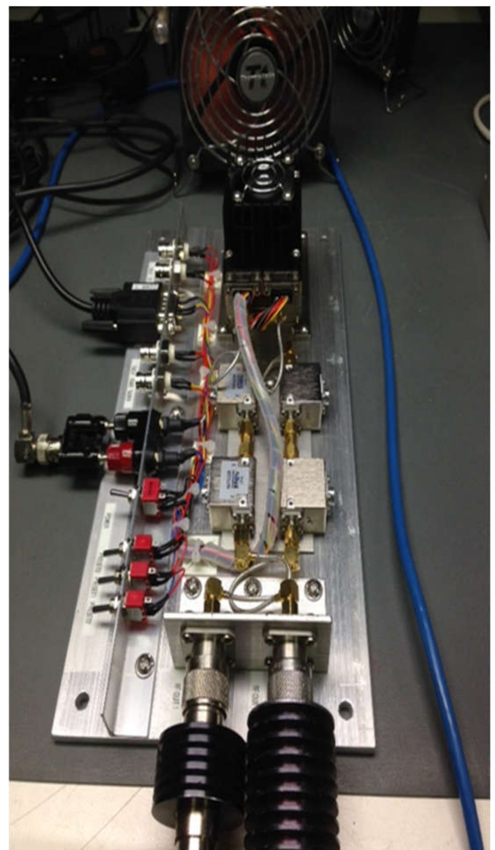
Multiple Receiving Sites



Best Source Selector used 6 inputs: Ch1, Ch2 from each source, but not the combiner outputs (not enough channels).

