Quasonix

Advanced Modulation Techniques for Telemetry

A Short Course at the
International Telemetering Conference
Glendale, AZ • October 21, 2024

Terry Hill, Quasonix

Course Outline

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

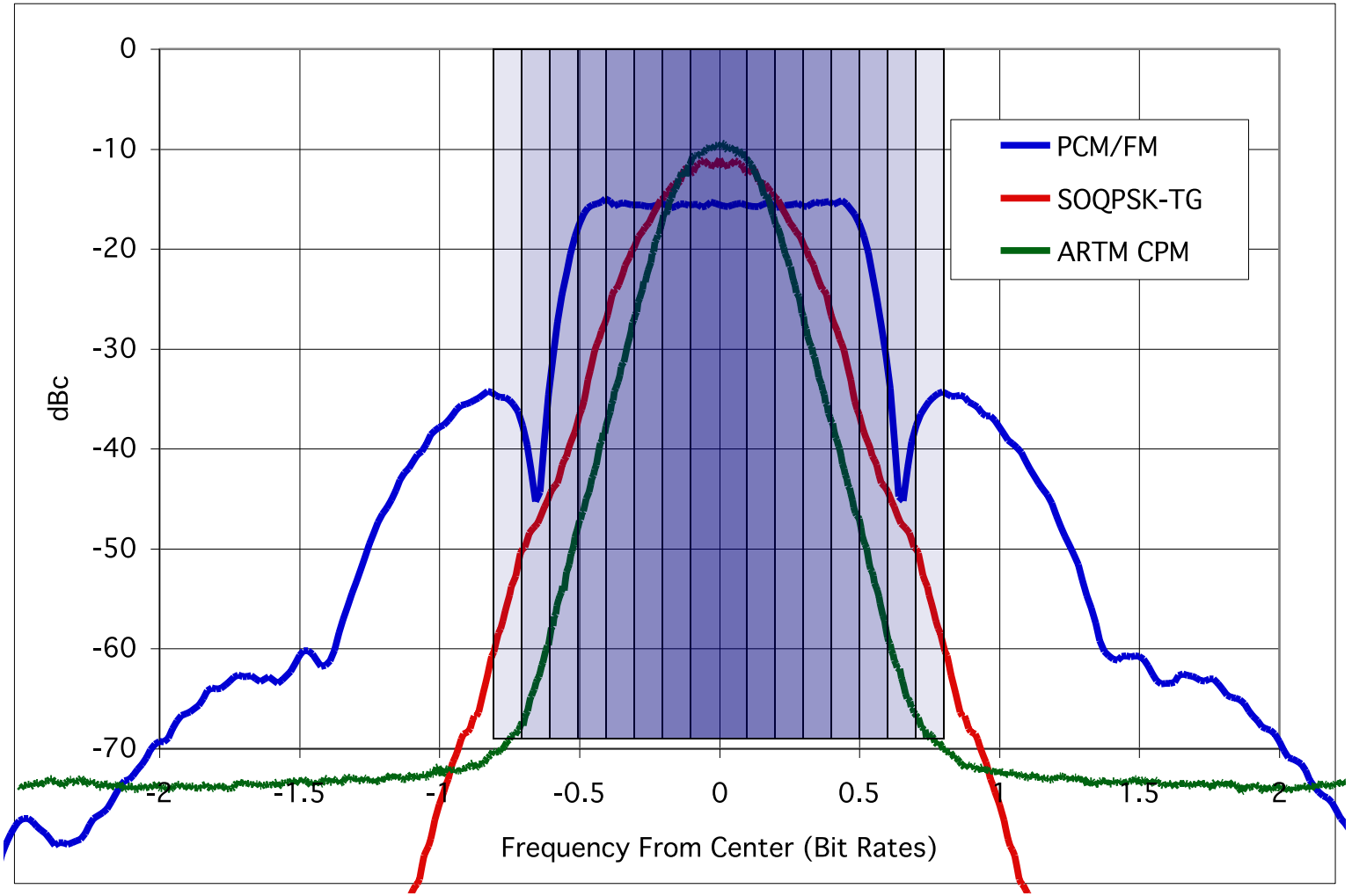
Performance Metrics

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

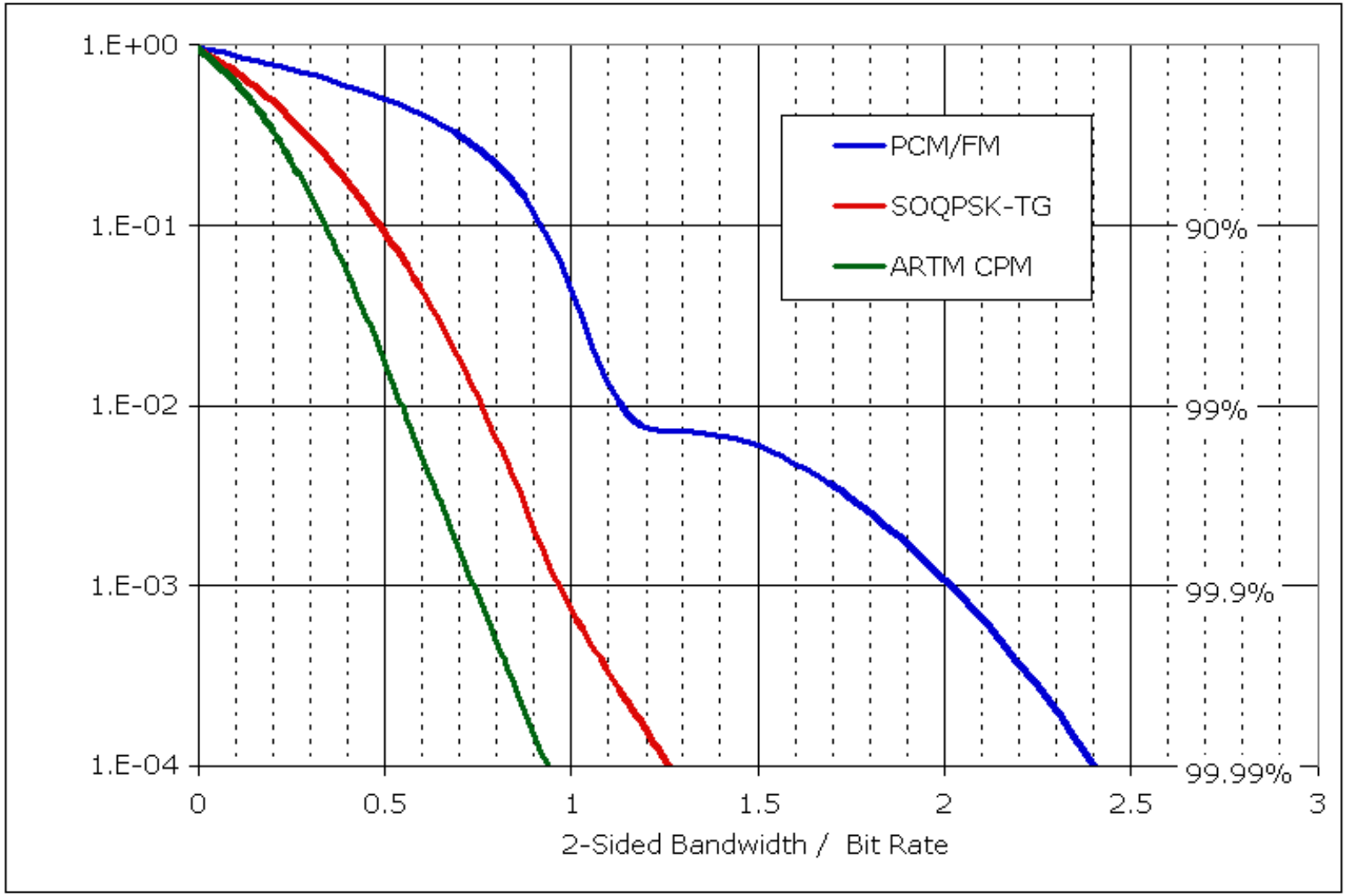
Bandwidth Efficiency

- Power spectral density
  - Function of transmitter only
- Fractional Out-of-band Power
- Channel spacing with adjacent channel interference
  - Function of transmitter and receiver
  - We'll review this in depth later
- DD1494
  - Spectrum manager's vantage point

Power Spectral Density (PSD)



Fractional Out-of-band Power



DD1494

CLASSIFICATION UNCLASSIFIED	PAGE of Pages

TRANSMITTER EQUIPMENT CHARACTERISTICS

1. NOMENCLATURE, MANUFACTURER'S MODEL NO. QSX-xxx	2. MANUFACTURER'S NAME Quasonix, Inc.
3. TRANSMITTER INSTALLATION	4. TRANSMITTER TYPE Digital Telemetry
5. TUNING RANGE xxx – yyy MHz	6. METHOD OF TUNING Synthesized
7. RF CHANNELING CAPABILITY 0.500 MHz	8. EMISSION DESIGNATOR(S) xxx
9. FREQUENCY TOLERANCE ±2 PPM, maximum	
10. FILTER EMPLOYED *(X one)* ☒ a. YES ☐ b. NO	
11. SPREAD SPECTRUM *(X one)* ☐ a. YES ☒ b. NO	12. EMISSION BANDWIDTH *(X and complete as applicable)* ☐ CALCULATED ☒ MEASURED
13. MAXIMUM BIT RATE 14 Mbps for PCM/FM	a. -3 dB xxx MHz b. -20 dB xxx MHz
14. MODULATION TECHNIQUES AND CODING	c. -40 dB xxx MHz d. -60 dB xxx MHz e. OC-BW xxx MHz
	15. MAXIMUM MODULATION FREQUENCY See block 24.
16. PRE-EMPHASIS *(X one)* ☐ a. YES ☒ b. NO	17. DEVIATION RATIO 0.7 for PCM/FM. 0.5 for SOQPSK
	18. PULSE CHARACTERISTICS
19. POWER	a. RATE NA
a. MEAN xxx W	b. WIDTH NA
b. PEP NA	c. RISE TIME NA
20. OUTPUT DEVICE Transistor, operated in class C	d. FALL TIME NA e. COMP RATIO NA
	21. HARMONIC LEVEL

DD1494 Calculator

	A	B	C	D	E	F	G	I
1	User bit rate (Mbps)	STC	LDPC	OTA bit rate (Mbps)			Data entry in Yellow cells	
2	10	No	None	10				
3		1	1					
4								
5								
6	OTA bit rate (Mbps)	-3 dB	-20 dB	-40 dB	-60 dB	Necessary BW (or Occupied BW)	Emission Designator	
7	10	3.50	9.30	14.30	19.90	7.80	7M80G1DDN	
8								
9	OTA bit rate (Mbps)	-3 dB	-20 dB	-40 dB	-60 dB	Necessary BW (or Occupied BW)	Emission Designator	
10	0.1	0.04	0.09	0.14	0.20	0.08	078KG1DDN	
11	0.2	0.07	0.19	0.29	0.40	0.16	156KG1DDN	
12	0.3	0.11	0.28	0.43	0.60	0.23	234KG1DDN	
13	0.4	0.14	0.37	0.57	0.80	0.31	312KG1DDN	
14	0.5	0.18	0.47	0.72	1.00	0.39	390KG1DDN	
15	0.6	0.21	0.56	0.86	1.19	0.47	468KG1DDN	
16	0.7	0.25	0.65	1.00	1.39	0.55	546KG1DDN	
17	0.8	0.28	0.74	1.14	1.59	0.62	624KG1DDN	
18	0.9	0.32	0.84	1.29	1.79	0.70	702KG1DDN	
19	1	0.35	0.93	1.43	1.99	0.78	780KG1DDN	
20	1.1	0.39	1.02	1.57	2.19	0.86	858KG1DDN	
21	1.2	0.42	1.12	1.72	2.39	0.94	936KG1DDN	
22	1.3	0.46	1.21	1.86	2.59	1.01	1M01G1DDN	
23	1.4	0.49	1.30	2.00	2.79	1.09	1M09G1DDN	
24	1.5	0.53	1.40	2.15	2.99	1.17	1M17G1DDN	
25	1.7	0.60	1.58	2.43	3.38	1.33	1M33G1DDN	
26	1.9	0.67	1.77	2.72	3.78	1.48	1M48G1DDN	
27	2.1	0.74	1.95	3.00	4.18	1.64	1M64G1DDN	

PCMFM | SOQPSK-TG | ARTM CPM | +

DD1494 Guides

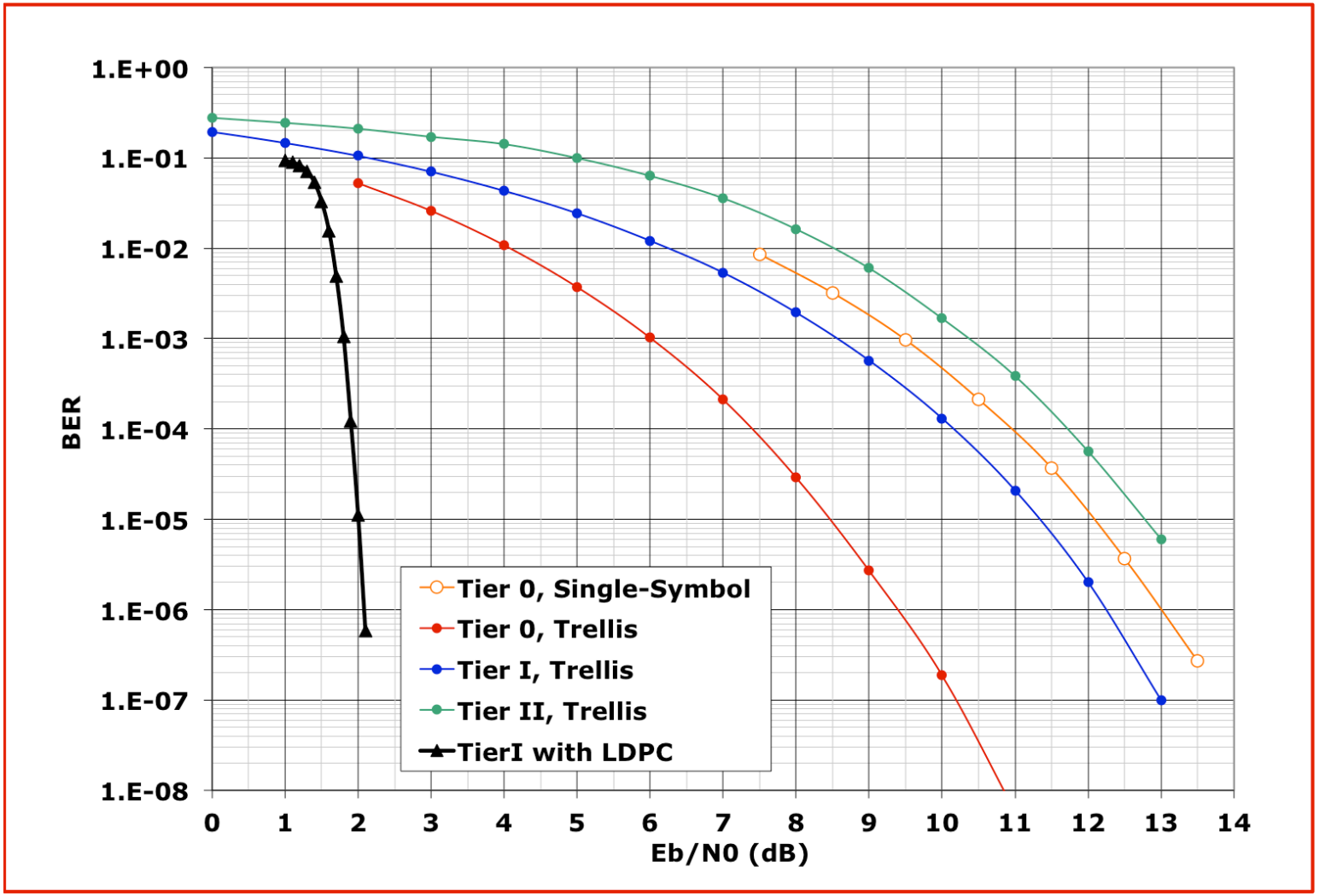
- https://www.trmc.osd.mil/wiki/display/publicRCC/120+Telemetry+%28TM%29+Radio+Frequency+%28RF%29+Handbook?preview=%2F113019785%2F122454132%2FWP-21-001.pdf&searchId=TDBZHC61S

- https://www.trmc.osd.mil/wiki/display/publicRCC/120+Telemetry+%28TM%29+Radio+Frequency+%28RF%29+Handbook?preview=%2F113019785%2F122454133%2F120-21_TM_RF_Handbook.pdf&searchId=C38AVRKXB

Information Fidelity

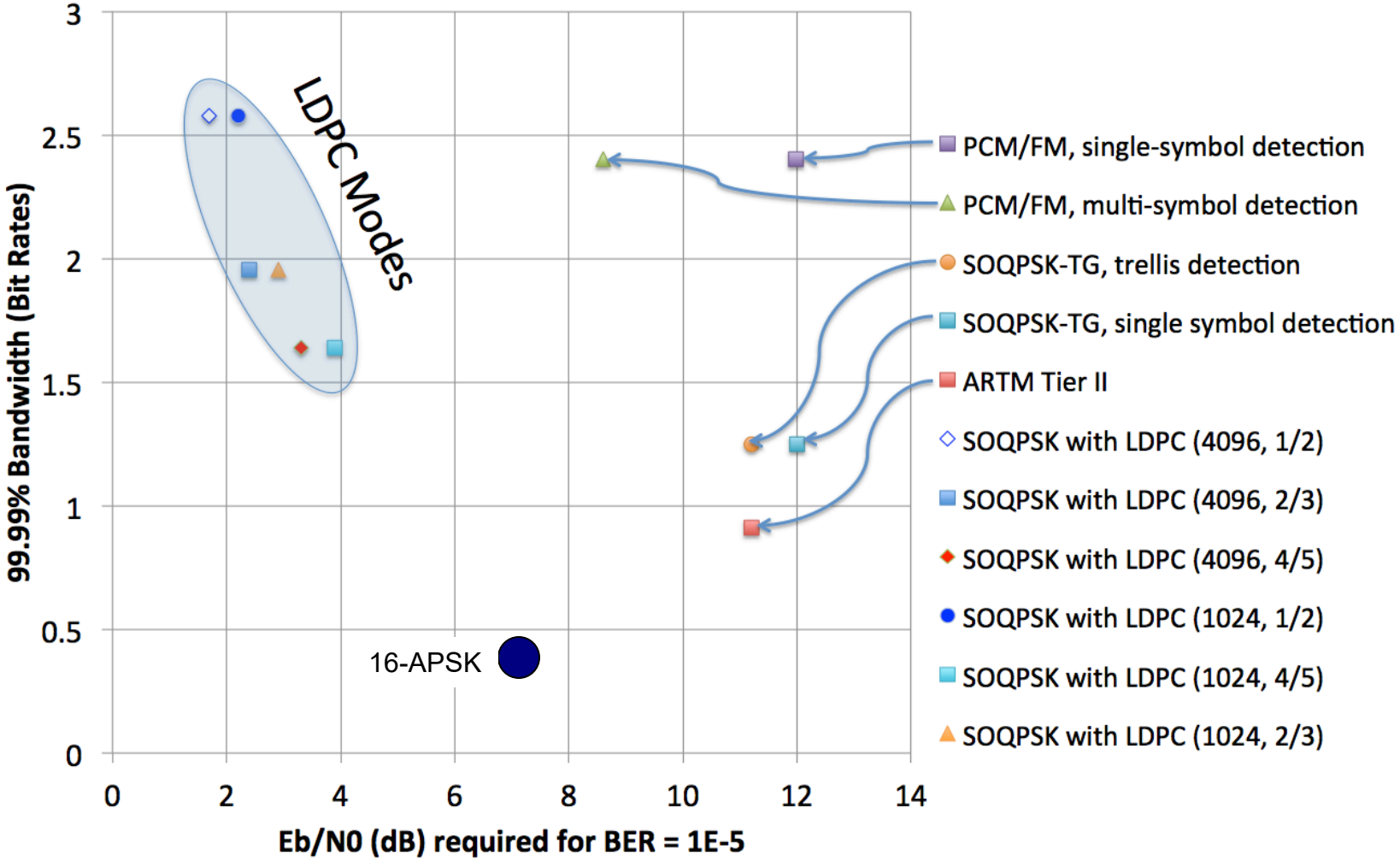
- Additive White Gaussian Noise (AWGN) channels
  - Bit Error Probability (BEP) or Bit Error Rate (BER)
- Bursty (dropout) channels
  - Cumulative error count
  - Link Availability
    - Percent of the 1-second intervals that the BER is less than 10^{-5}
- Data Quality Metric (DQM)
  - Come back after lunch!

BER Performance Comparison



Terry Hill - thill@quasonix.com

Today's Modulation Tour



Terry Hill - thill@quasonix.com

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Continuous Phase Modulation

The Modulation Universe

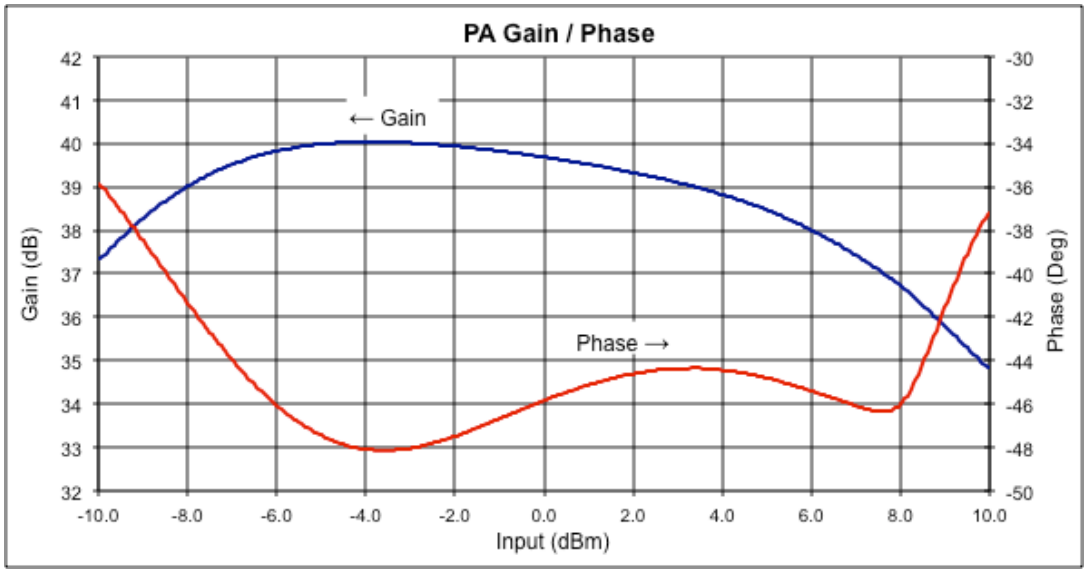
- Analog, Digital
- Amplitude modulation
- Quadrature amplitude modulation
- Angle modulations
  - Frequency modulation
  - Phase modulation
- Amplitude/Phase Shift Keying (APSK)

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 constant envelope waveforms

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

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

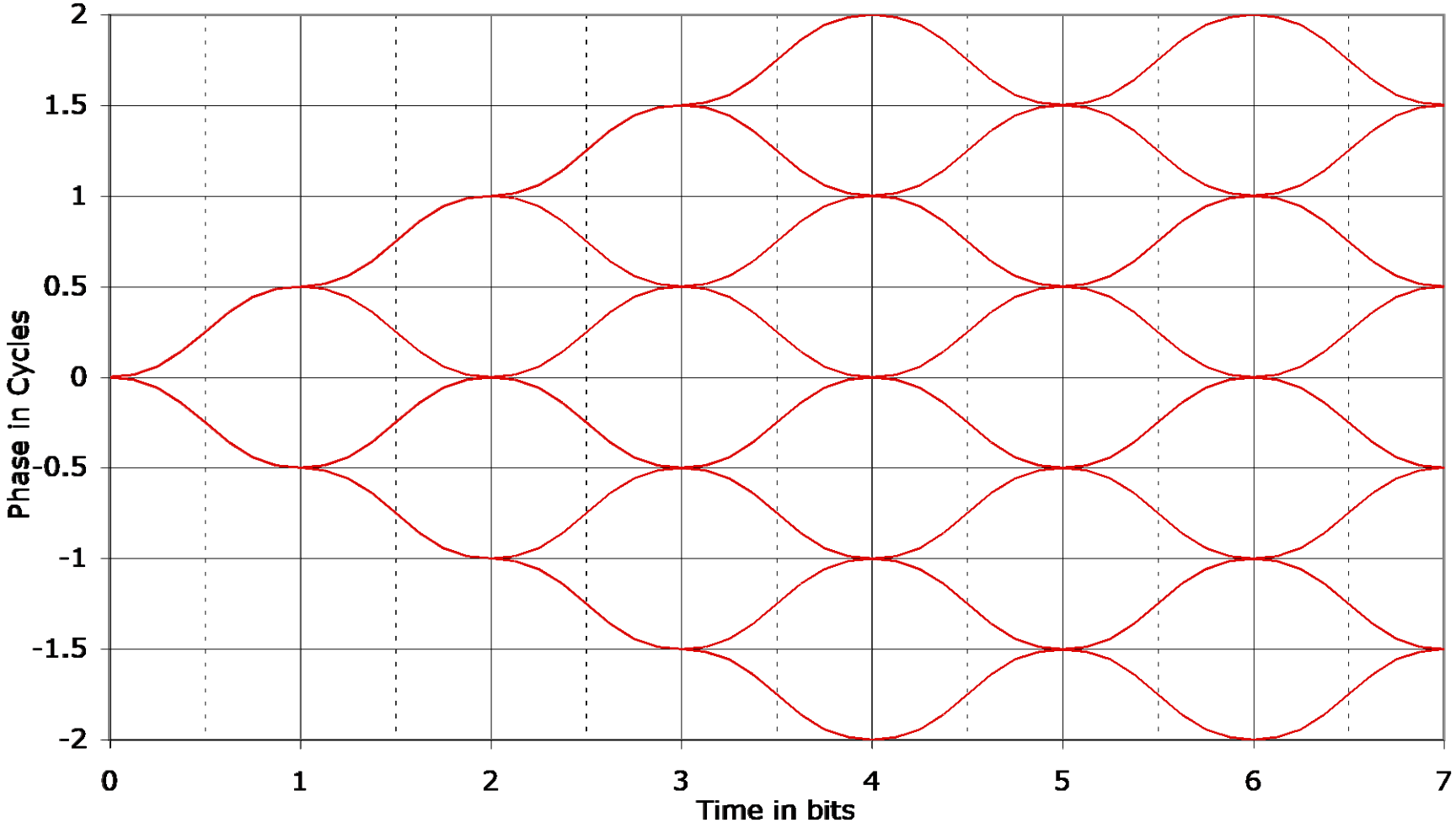
$$\phi(t,\overline{\alpha}) = 2\pi h \int_{-\infty}^{t} \sum_{i=-\infty}^{+\infty} \alpha_i g(\tau - iT) d\tau \quad -\infty < t < +\infty$$

- 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.

CPM Characteristics

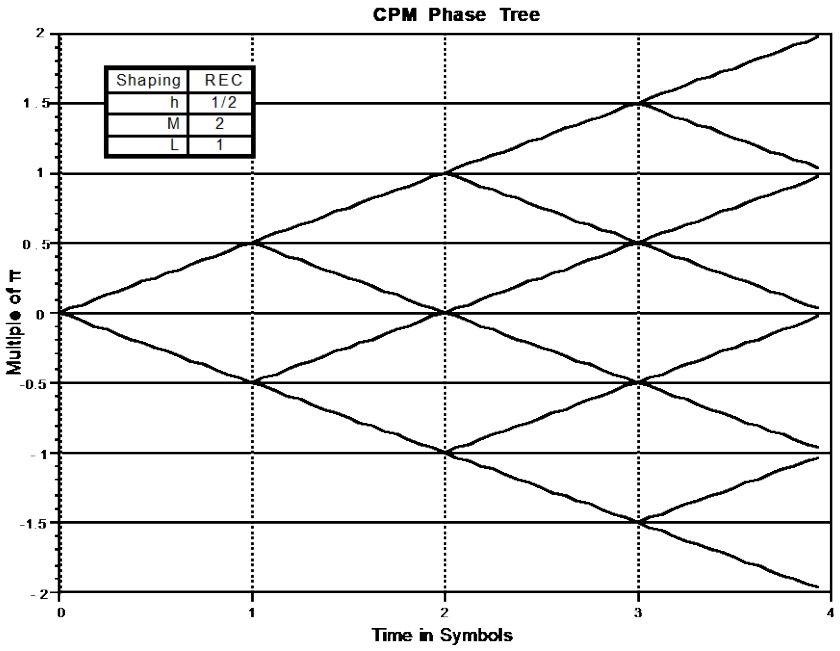
- Continuous Phase
- Constant envelope
- Signals are described by their phase trajectories
  - Phase tree representation is complete
- PSD and BER can be “traded” by
  - Varying h, modulation index
  - Changing g(t), the frequency pulse shape
- Phase trellis decoder is optimum for any variant of CPM

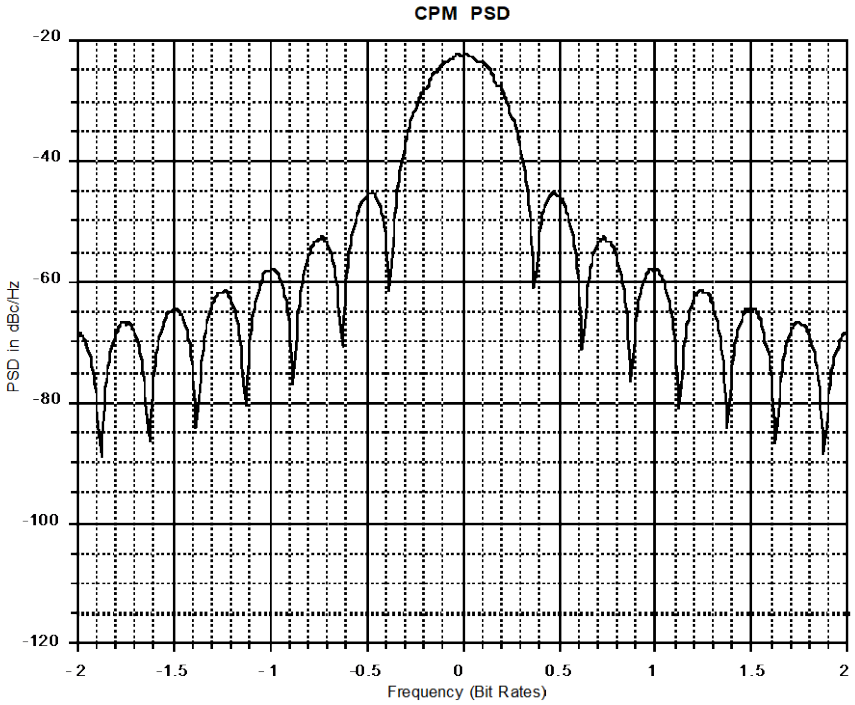
Phase Tree Representation



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

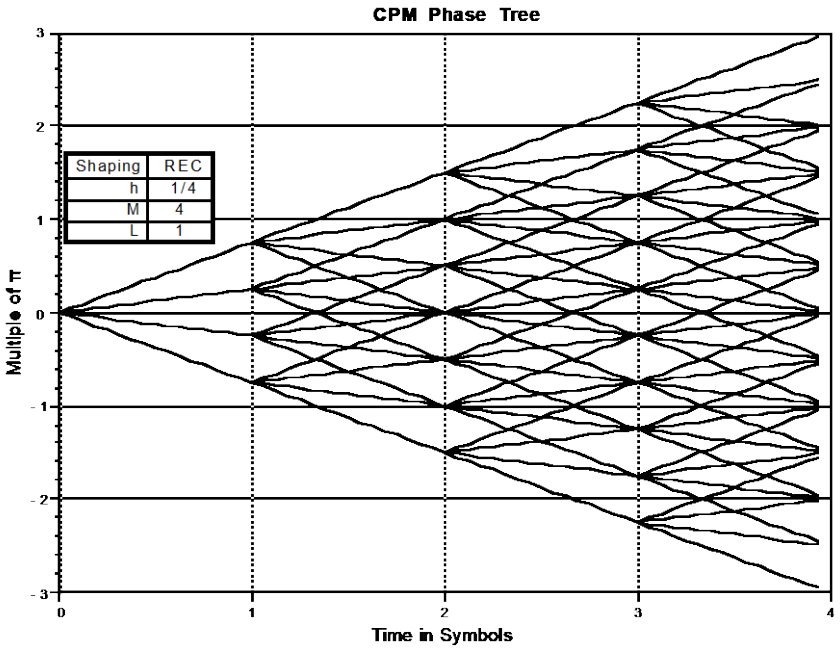
PSD vertical axis is dBc per FFT bin
1 FFT bin = 1/64 * symbol rate

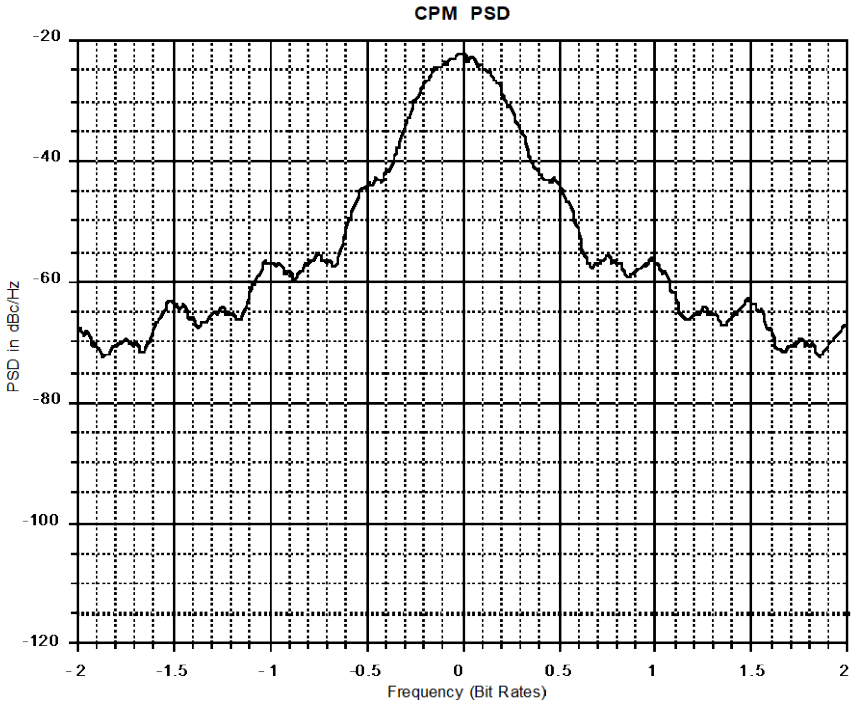




M=4, h=1/4, 1REC

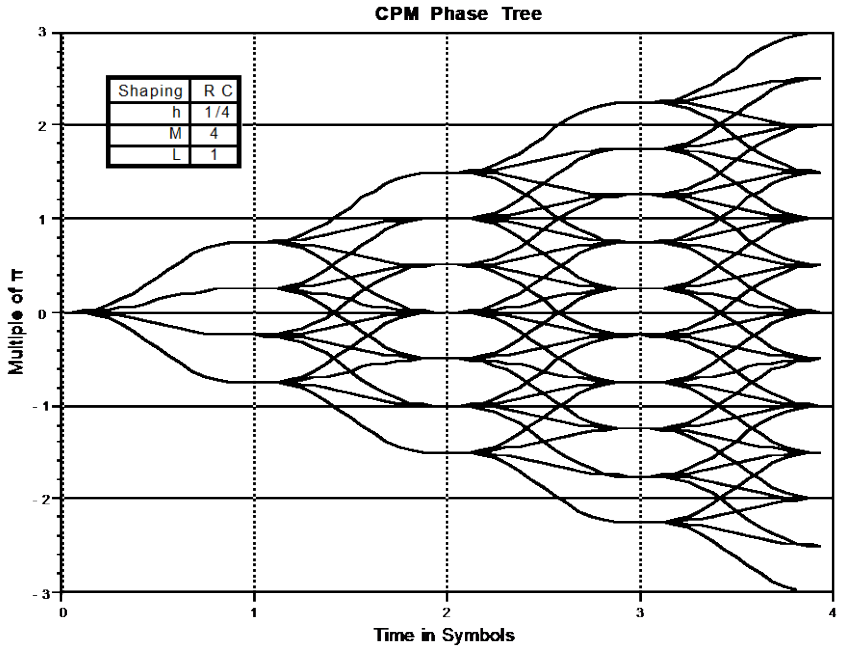
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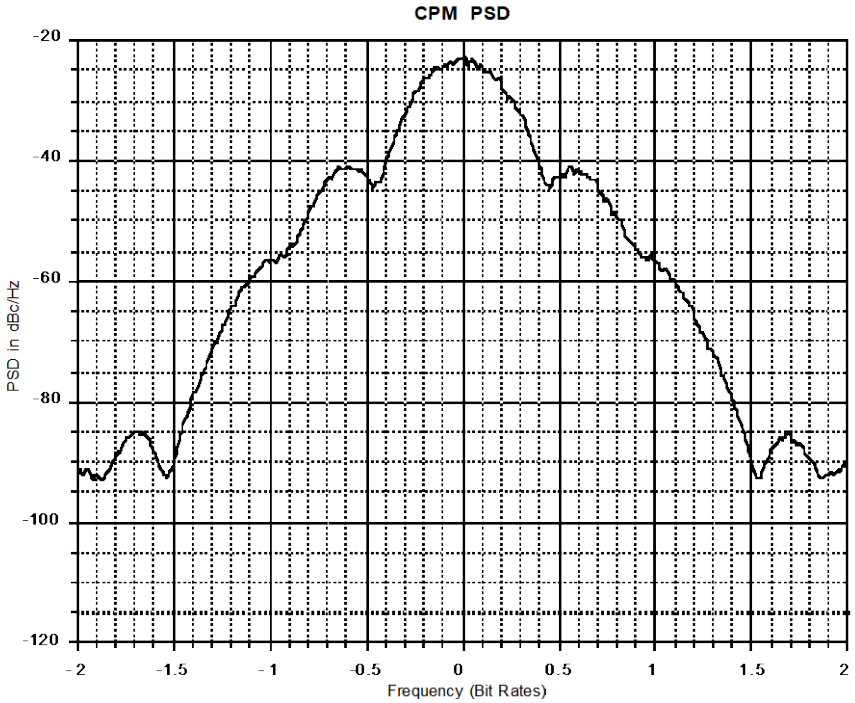




M=4, h=1/4, 1RC

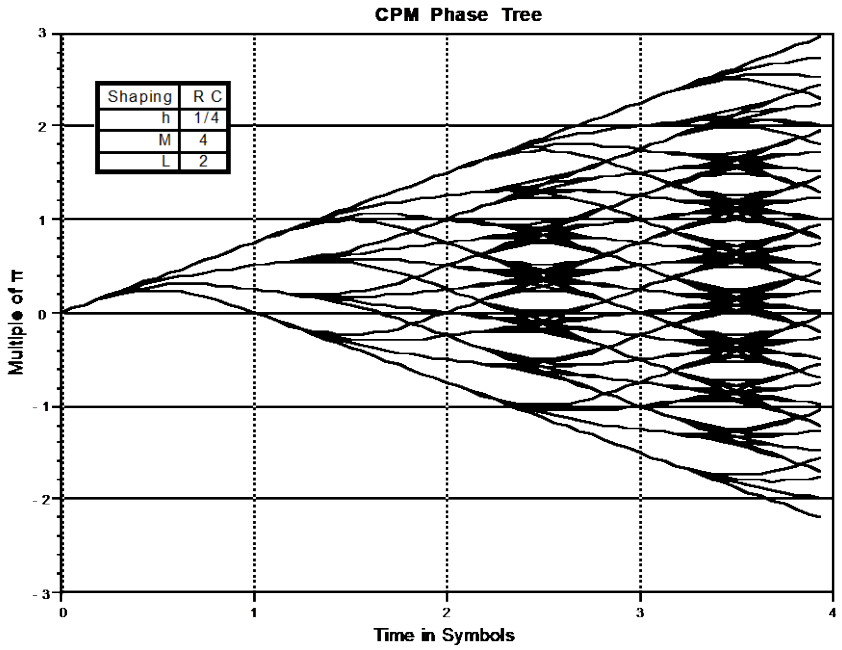
PSD vertical axis is dBc per FFT bin
1 FFT bin = 1/64 * symbol rate

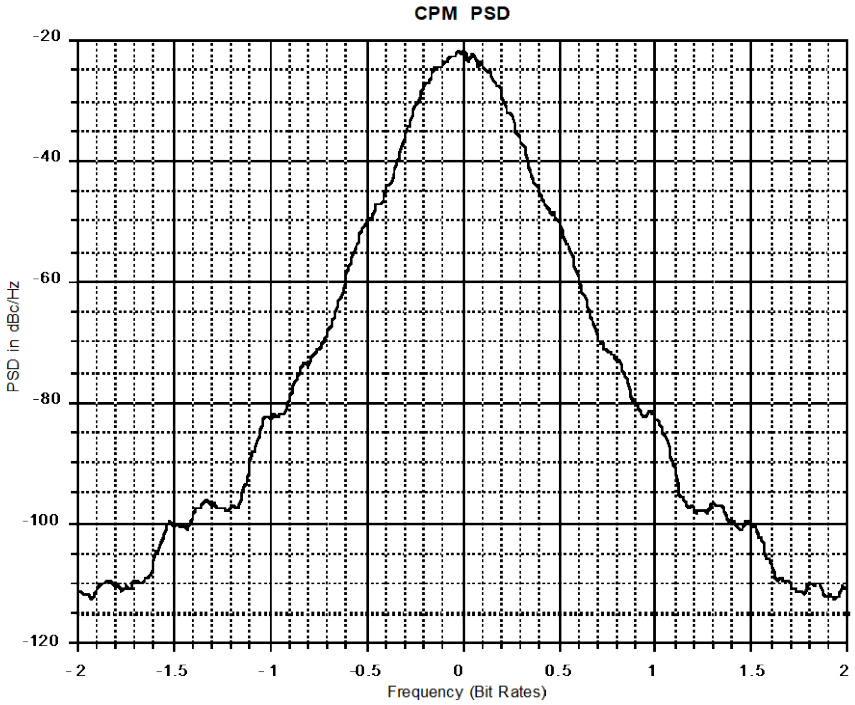




M=4, h=1/4, 2RC

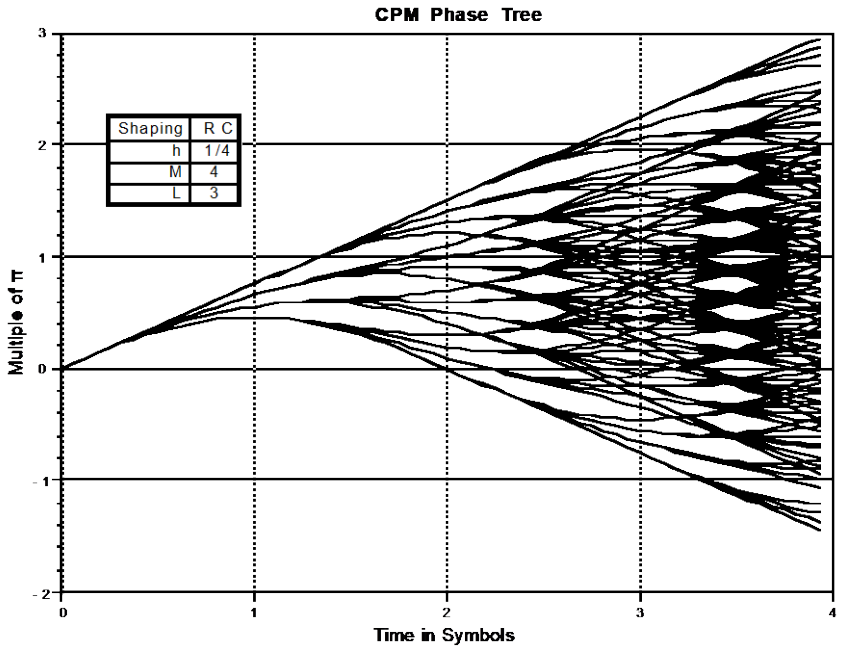
PSD vertical axis is dBc per FFT bin
1 FFT bin = 1/64 * symbol rate