Dual Transmitter – S band – 10 W each output





Installed in UH-1 (Huey) helicopter with top and bottom blade antennas

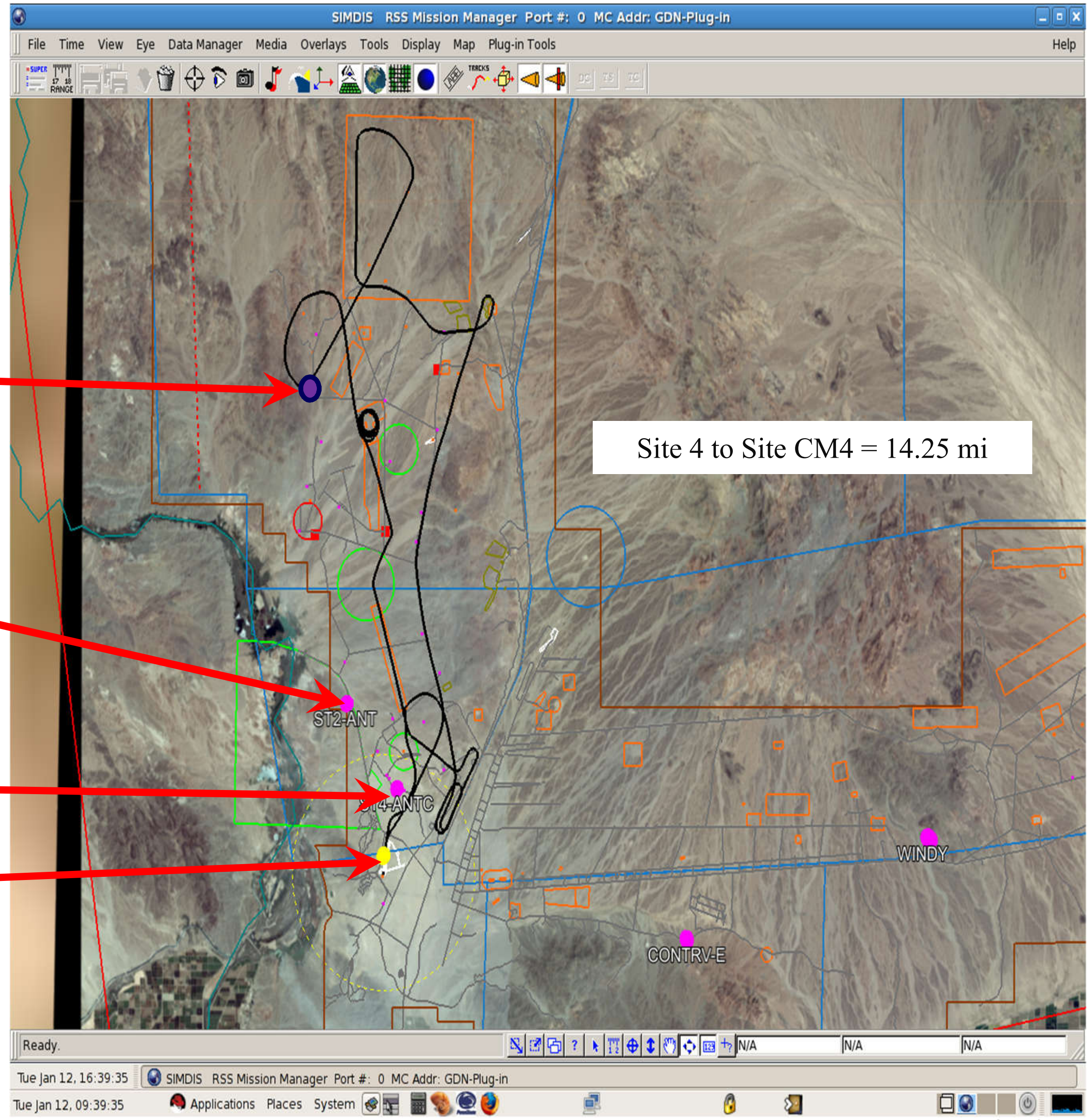
YPG Test Sites

Site CM4

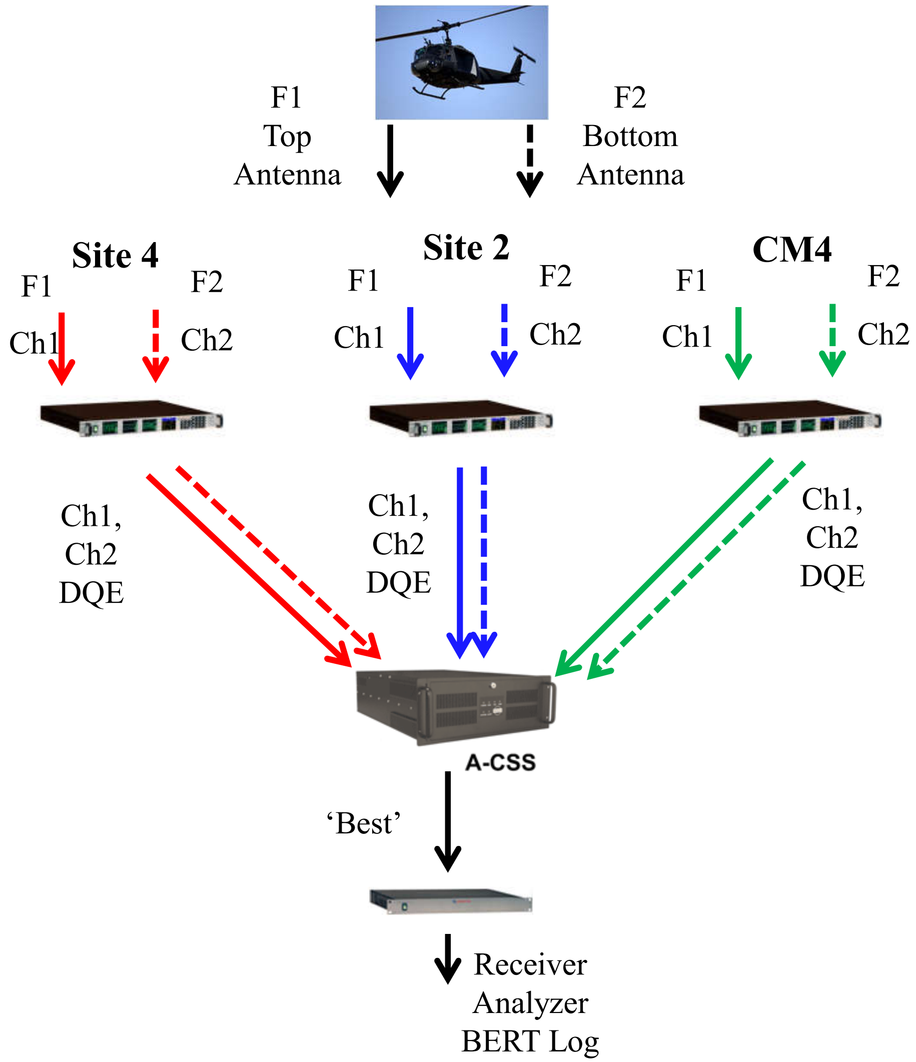
Site 2

Site 4

Laguna Airfield



Analysis using Data Logs



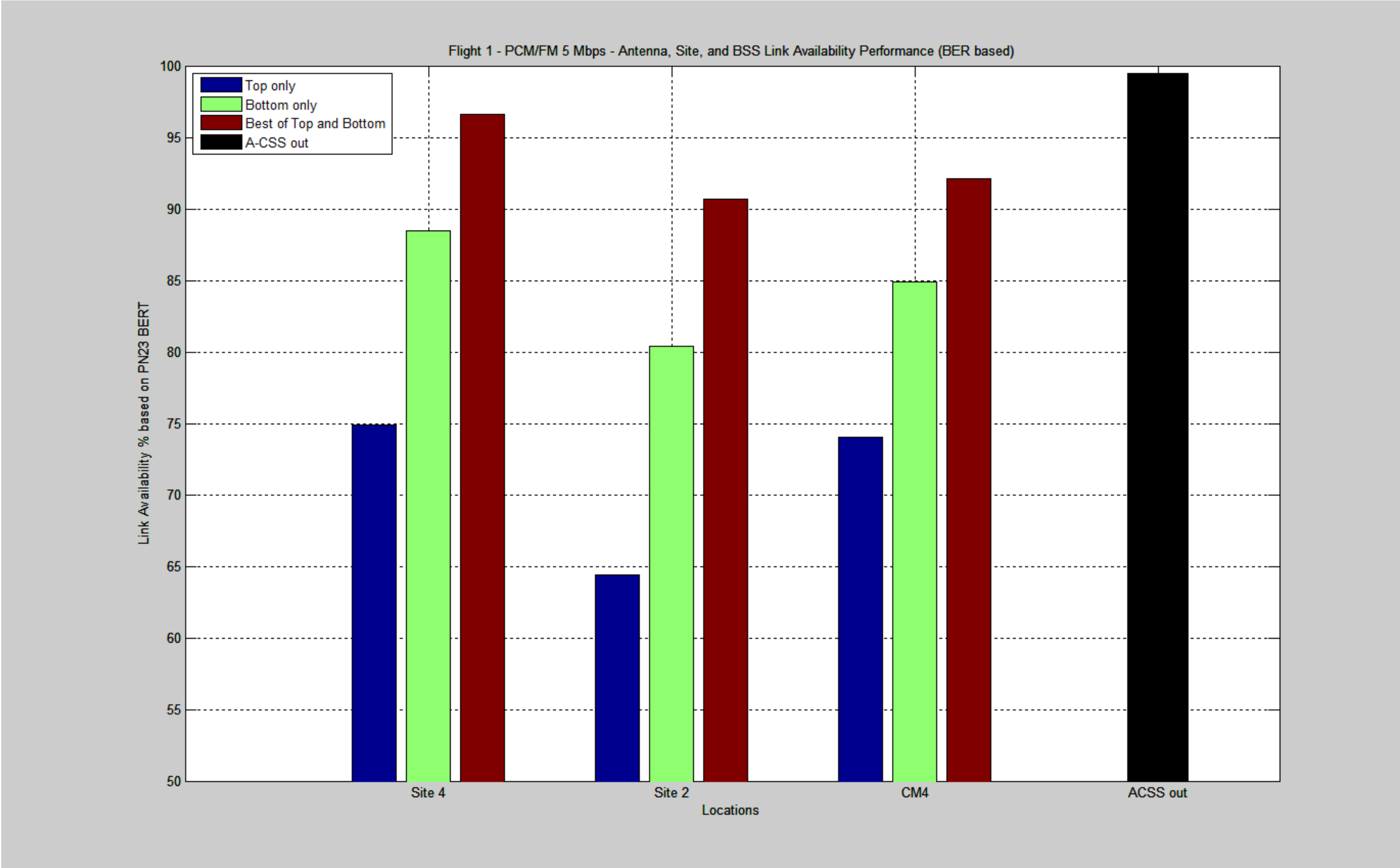
Data Log on
Each Receiver
(BEP, BER, RSSI,...)