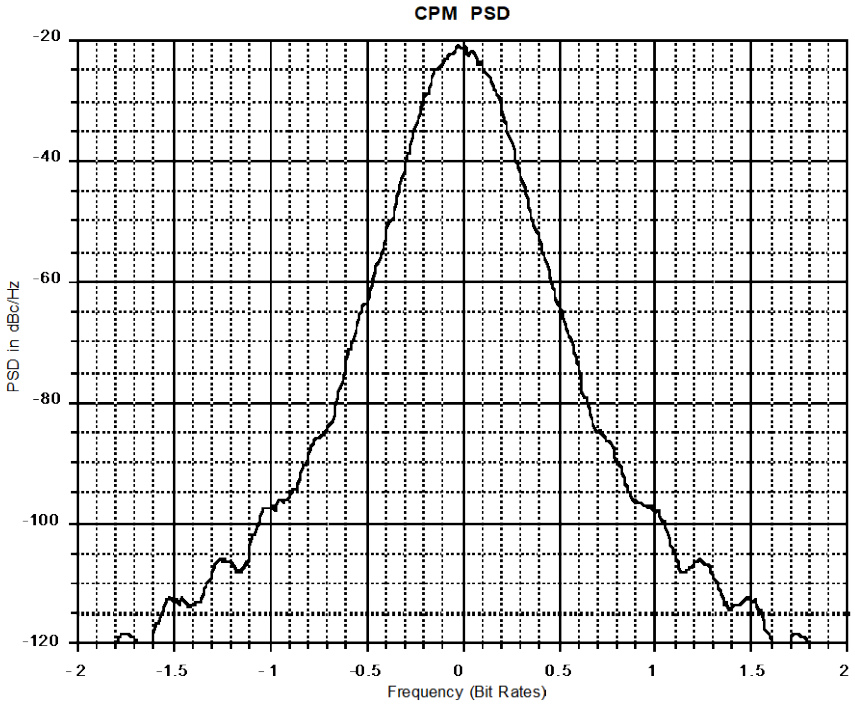




M=4, h=1/4, 3RC

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



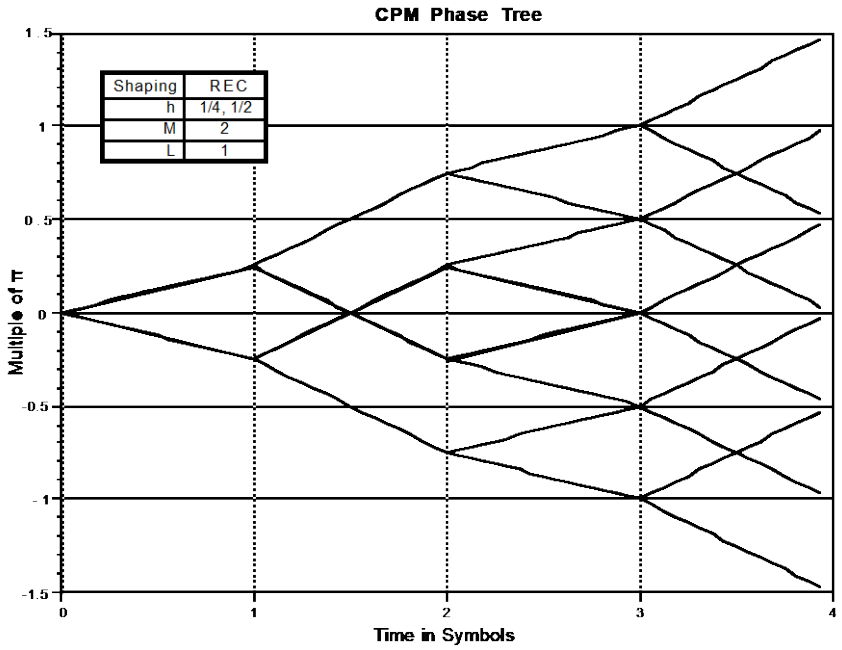


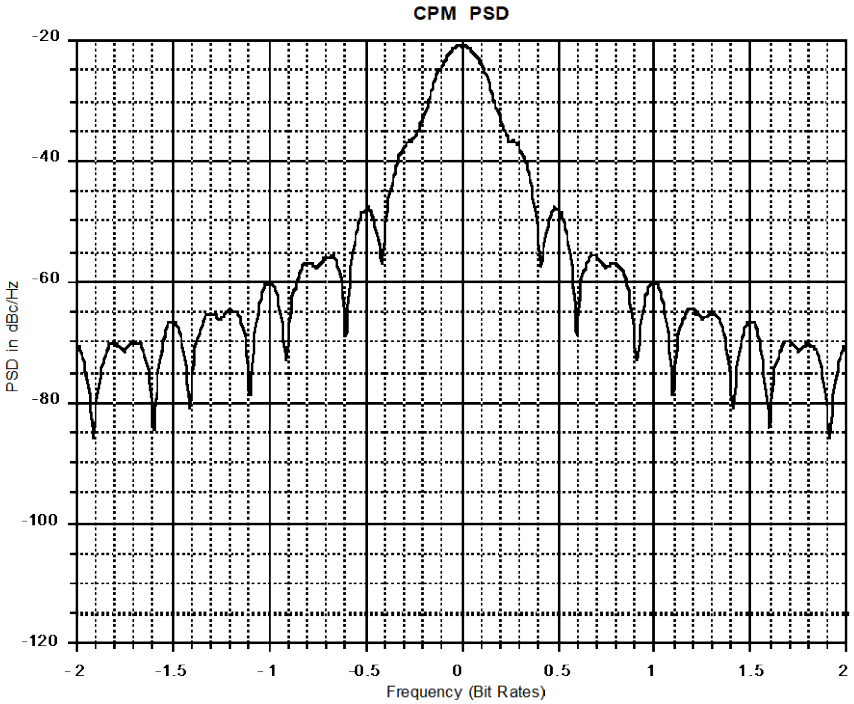
Multi-h CPM

- 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

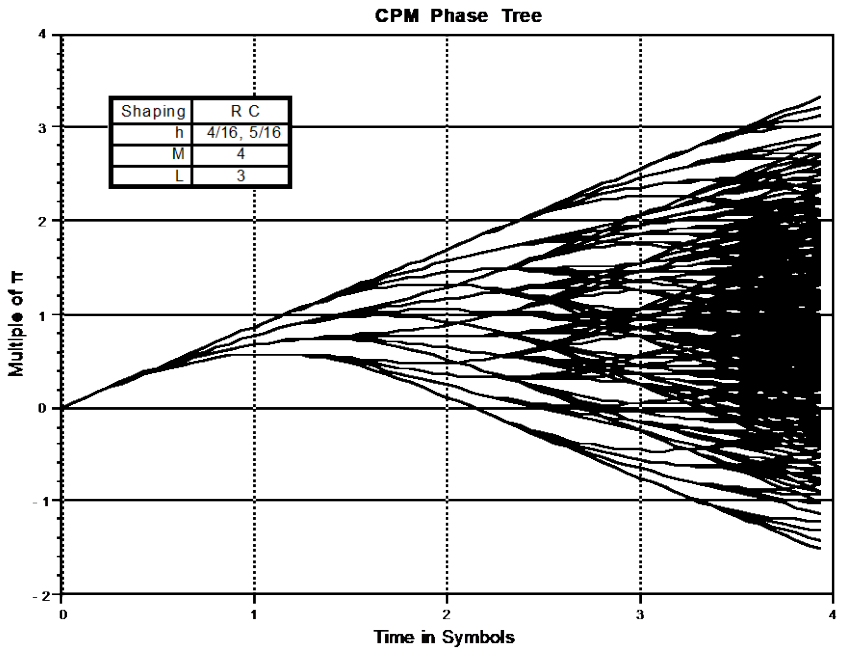


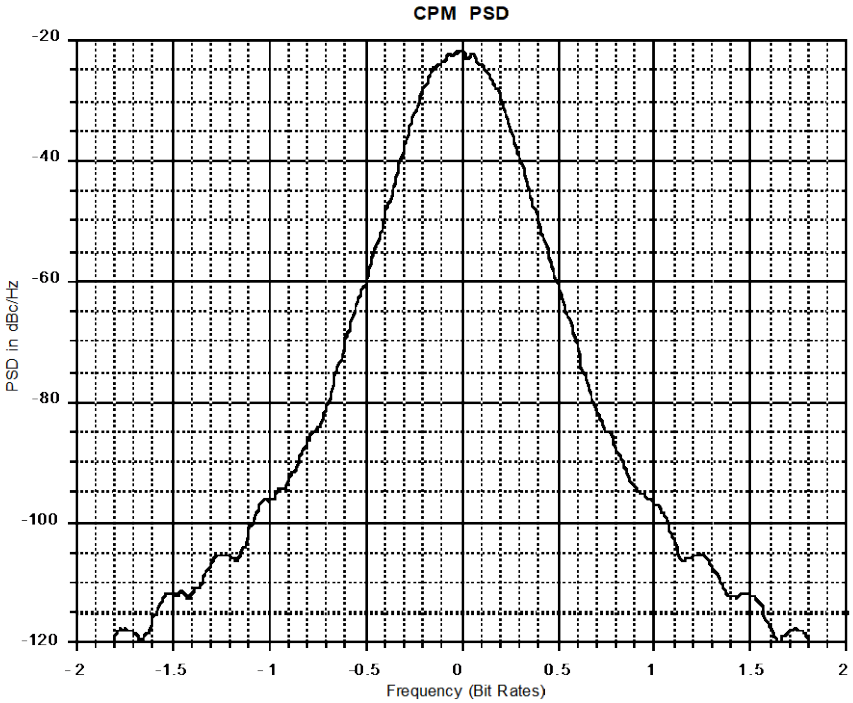


M=4, h_1=4/16, h_2=5/16, 3RC

ARTM Tier II Waveform

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





CPM Summary

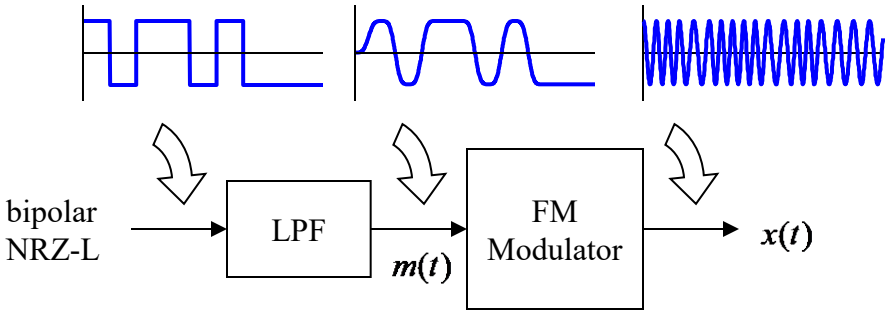
- To reduce bandwidth of a CPM signal, the phase transitions must be smoothed by:
  - Requiring phase to have more continuous derivatives
  - Spreading the phase change over more intervals (i.e., L > 1)
  - Reducing h
- The shape of g(t) determines the smoothness of the information-carrying phase
- An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

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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.

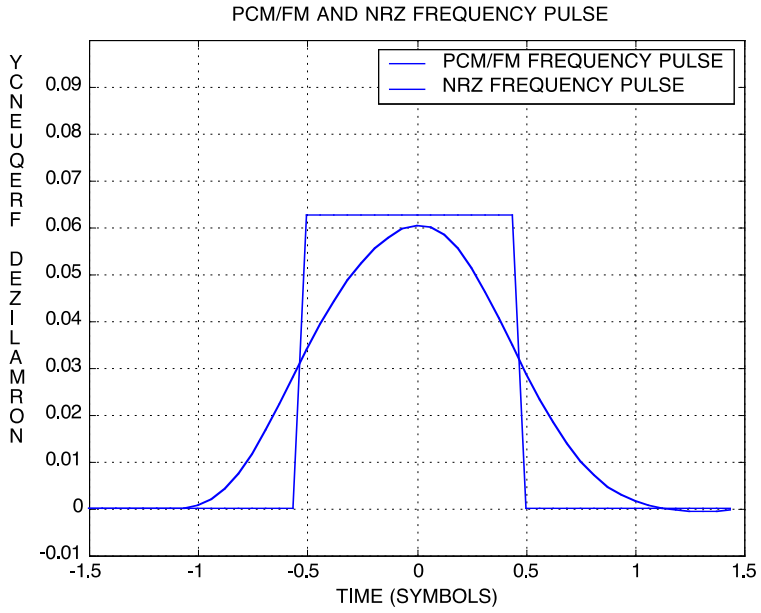
Tier 0 in CPM Notation

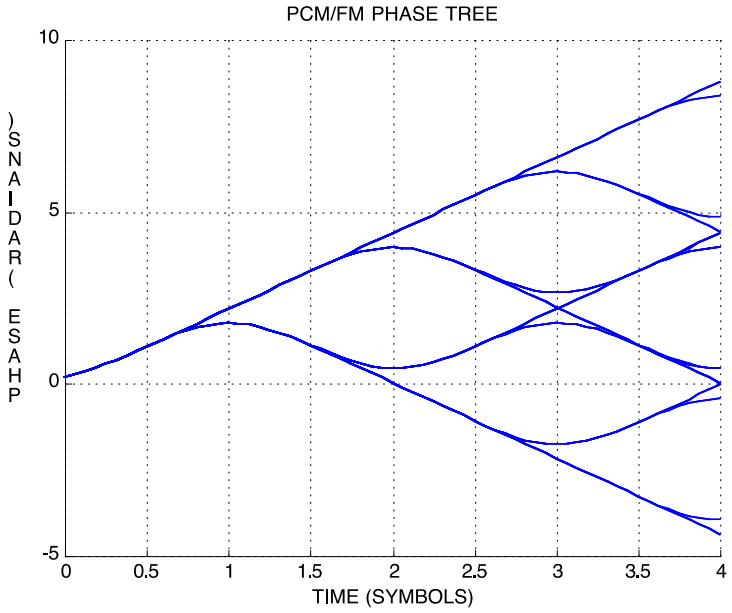
$$s(t) = \sqrt{2E/T}\cos[2\pi f_o t + \phi(t,\overline{\alpha}) + \phi_o]$$

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

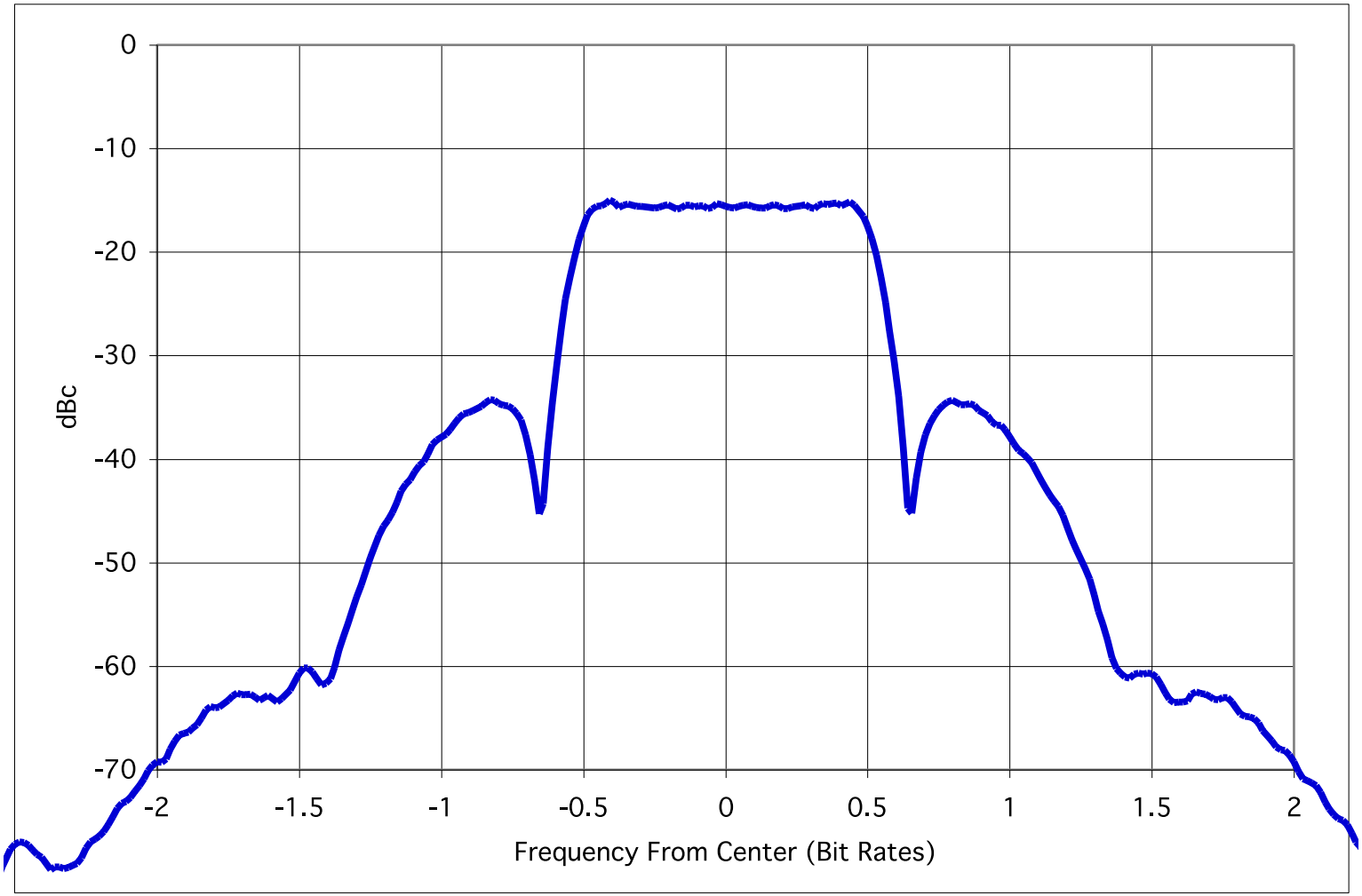
- M = 2 (binary)
- $\alpha_i = 2d_i - 1$
  - $d_i = \{0, 1\}$, $\alpha_i = \{-1, +1\}$
- h = 0.7
- g(t) is the normalized impulse response of a high order Bessel filter with 3 dB bandwidth = 0.7 * bit rate
  - Normalized such that the integral over all time = 1/2

PCM/FM as a Phase Modulation

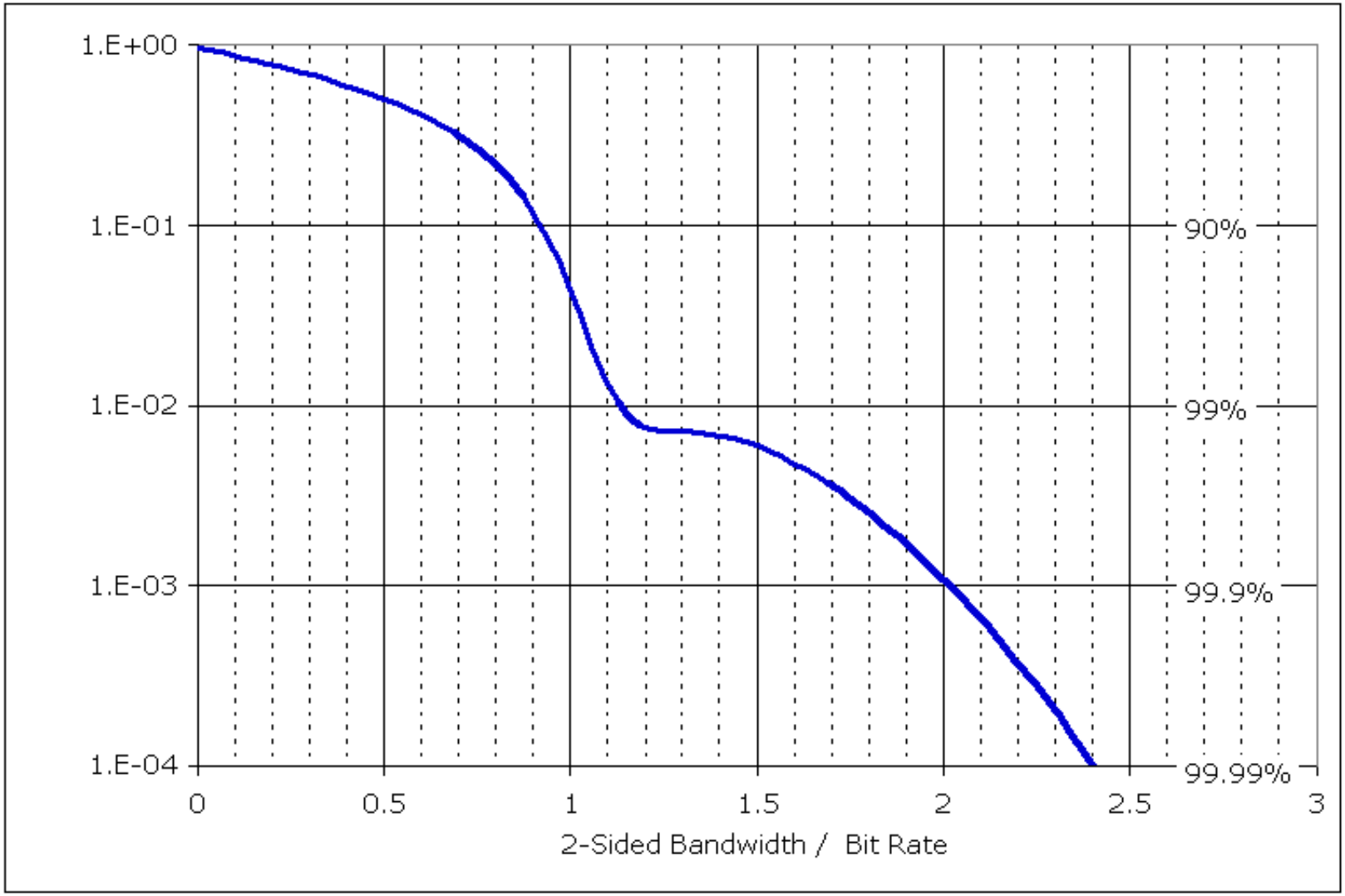




Power Spectral Density (PSD)



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

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

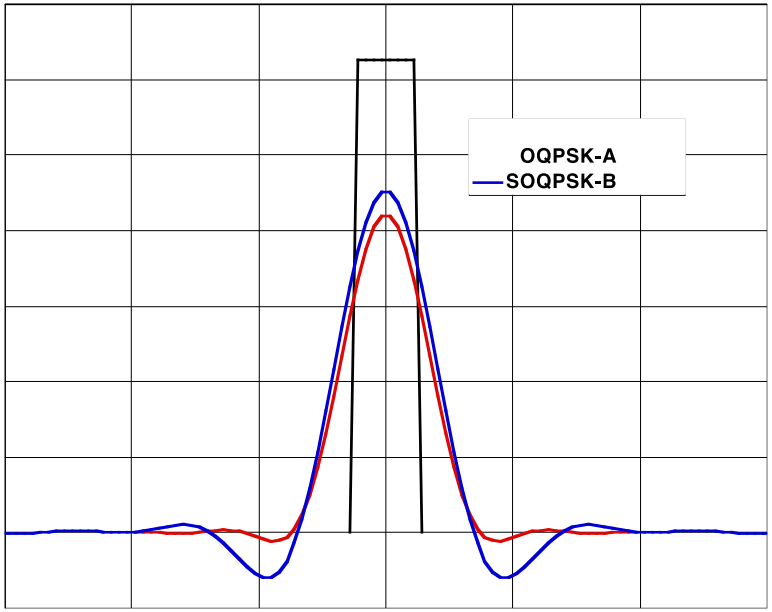
Definition of SOQPSK Pulse

$$g(t) = n(t) * w(t), \text{ where}$$

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

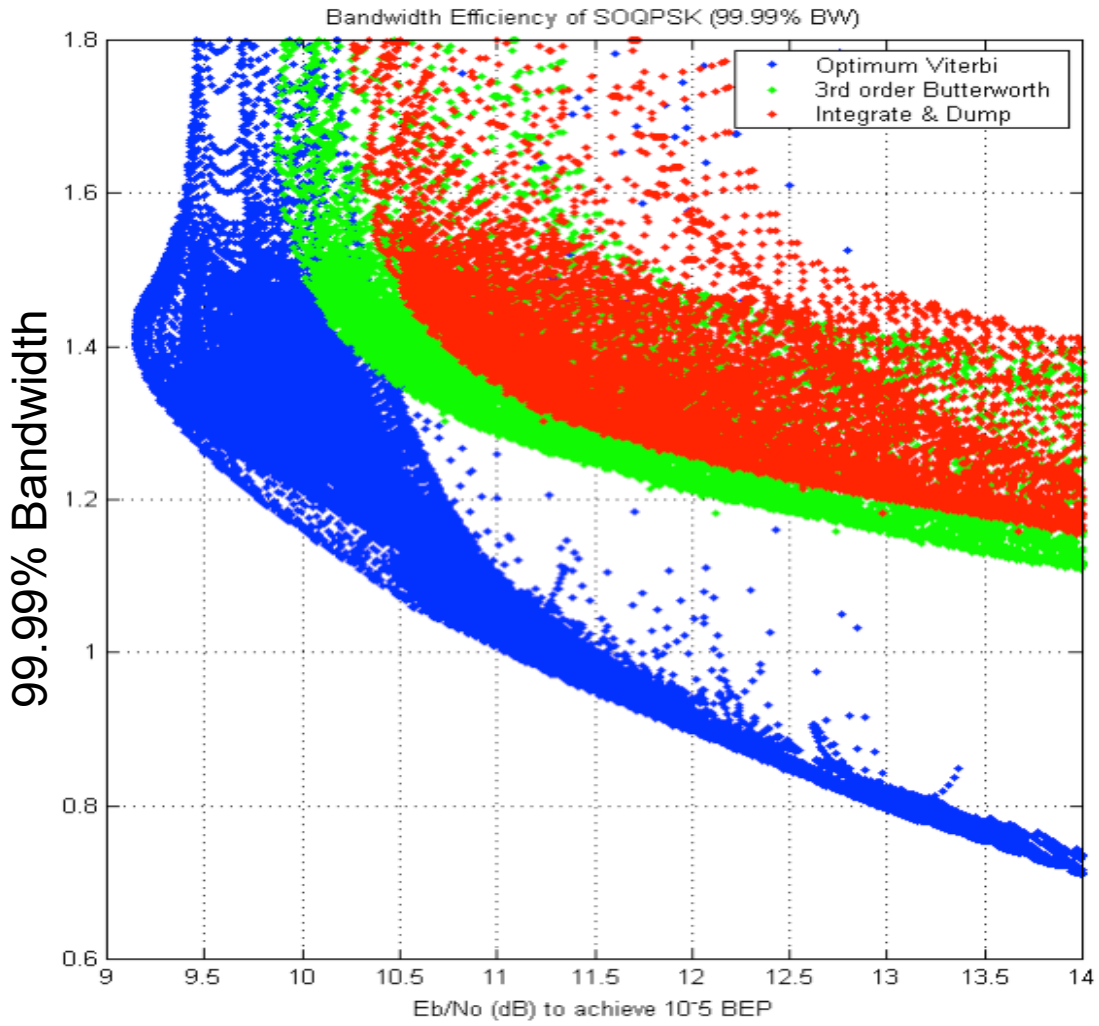
$$w(t) = \begin{cases} 1, & for \quad |t/T| < T_1 \\ \frac{1}{2} + \frac{1}{2}\cos\frac{\pi(|t/T| - T_1)}{T_2}, & for \quad T_1 < |t/T| < T_1 + T_2 \\ 0, & for \quad |t/T| > T_1 + T_2 \end{cases}$$

Frequency Pulse Shape, g(t)