A-CSS Log
(BEP of each time-aligned source)

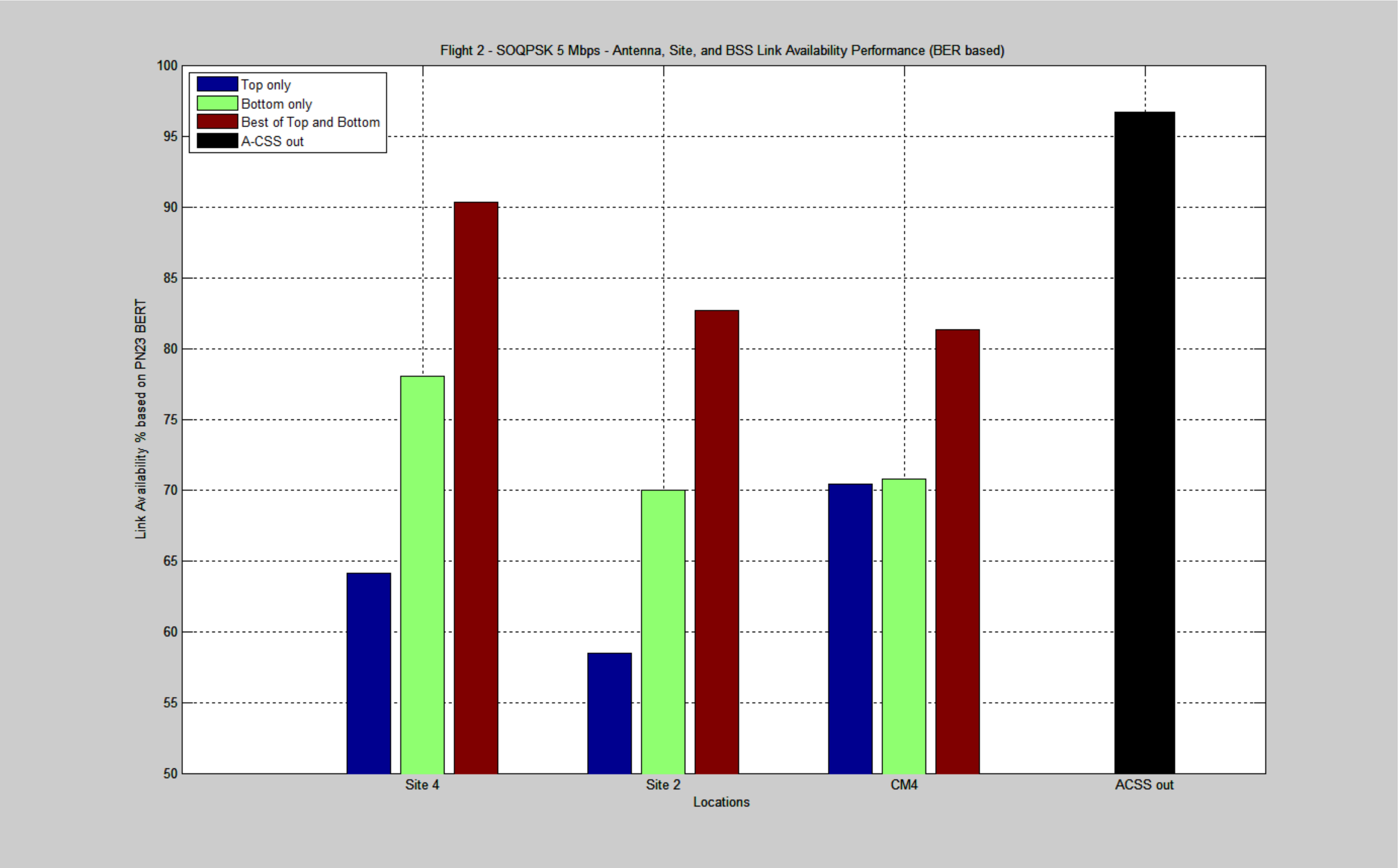
Receiver Analyzer Log
(BER of A-CSS output)