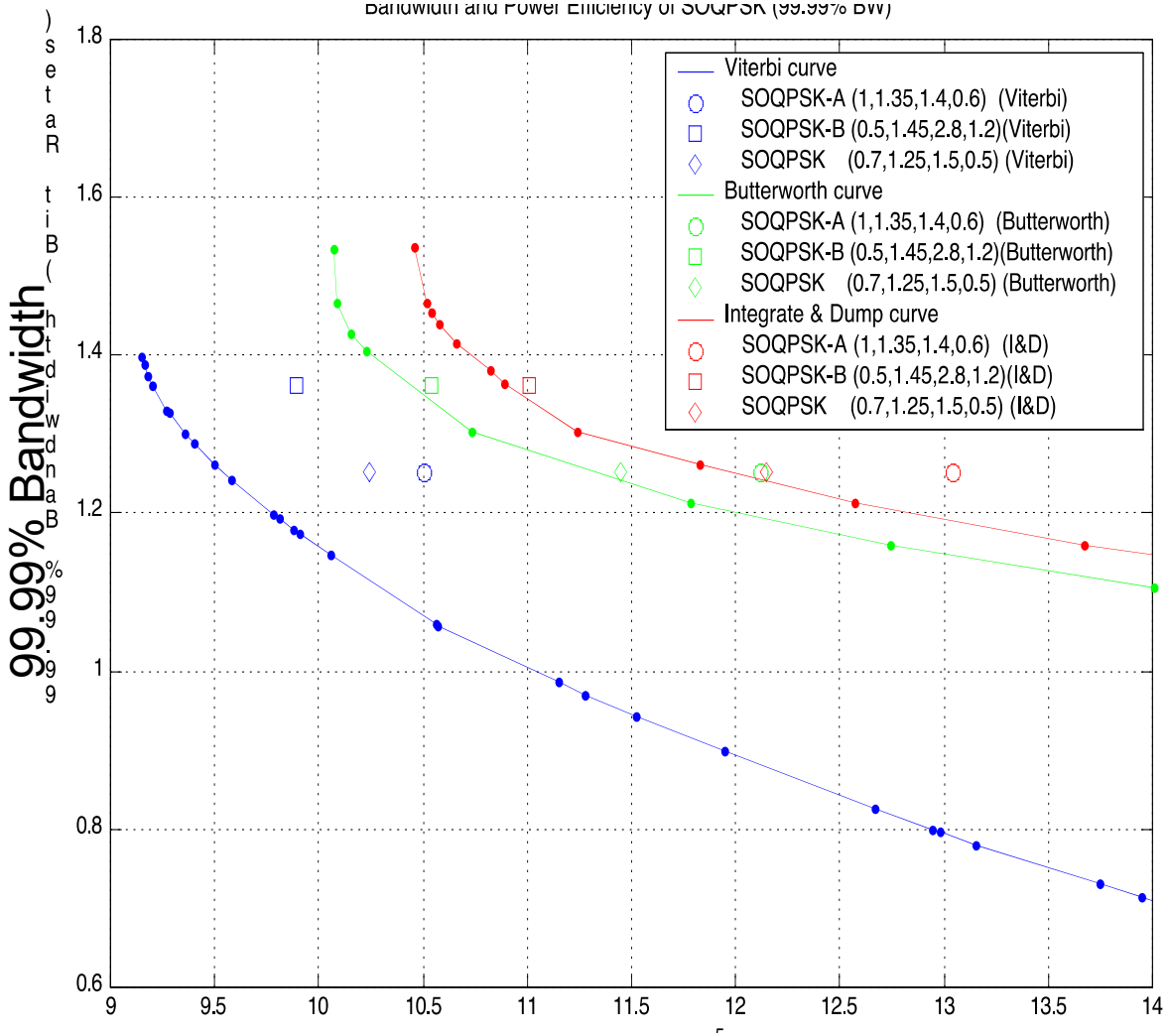


Parameter	SOQPSK-A	SOQPSK-B
ρ	1.0	0.5
B	1.35	1.45
T_1	1.4	2.8
T_2	0.6	1.2

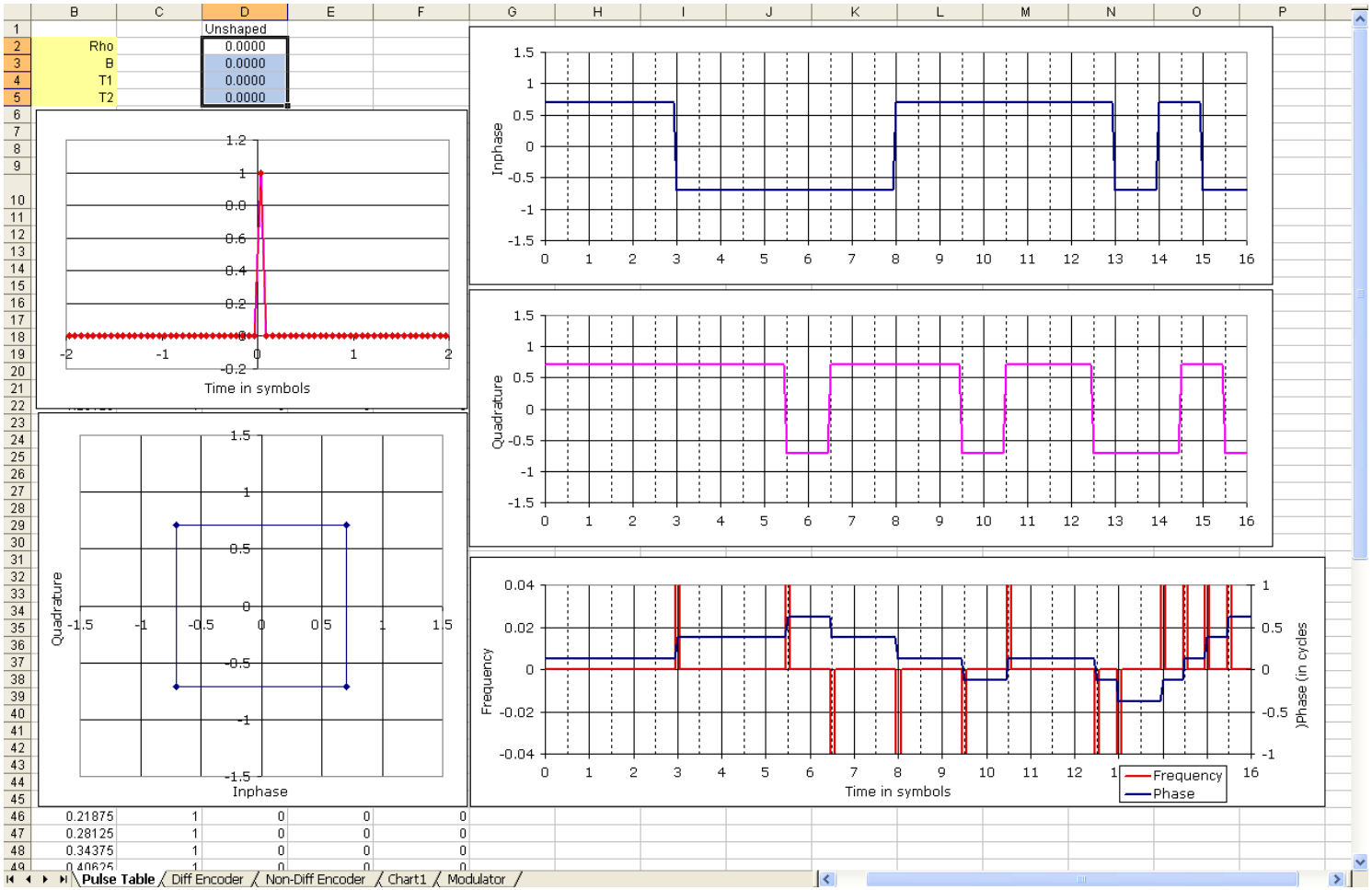
SOQPSK Variants



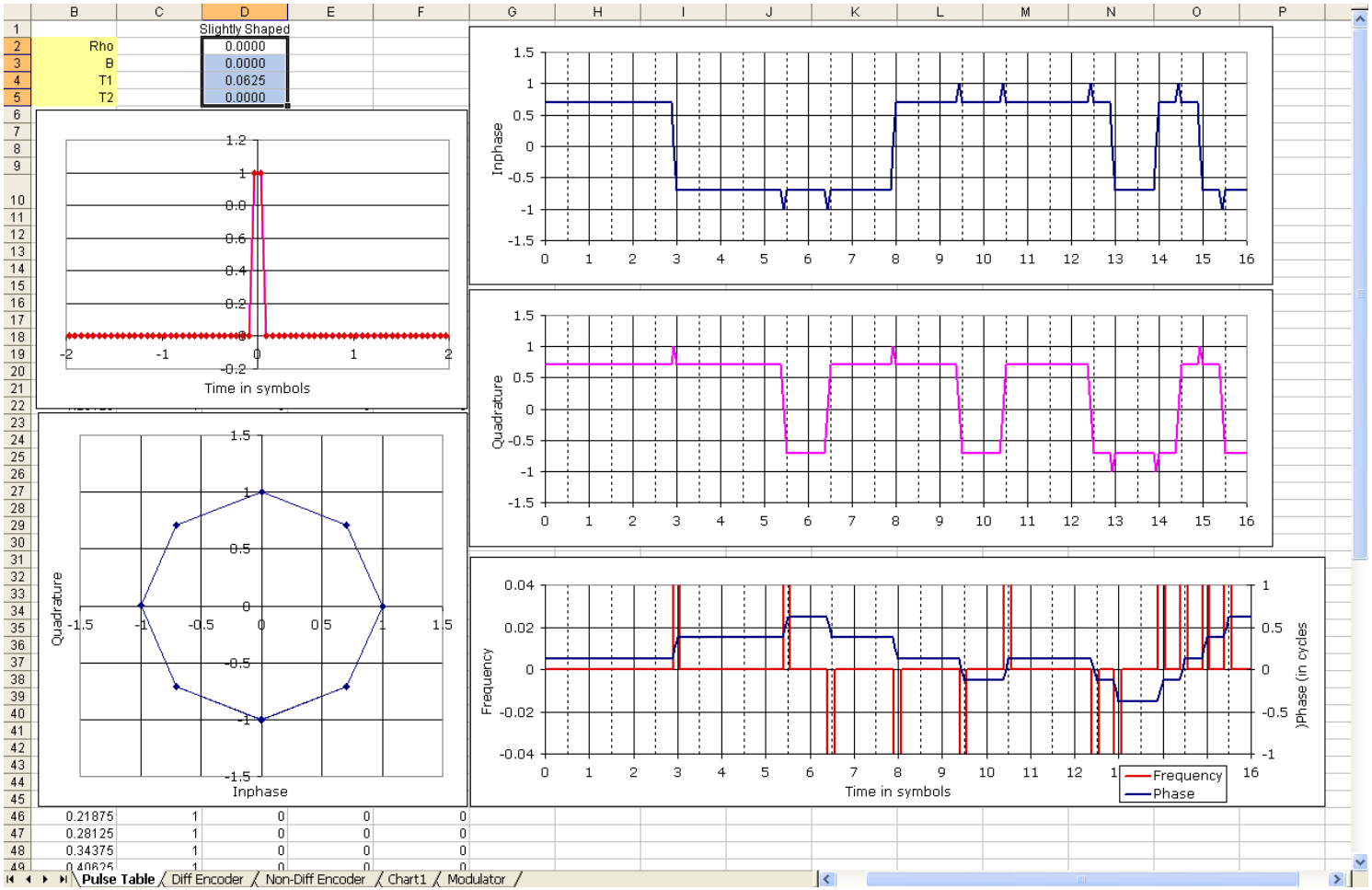
Optimal SOQPSK Variants



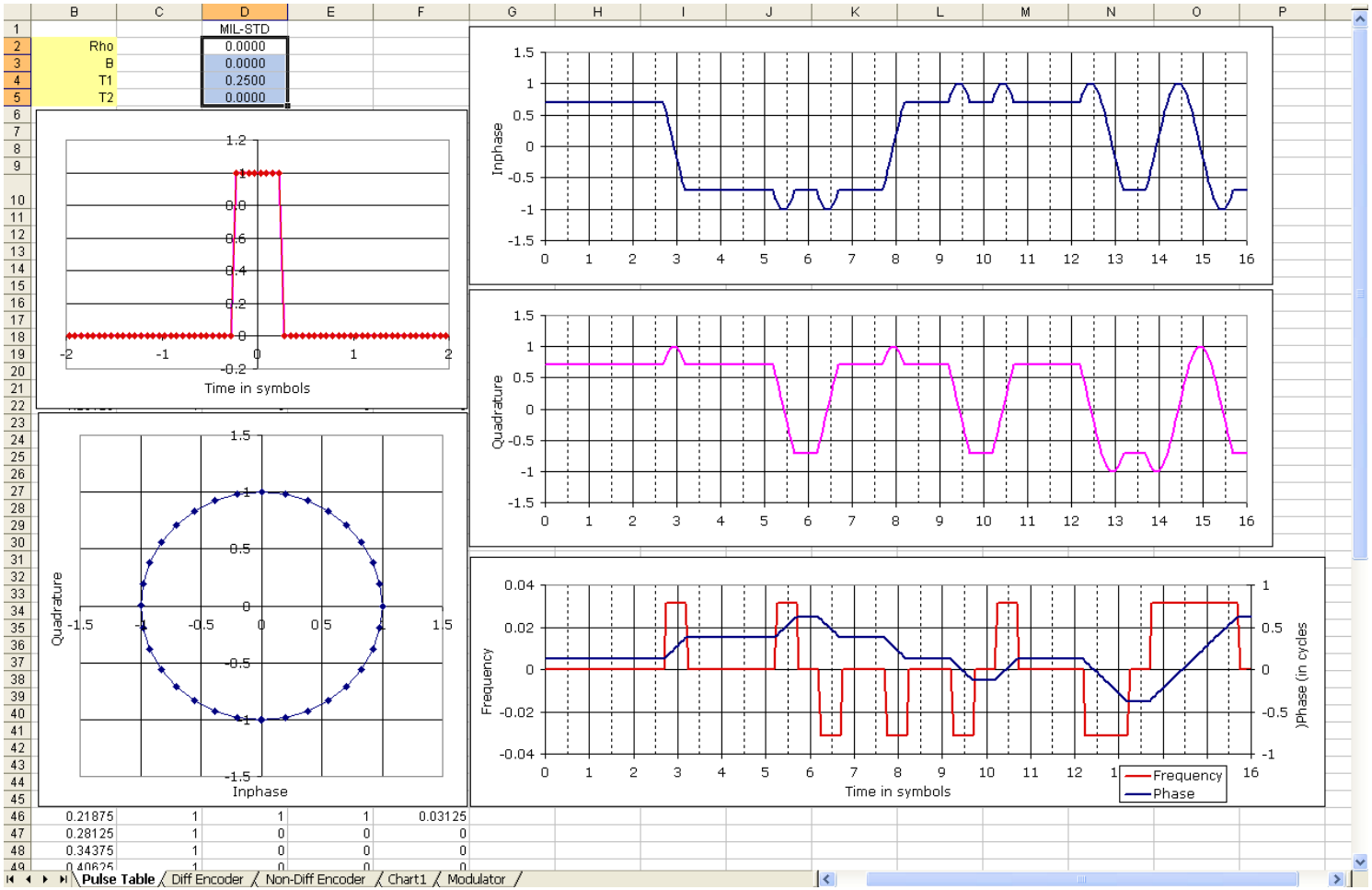
Unshaped Offset QPSK



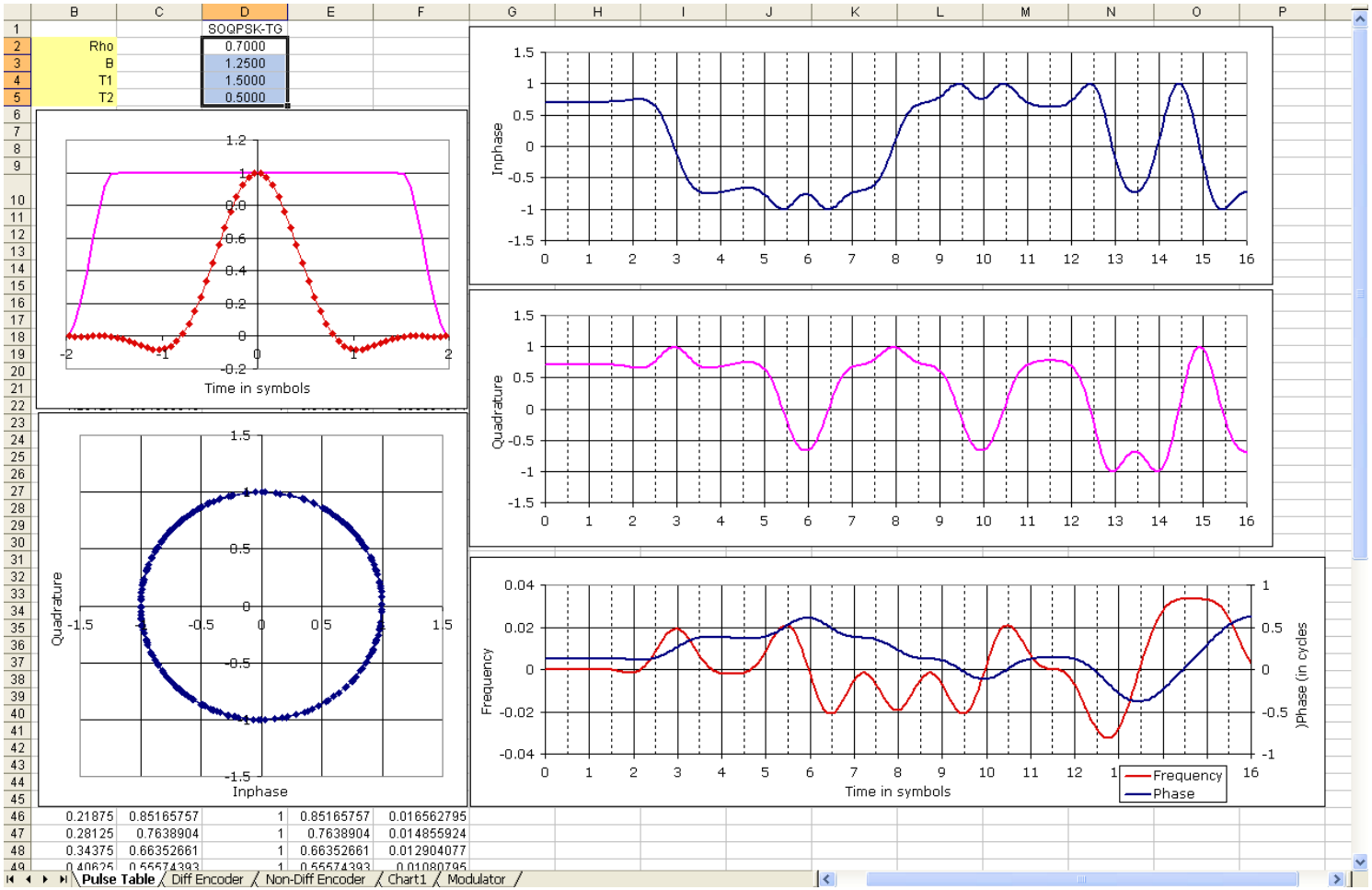
Slightly Shaped OQPSK



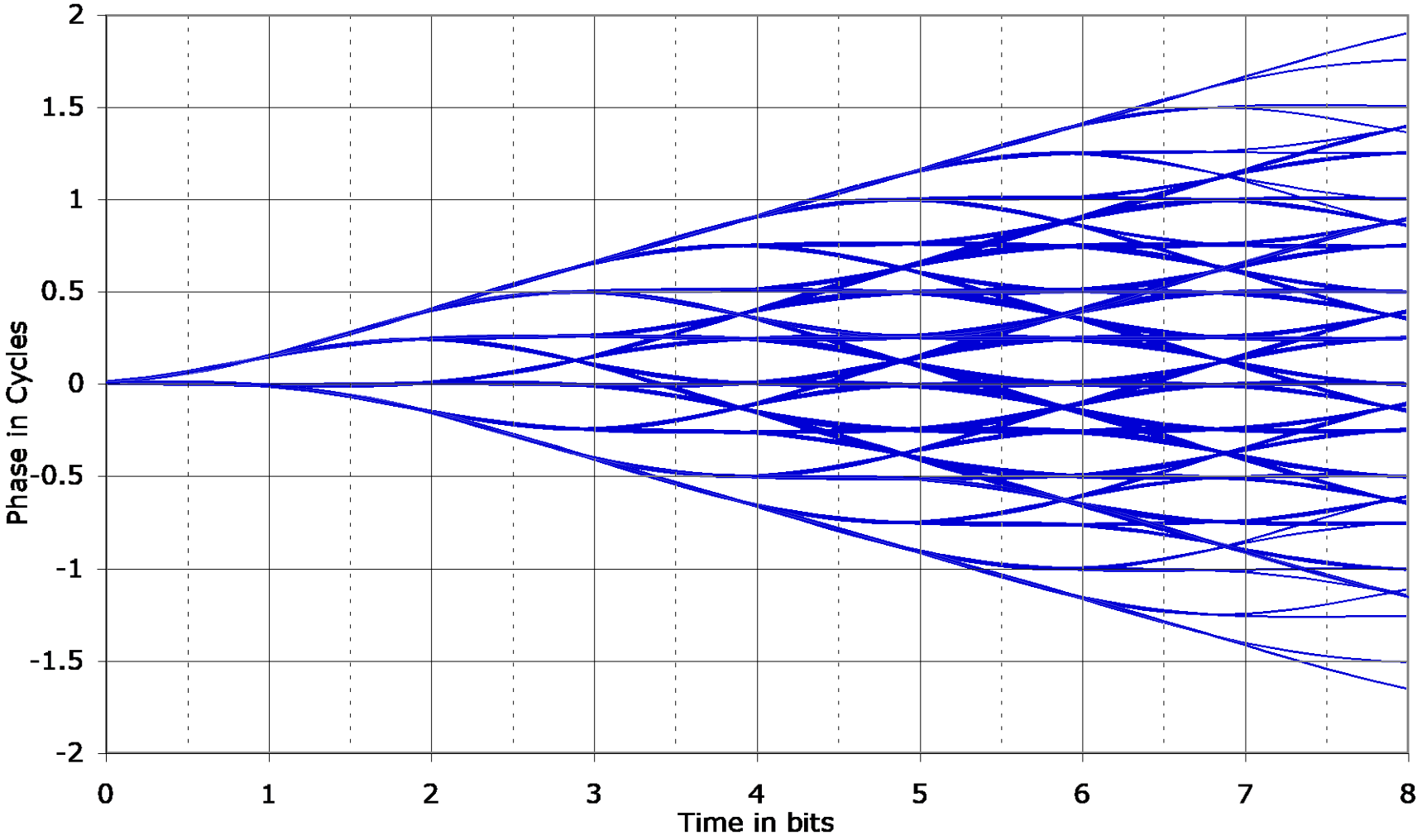
MIL-STD SOQSPK



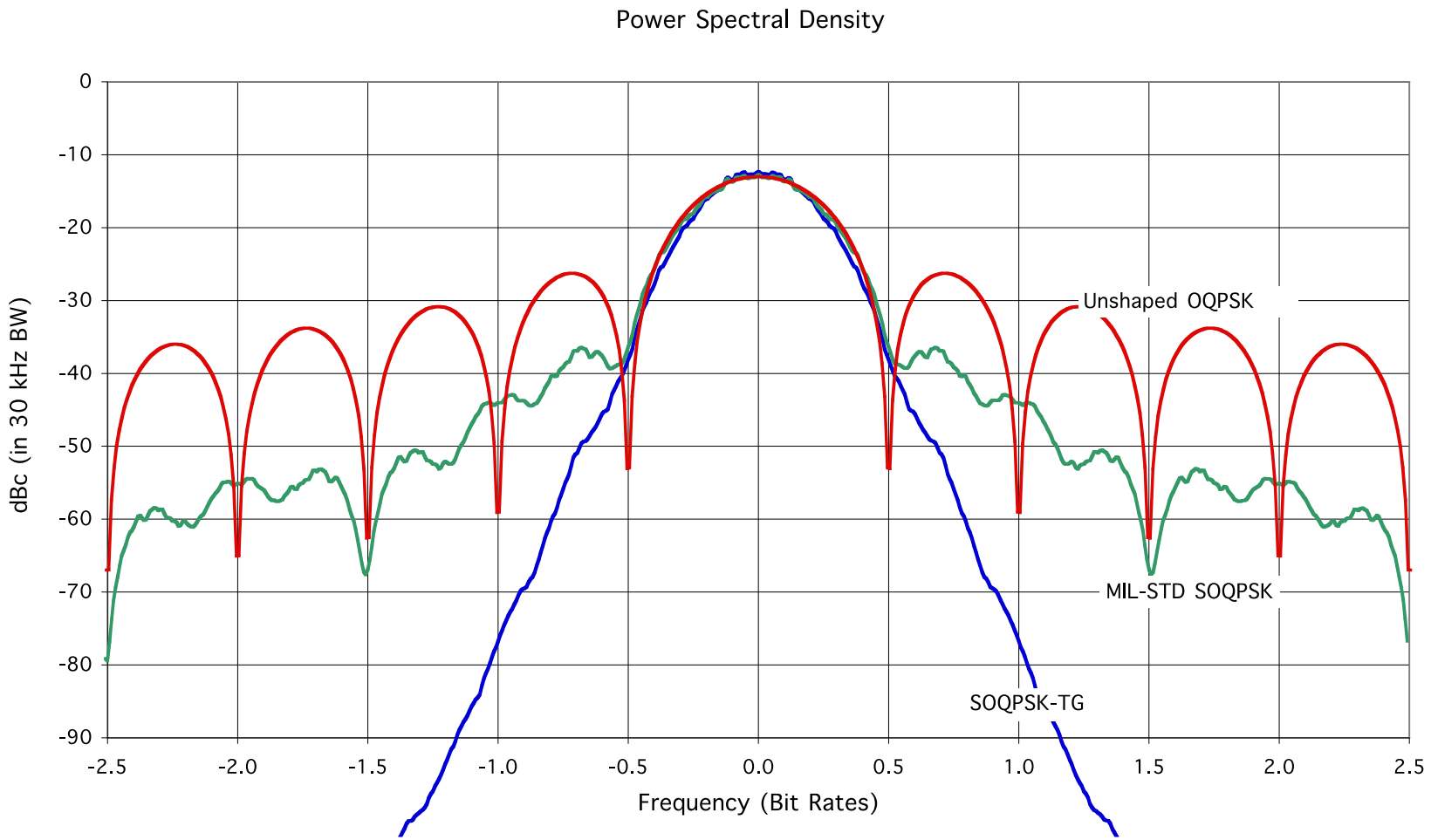
SOQPSK-TG


SOQPSK-TG
Rho 0.7000
B 1.2500
T1 1.5000
T2 0.5000
Time in symbols
Quadrature
Inphase
Inphase
Quadrature
Frequency
Phase (in cycles)
Time in symbols
Frequency
Phase
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

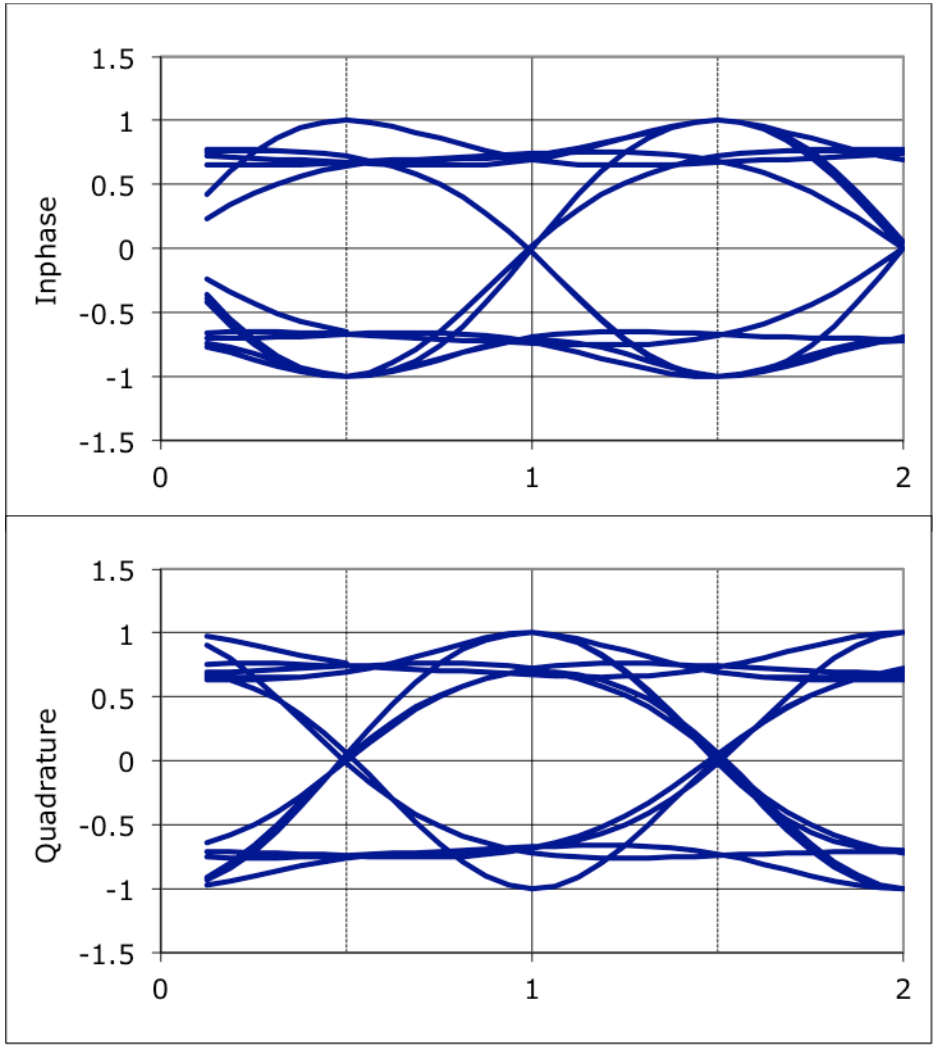
SOQPSK-TG Phase Tree



Power Spectral Density

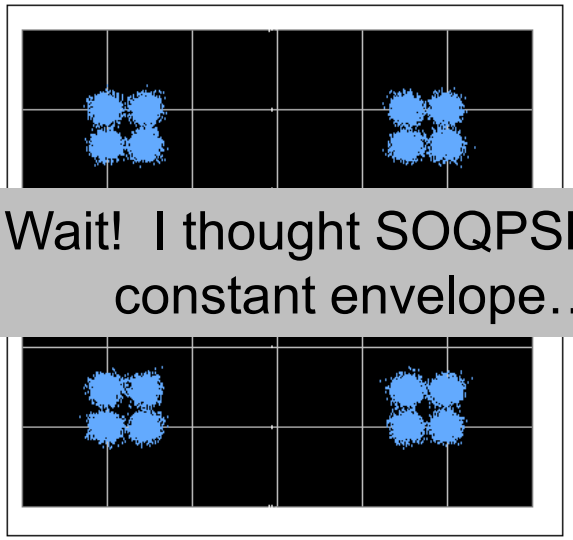


SOQPSK-TG Eye Patterns

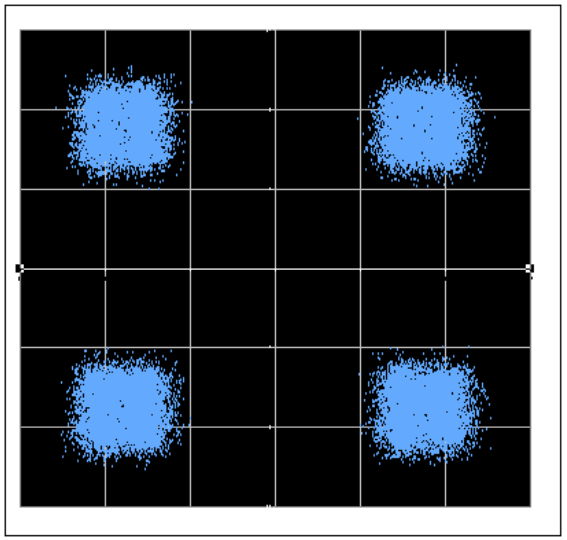


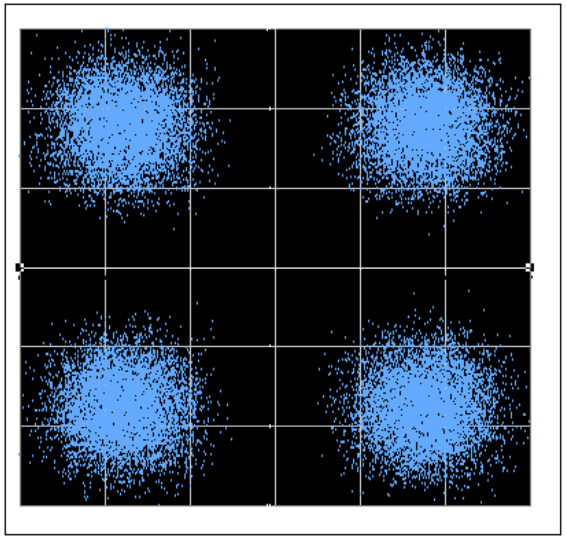
- Single-symbol detection is sub-optimal, but practical

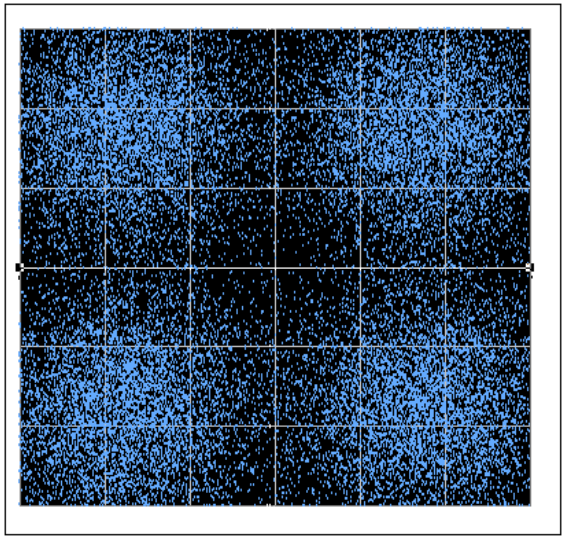
SOQPSK Constellations



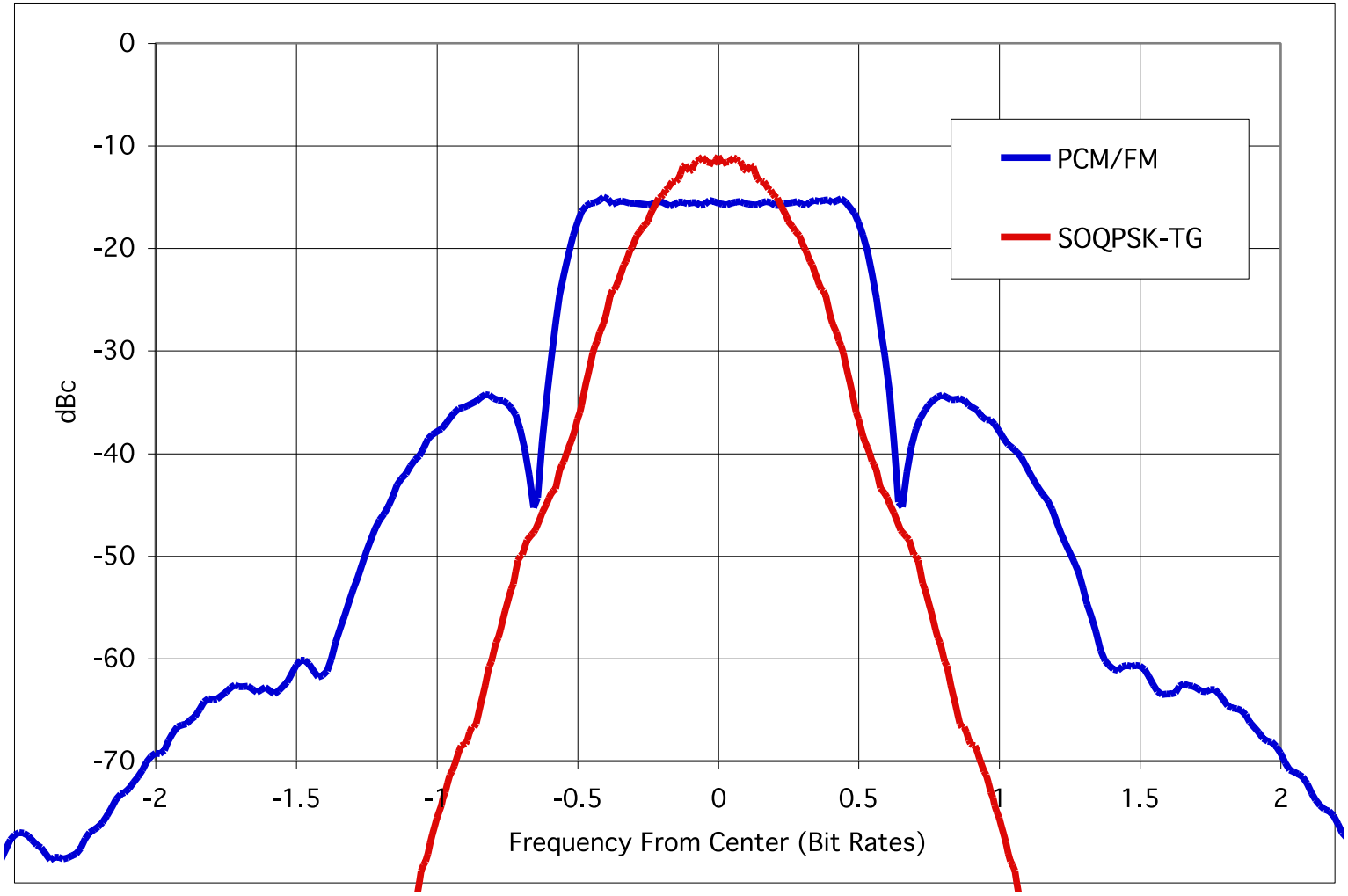
Wait! I thought SOQPSK was constant envelope…



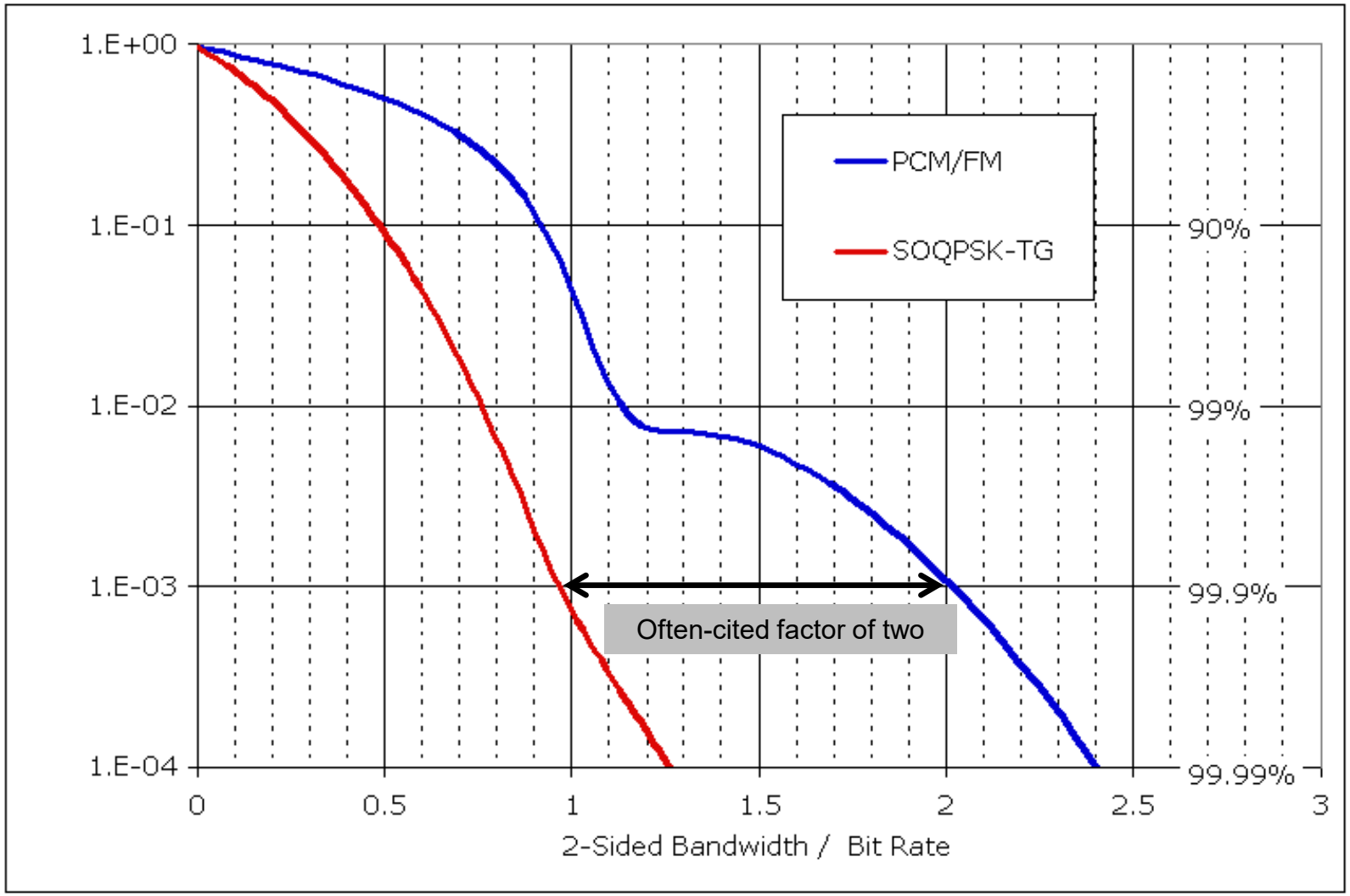




Measured PSD (Tier 0 & 1)



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.

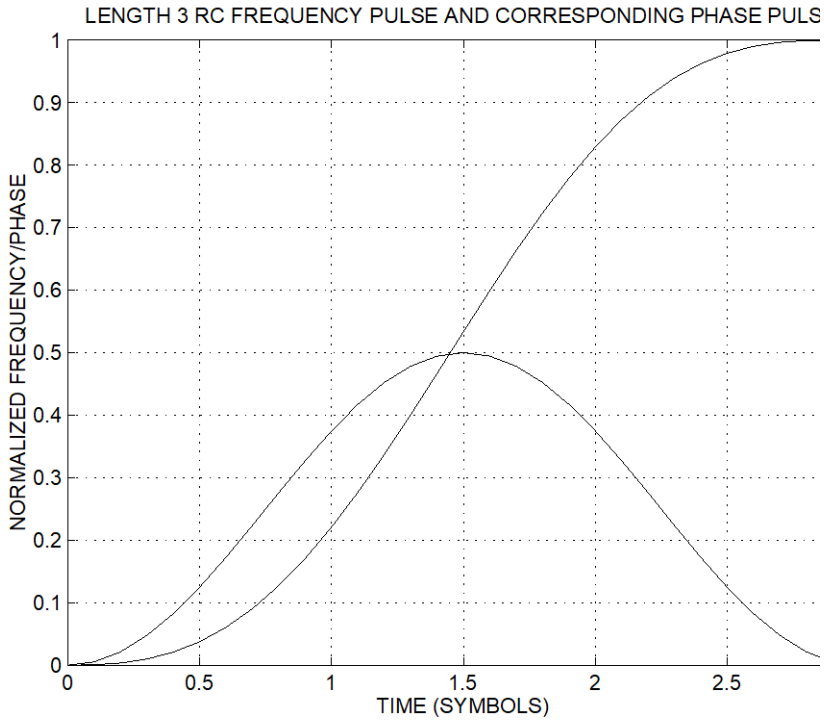
ARTM Tier II in CPM Notation

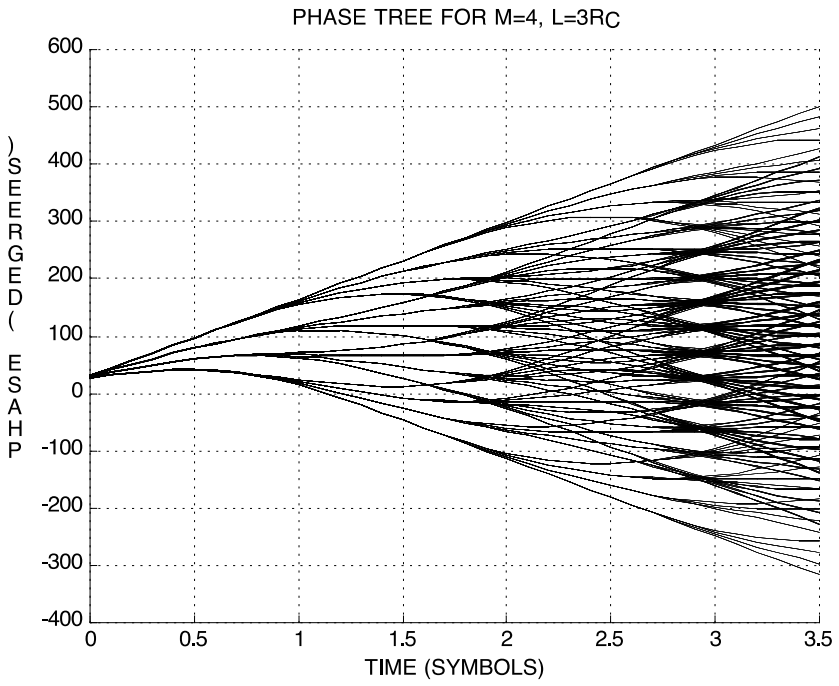
$$s(t) = \sqrt{2E/T}\cos[2\pi f_o t + \phi(t,\overline{\alpha}) + \phi_o]$$

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

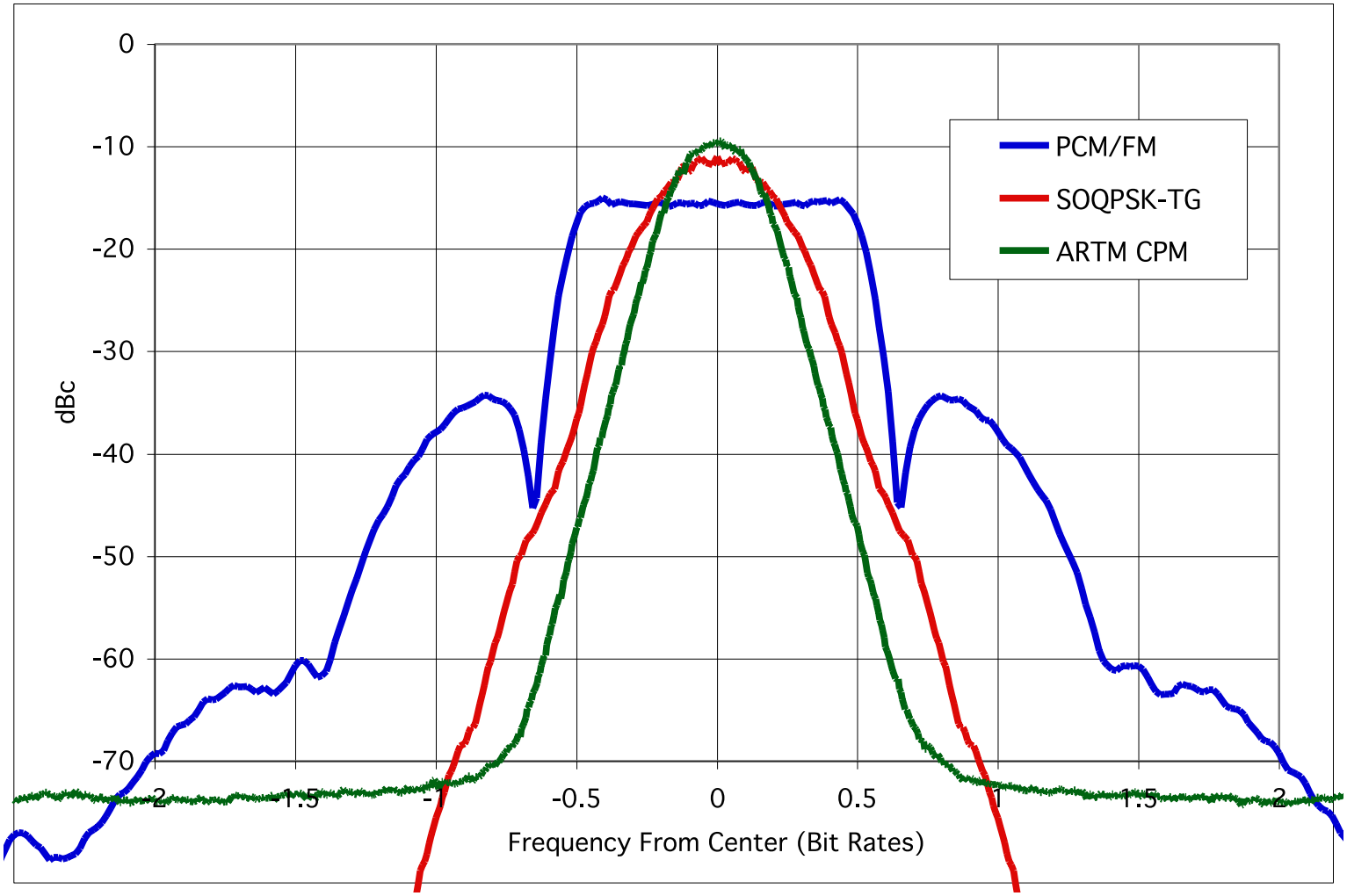
- M = 4 (quaternary)
- $\alpha_i = 2\,[2d_{1i} + d_{0i}] - 3$
  - $\alpha_i = \{-3, -1, +1, +3\}$
  - $d_i = \{0, 1\}$
- h = {4/16, 5/16}, alternating
- g(t) = raised cosine, 3 symbols (6 bits) in duration
  - Normalized such that the integral over all time = 1/2

Frequency Pulse & Phase Tree

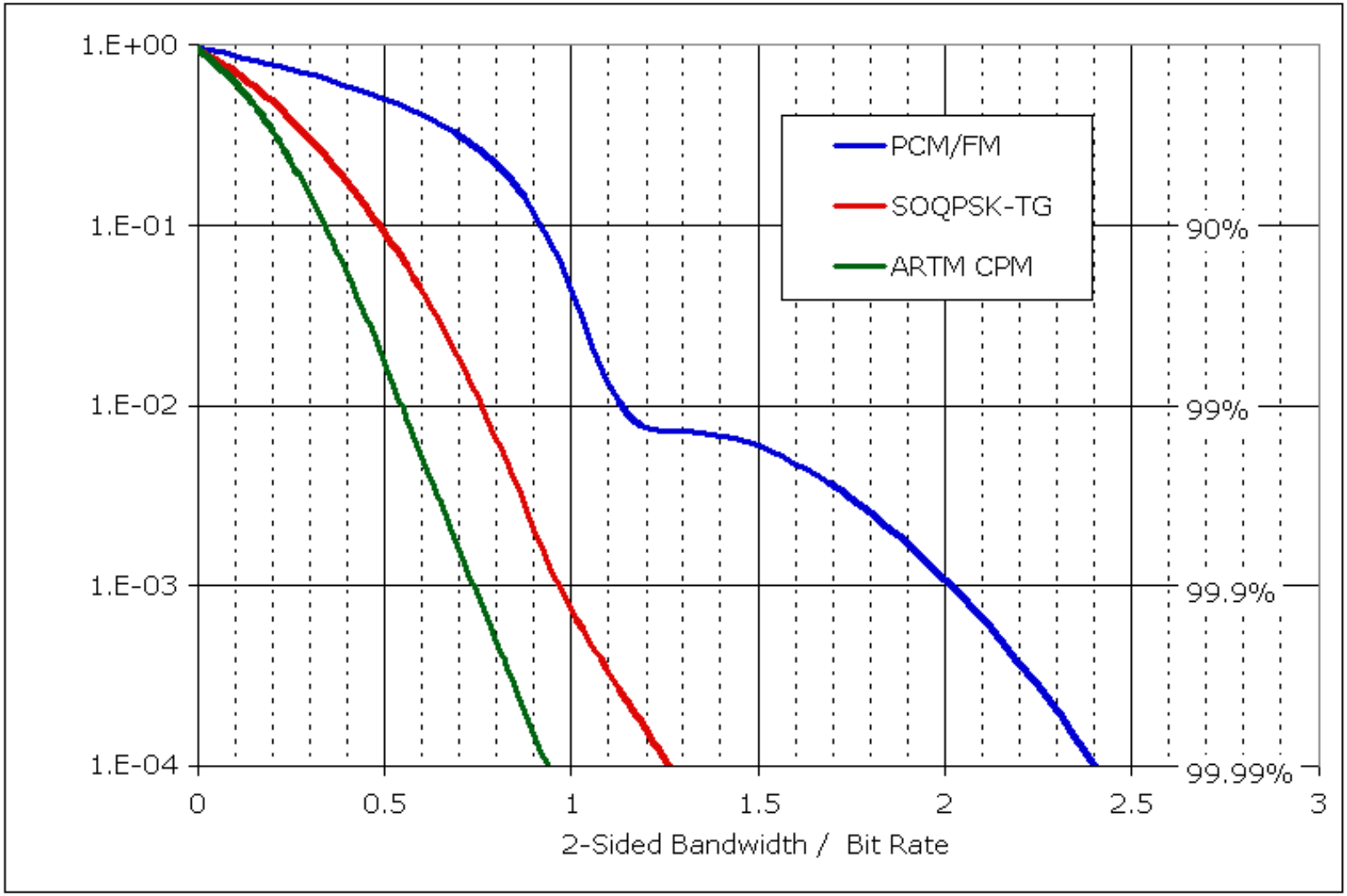




PSD (Tier 0, I, & II)



Fractional Out-of-band Power



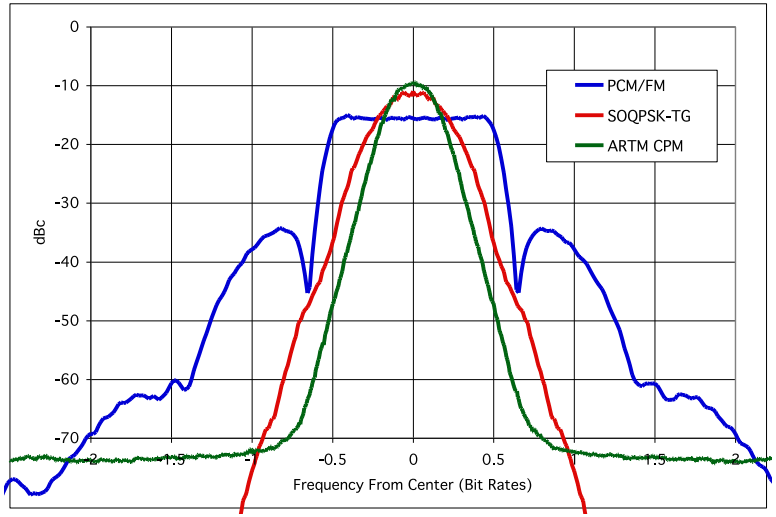
Tier II Multi-h CPM Summary

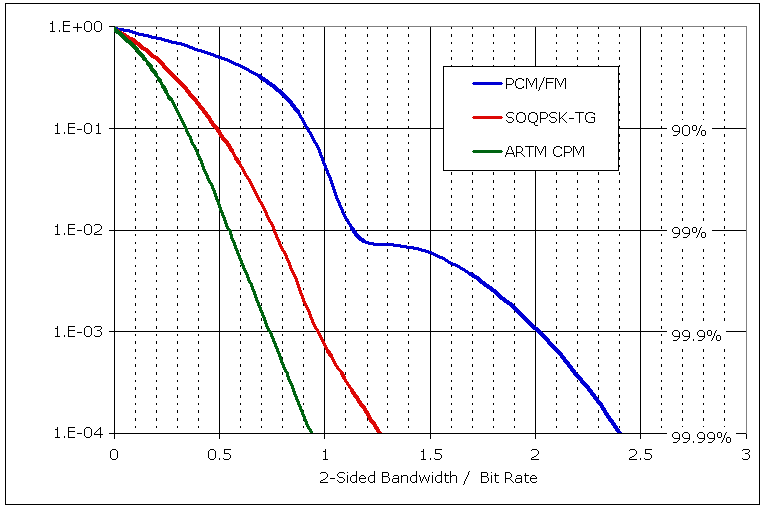
- Similar detection efficiency to PCM/FM.
- Constant envelope waveform is ideal for efficient non-linear PA's.
- Enhanced performance gained by increasing demodulator complexity.
- 99.9% bandwidth: 0.75 times bit rate

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



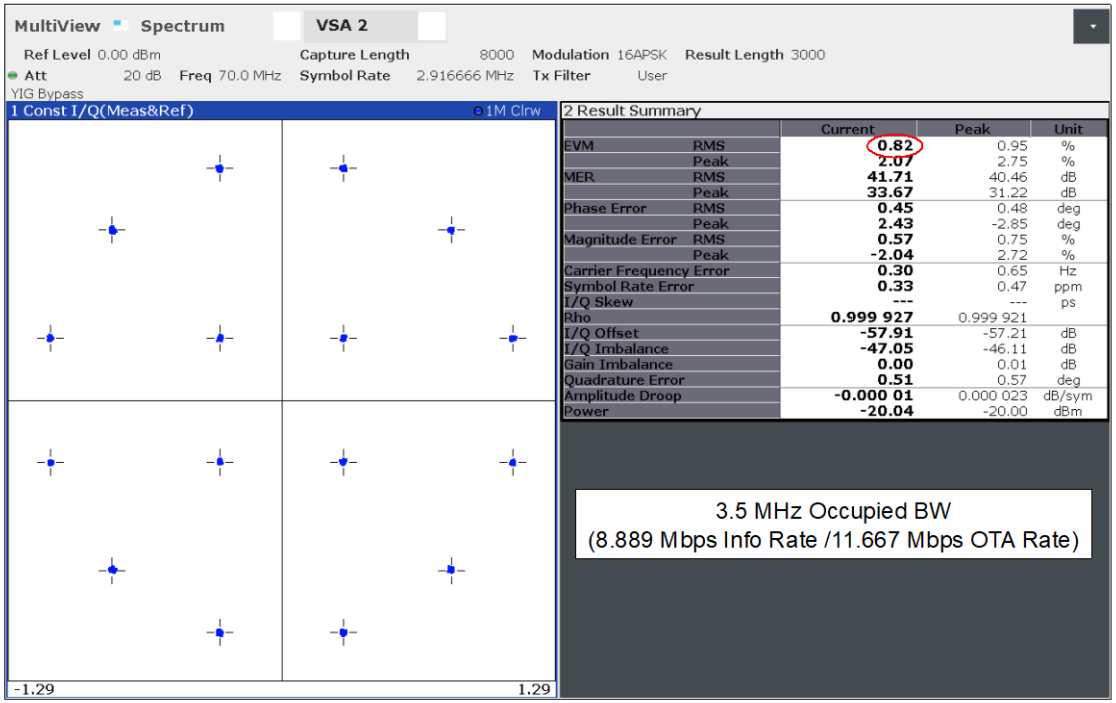


Quasonix

Amplitude/Phase Shift Keying (APSK)

Things to come?

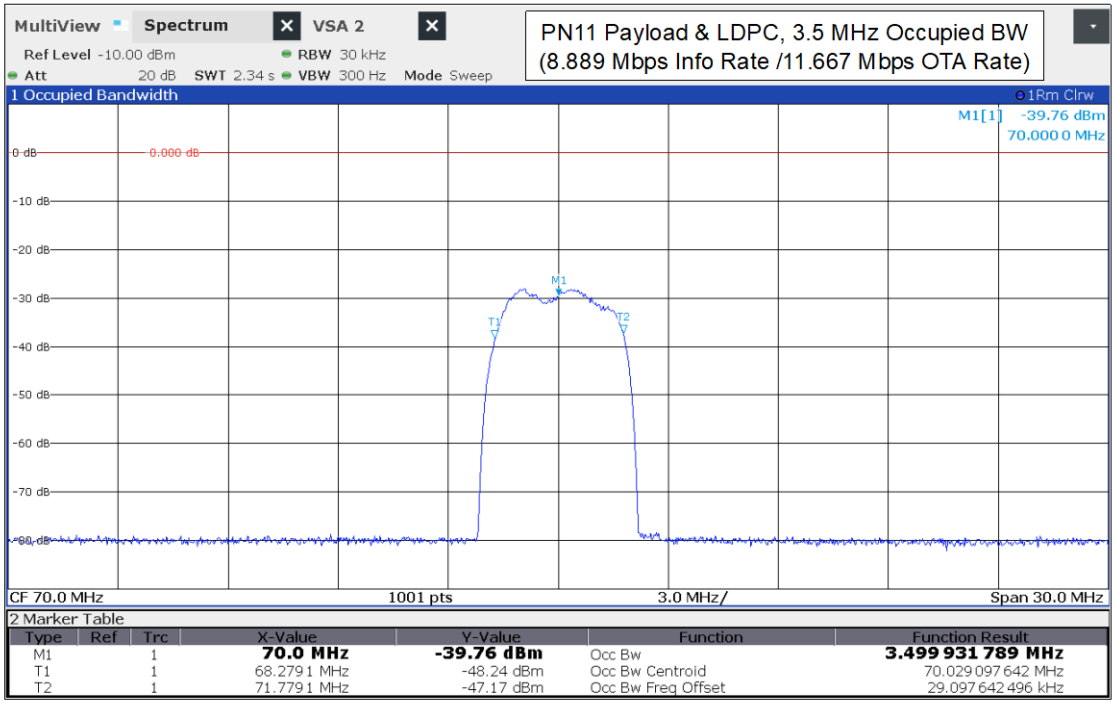
16-APSK Constellation - Ideal



Observed PRBS Payload Spectral Effects Are
Not Reflected in 16-APSK Constellation

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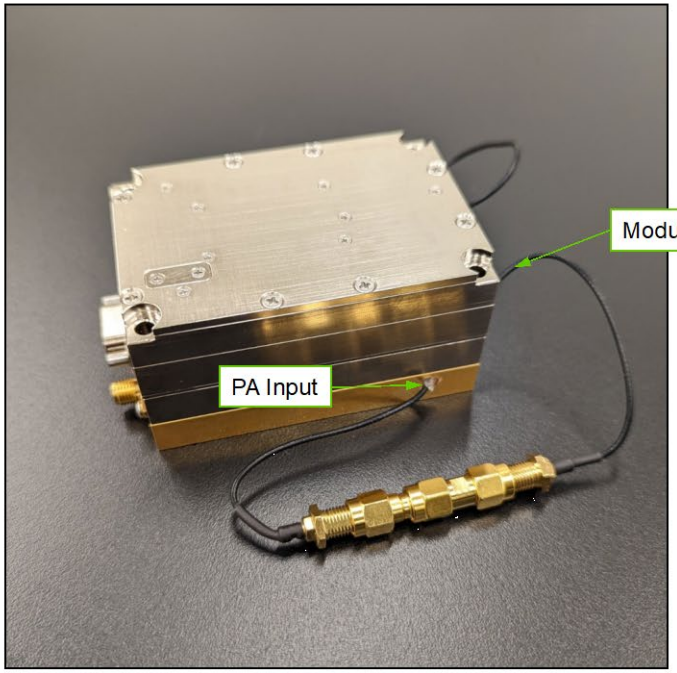
16-APSK Spectrum - Ideal



Vector Signal Generator 70 MHz 16-APSK

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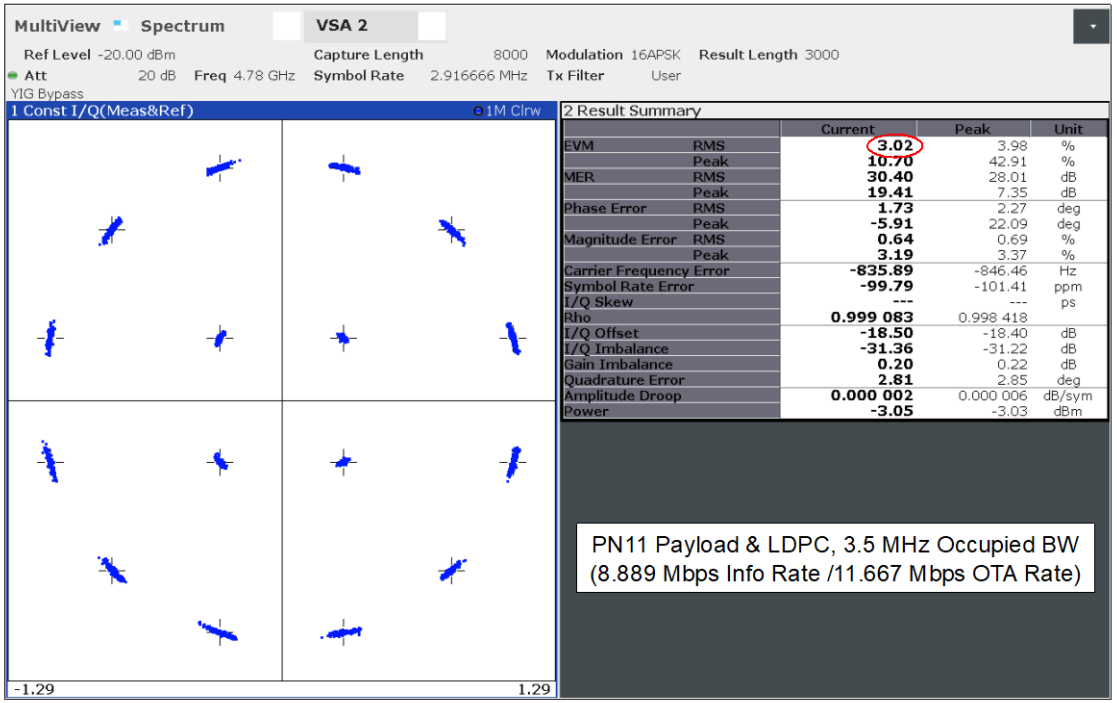
16-APSK Transmitter



Prototype C-Band 16-APSK Transmitter

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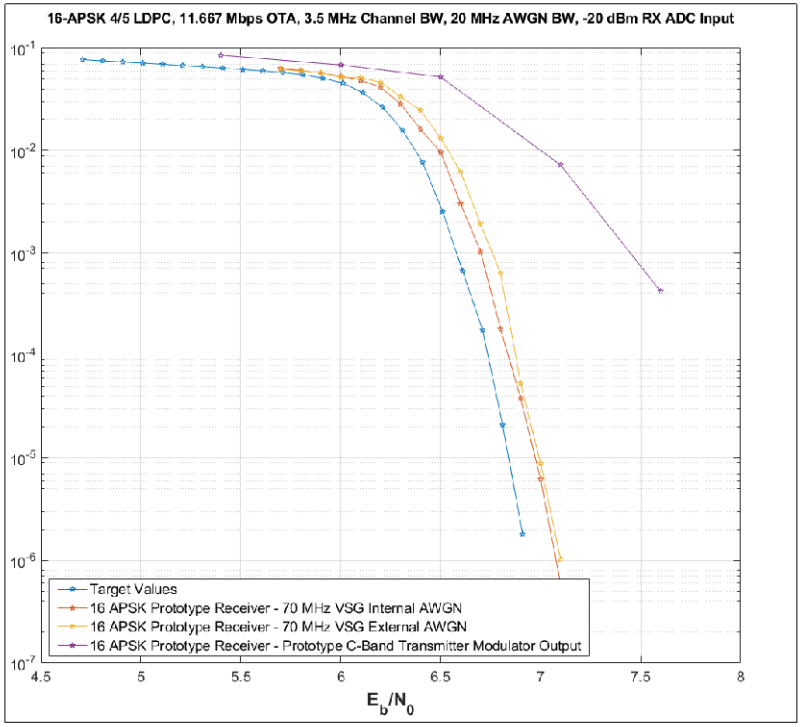
16-APSK TX Output



Prototype C-Band 16 APSK Transmitter
0.0005 W Min RF Power Output

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16-APSK BER

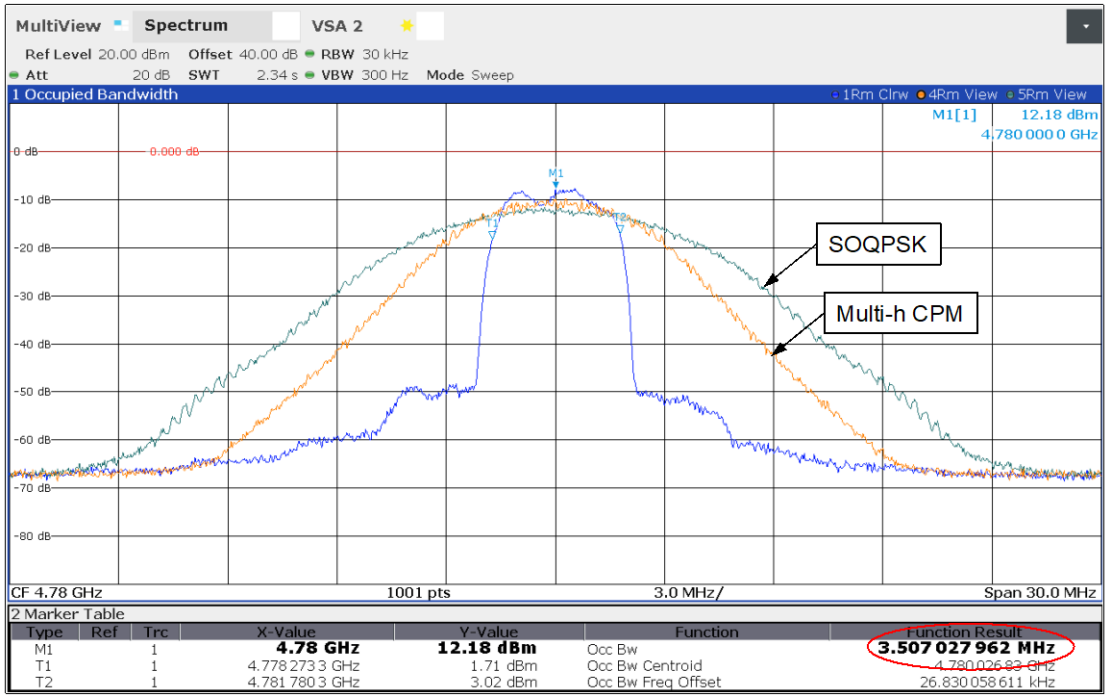


Prototype C-Band APSK Transmitter			8.889 Mbps Info Bit Rate	
3.5 MHz BW APSK Channel Power (C dBm)	Noise Power in Channel (N dBm)	Eb/N0 (dB)	1M Packets	
			BER	Errors
-23.7	-33.1	5.4	8.478E-02	347236682
-23.1	-33.1	6.0	6.841E-02	280196965
-22.6	-33.1	6.5	5.209E-02	213359992
-22.0	-33.1	7.1	7.212E-03	29538623
-21.5	-33.1	7.6	4.225E-04	1730452

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Prototype C-Band 16 APSK Transmitter – Modulator Output (PA Bypassed)
Downconverted 4780 MHz with PN11 Payload & LDPC
20 MHz AWGN Noise Bandwidth

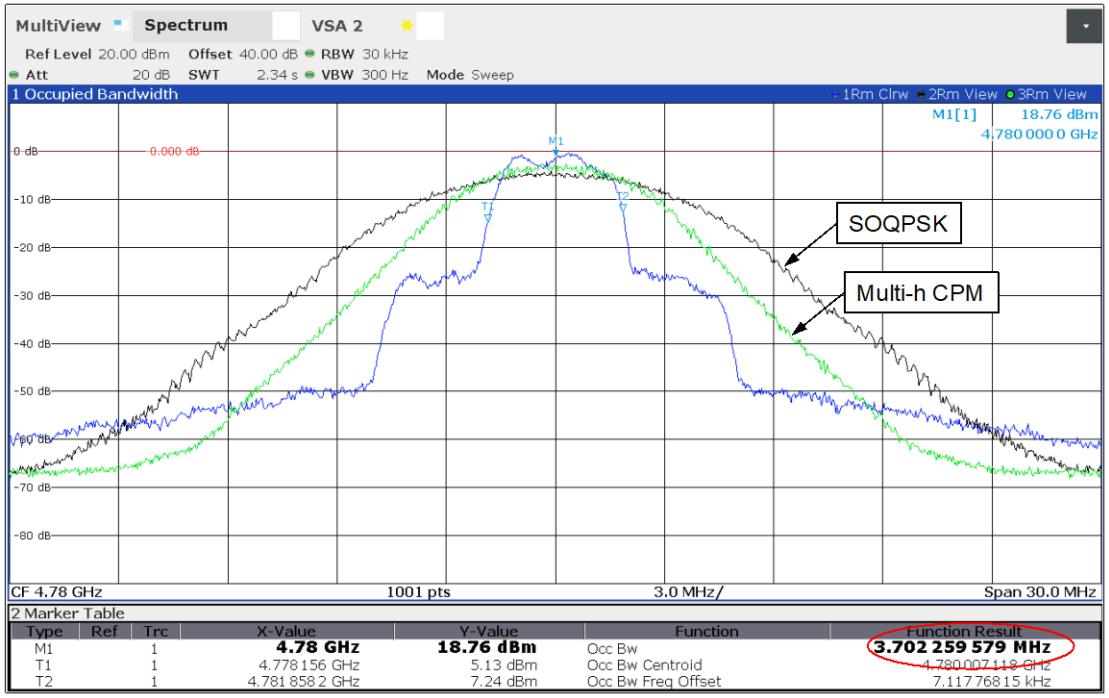
16-APSK Spectrum @ 1 Watt



16-APSK vs. SOQPSK vs. Multi-h CPM
8.889 Mbps PN11 & LDPC
1 W Channel Power

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16-APSK Spectrum @ 6 Watts



16-APSK vs. SOQPSK vs. Multi-h CPM
8.889 Mbps PN11 & LDPC
6 W Channel Power

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16-APSK Conclusions

- The math is willing
- The circuits need work
- Smart people are working hard
- More to come

Quasonix

Demodulation

Short Break

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

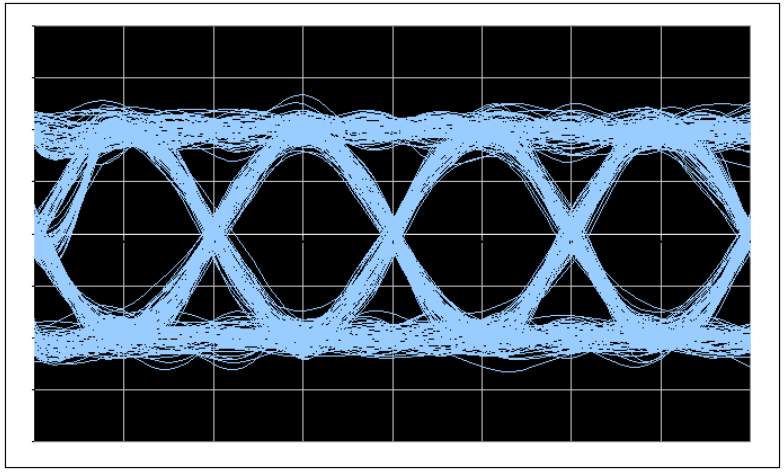
Tier 0 Single-Symbol Detection

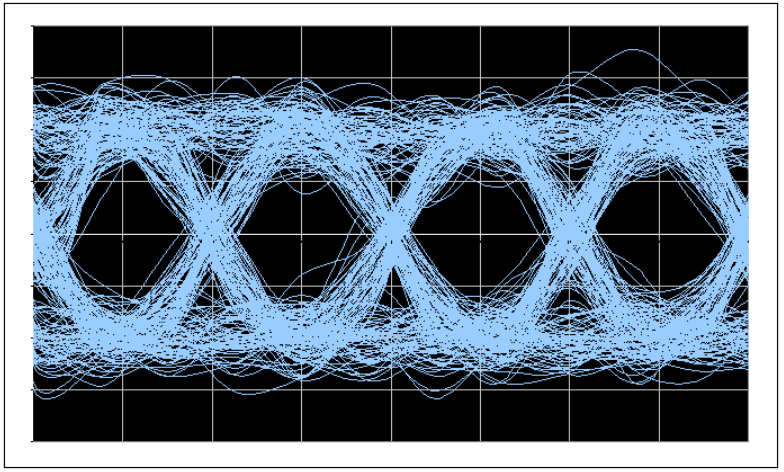
$$s(t) = \sqrt{2E/T}\cos[2\pi f_o t + \phi(t,\overline{\alpha}) + \phi_o]$$

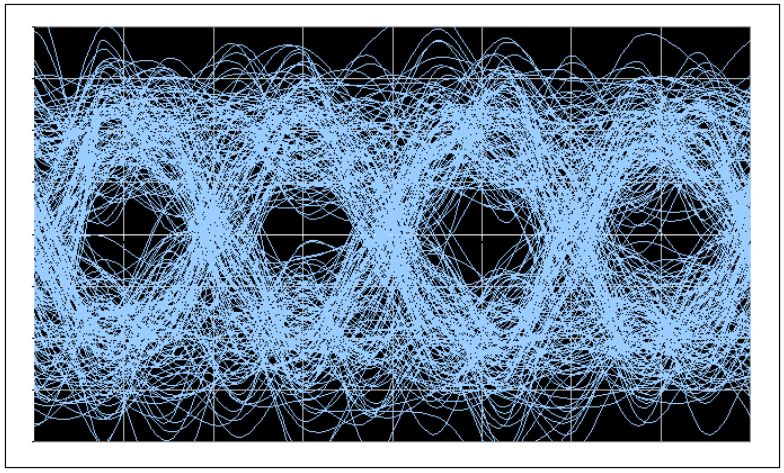
$$\phi(t,\overline{\alpha}) = 2\pi h \int_{-\infty}^{t} \sum_{i=-\infty}^{+\infty} \alpha_i g(\tau - iT) d\tau$$

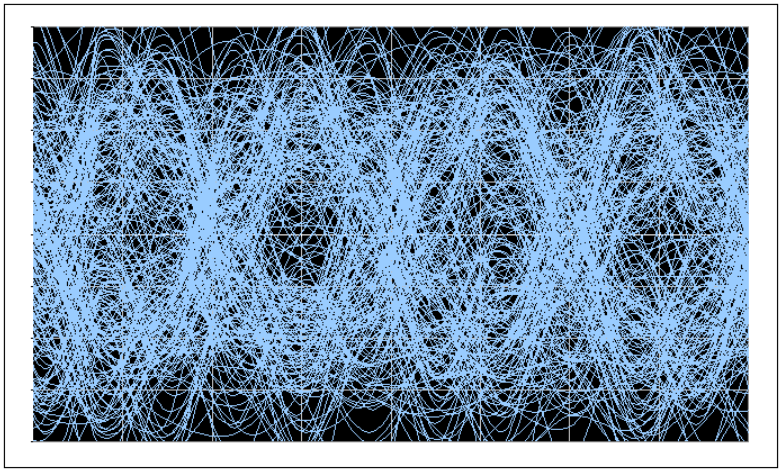
- Differentiate the phase to get frequency
  - Limiter-discriminator
  - Phase locked loop
  - Digital processing
- If the frequency in this symbol > 0, data = 1
- If the frequency in this symbol < 0, data = 0

Tier 0 Frequency Detection

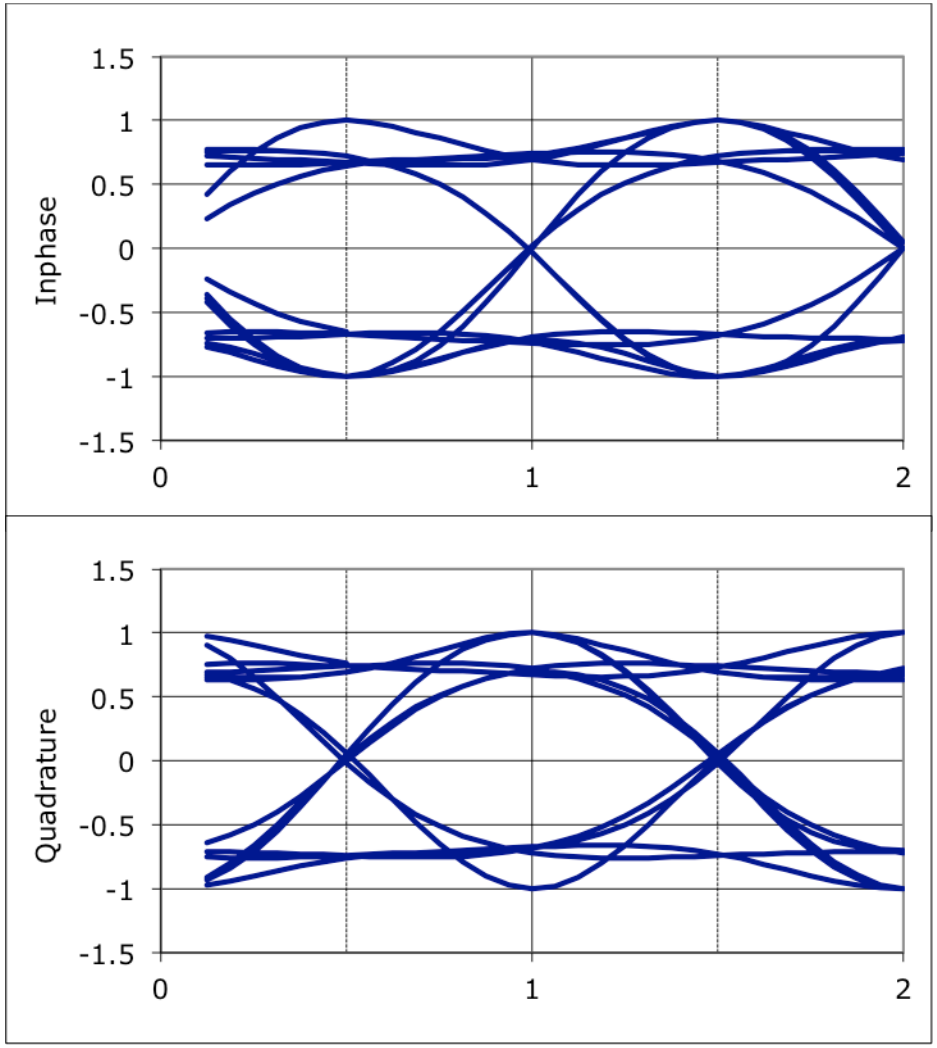






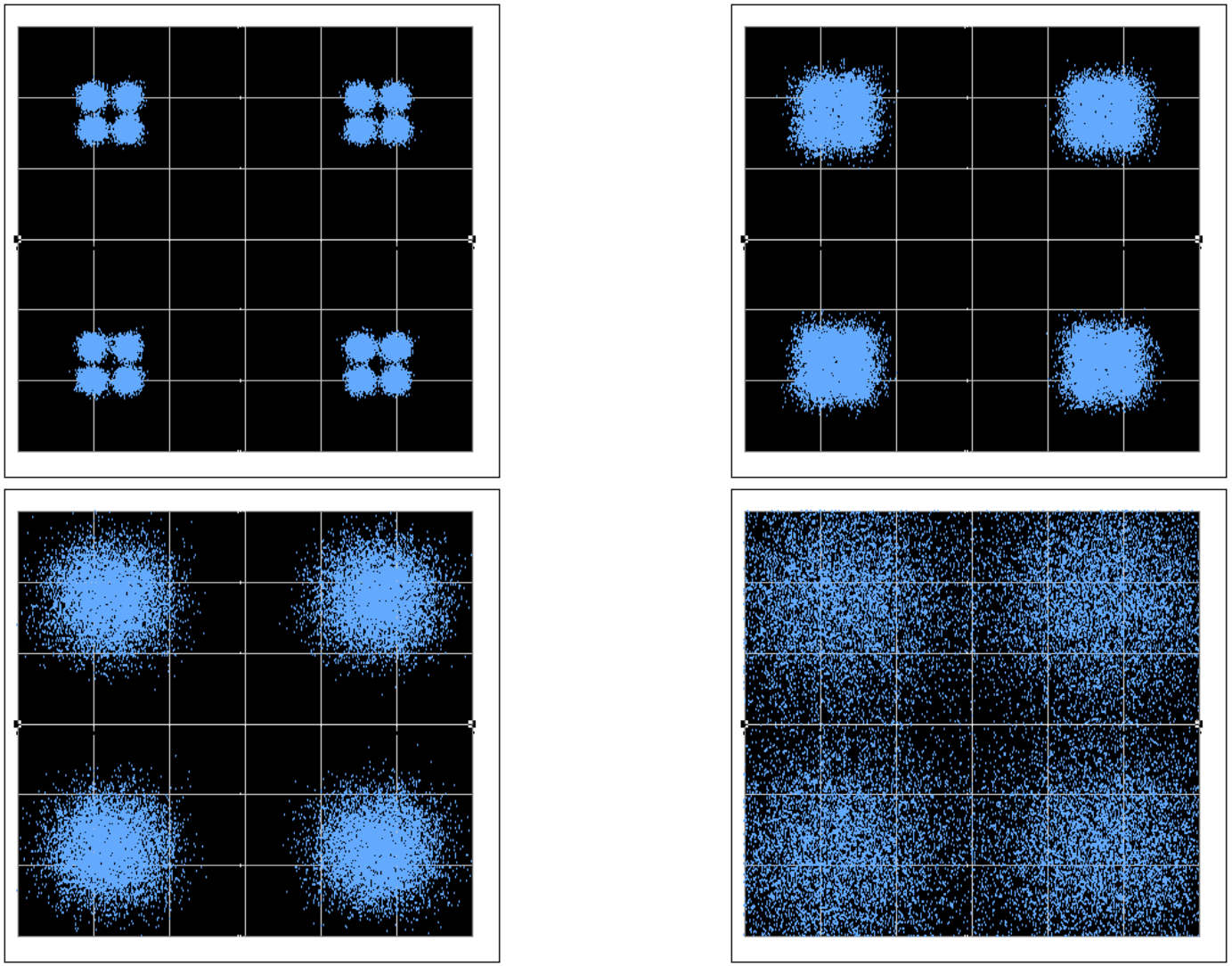


SOQPSK-TG Eye Patterns



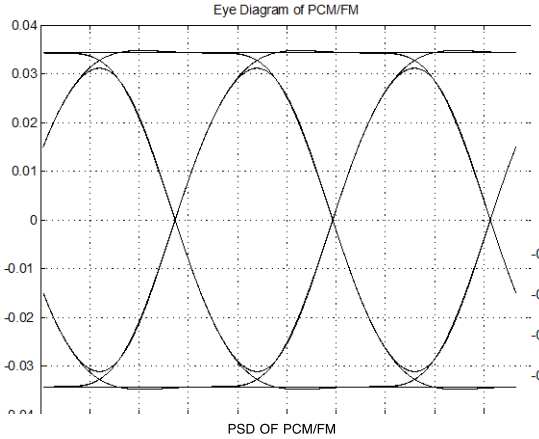
- Single-symbol detection ignores memory inherent in waveform
- Can be detected by conventional (non-shaped) offset QPSK demod
- I&D detector endures additional loss due to waveform mismatch

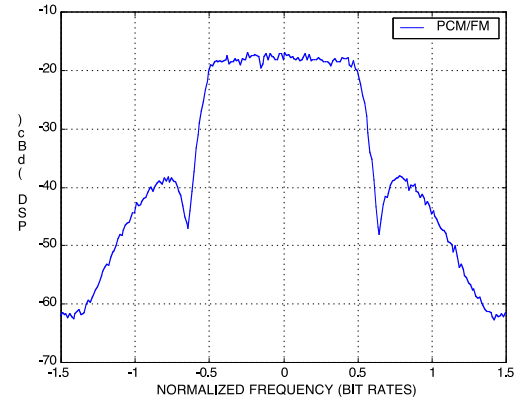
SOQPSK Constellations



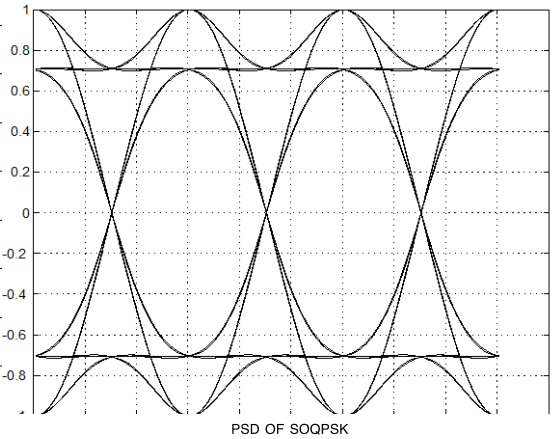
Waveform Comparison

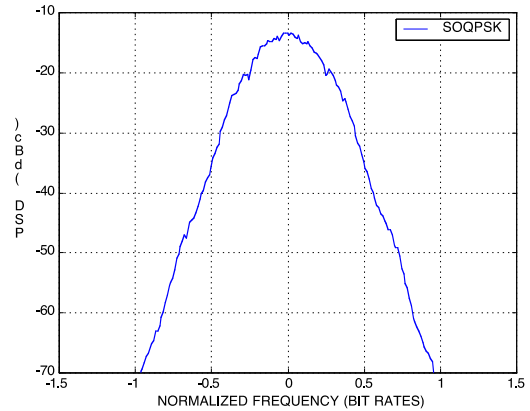
PCM/FM (1x)



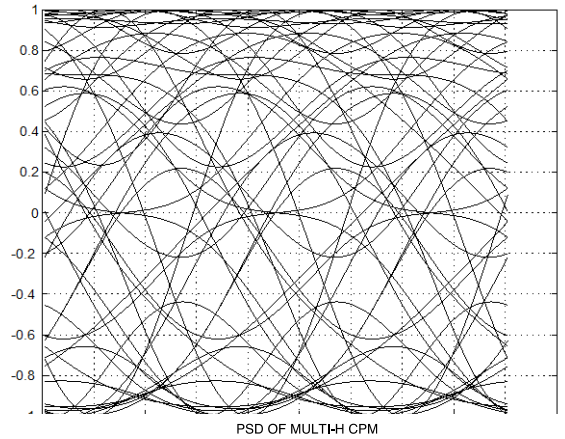


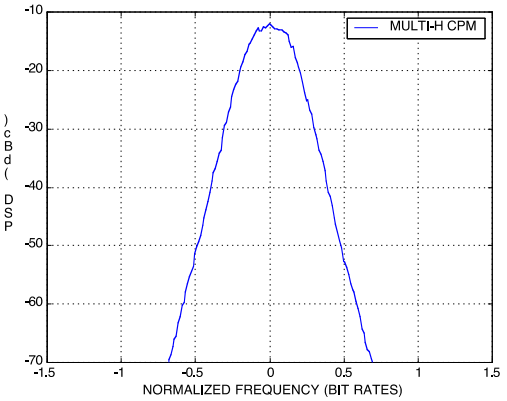
SOQPSK (2x)





Multi-h CPM (2.5x)

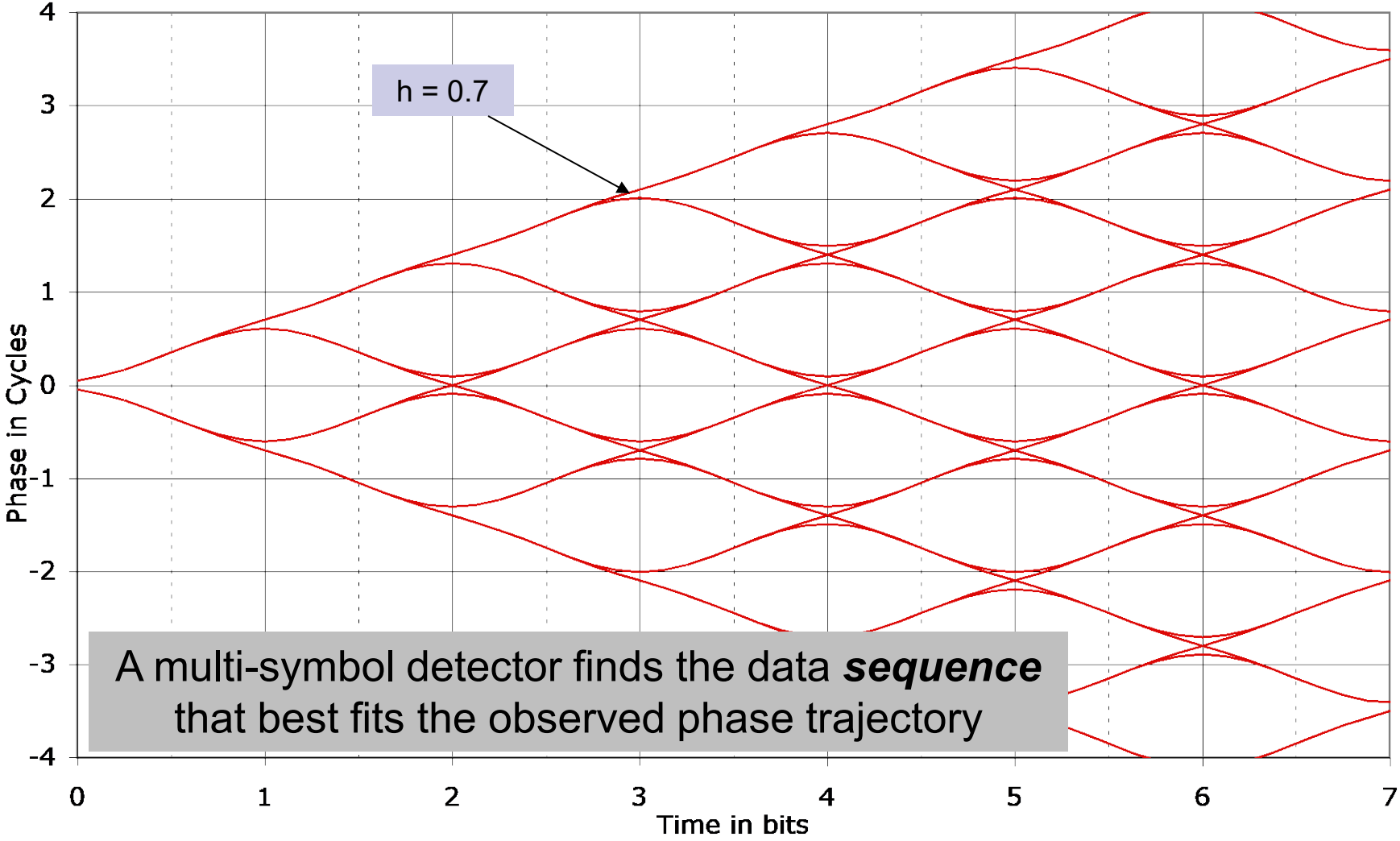




Trellis Demodulation Overview

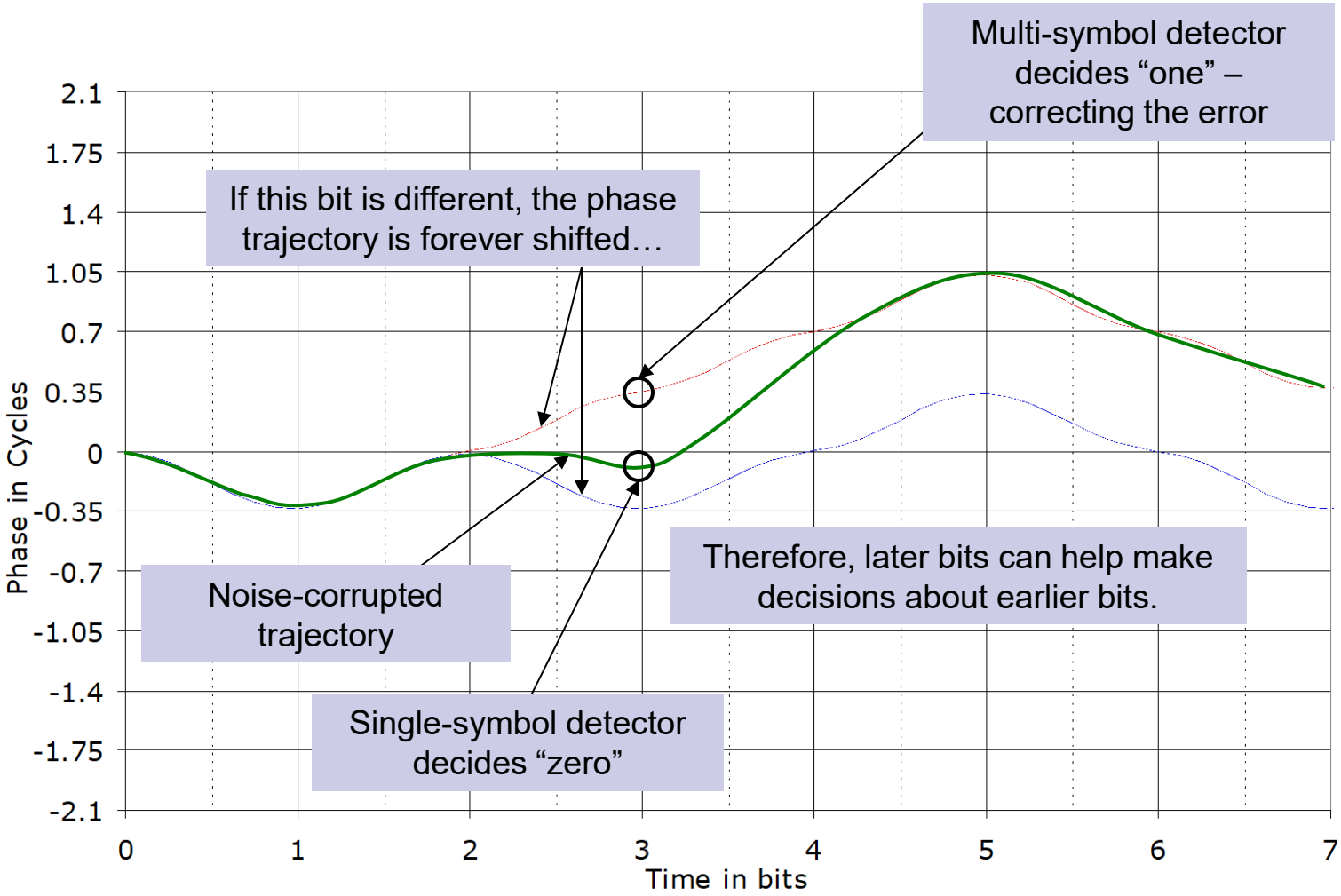
- Tier 0
  - Invented in 1974, introduced in 2001
    - Osborne & Luntz, “Coherent and Noncoherent Detection of CPFSK”, IEEE T-COM, August 1974
  - Requires significant signal processing power
  - Signal defects and channel impairments require attention
    - DSP techniques can be applied to solve these 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

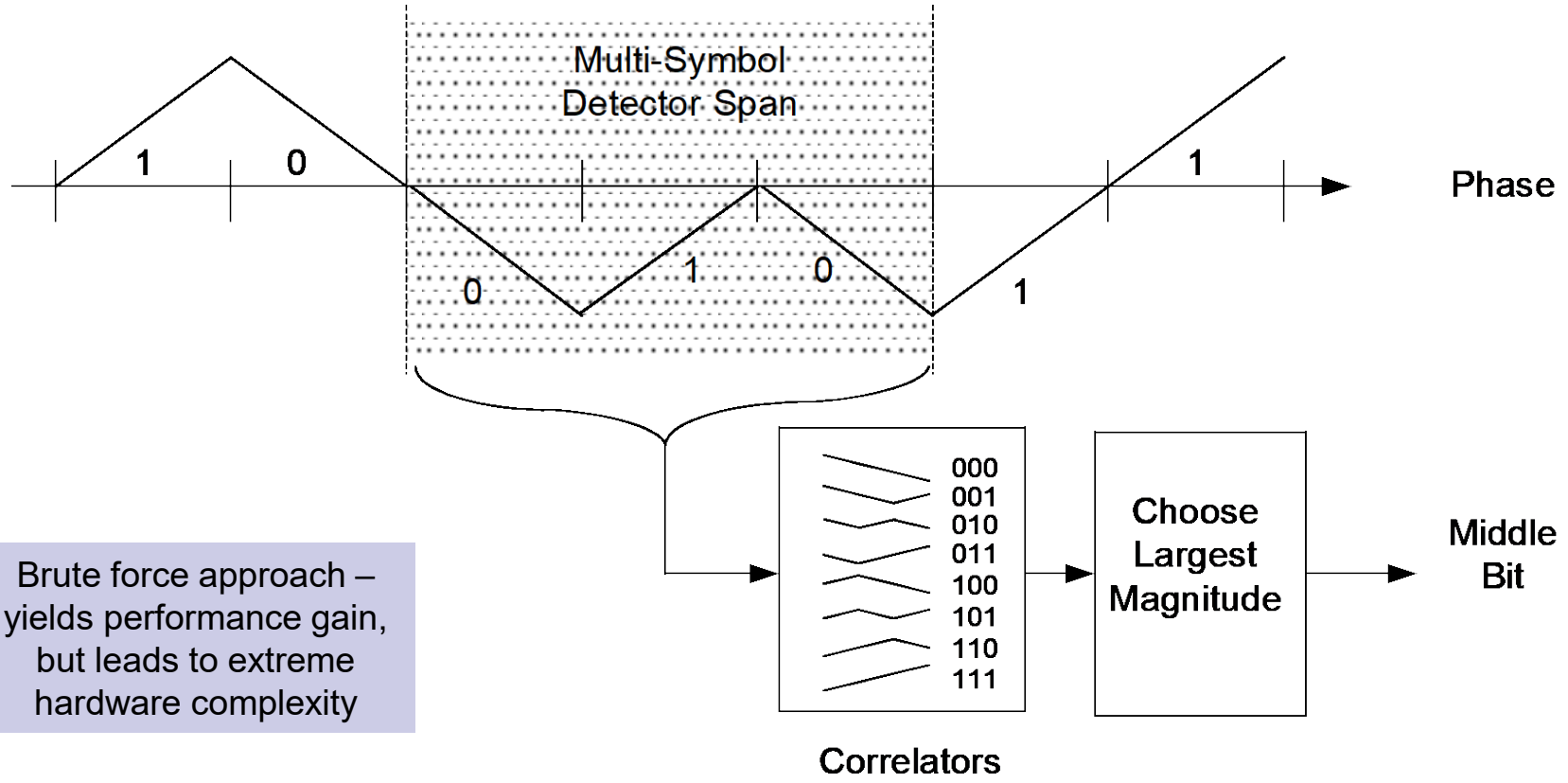


A multi-symbol detector finds the data ***sequence*** that best fits the observed phase trajectory

Why Does It Matter?



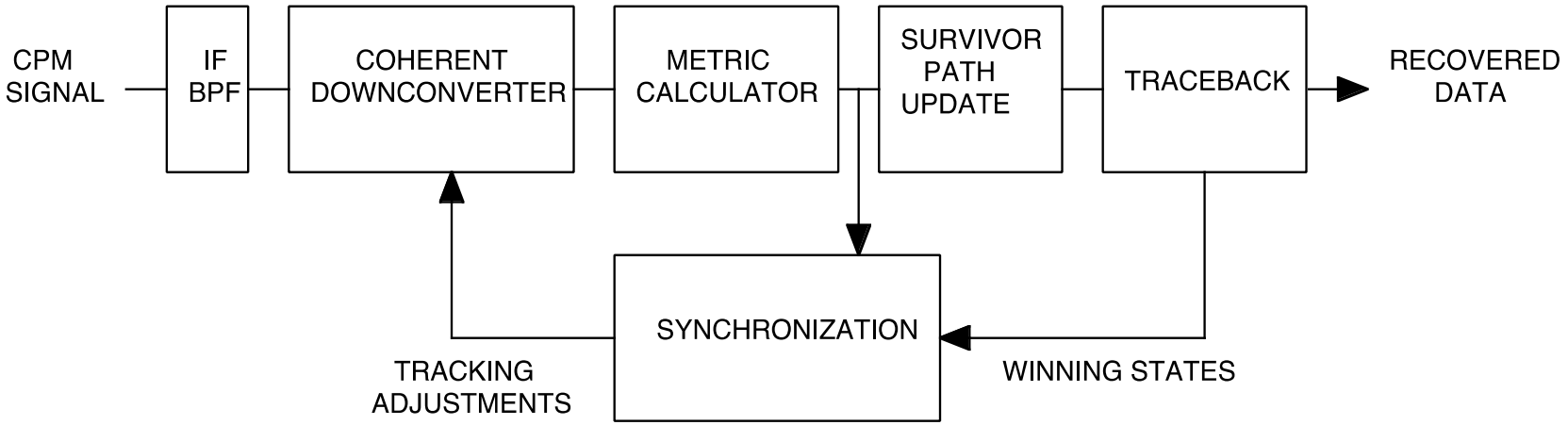
Multi-Symbol Detector Example



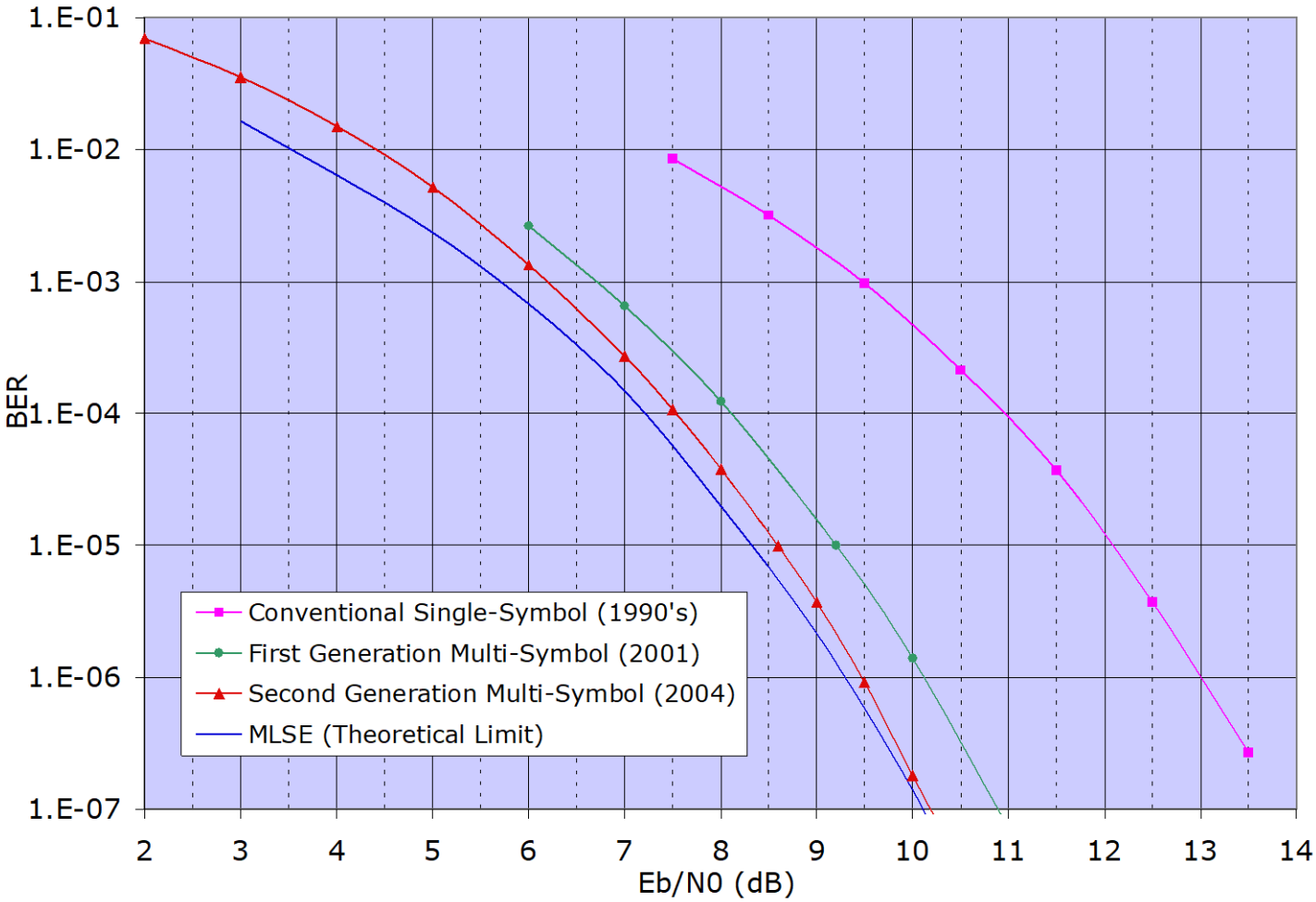
Brute force approach – yields performance gain, but leads to extreme hardware complexity

Generic Trellis Demodulator

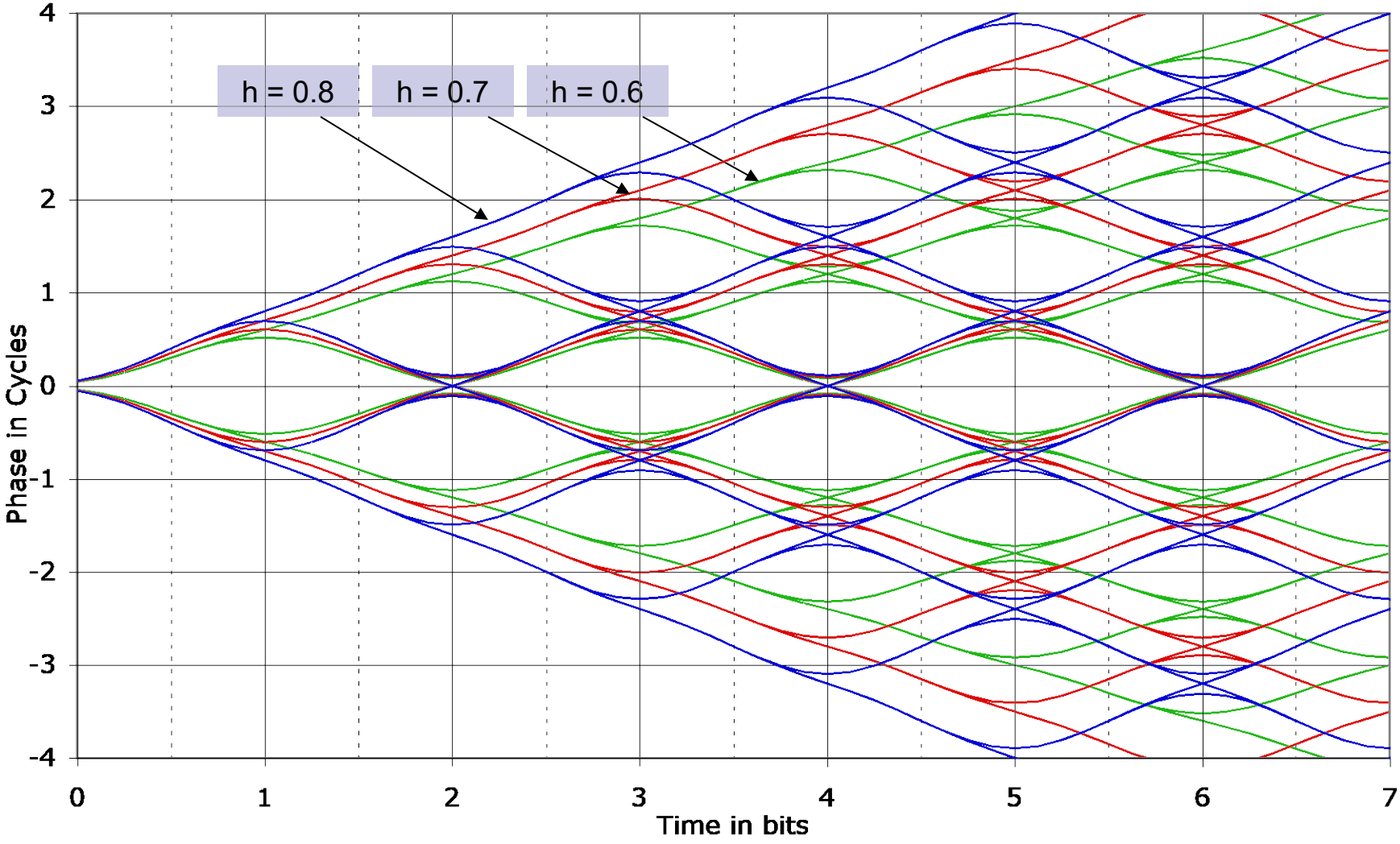
Brains over brawn – Efficient computation yields the same performance as the brute force approach, with far less hardware