- Transmit F1-Top, F2-Bottom
- 3 Receive Sites
- 6 Clock & Data streams provided to A-CSS with Data Quality Encapsulation (DQE)
- DQE = Receiver inserts periodic estimate of instantaneous BEP
- Items of interest
  - Top vs Bottom Antenna
  - Individual Site Performance
  - Source Selector Performance

Flight 1 – PCM/FM 5 Mbps
Link Availability Summary (PN23 BER)



Flight 2 – SOQPSK 5 Mbps
Link Availability Summary (PN23 BER)



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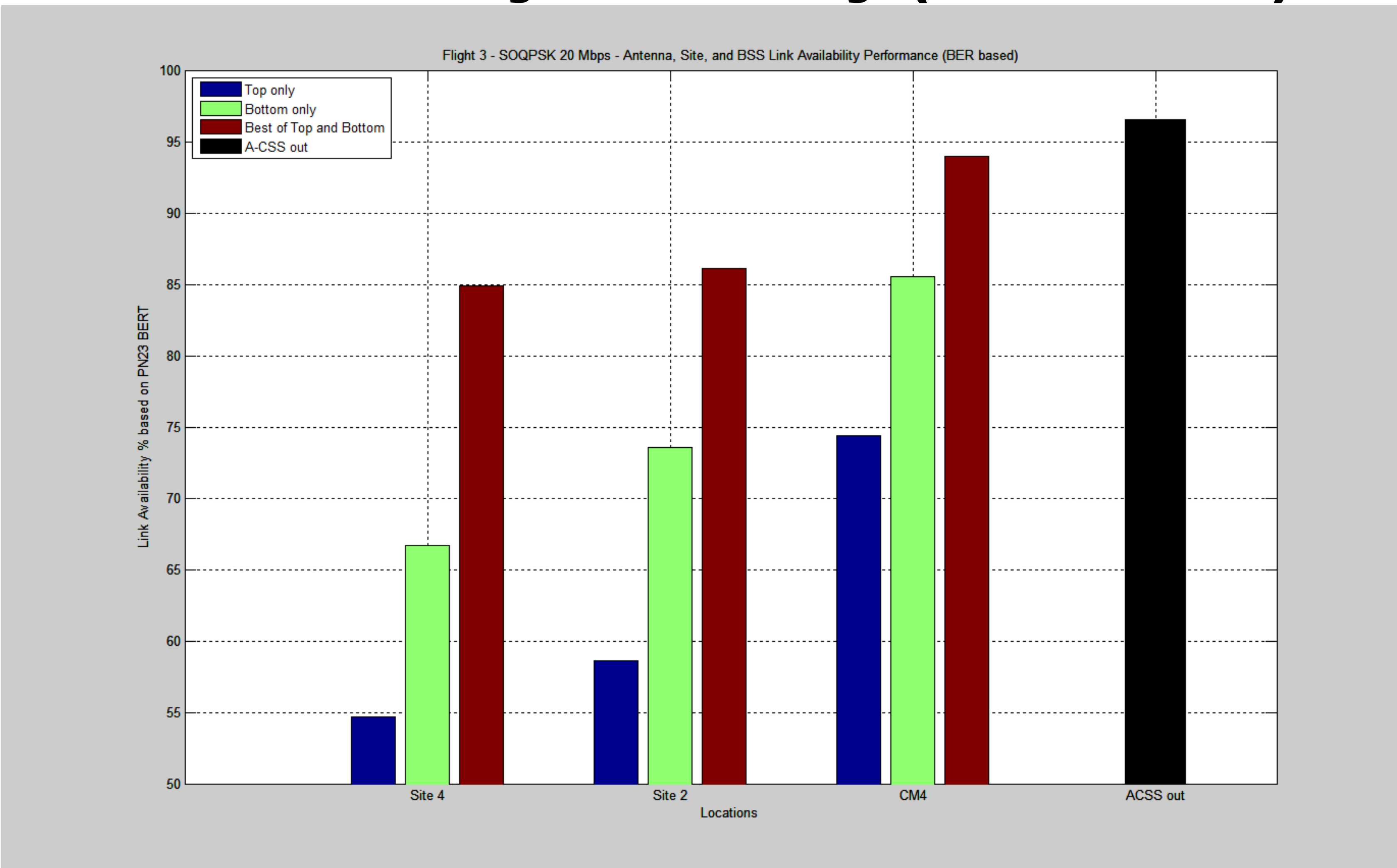
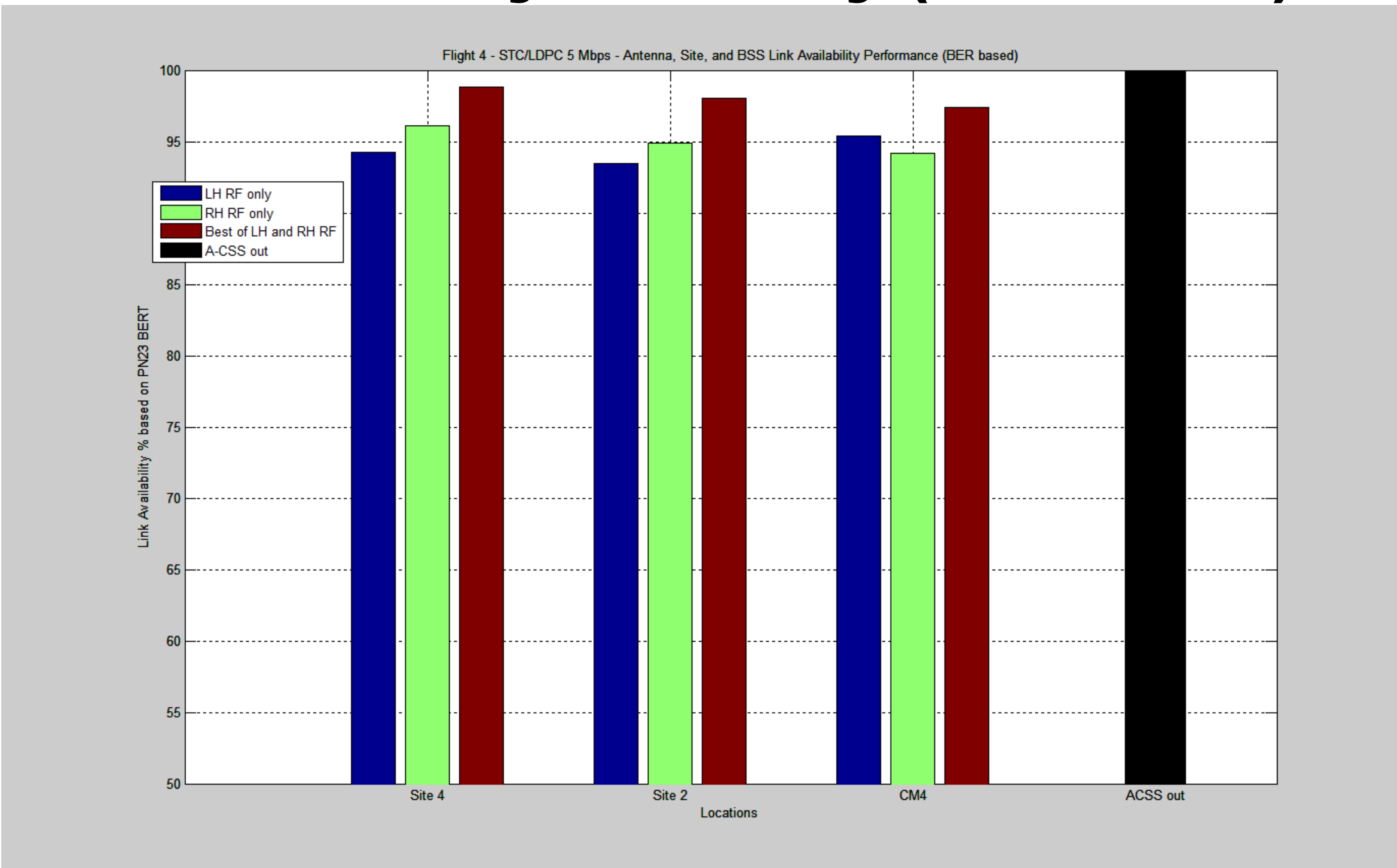
Flight 3 – SOQPSK 20 Mbps Link Availability Summary (PN23 BER)