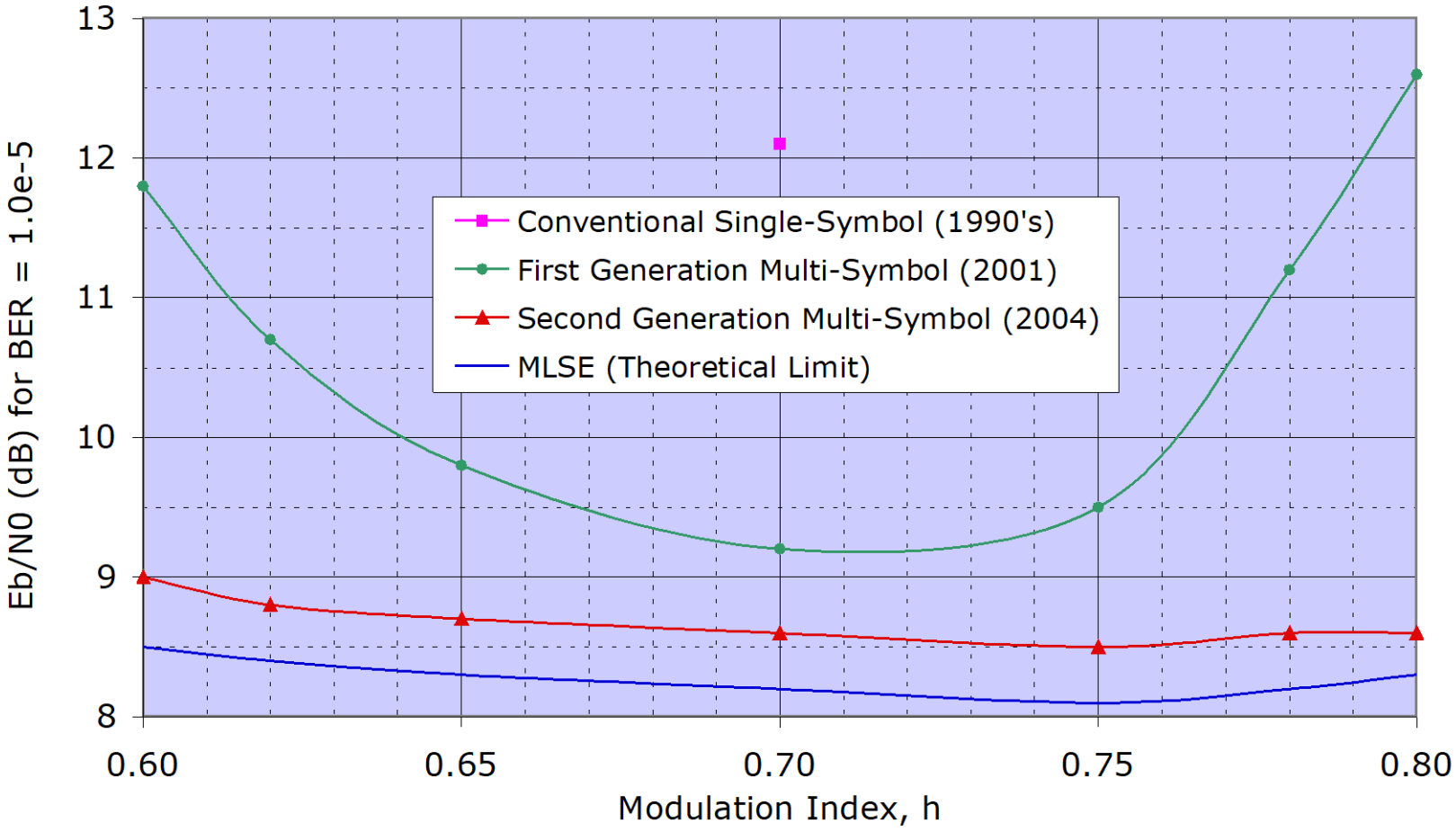
Tier 0 BER Performance



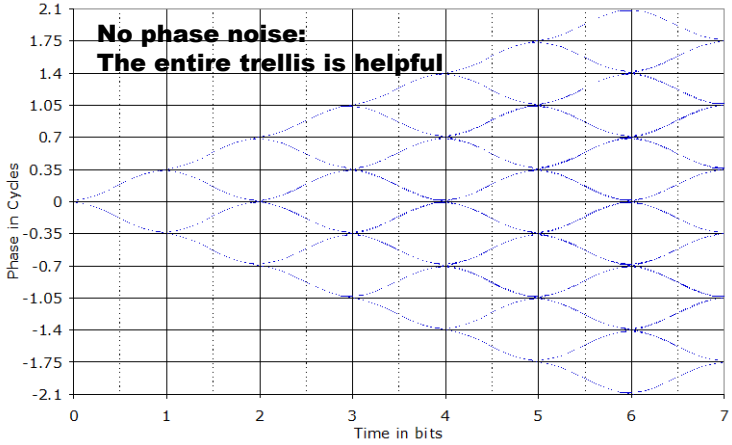
Legacy PCM/FM Transmitters

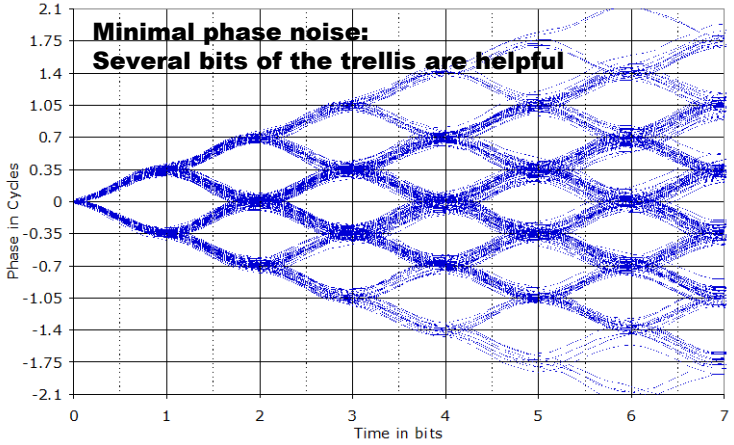


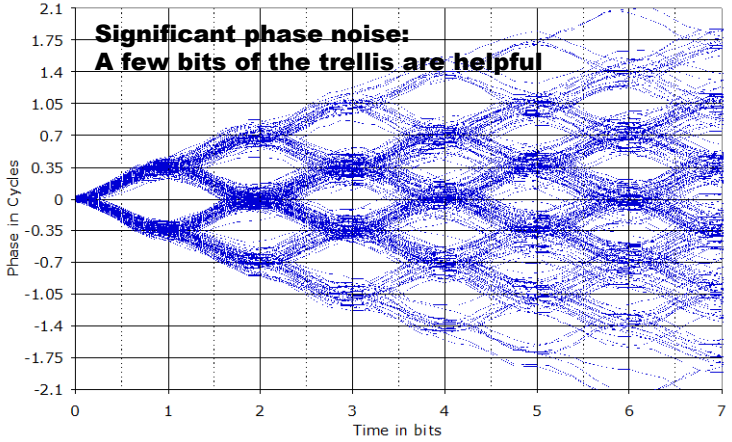
Effect of TX Deviation Error

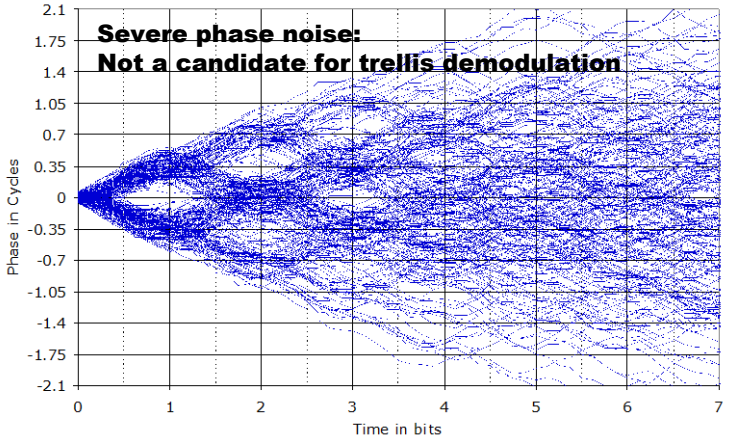


What About Phase Noise?









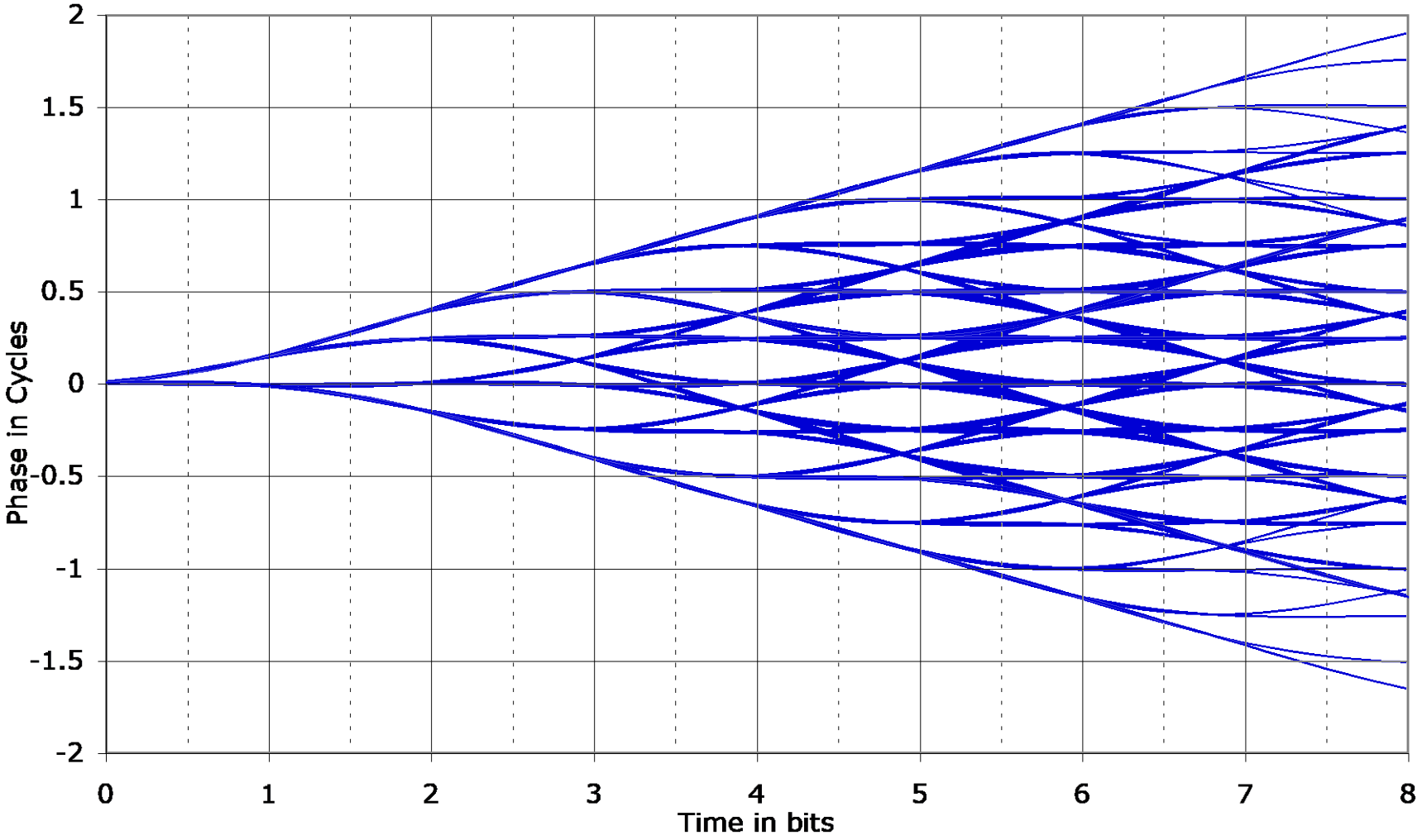
Phase Noise

- 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.

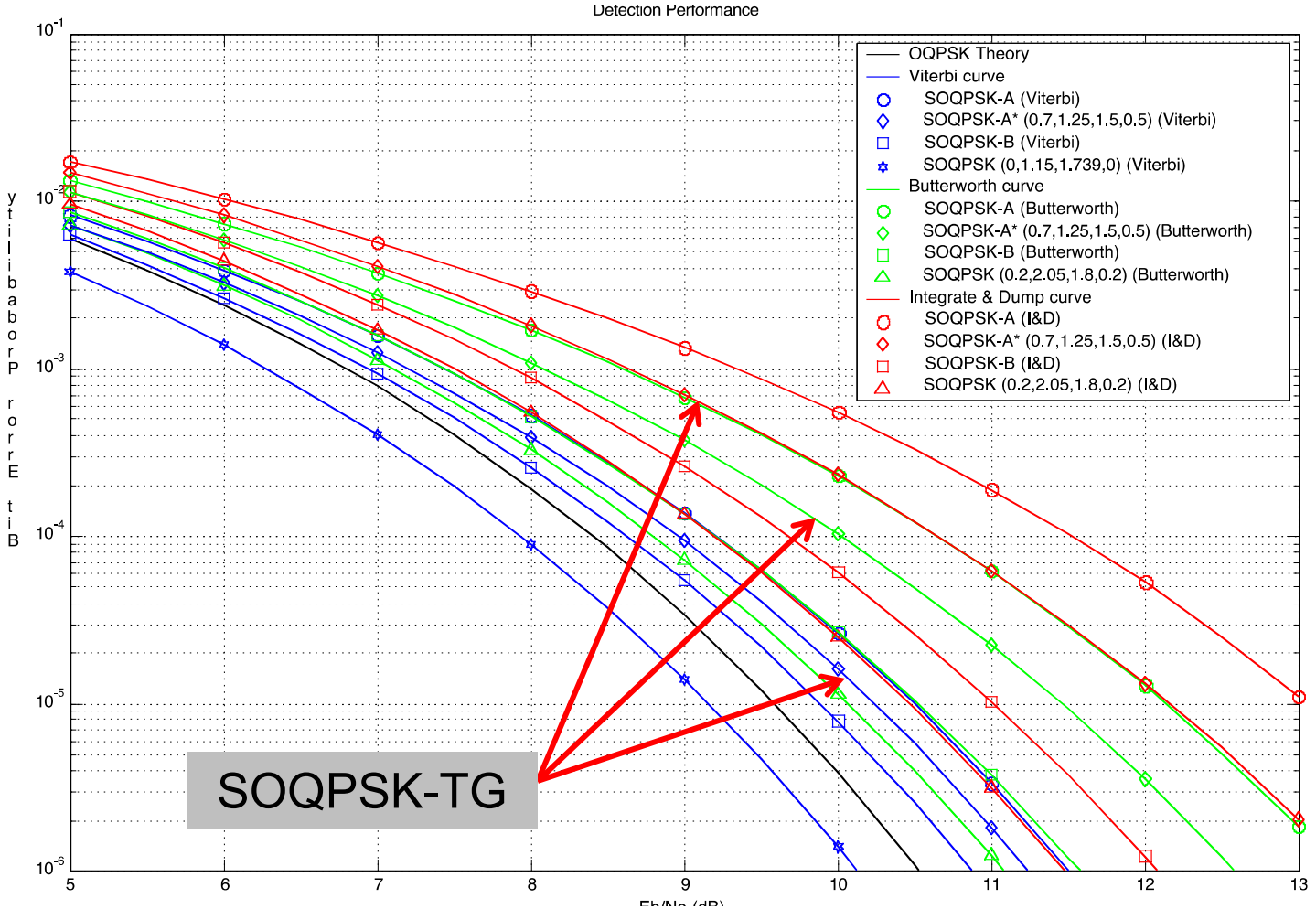
SOQPSK Detection

- 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



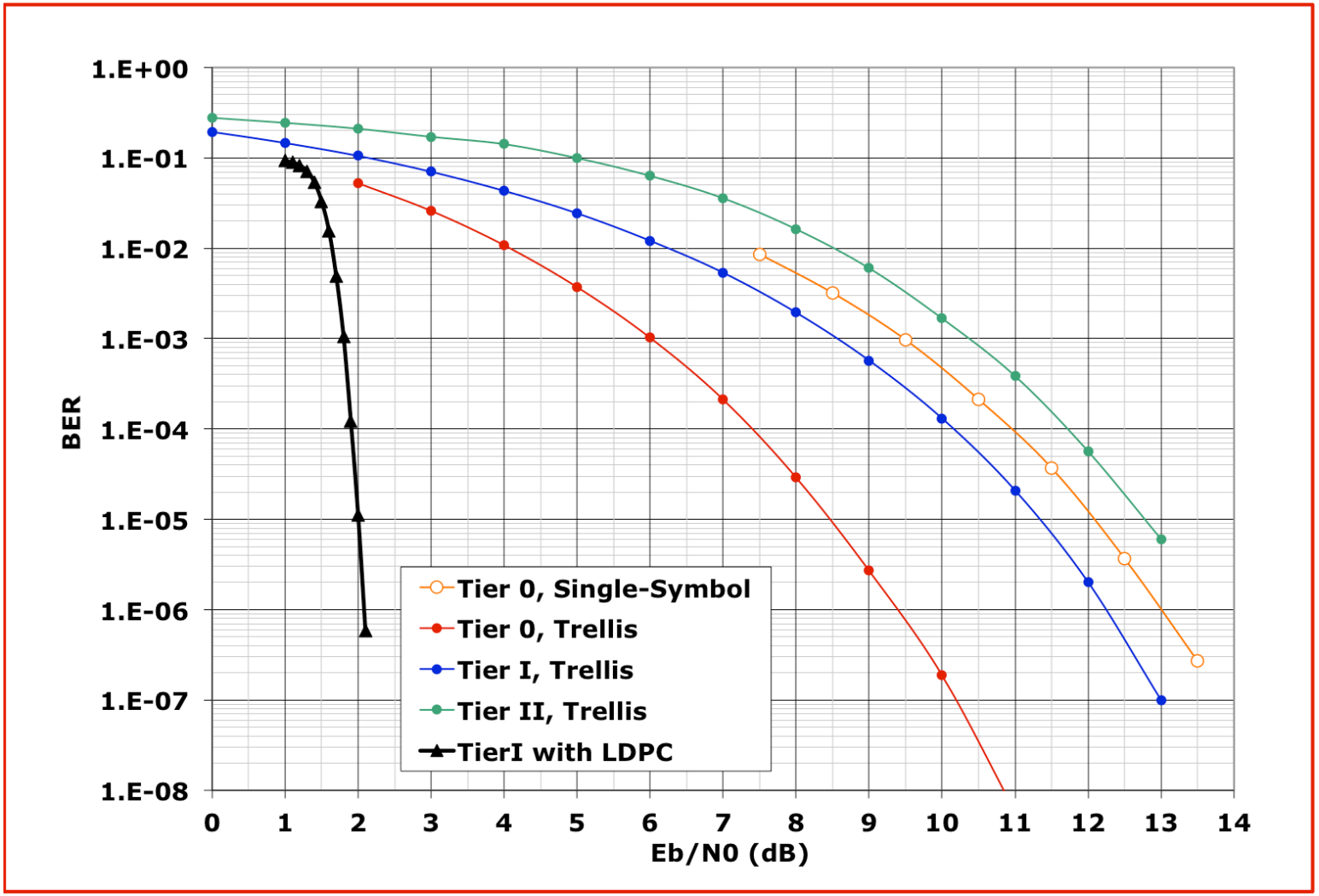
SOQPSK Detection Efficiency



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

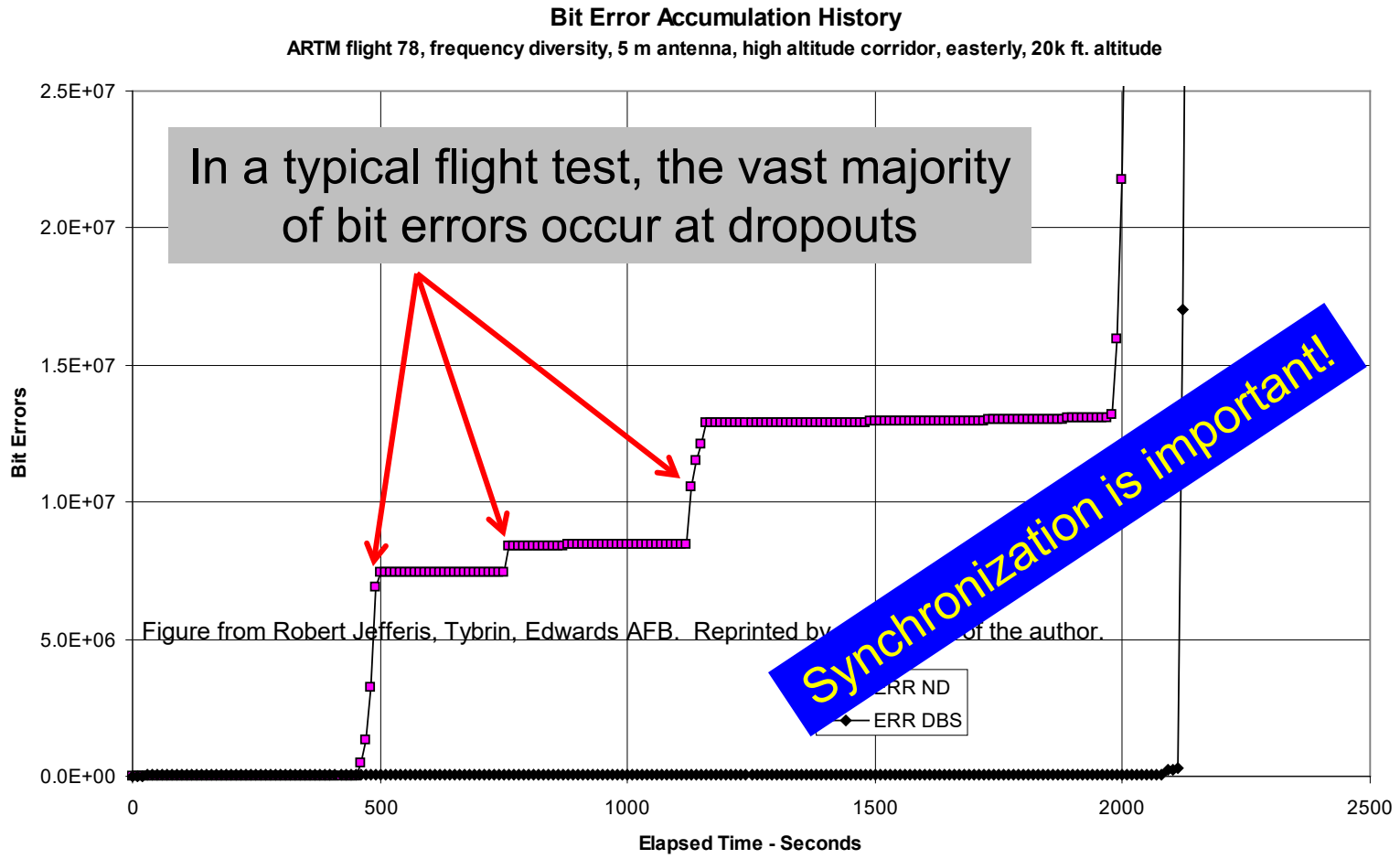
BER Performance Comparison



Quasonix

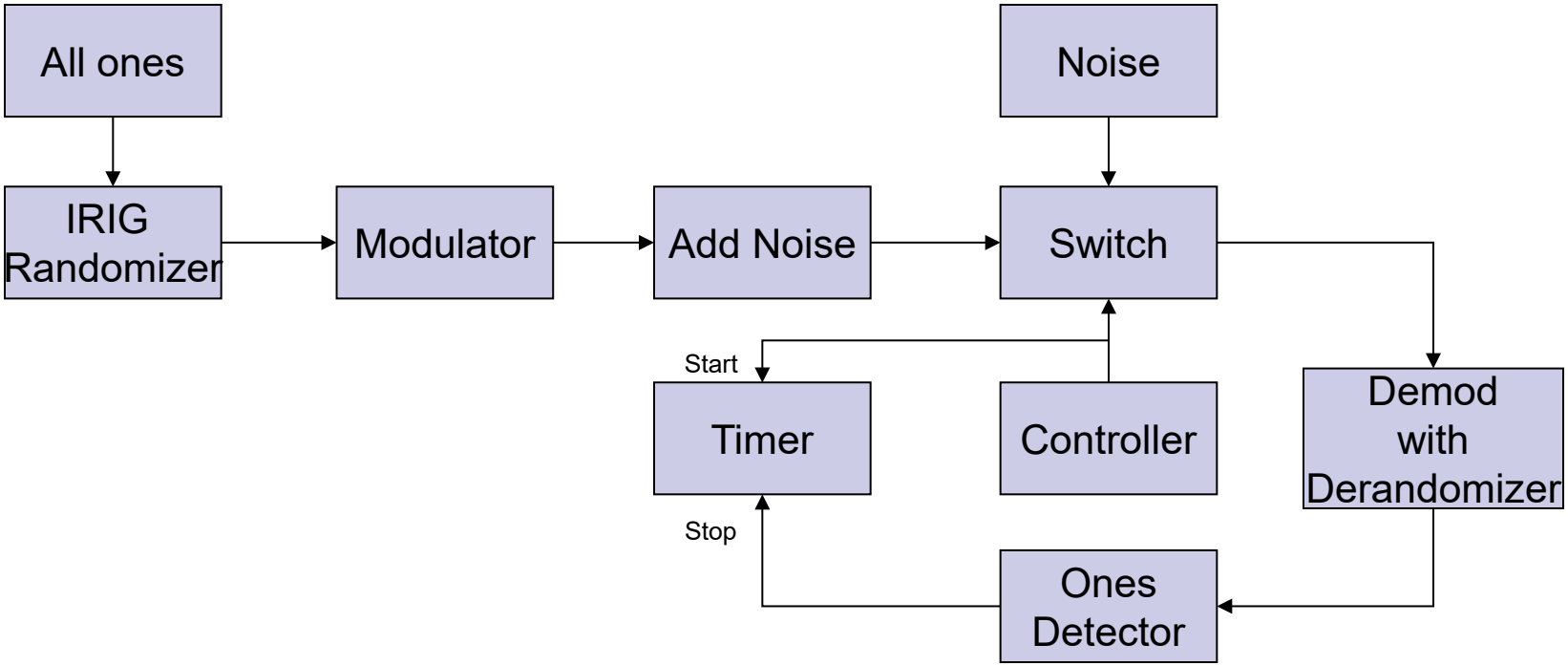
Synchronization

Telemetry Channels are Bursty



Synchronization Test

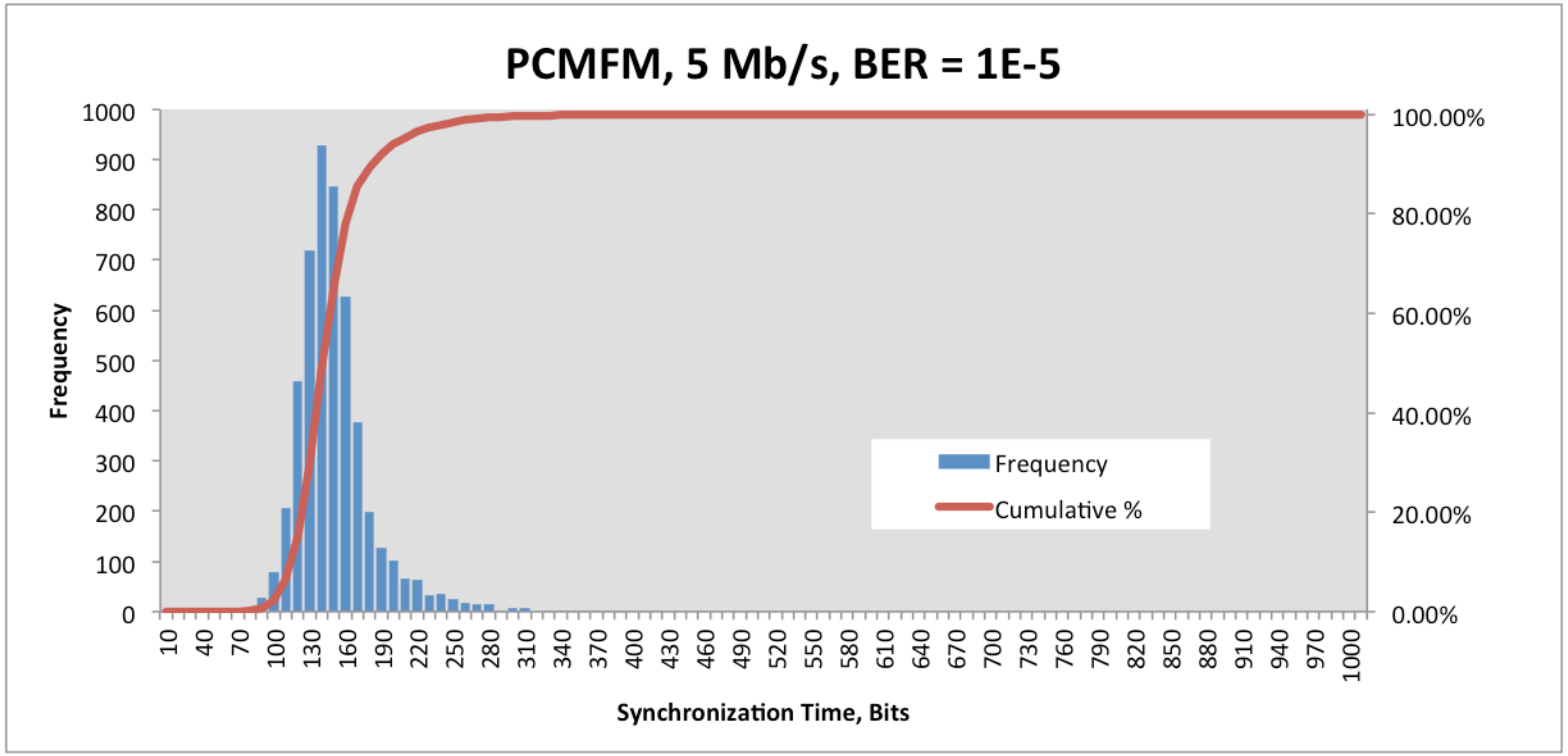
- IRIG 118-12, Procedure 7.4 (Flat Fade Recovery Test)
- Transmit randomized ones pattern
- Measure time at which output becomes “all (or mostly) ones”