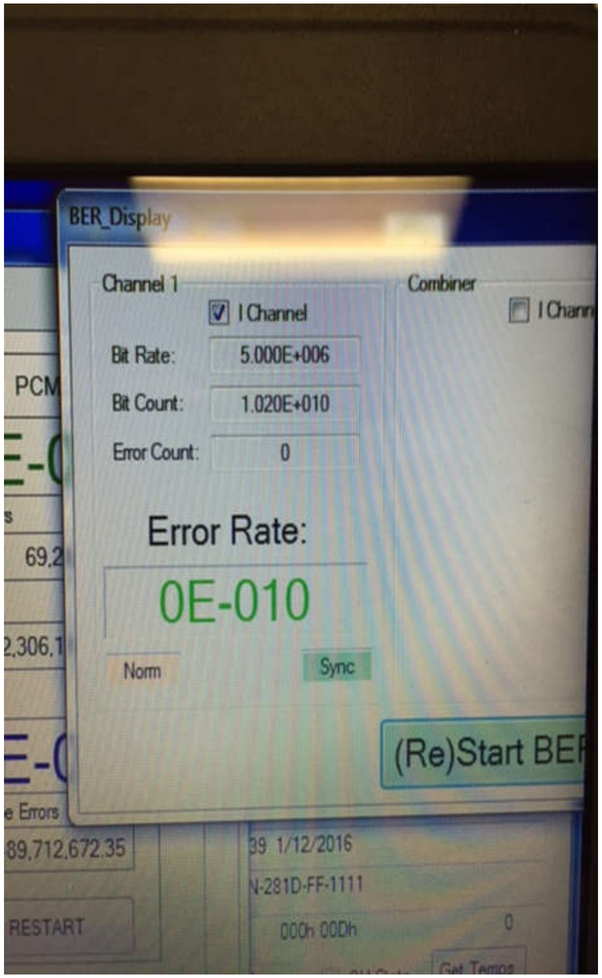


Flight 4 – STC/LDPC 5 Mbps
Link Availability Summary (PN23 BER)