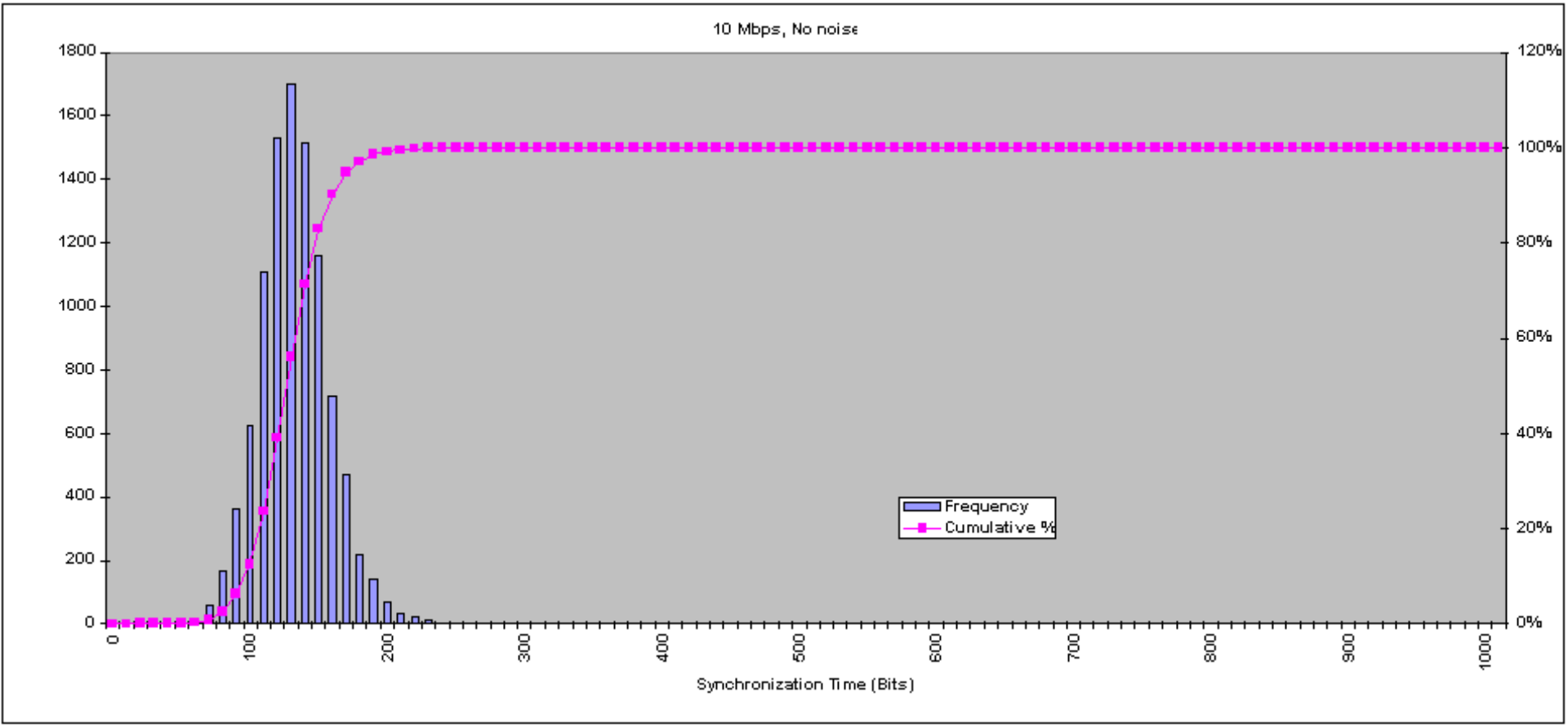
Synchronization Parameters

- 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

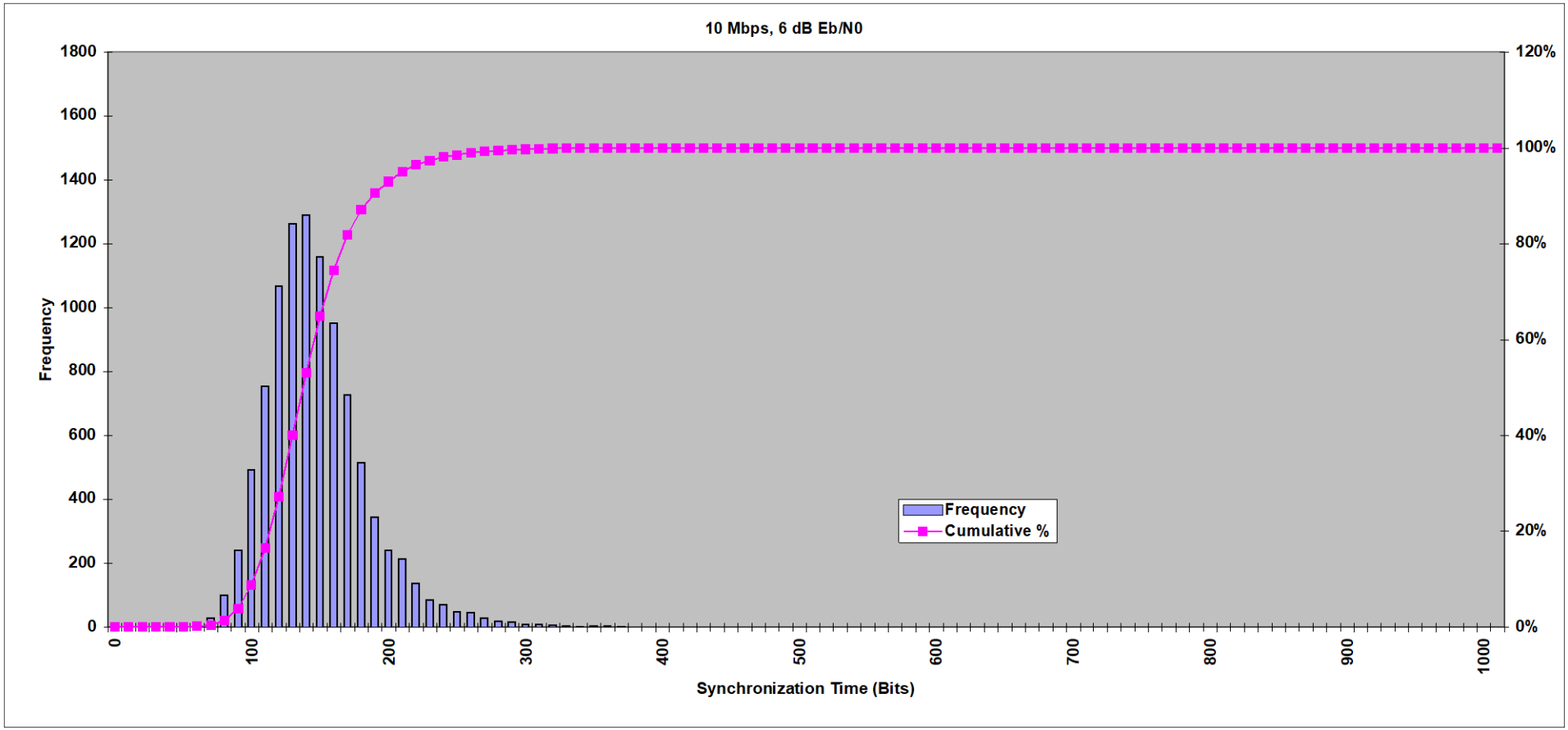
Tier 0 Synchronization, BER = 1e-5



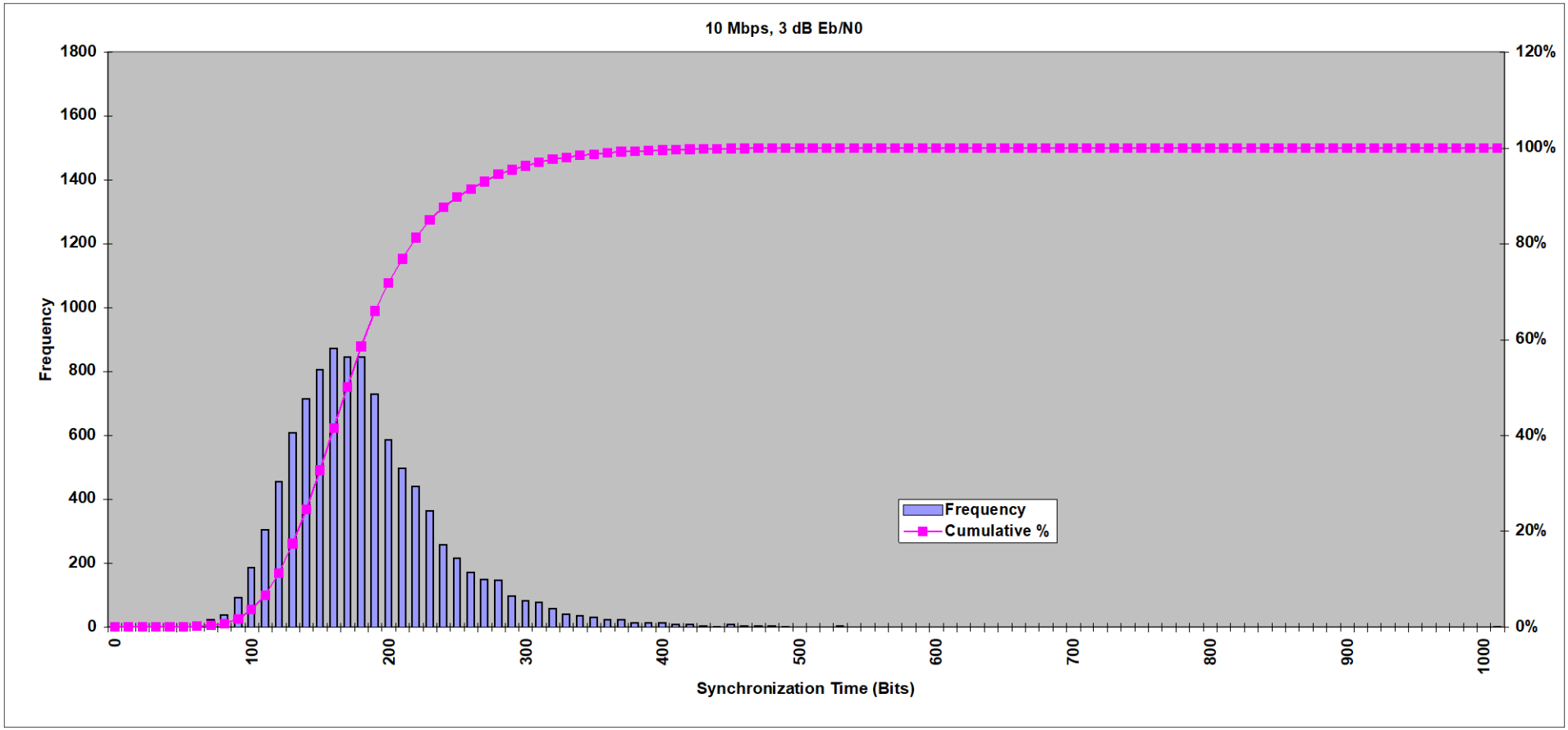
SOQPSK Synchronization, No Noise



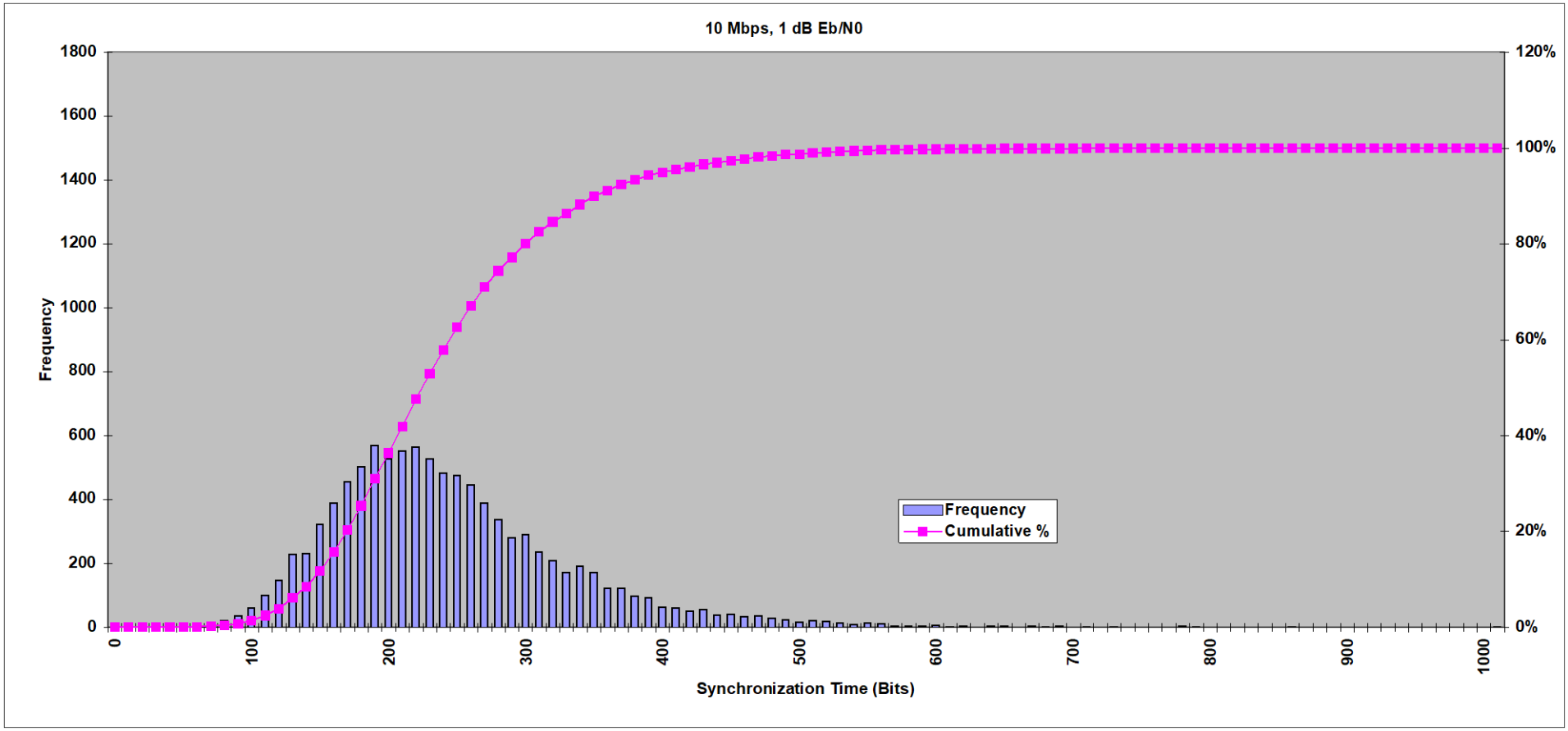
SOQPSK Synchronization, 6 dB



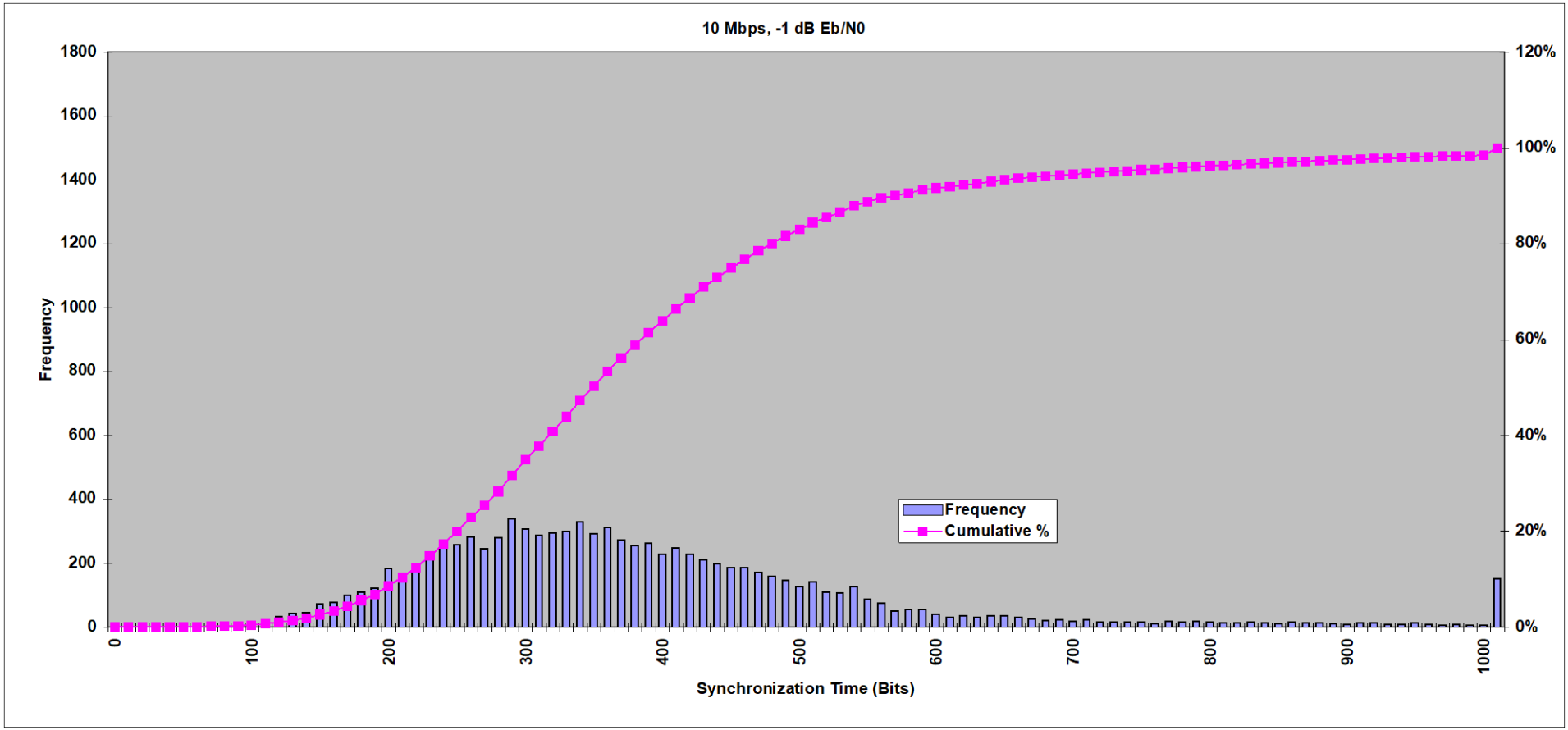
SOQPSK Synchronization, 3 dB



SOQPSK Synchronization, 1 dB



SOQPSK Synchronization, -1 dB



Synchronization Summary

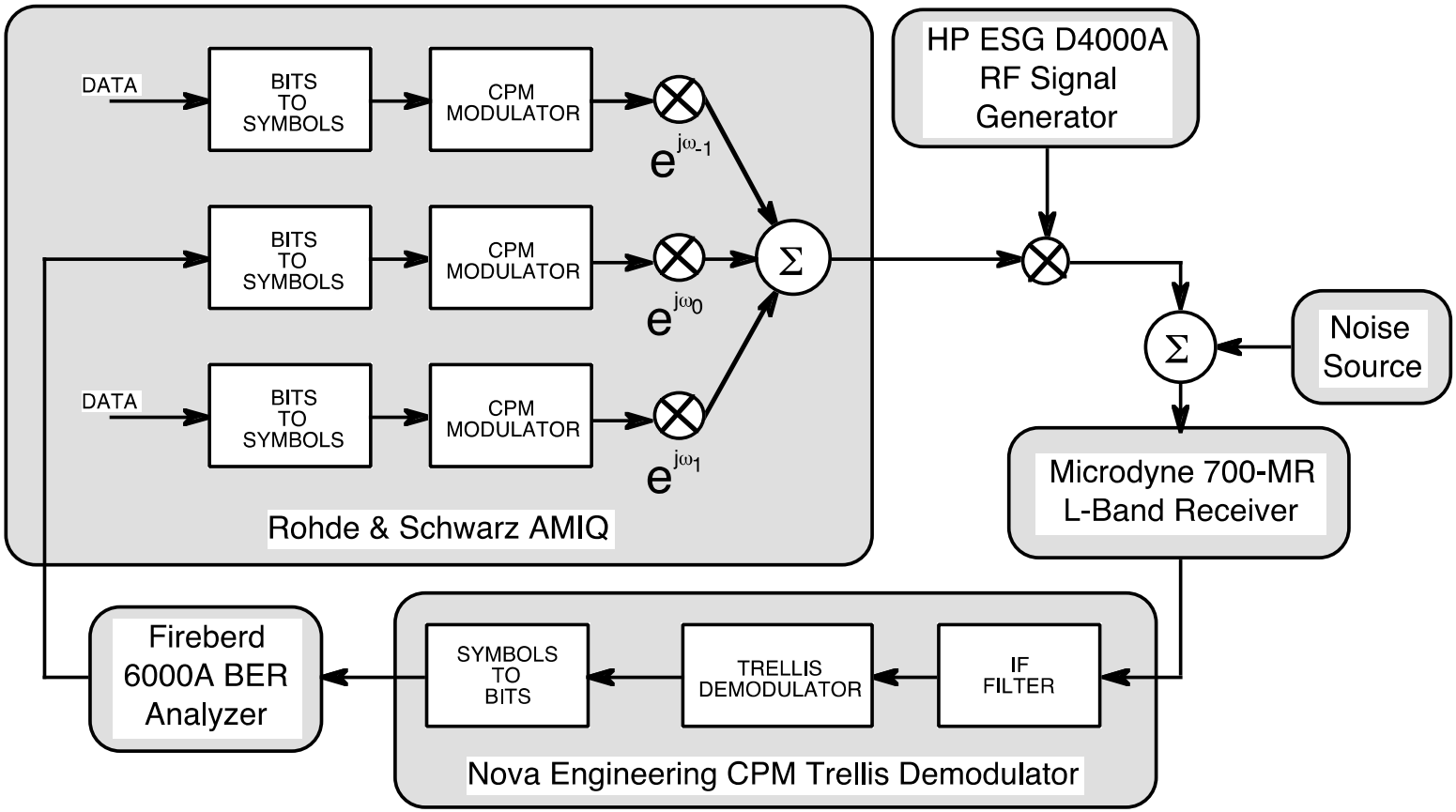
- The aeronautical telemetry channel is plagued with dropouts
- Rapid synchronization, and synchronization at low SNR, is the best means of minimizing the impact of these dropouts
- IRIG 118 defines test procedures for measuring sync time and sync thresholds
- Pay attention to synchronization performance!

Adjacent Channel Interference

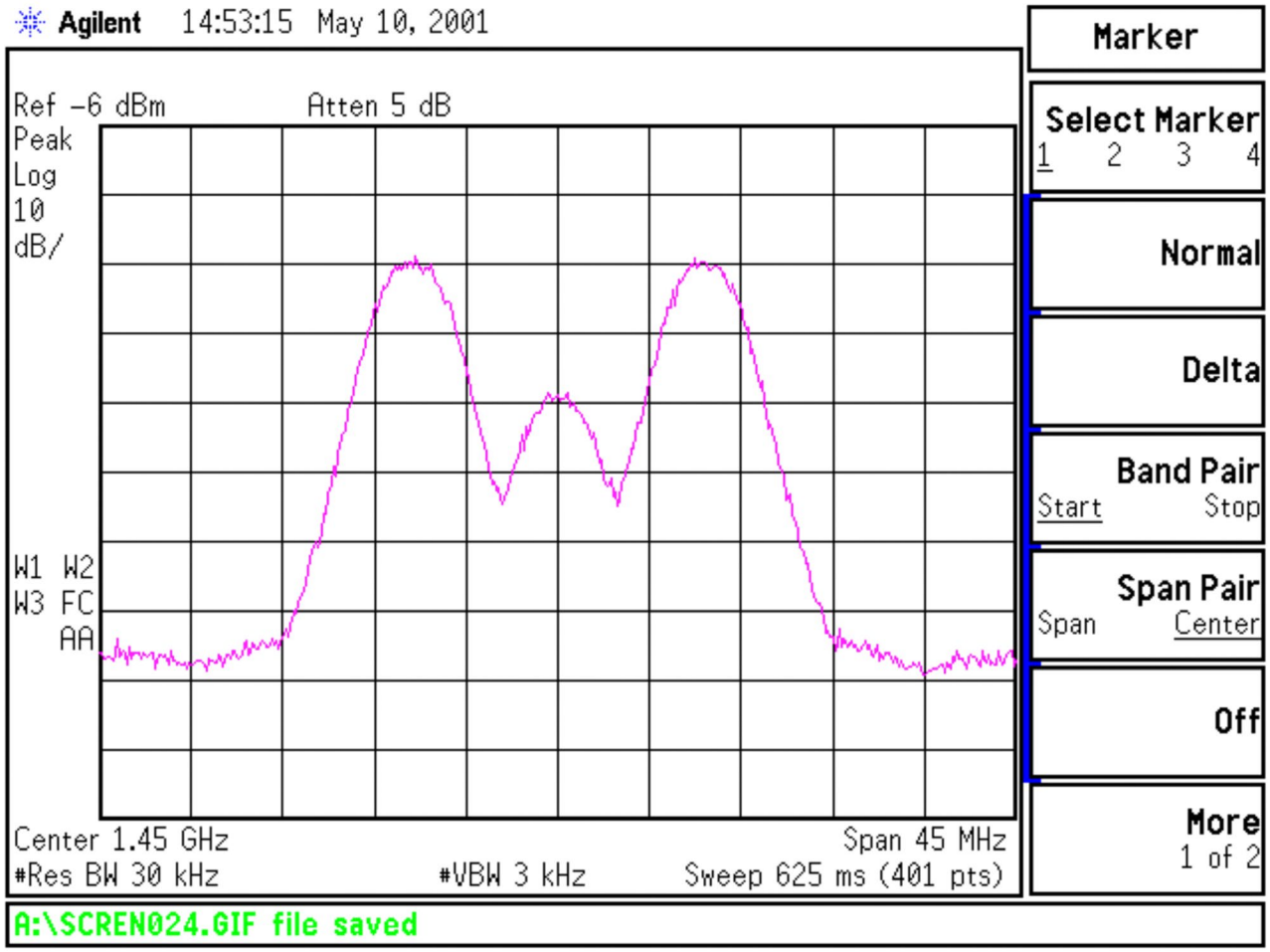
PSD is Half the Story

- 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**

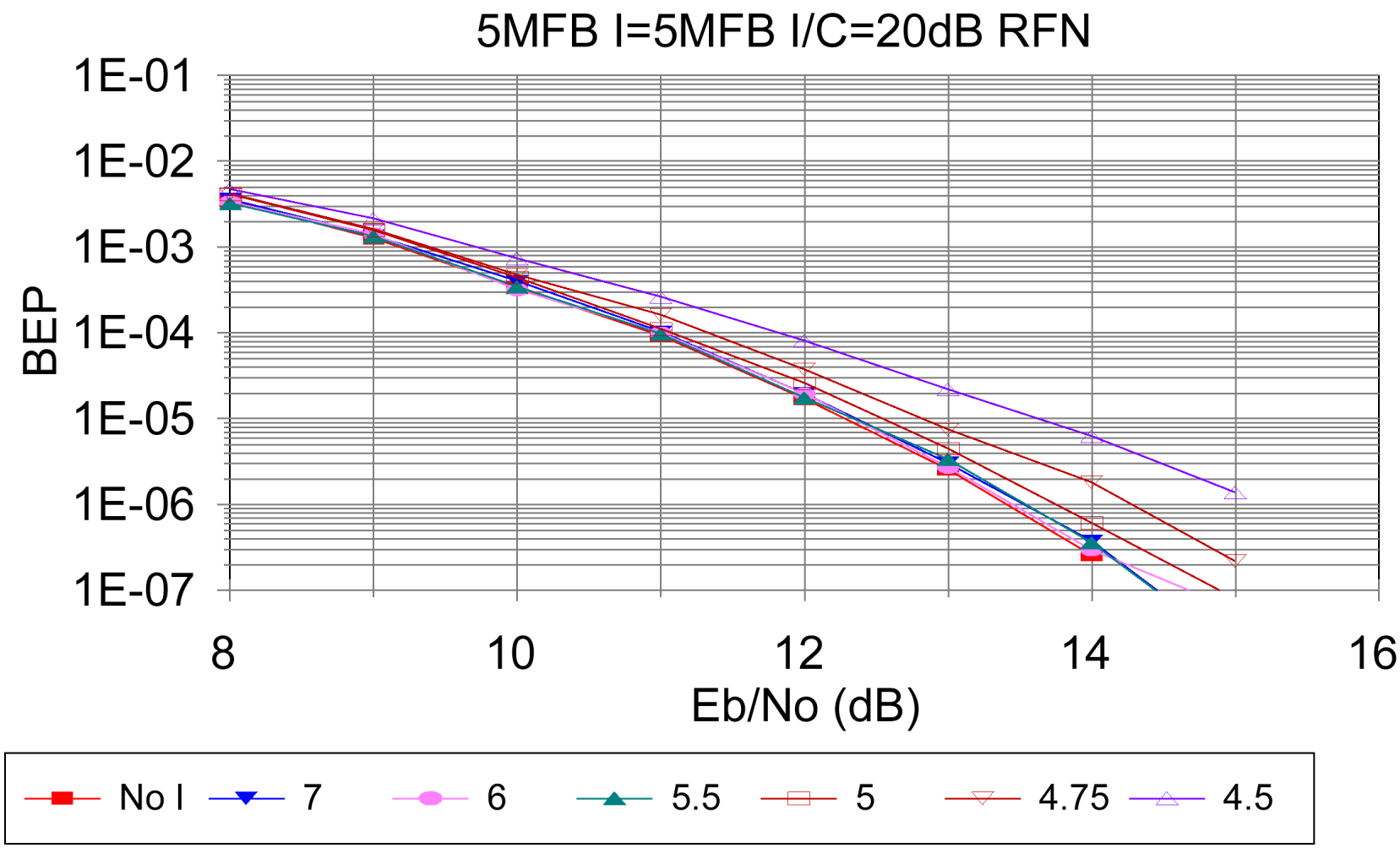
Multi-channel ACI Test Set



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

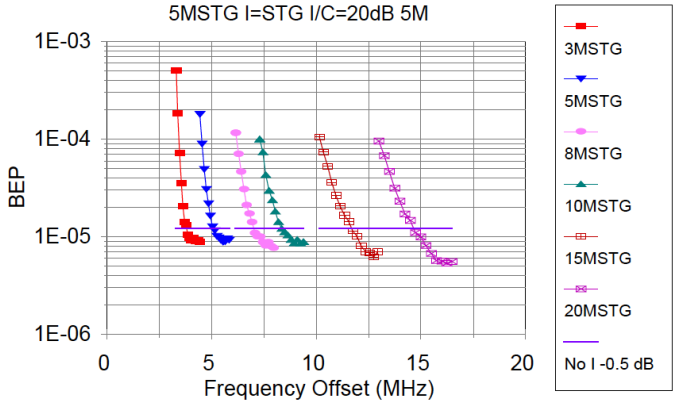


Figure 5. 5 Mbps SOQPSK-TG.

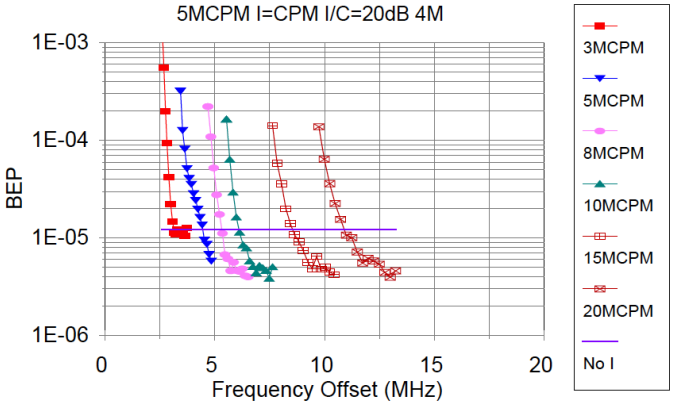


Figure 6. 5 Mbps multi-h CPM.

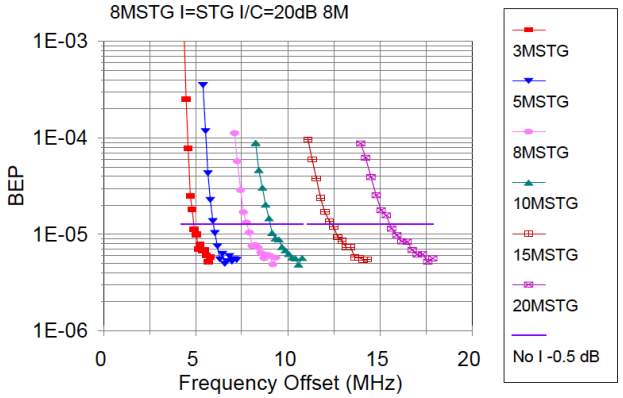


Figure 7. 8 Mbps SOQPSK-TG with 8 MHz IF BW.

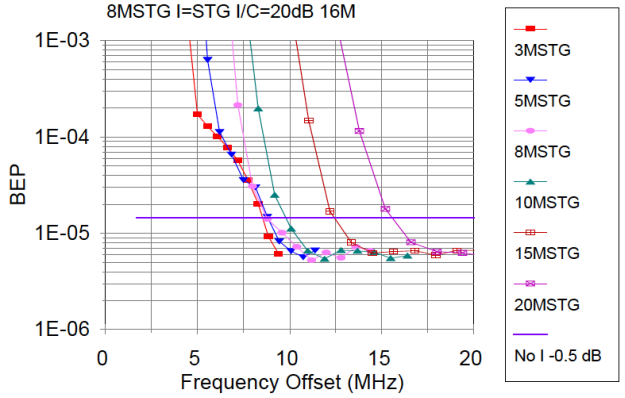
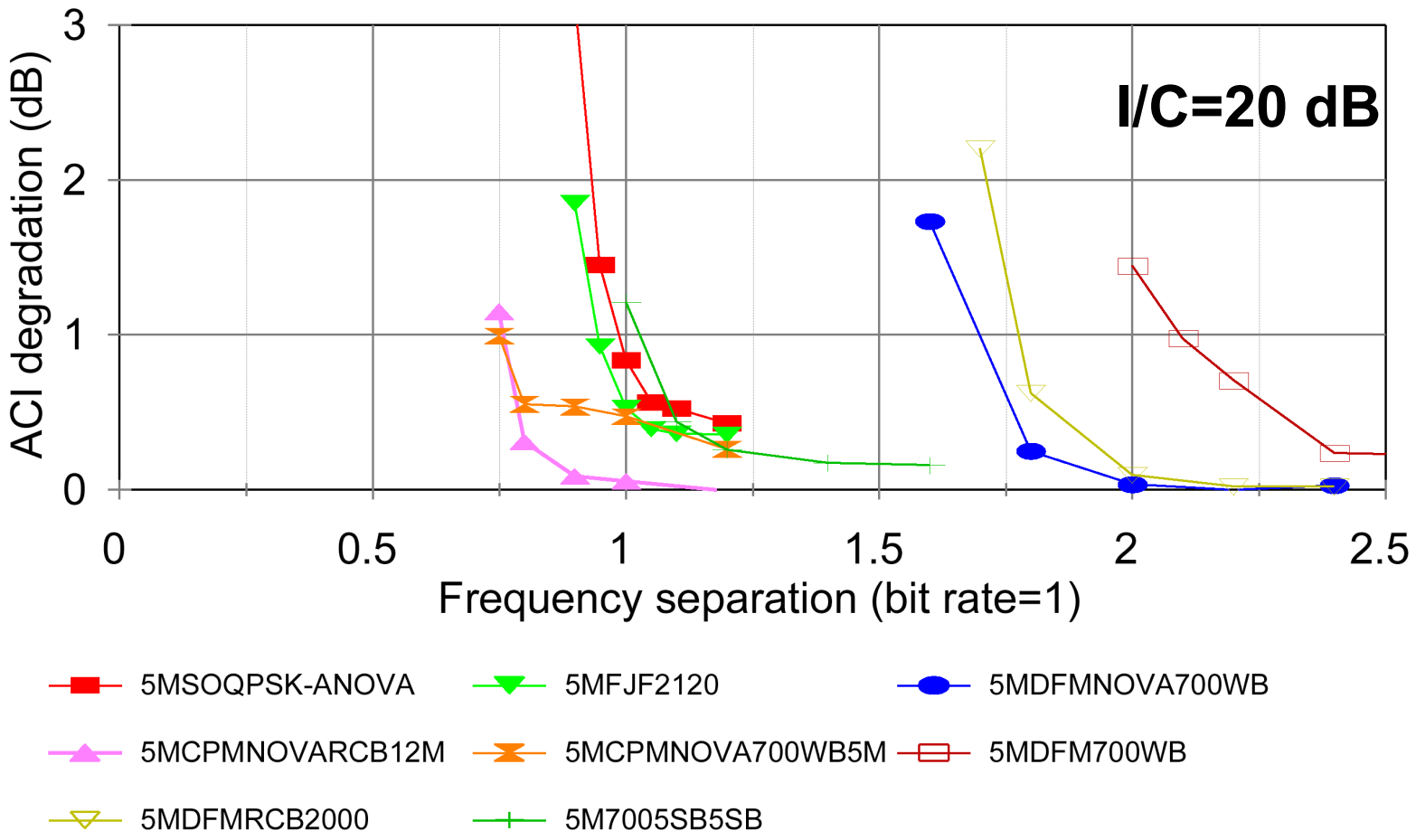


Figure 8. 8 Mbps SOQPSK-TG with 16 MHz IF BW.

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

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.

Quasonix

Multipath Propagation

Brace yourself!

Greek symbols ahead!

Multipath Propagation

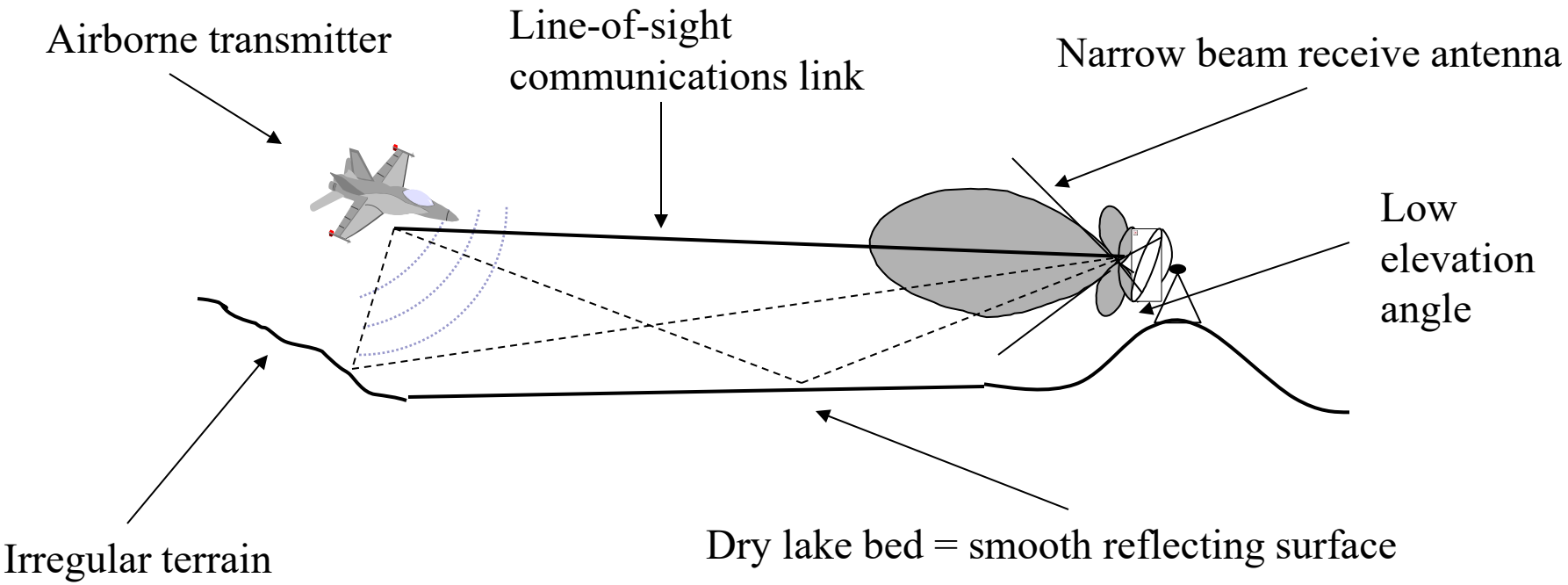


Figure from Dr.Michael Rice, BYU Telemetry Laboratory, Provo, Utah. Reprinted by permission of the author.

Assumptions

- Channel can be modeled as a linear time-invariant (LTI) system over "short enough" time interval

Complex-valued path loss

$$h(t) = \sum_{k=0}^{L-1} \Gamma_k e^{-j\omega_c \tau_k} \delta\left(t - \tau_k\right)$$

$$= \delta(t) + \underbrace{\sum_{k=1}^{L-1} \Gamma_k e^{-j\omega_c \tau_k} \delta\left(t - \tau_k\right)}$$

Line-of-sight propagation path

L-1 multipath propagation paths

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

2-Ray Transfer Function

- Magnitude of first multipath reflection: Γ_1
- "sweep rate" of multipath null ~ $\omega_c \dot{\tau}_1 + \dot{\theta}_{\Gamma_1}$

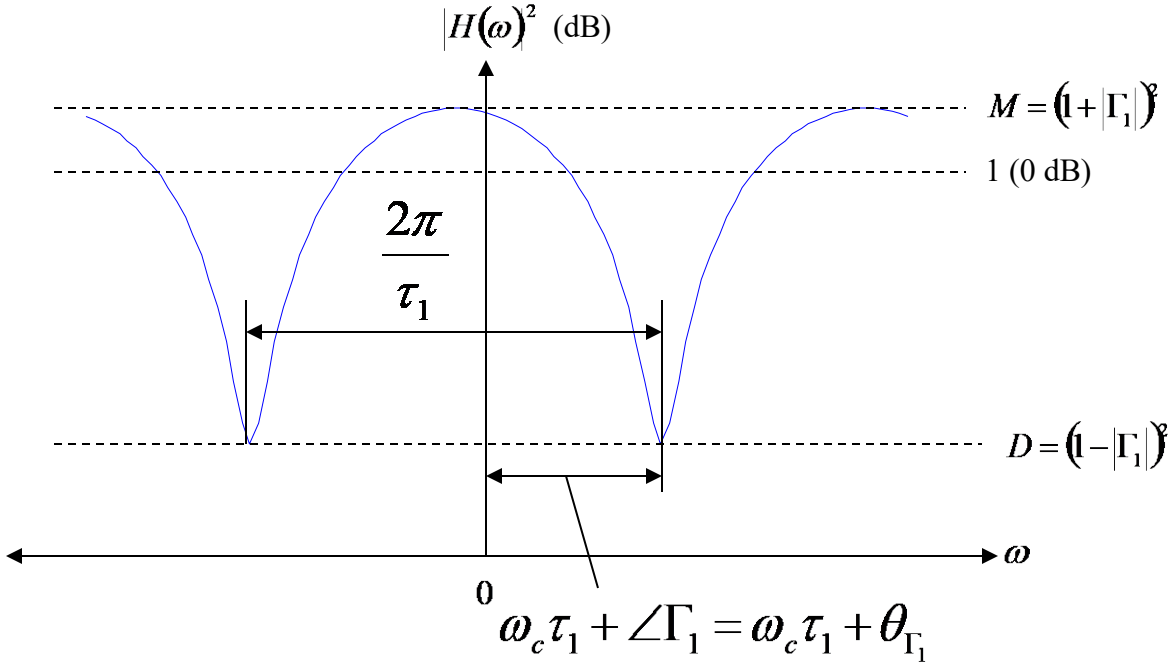
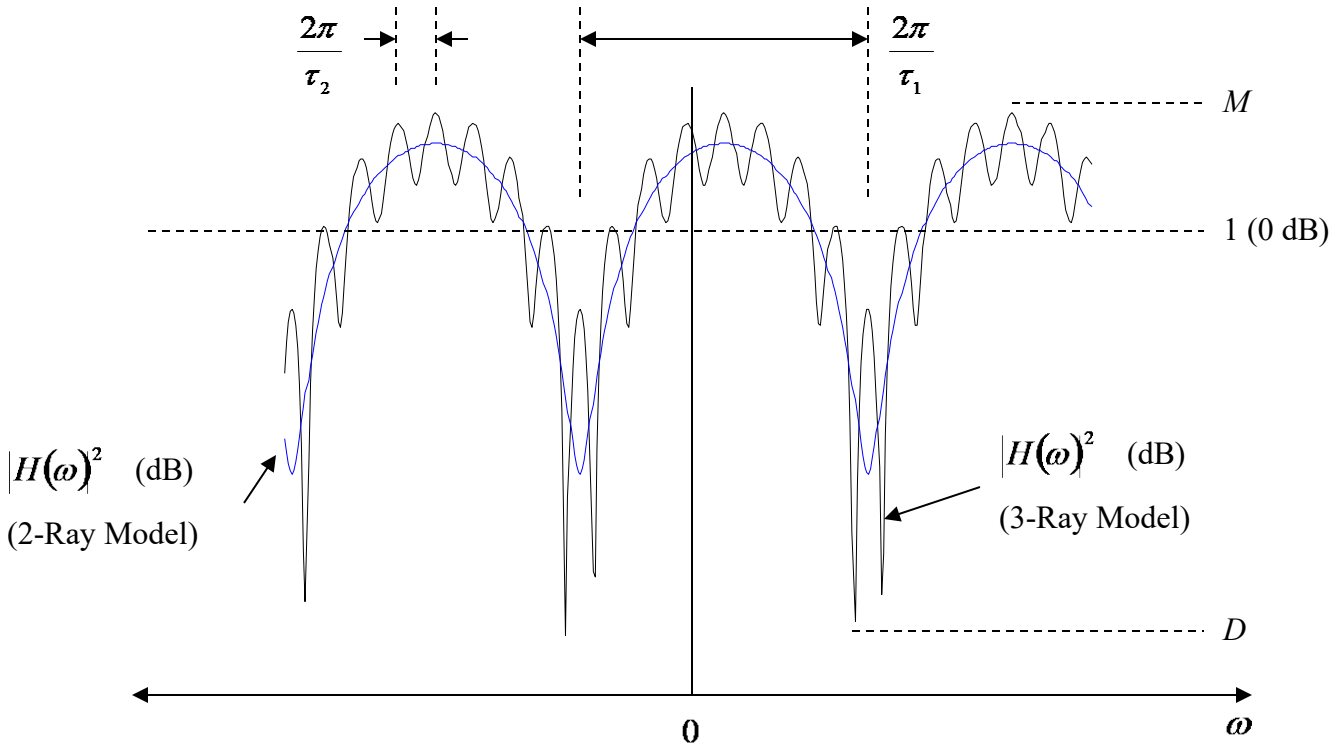


Figure from Dr.Michael Rice, BYU Telemetry Laboratory, Provo, Utah. Reprinted by permission of the author.

3-Ray Transfer Function

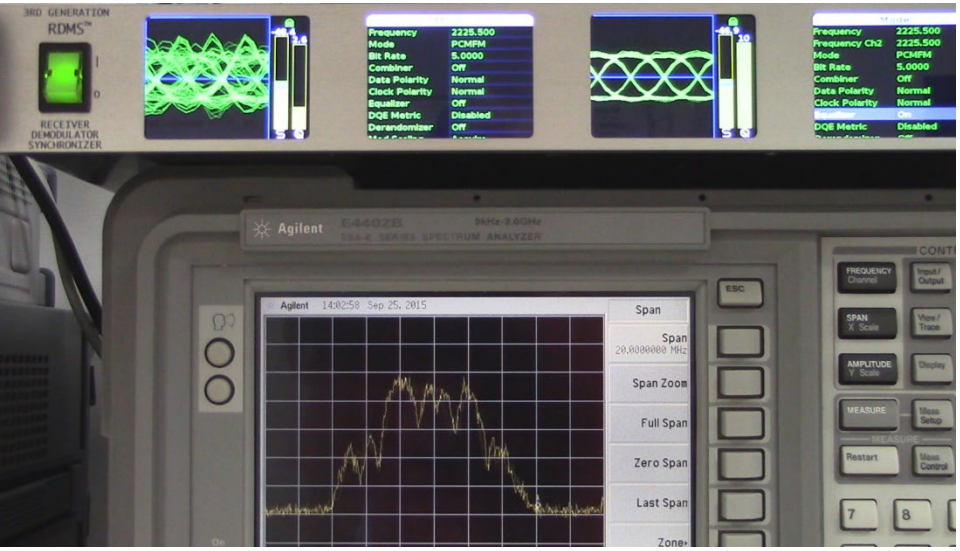


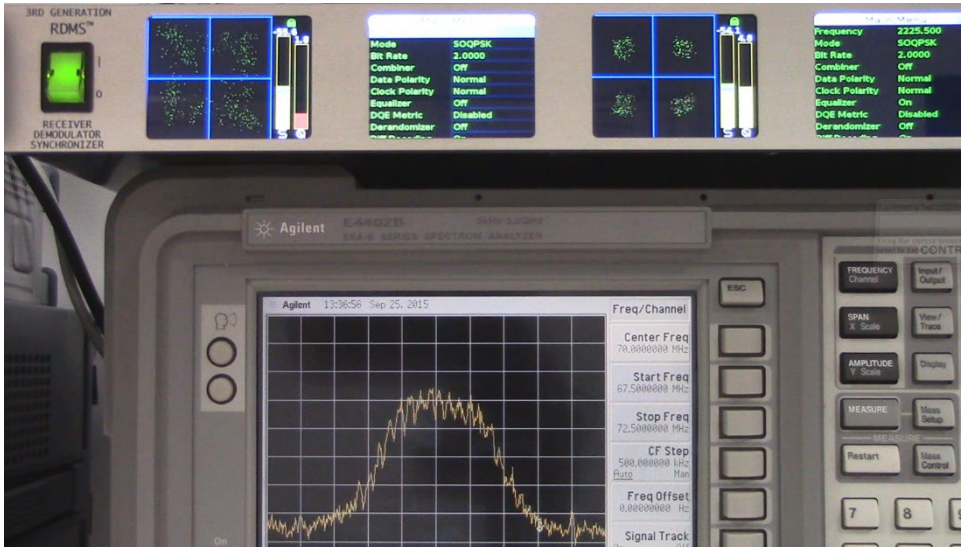
$$\text{Assumes } \tau_1 < \tau_2 \text{ and } |\Gamma_1| > |\Gamma_2|$$

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

Multipath on the Tarmac

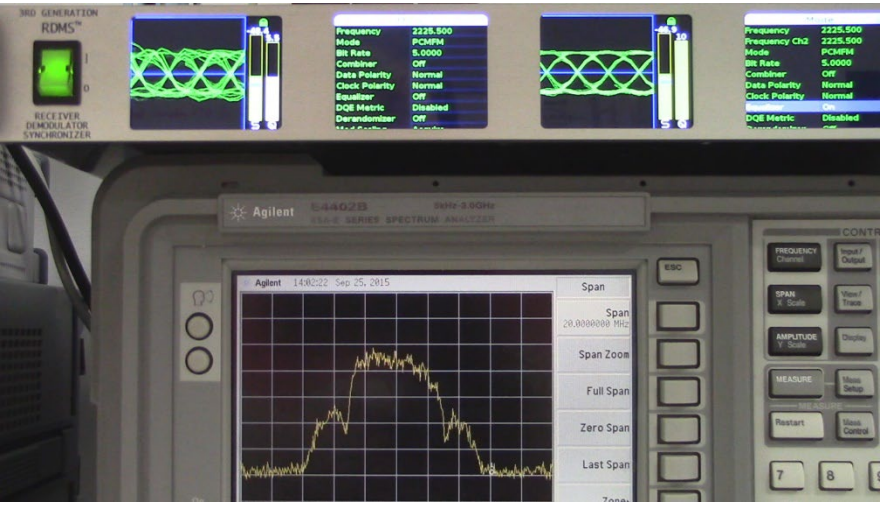
- Nearly static, frequency selective, long delays



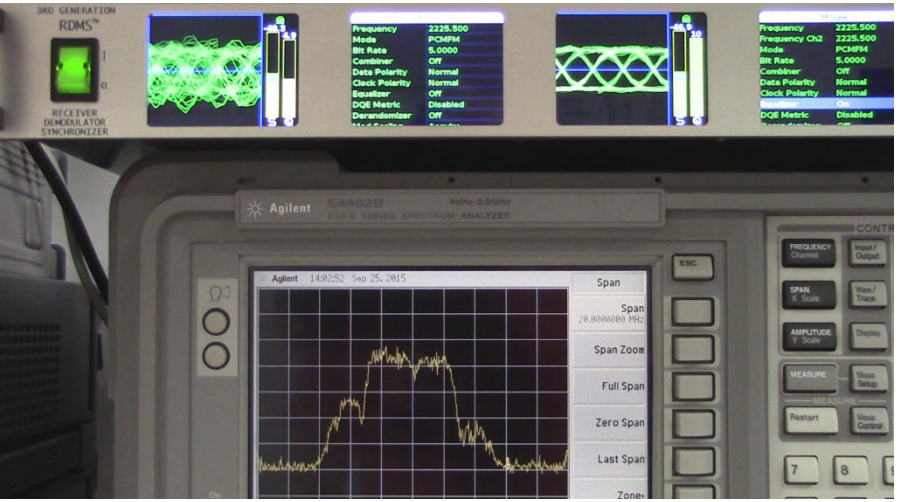


Multipath in Flight

- Dynamic, frequency selective and flat fading, various delays









ference
nix.com

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 “Adaptive Equalizer” discussion

Quasonix

DSP Techniques for Telemetry

Receiver-Only DSP Techniques

- Receive-side processing, no transmitter impact
- Maximal ratio combining – optimal against AWGN
  - Polarization diversity
  - Frequency diversity
- Data Quality Metric (DQM) / Data Quality Encapsulation (DQE)
  - IRIG 118-22, Chapter 11
- Adaptive equalization
  - Powerful tool against multipath
- Best channel selection
  - Handles the “non-combinable” cases
- Best source selection
  - Combats all forms of signal impairment

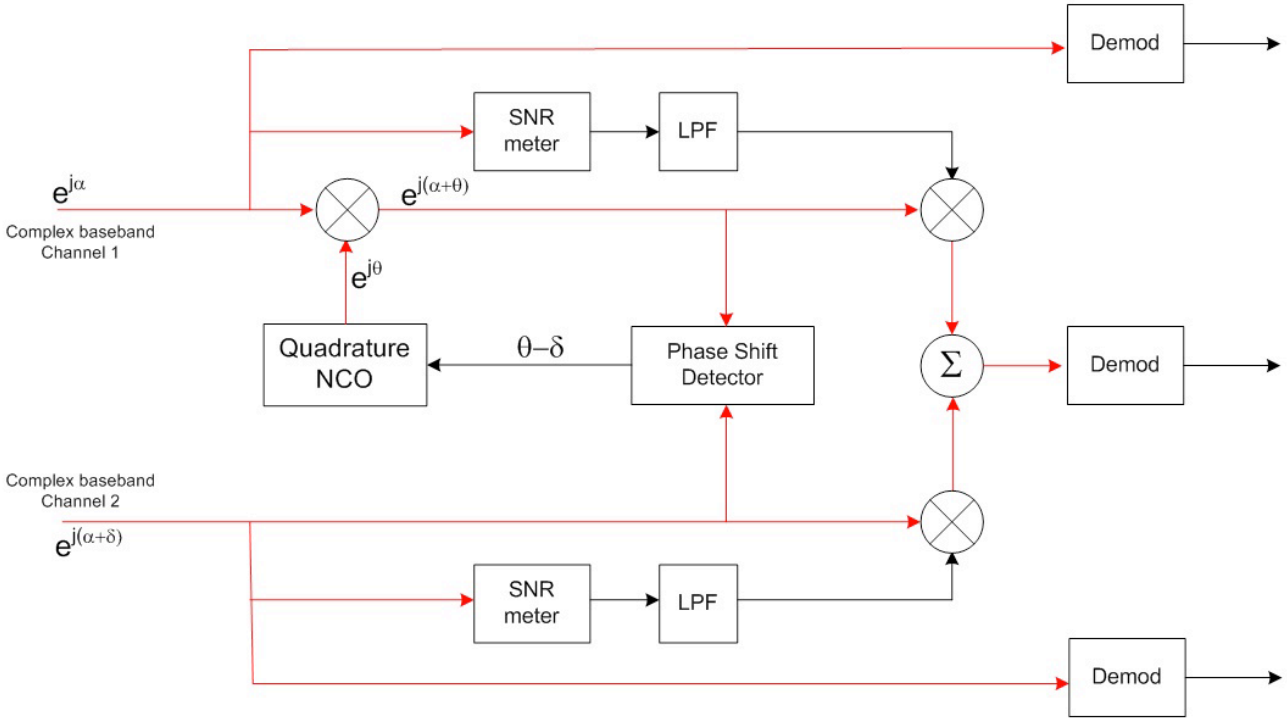
Quasonix

Diversity Combining

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

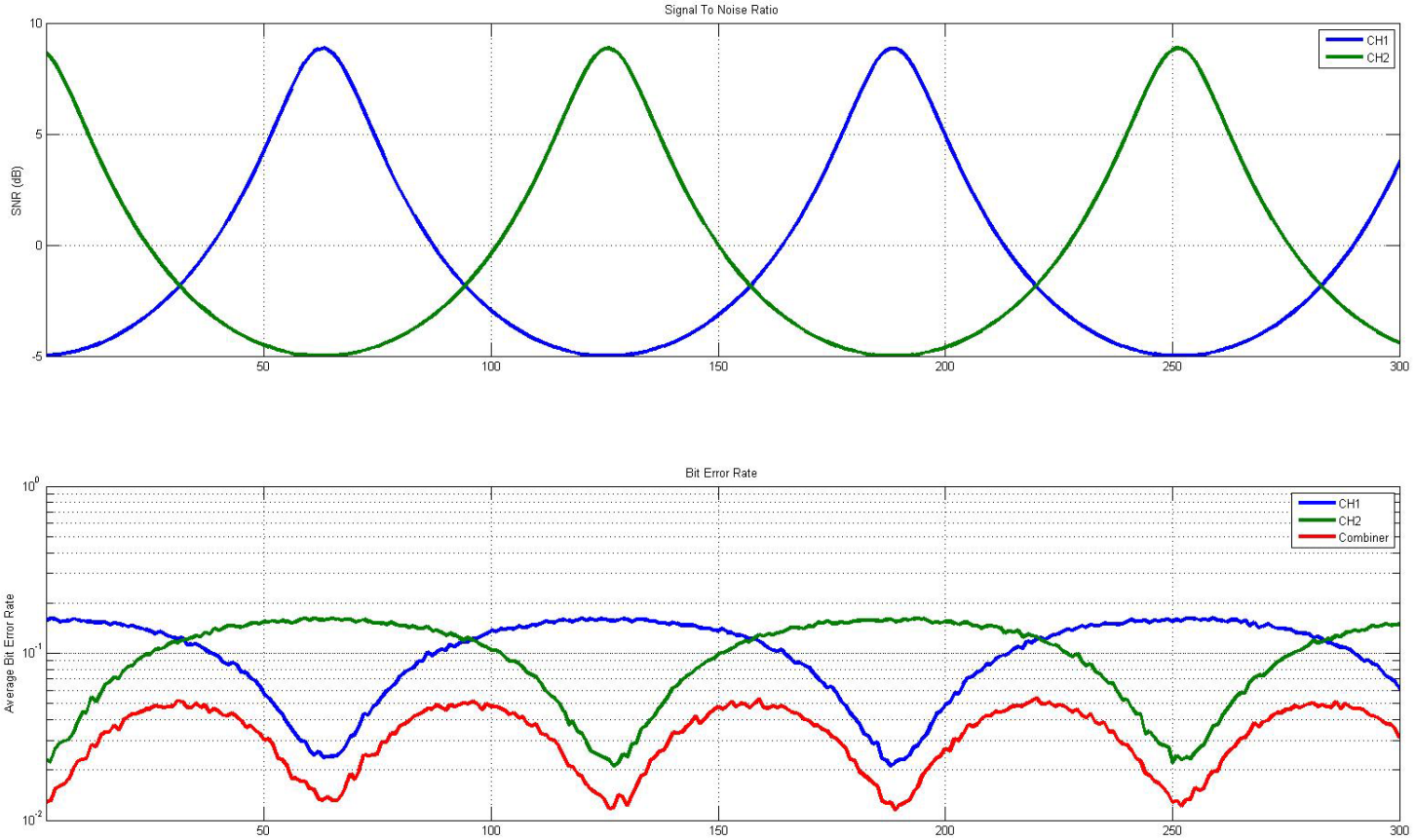
Maximal Ratio Combining



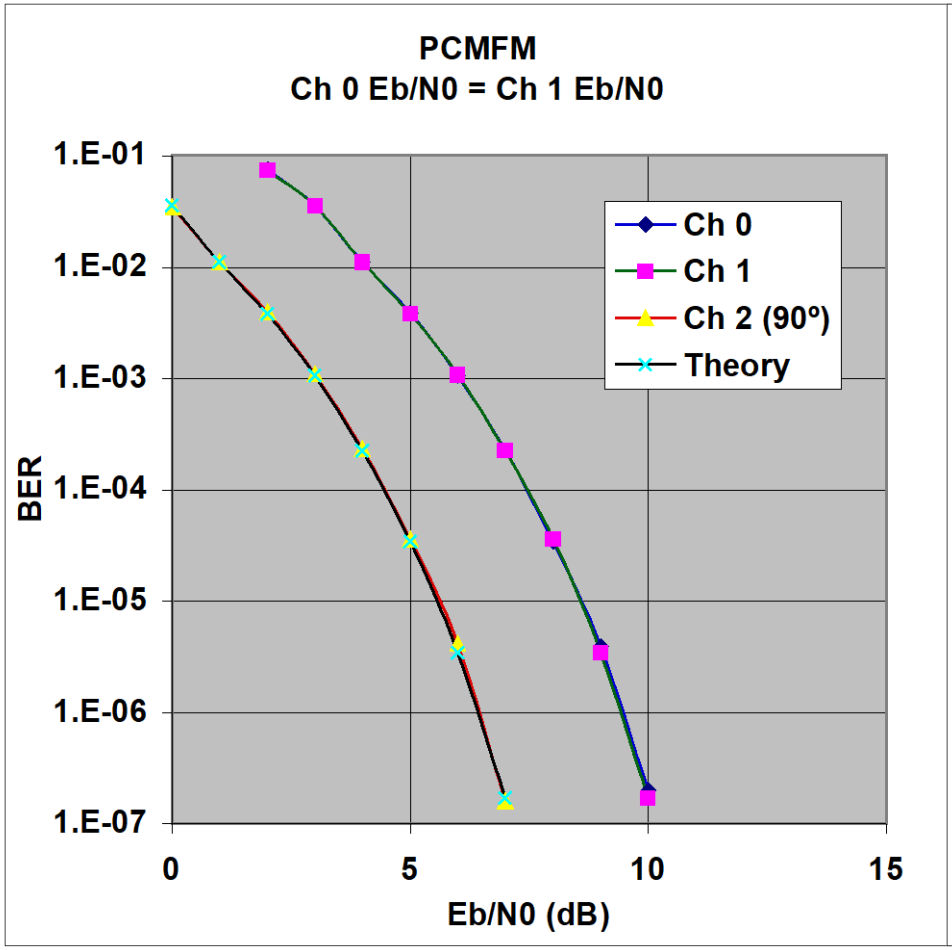
- Weight each signal in proportion to its SNR and add
- Yields optimum SNR on combined channel **<u>in AWGN</u>**
- $SNR_{combined} = SNR_a + SNR_b$