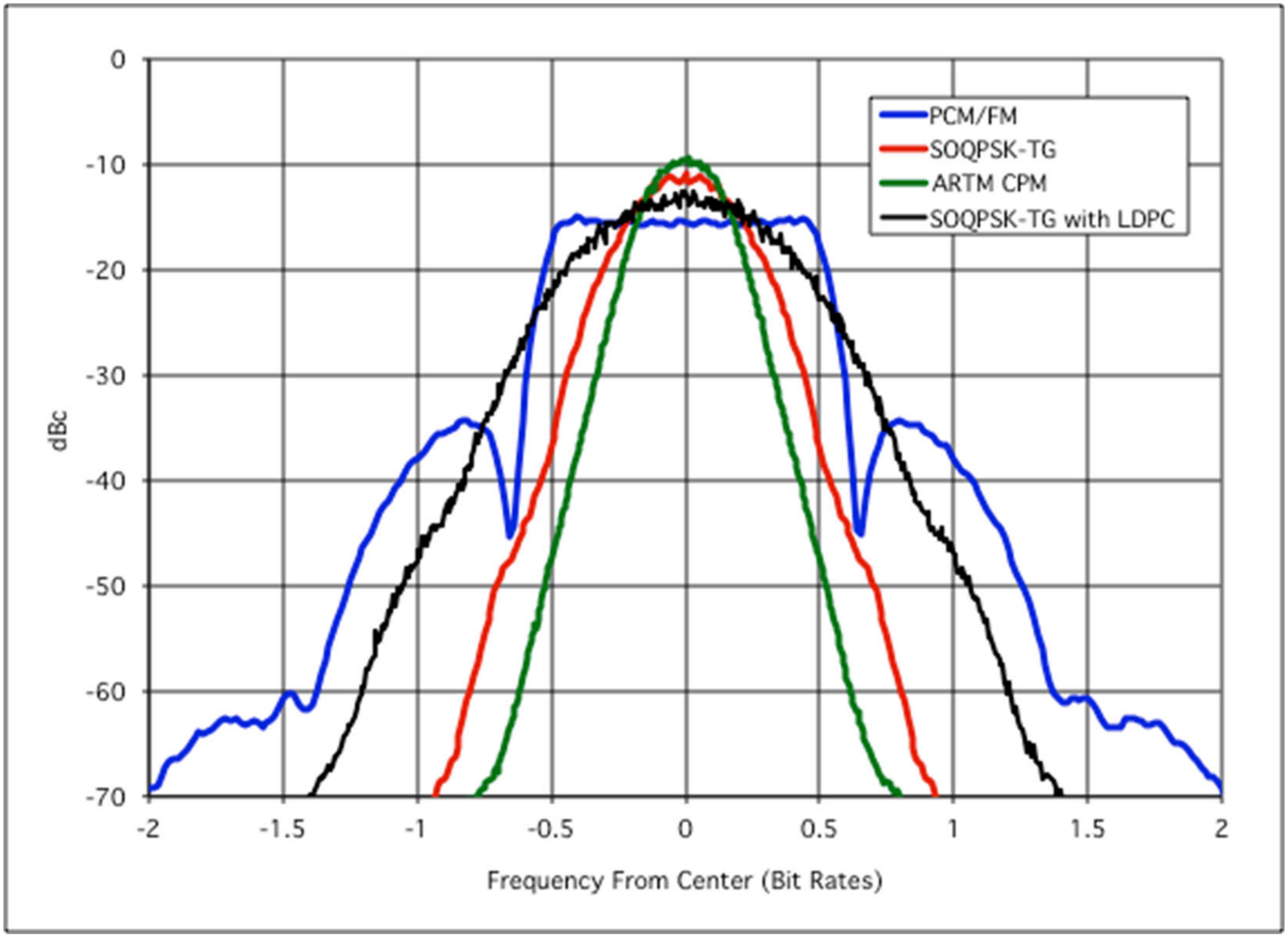
The elusive zero-error link…..

- STC/LDPC from 3 sites at 5 MBPS
- 1st pass PN23 -- 34 minutes of helicopter flight across YPG…
- Error-free!
- 2nd pass video with no freeze ups or blackouts!

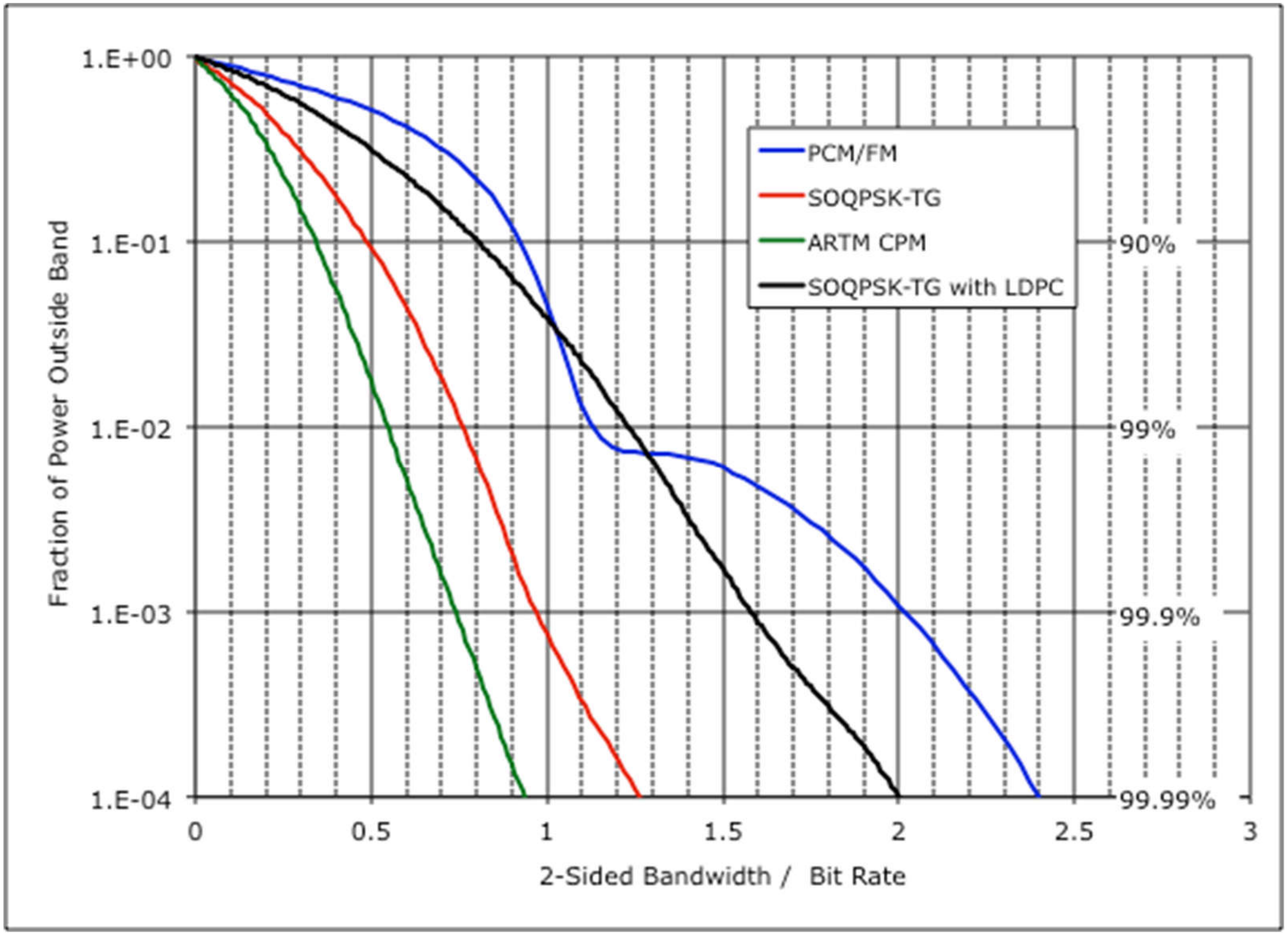


Performance Comparison and Summary

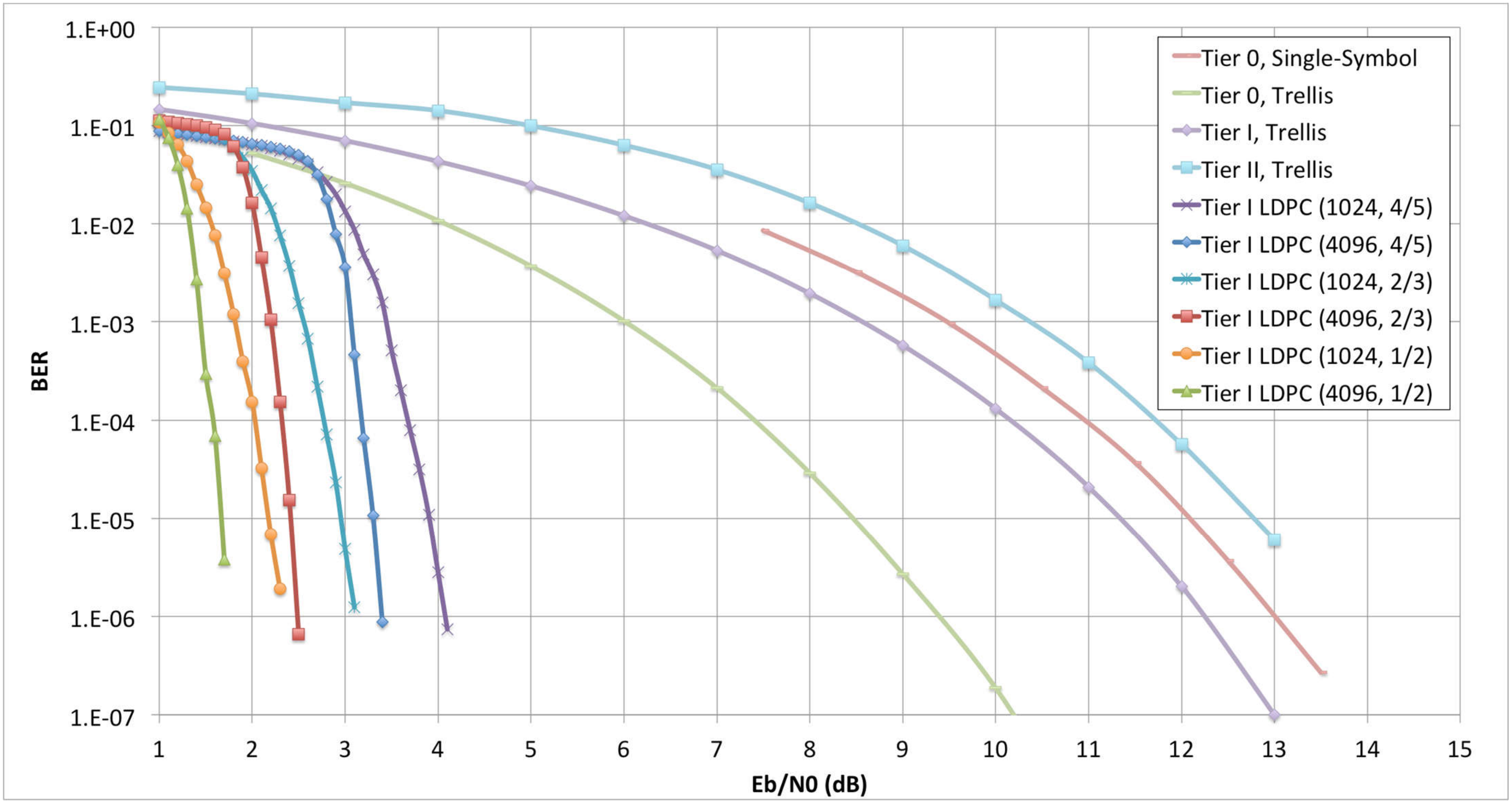
Power Spectral Densities



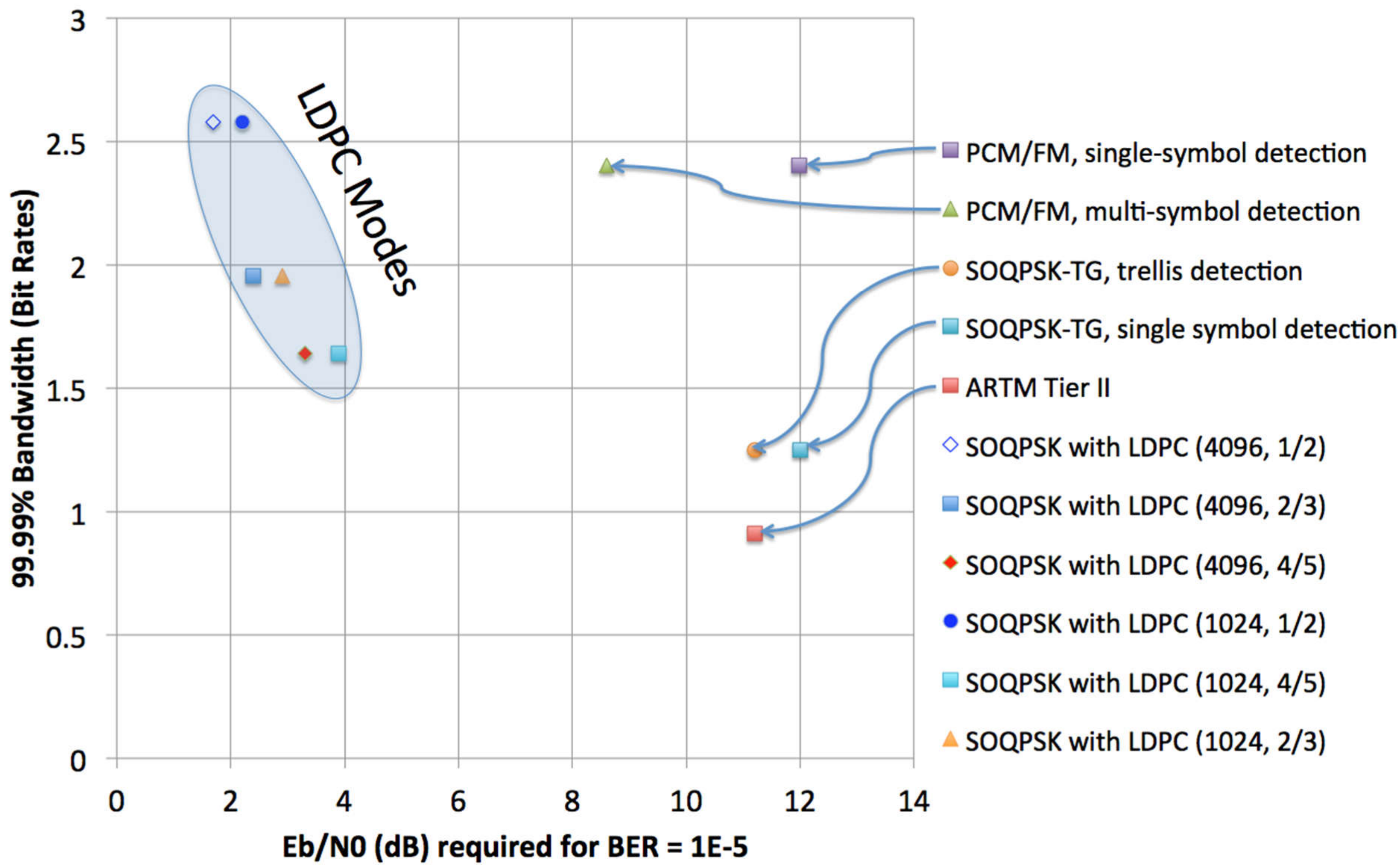
Out-of-Band Power



BER Performance Comparison



Bandwidth-Power Plane



Acknowledgements

- Mark Geoghegan, Quasonix
- Dr. Michael Rice, Brigham Young University
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- Kip Temple, ARTM, Edwards AFB
- Gene Law, NAWCWD, Pt. Mugu
- Vickie Reynolds, White Sands Missile Range

Questions/Comments