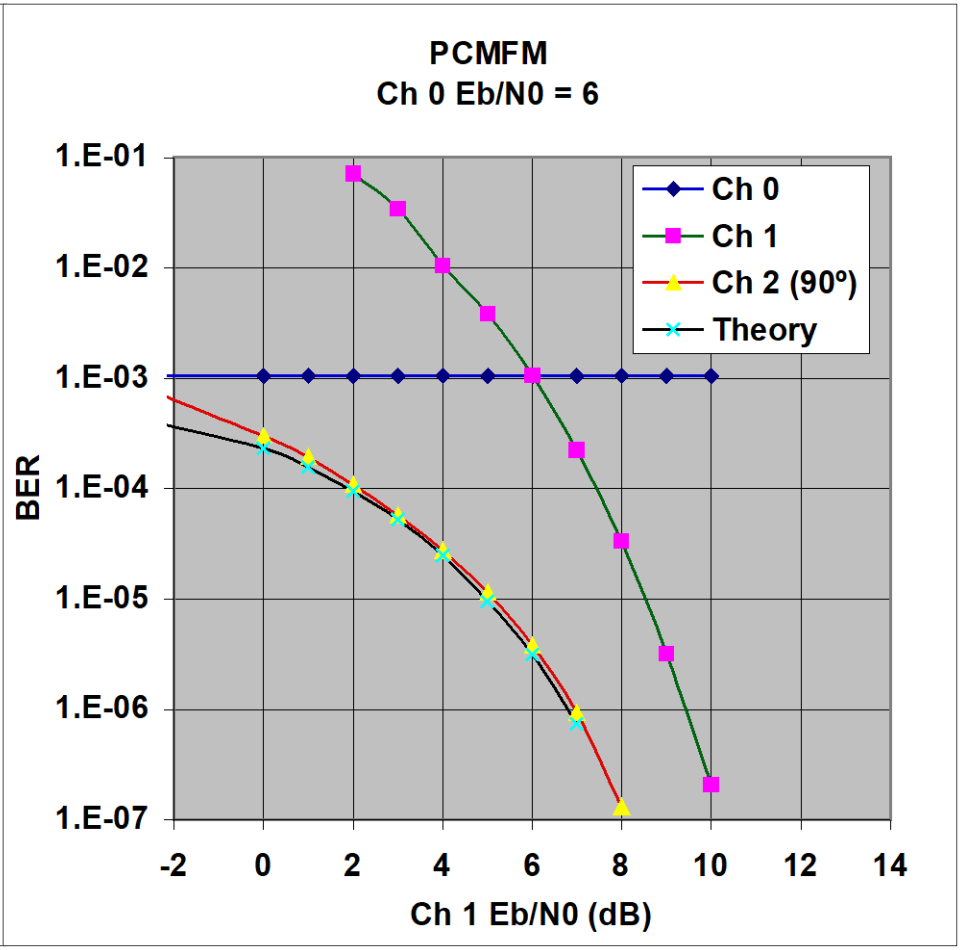
Maximal Ratio Combining

BER Results - Fading Signals

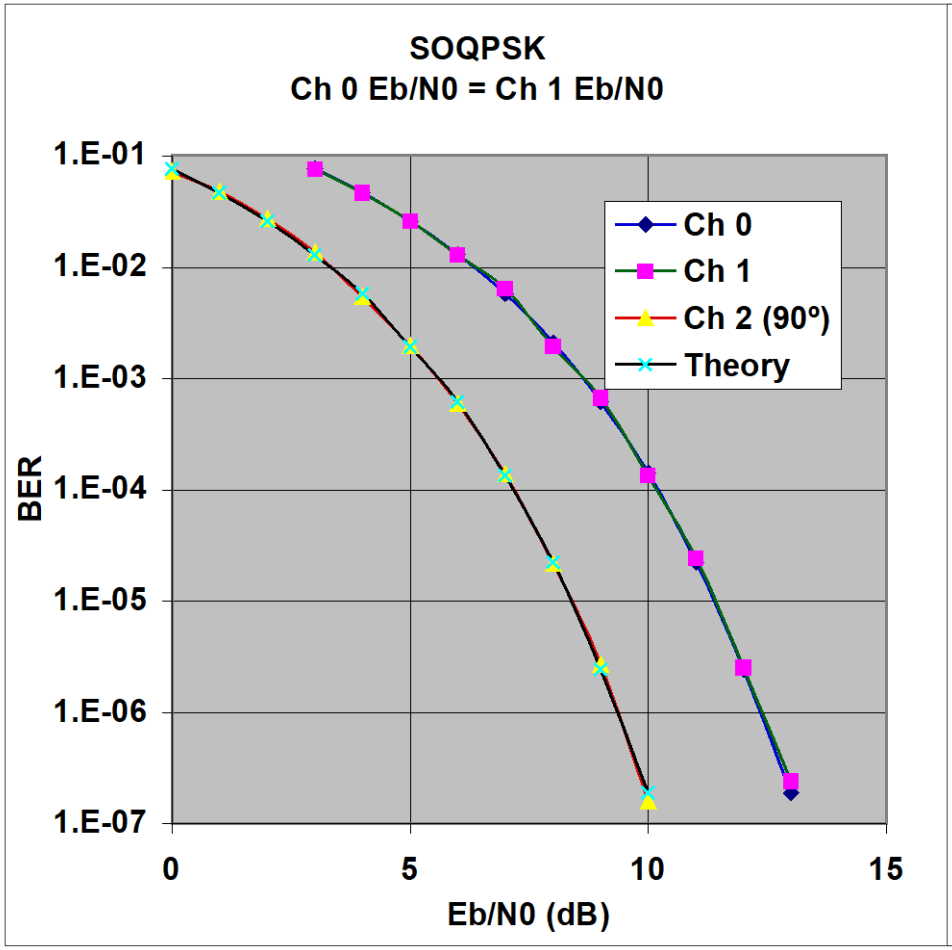


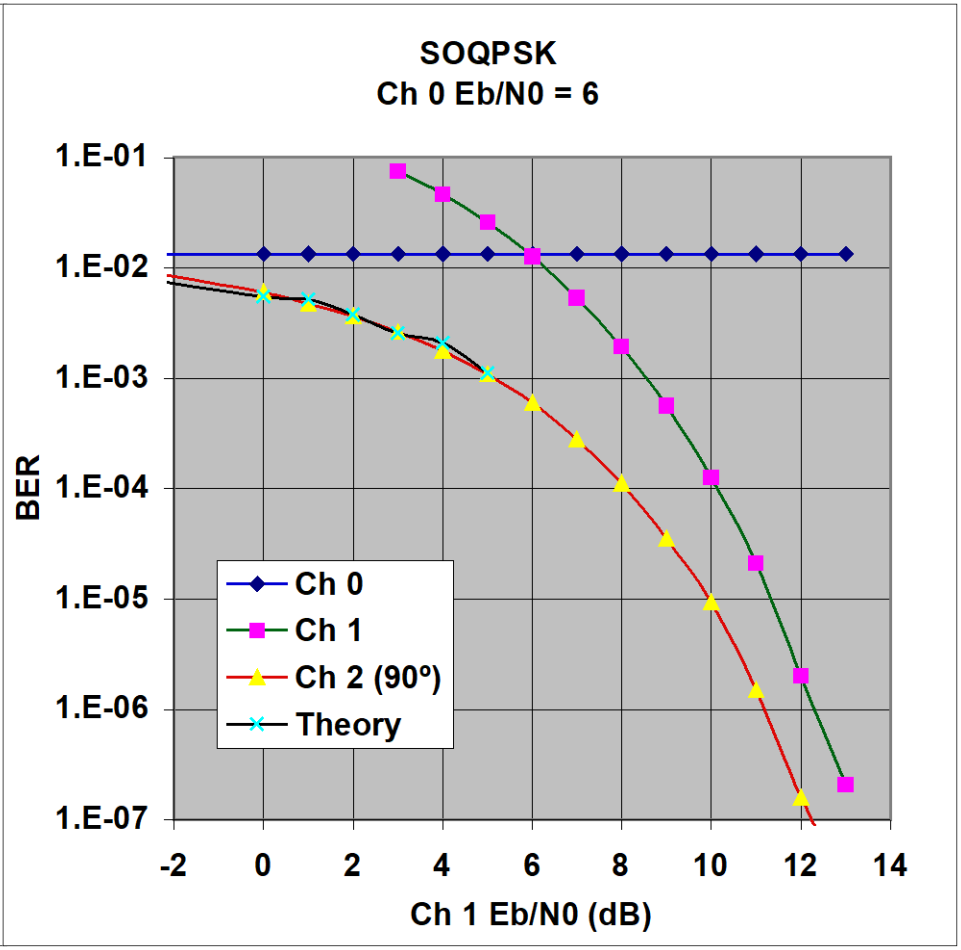
Measured Combiner BER - Tier 0



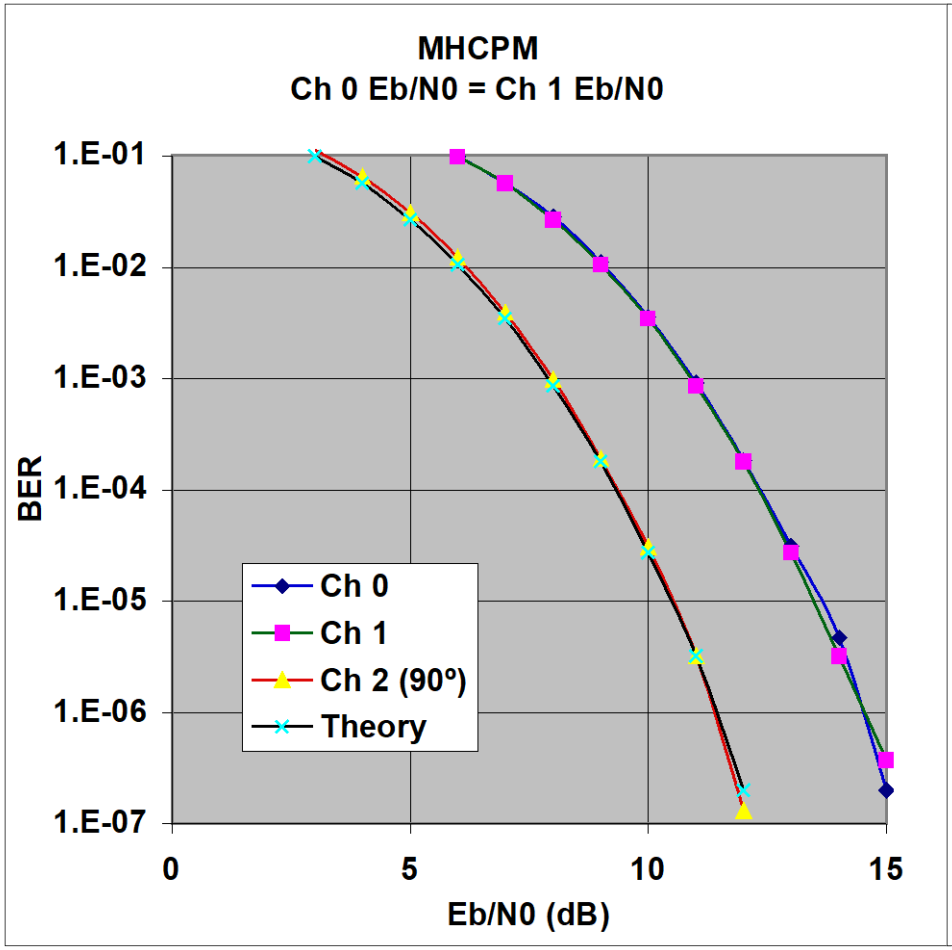


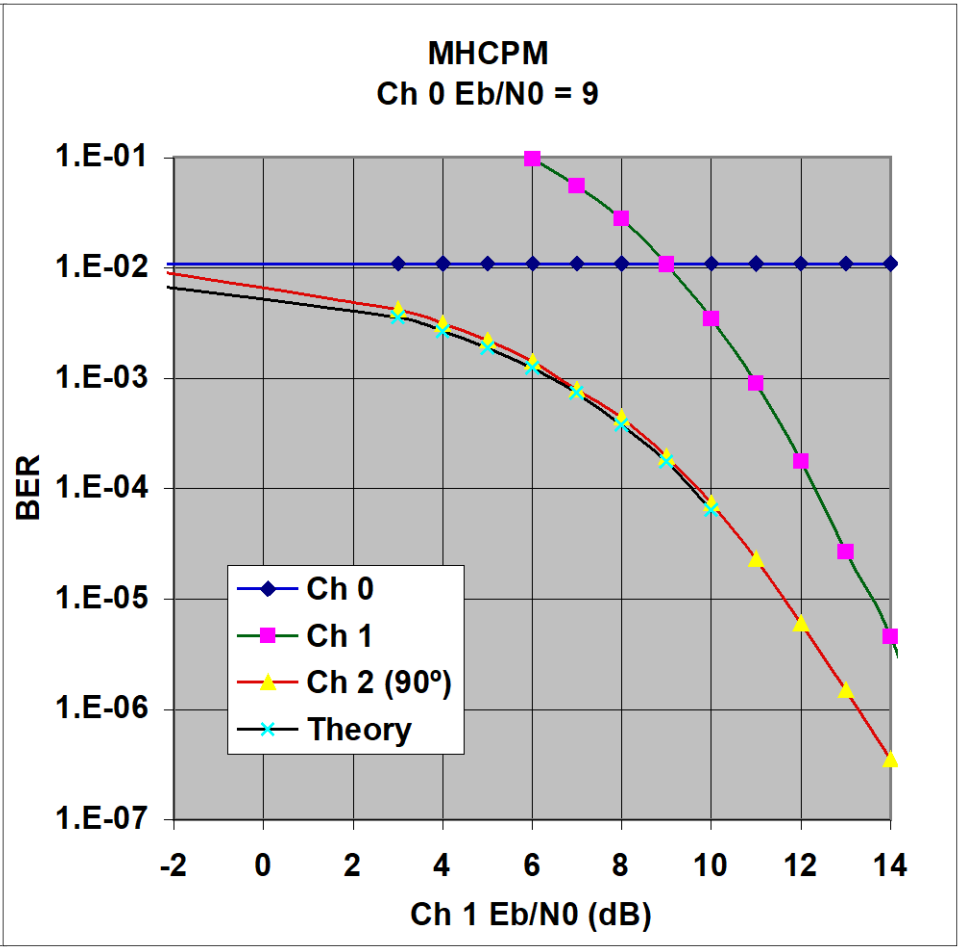
Measured Combiner BER - Tier I





Measured Combiner BER - Tier II





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!

Quasonix

~~Let's Eat Students!~~

Let's Eat, Students!

Commas Save Lives

See you back here at _____ PM

Quasonix

Data Quality Metric (DQM)

DQE/DQM Evolution

Milestones	Contributions
2015 Hill ITC Paper - "Metrics and Test Procedures for Data Quality Estimation in the Aeronautical Telemetry Channel"	DQE/DQM transport protocol to support efficient multiple source TM combining
2015 Rice/Perrins ITC Paper -"Maximum Likelihood Detection from Multiple Bit Sources"	Optimal combining recipe and performance analysis - Maximum Likelihood Bit Detection (MLBD)
IRIG 106-22 Chapter 2, Appendix 2-G - "Standards for Data Quality Metrics and Data Quality Encapsulation"	Standardized in IRIG 106-22
2022 Temple ITC Paper - "Some Thoughts on Testing the Data Quality Metric"	Proposed DQE/DQM verification test methods
IRIG 118-22 Release 2 Volume 2., Chapter 11, 2022 -"Test procedures for assessing telemetry receiver data quality metrics"	DQE/DQM verification test methods standardized in IRIG 118-22
Industry Day on DQE/DQM assessment 10/28/22	Initial multi-vendor DQE/DQM performance/compatibility testing
2023 Geoghegan ITC Paper -"Data Quality Metric (DQM) – How accurate does it need to be?"	Determined relationship between worst case system MLBD performance loss and DQM estimation error
****** Industry Day 2 on DQE/DQM assessment 10/25/24 ******	Multi-vendor DQE/DQM performance/compatibility testing (all tests with real-time results)

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

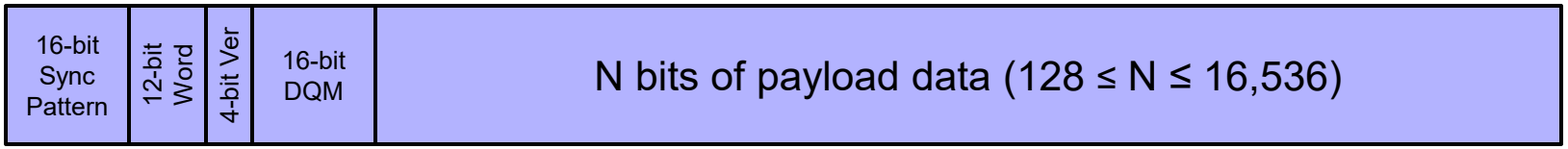
Definition of DQM

- 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

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	11.00
1E-12	1.00000E-12	65535	12.00

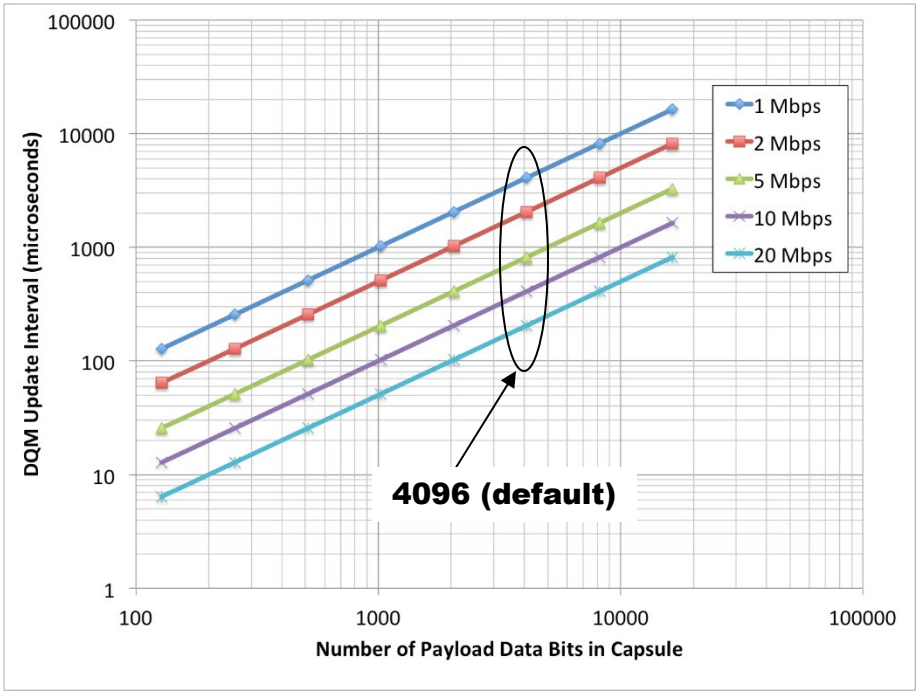
DQE Format

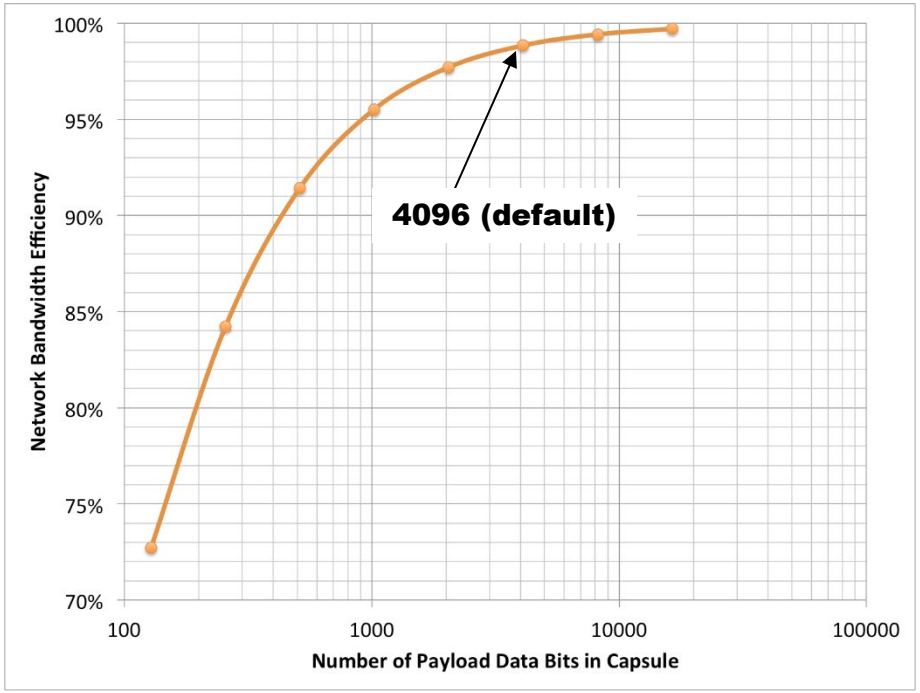
- Header
  - 16-bit sync pattern (0xFAC4)
    - MSB first: 1111101011000100
  - 12-bit word, reserved for future use (currently 0)
  - 4-bit IRIG 106 version number
  - 16-bit DQM
- Payload data
  - User selectable length, (128 ≤ N ≤ 16,536)
  - Defaults to 4096



DQM Parameter Trades

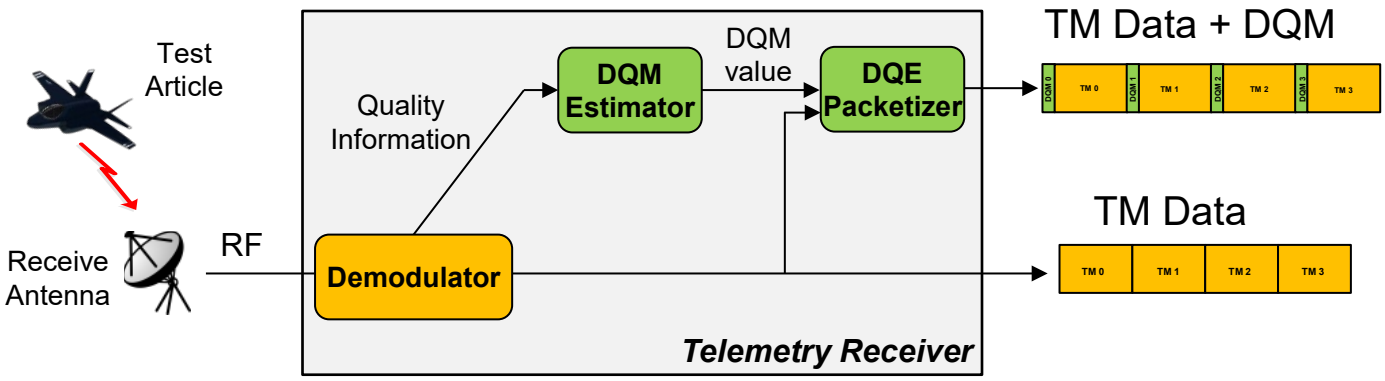
- Choice of N impacts both DQM update rate and network efficiency





DQE Stream Builder

- Insert DQM value
  - 16-bit value that indicates the BEP for a 'single' block of data bits
  - Periodically inserted in TM data output stream
  - Some receivers can do DQE and non-DQE simultaneously

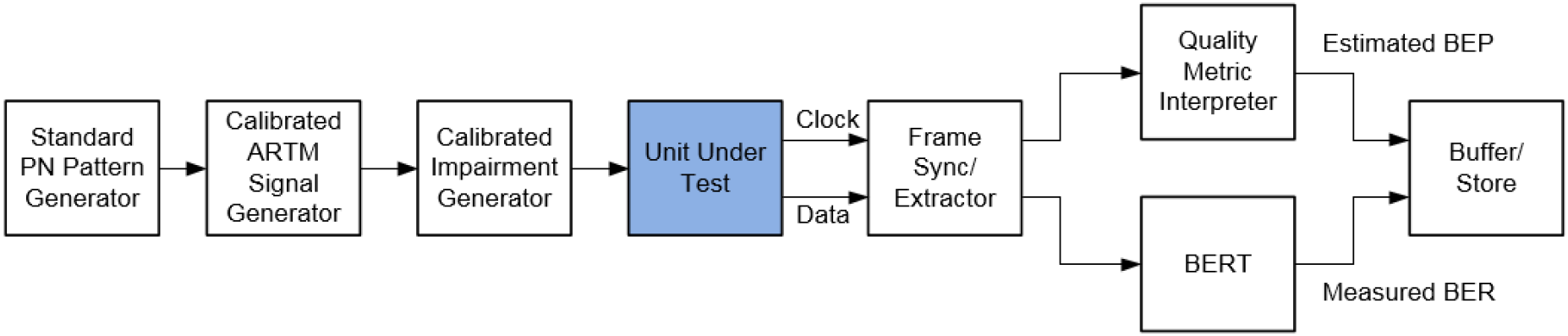


Calibration of DQM

- 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
  - Multipath
- Test procedures have been developed to evaluate accuracy of DQM
  - DQE/DQM verification test methods standardized in IRIG 118-22 V2 R2

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 analyzed on a frame-by-frame basis



IRIG 118-22 Ch. 11

- Defines 6 standard DQM tests

Table 11-2. Test Matrix for Data Quality Metric Testing	
Test Number	**Test Description**
11.1	BER vs BEP with Additive Noise
11.2	DQM (BEP) Step and Dwell Response
11.3	BER vs BEP with Adjacent Channel Interference
11.4	BER vs BEP for Static 3-Ray Multipath Channel Conditions
11.5	BER vs BEP for Static 2-Ray Multipath Channel Conditions
11.6	DQM (BEP) Resynchronization Response

IRIG 118-22 Ch. 11

- Defines standard test fixture
- Each DQE frame must be scored individually

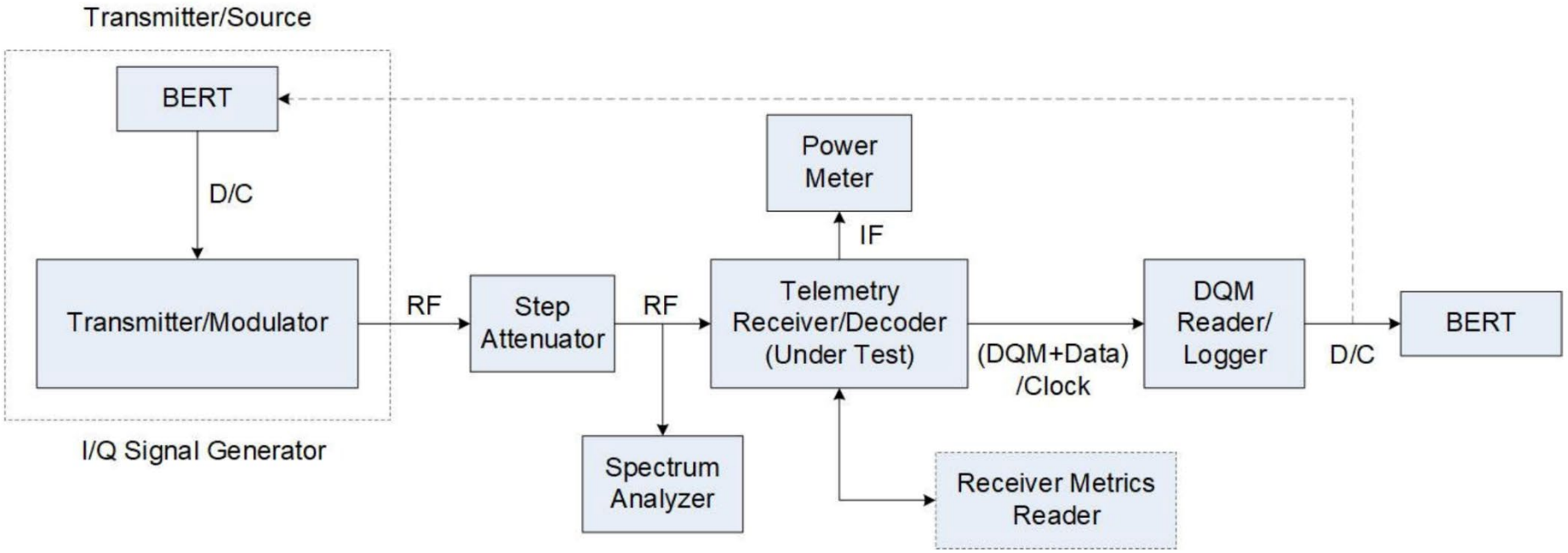
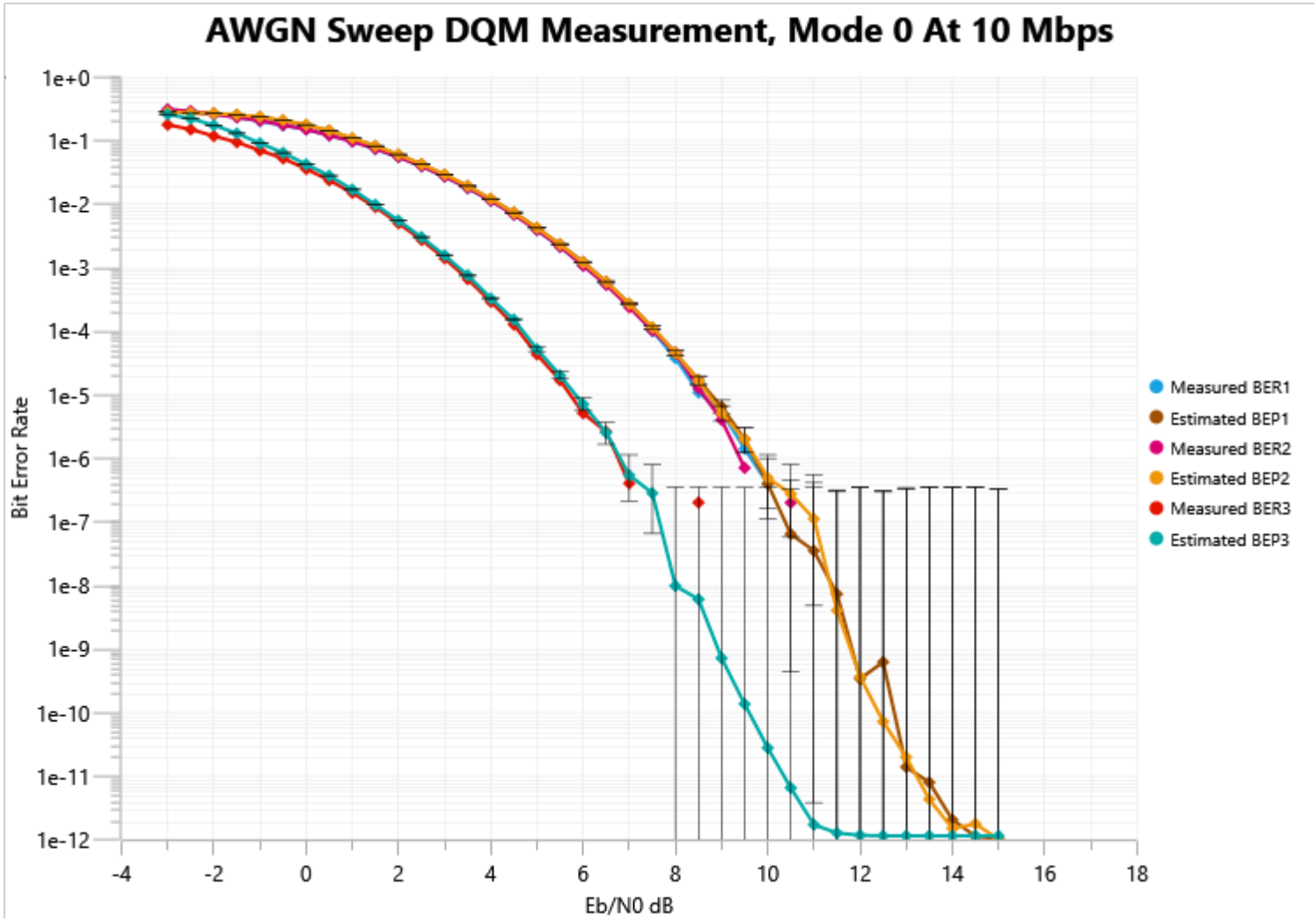


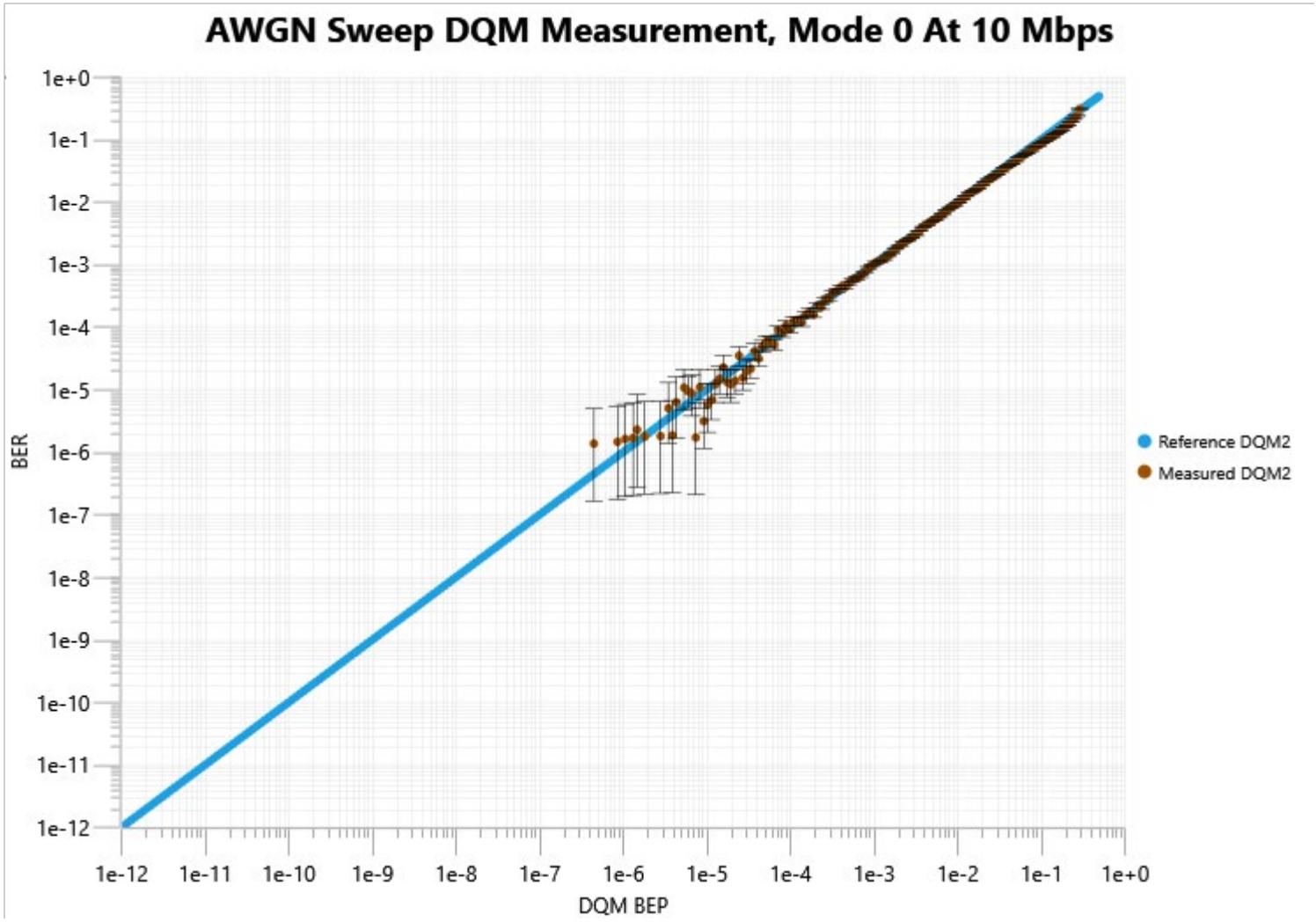
Figure 11-1. Setup for Step Attenuator/Power Meter for BER versus BEP Test

Basic AWGN Sweep

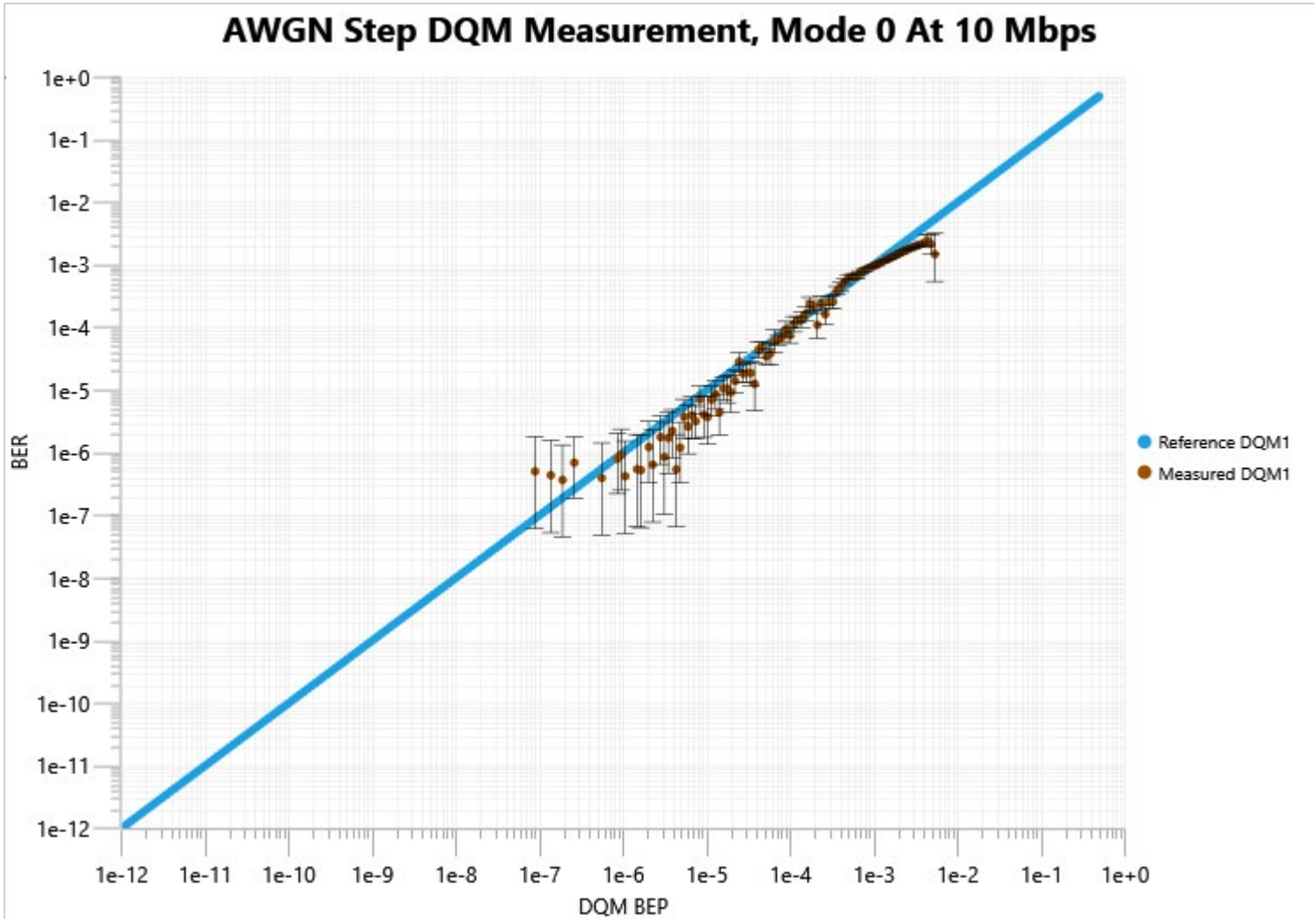


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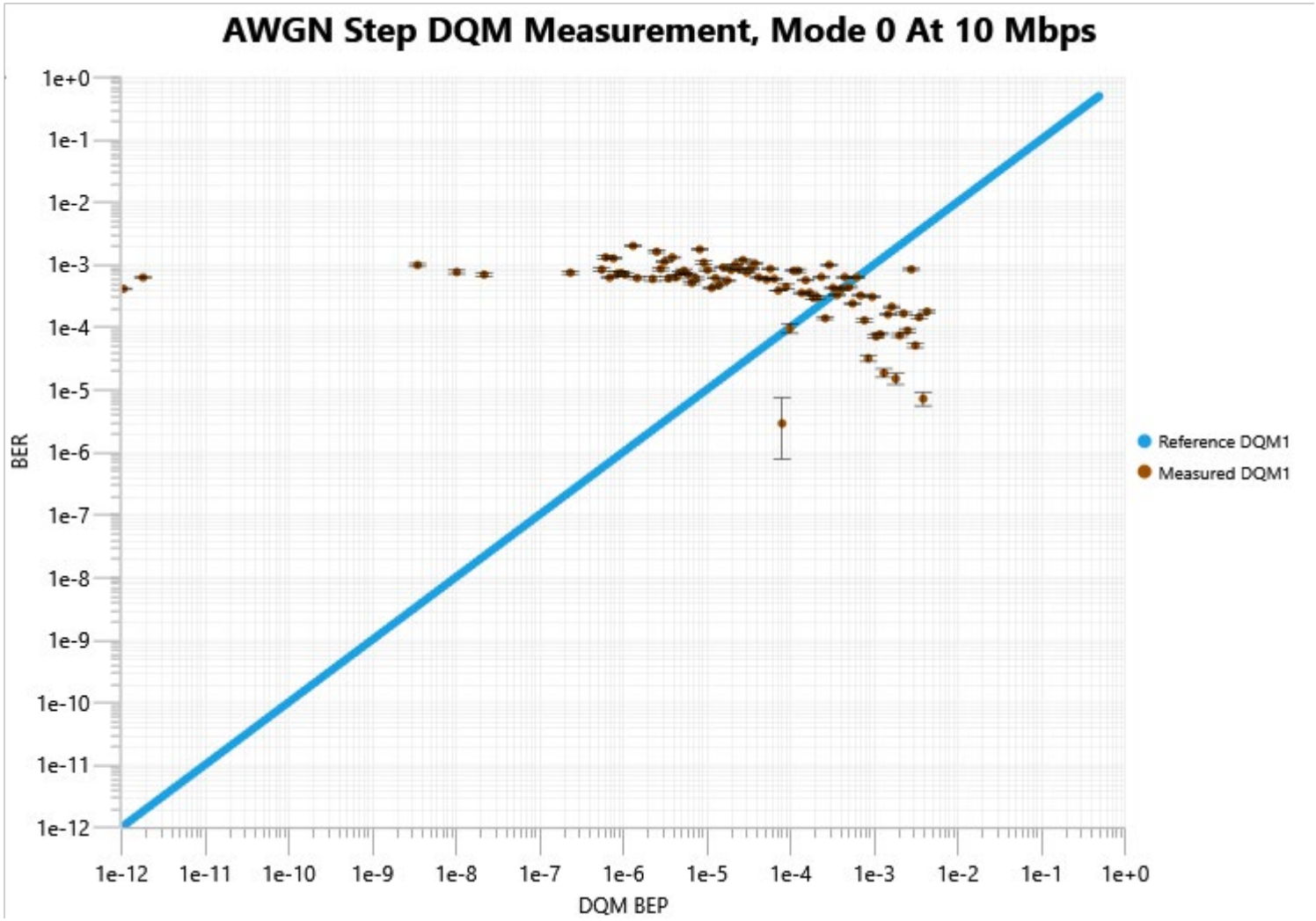
Basic AWGN BER v. BEP



Step AWGN BER v. BEP



Not All DQMs are Created Equal



Assessing Telemetry Receiver Data Quality Metrics using RCC 118-22 Test Procedures

ITC 2024

Mark Geoghegan, Sean Wilson, Jim Uetrecht
Quasonix, West Chester, OH
markg@quasonix.com

Excerpted from ITC 2024 Best Conference Paper

DQE Tests / Signal Types

- Cannot verify all modulation/coding/block size/bit rate combinations (objective is functional interoperability NOT design verification)
- 8 representative signal types were agreed upon for DQE/DQM testing after RCC meeting with receiver vendors and Govt personnel

DQE Test
11.1 AWGN
11.2 Step & Dwell
11.3 ACI
11.4 MP 3 Ray
11.5 MP 2-Ray
11.6 Resync

Signal Types	DQE Block Size (bits)	Bit Rate (Mbps)	Signal Type ID
PCM/FM	4096	5	ST1
SOQPSK	4096	20	ST2
STC	3200	10	ST3
ARTM-CPM	16384	15	ST4
SOQPSK-LDPC (r=2/3 k=4096)	4096	20	ST5
SOQPSK-LDPC (r=4/5 k=1024)	1024	5	ST6
SOQPSK-LDPC (r=1/2 k=4096)	4096	5	ST7
STC-LDPC (r=2/3 k=4096)	4096	5	ST8

6 Tests x 8 Signal Types → 48 Combinations

Automated Testing Approach

- Each Signal Type is run through all 6 tests (11.1-11.6)
  - Repeat with remaining Signal Types until all 48 combinations are complete

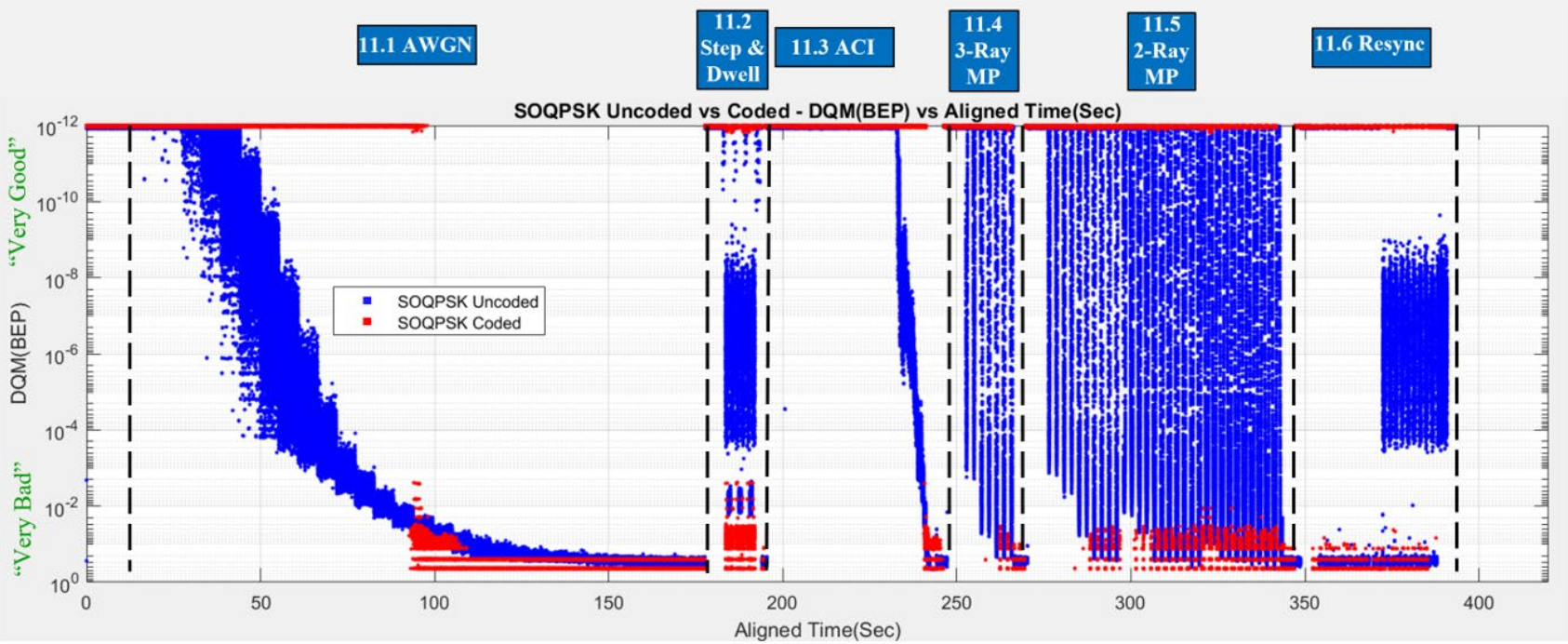
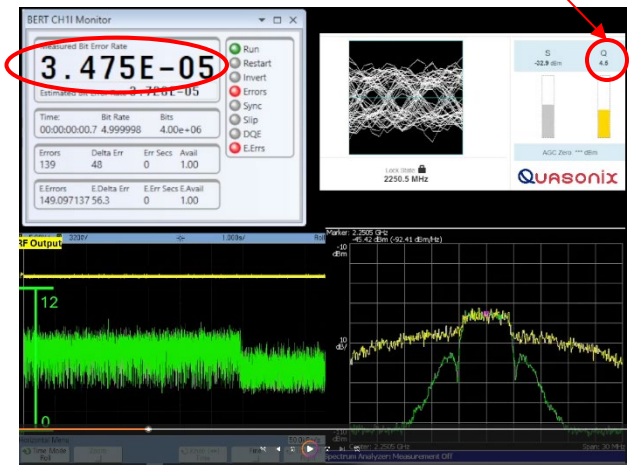


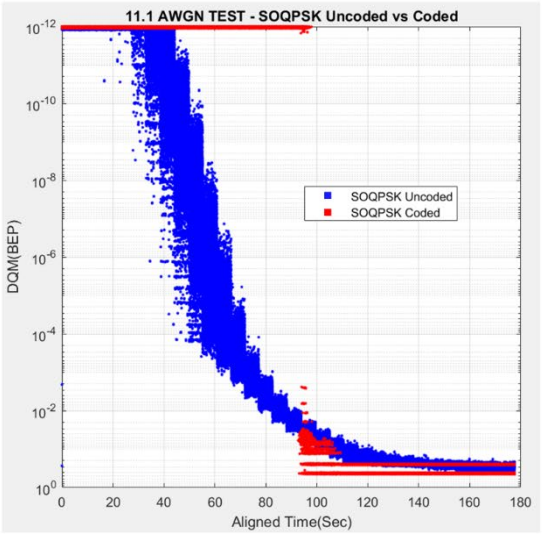
Figure 2: Example of DQE 11.1-11.6 automated testing (DQM/BEP vs Time)

11.1 AWGN

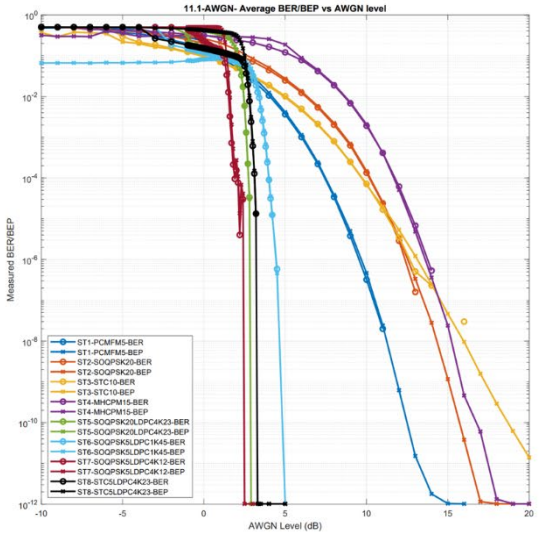
- BER vs BEP/DQM in AWGN
- DQM correlation is tight (Worst case Qrms = 0.38)
- Averages values match very well
- All 8 Signal Types are shown

Q=4.5 => $10^{-4.5}$ =>BEP=3.16e-5

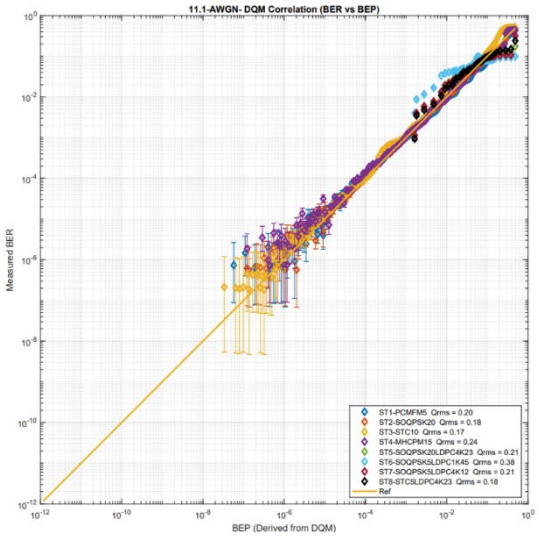




A) DQM/BEP vs Time



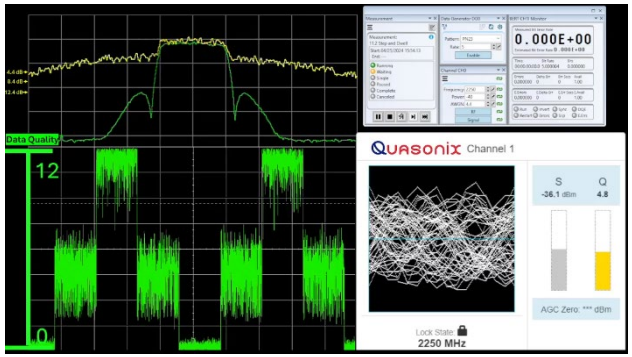
B) Average BER/BEP vs AWGN

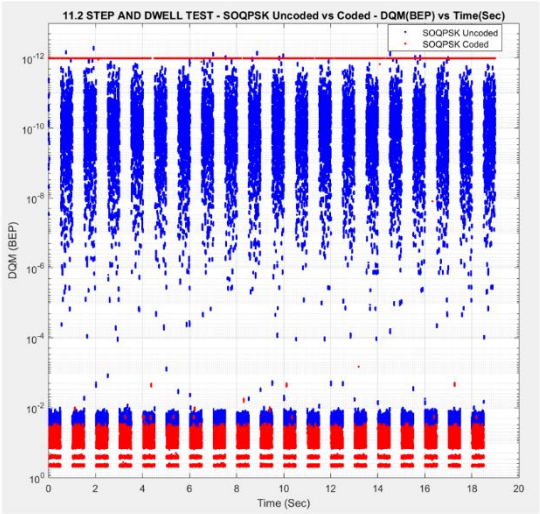


C) DQM Correlation

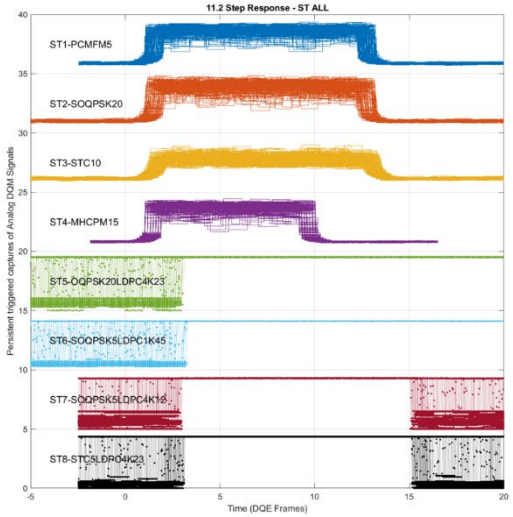
11.2 Step & Dwell

- BER vs BEP/DQM in dynamic AWGN
- DQM correlation is tight (Worst case Qrms = 0.43)
- Step response quickly indicates changes in channel (≈1 DQE frame)
- All 8 Signal Types are shown

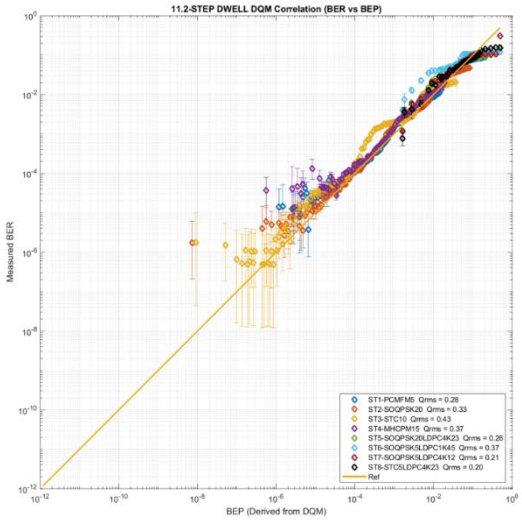




A) DQM/BEP vs Time



B) DQM Step Responses



C) DQM Correlation

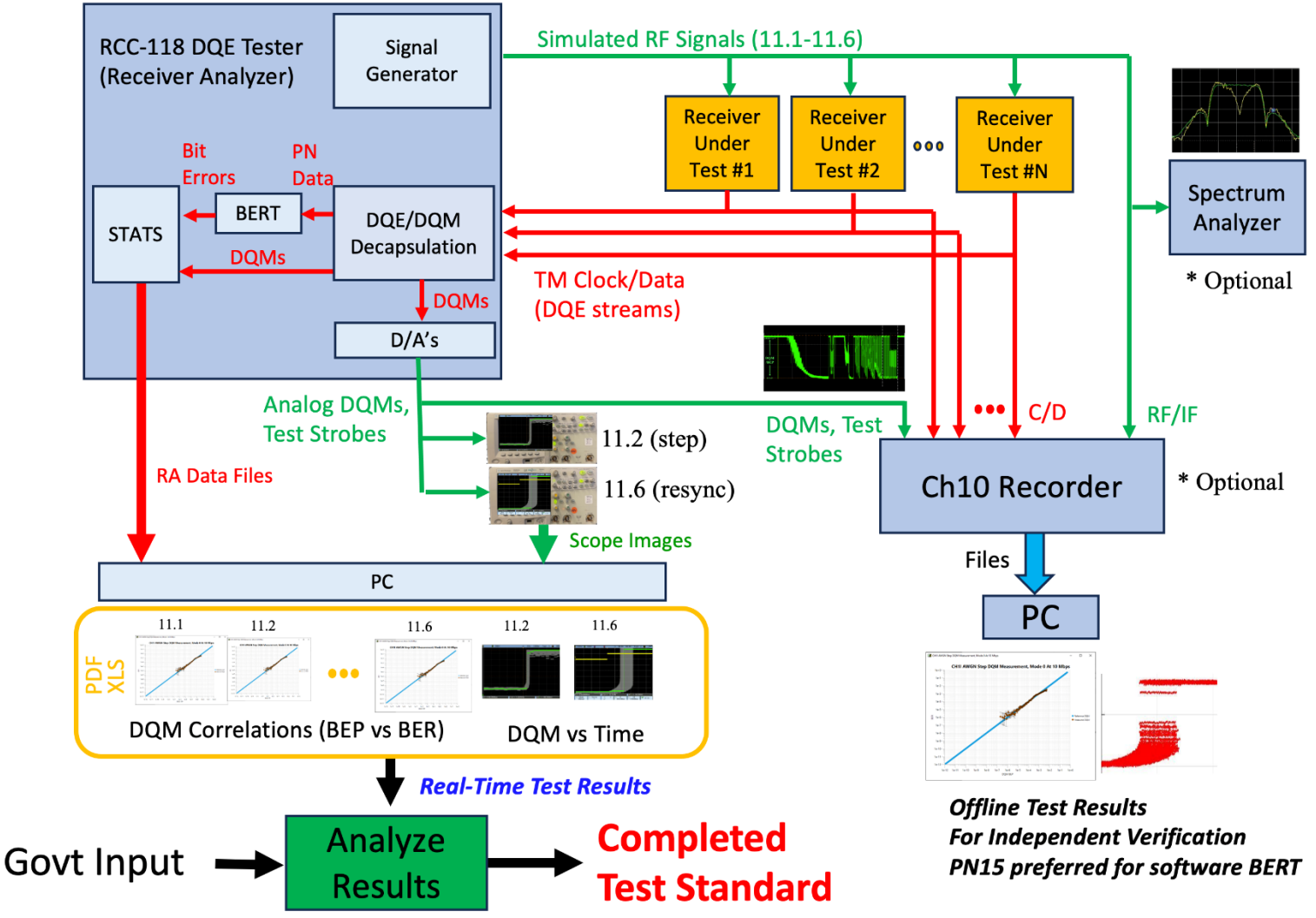
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Industry Day 2

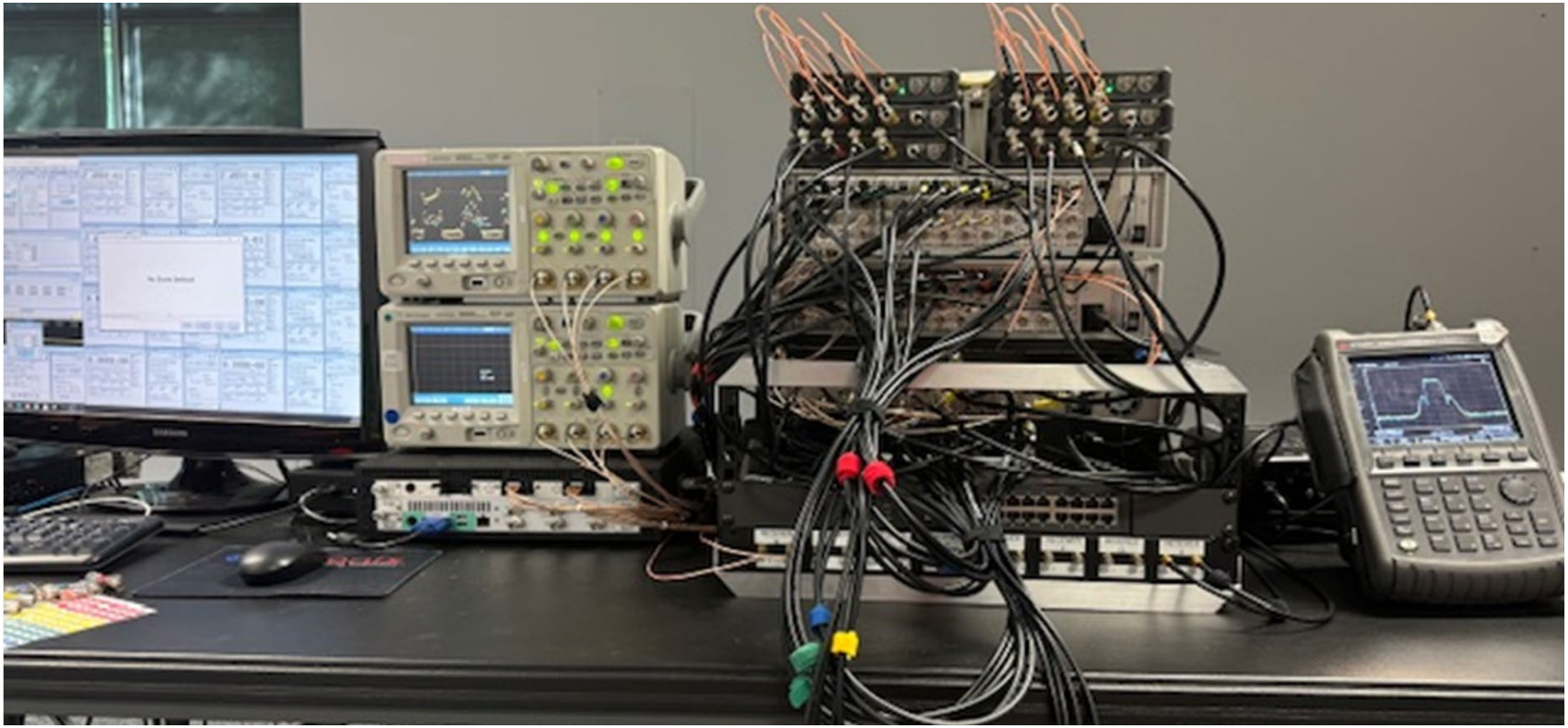
DQE/DQM Assessment Testing

Friday Oct 25th, 2024
Meeting room Cascade B (Renaissance Hotel)

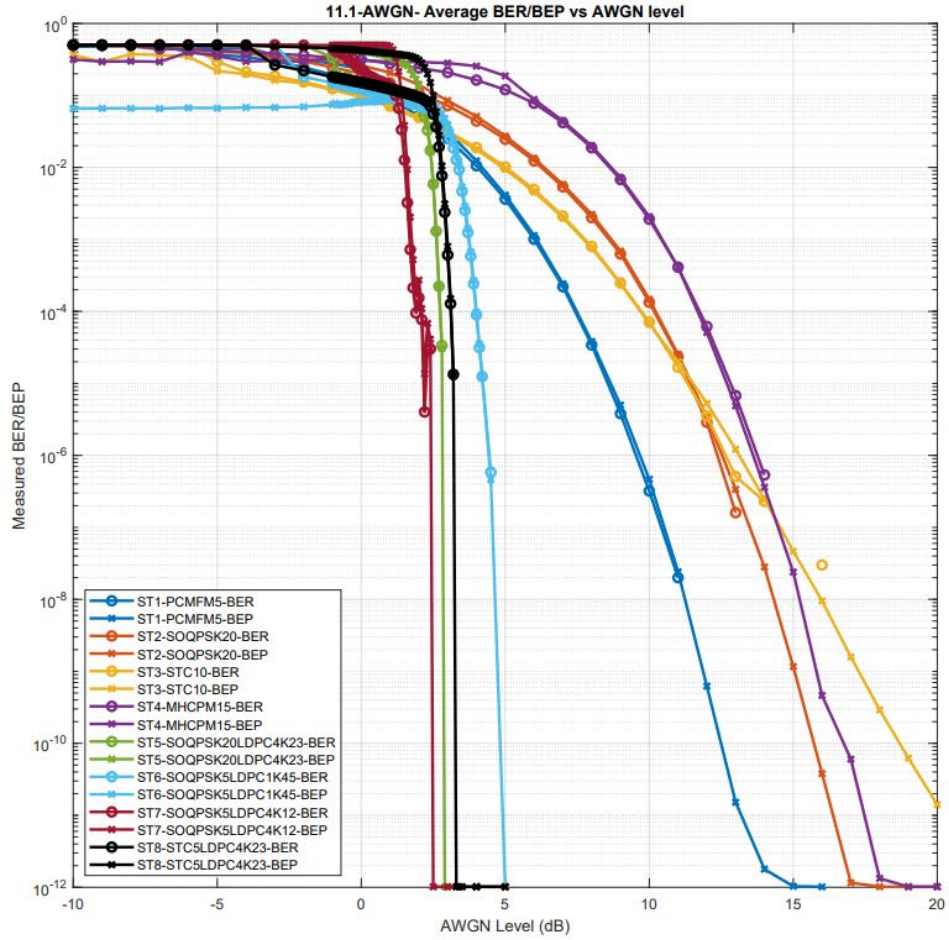
Test Setup

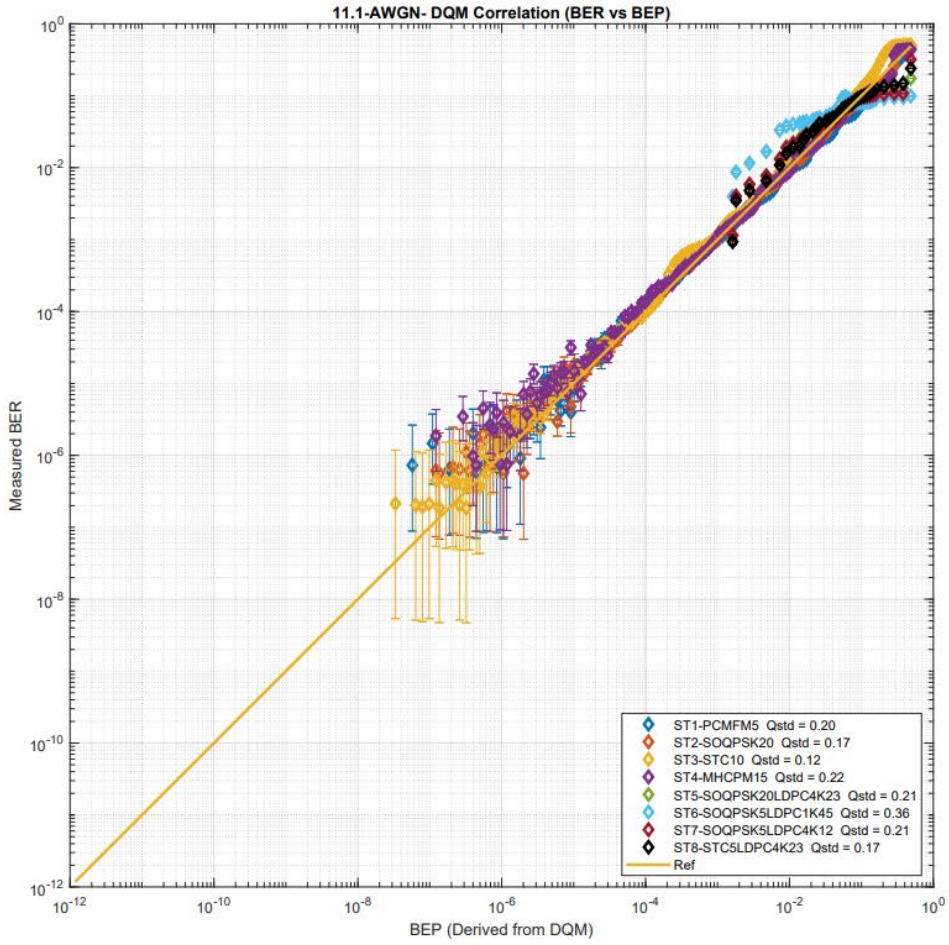

RCC-118 DQE Tester
(Receiver Analyzer)
Signal Generator
Simulated RF Signals (11.1-11.6)
Receiver Under Test #1
Receiver Under Test #2
Receiver Under Test #N
Spectrum Analyzer
* Optional
Bit Errors
PN Data
STATS
BERT
DQE/DQM Decapsulation
DQMs
DQMs
D/A's
TM Clock/Data (DQE streams)
Analog DQMs, Test Strobes
11.2 (step)
11.6 (resync)
DQMs, Test Strobes
C/D
RF/IF
RA Data Files
Ch10 Recorder
* Optional
Scope Images
Files
PC
PC
11.1
11.2
11.6
11.2
11.6
PDF
XLS
DQM Correlations (BEP vs BER)
DQM vs Time
Real-Time Test Results
Govt Input
Analyze Results
Completed Test Standard
Offline Test Results
For Independent Verification
PN15 preferred for software BERT

Equipment



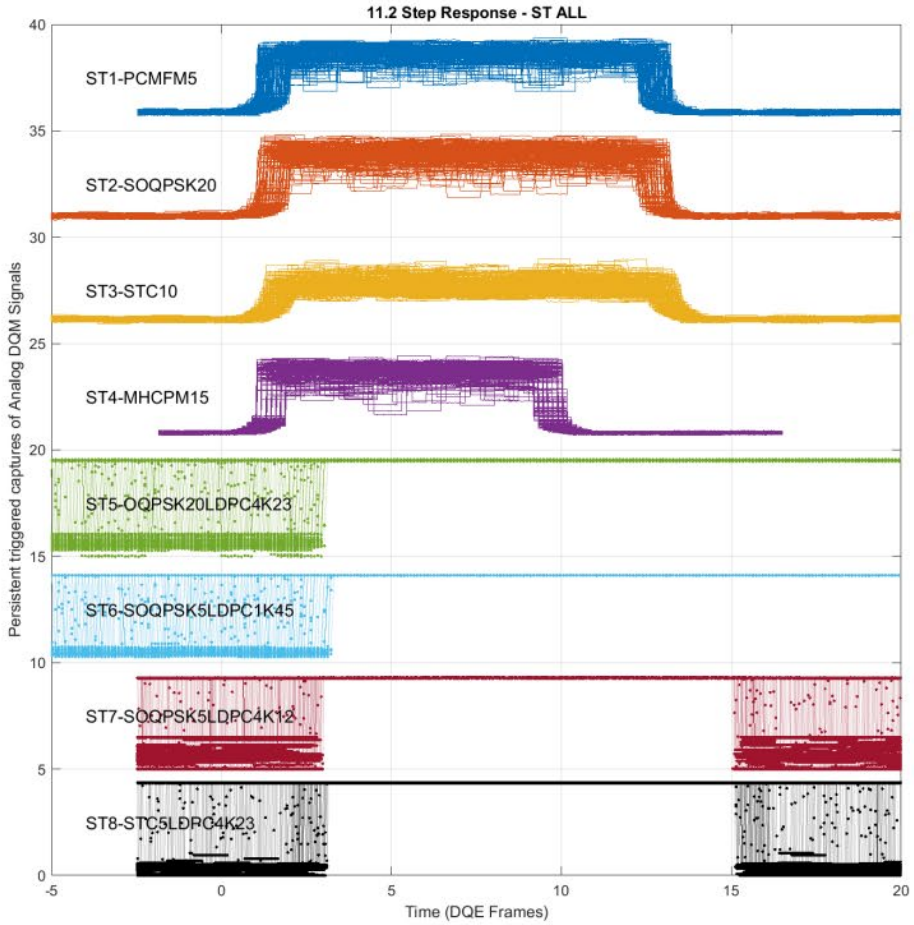
11.1 (AWGN) Report

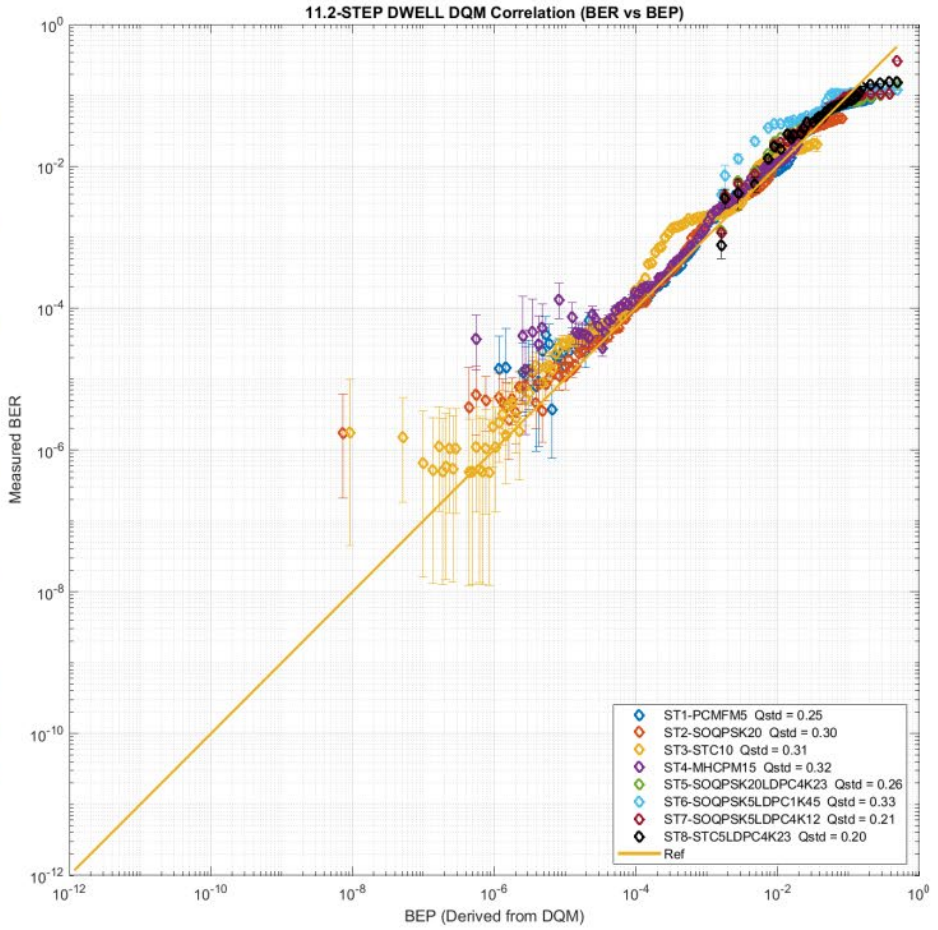




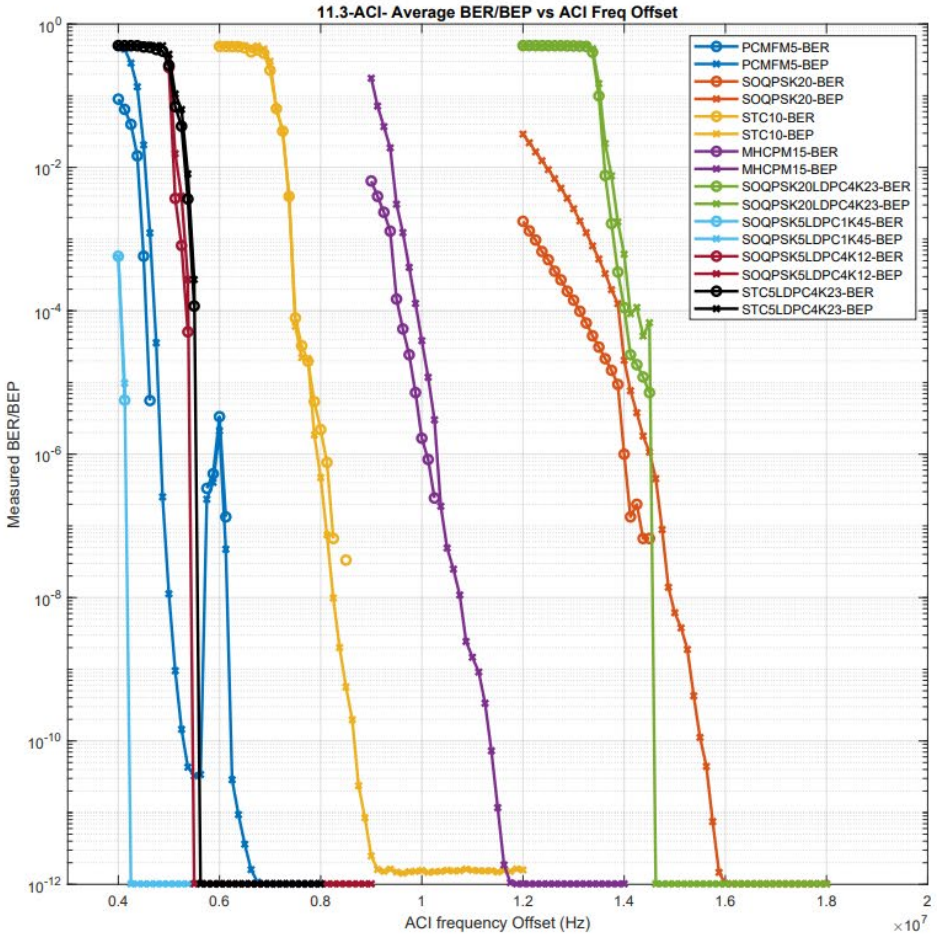
Terry Hill - thill@quasonix.com

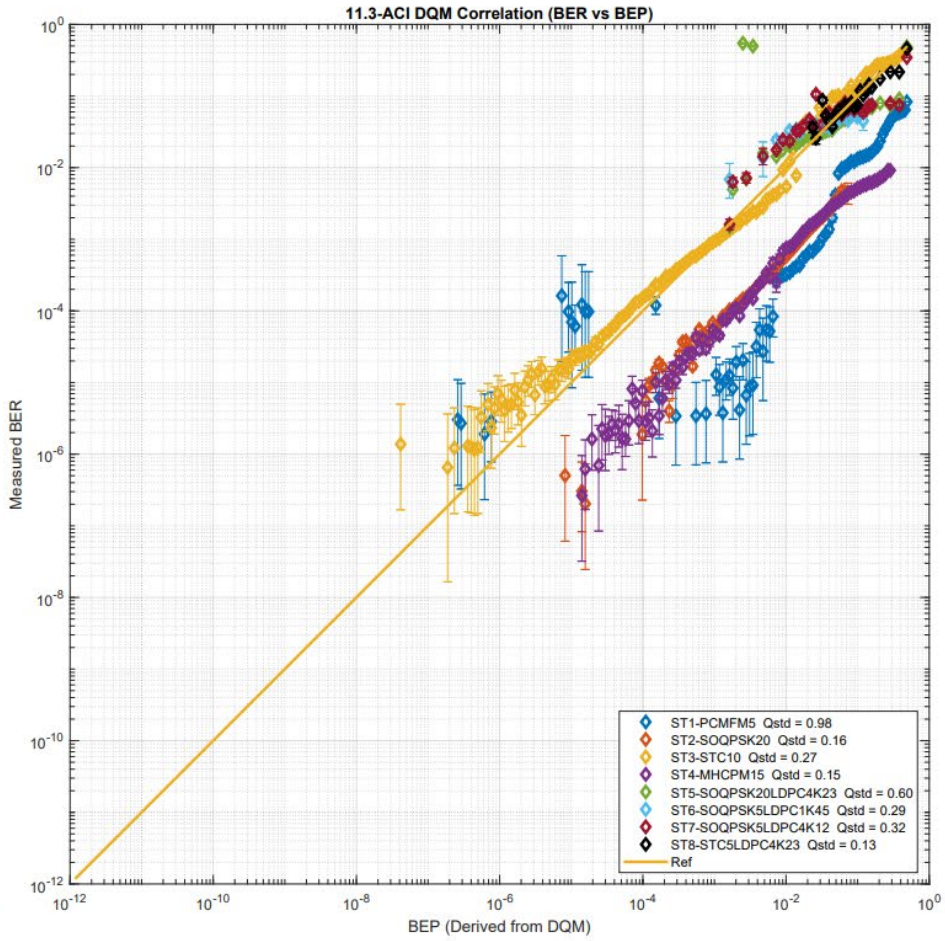
11.2 (Step & Dwell) Report



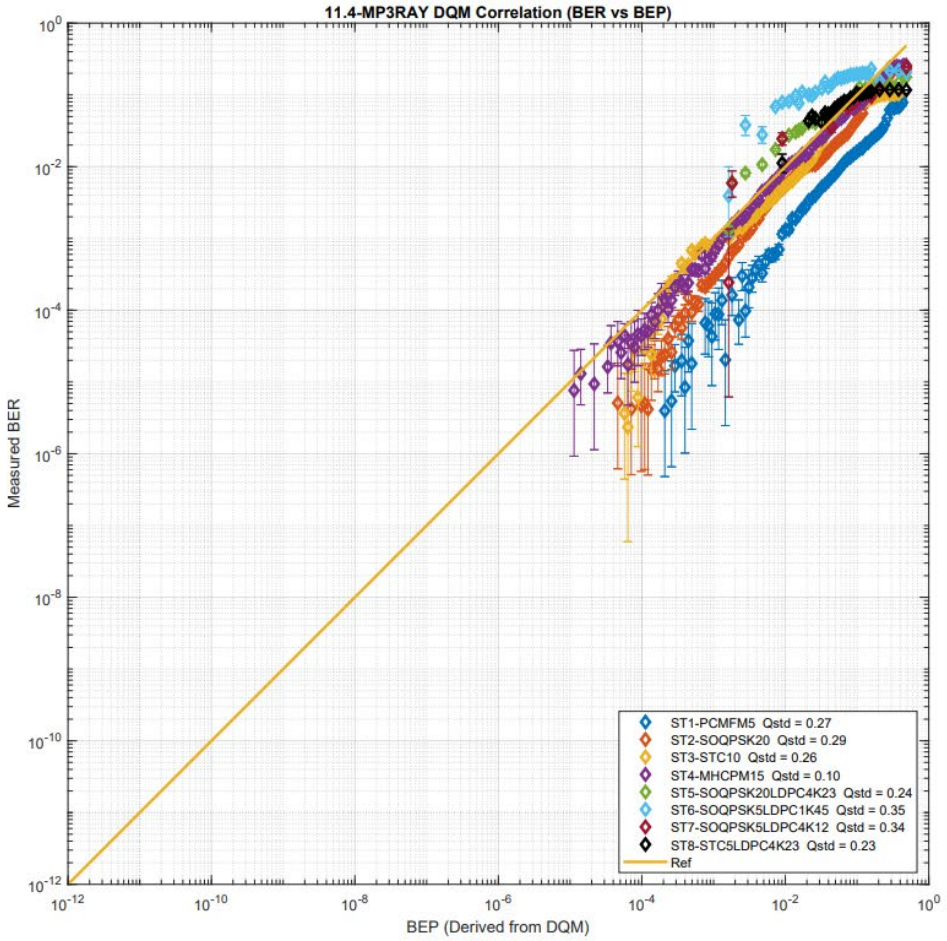


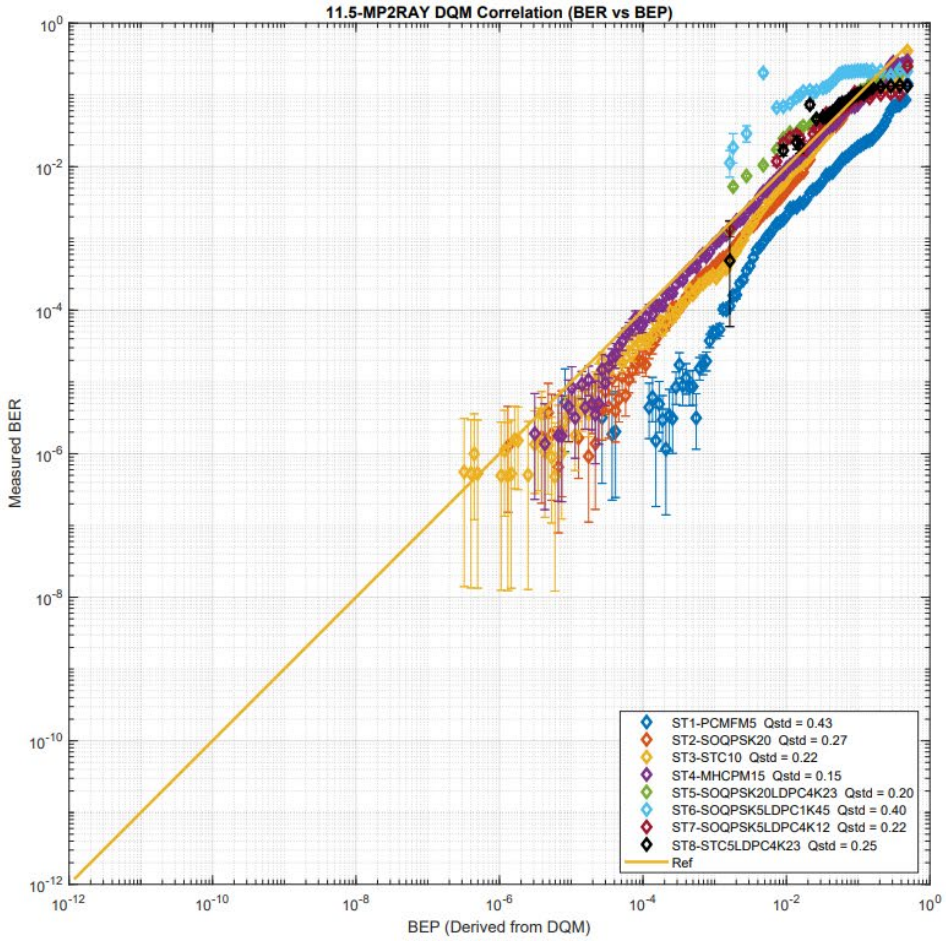
11.3 (ACI) Report





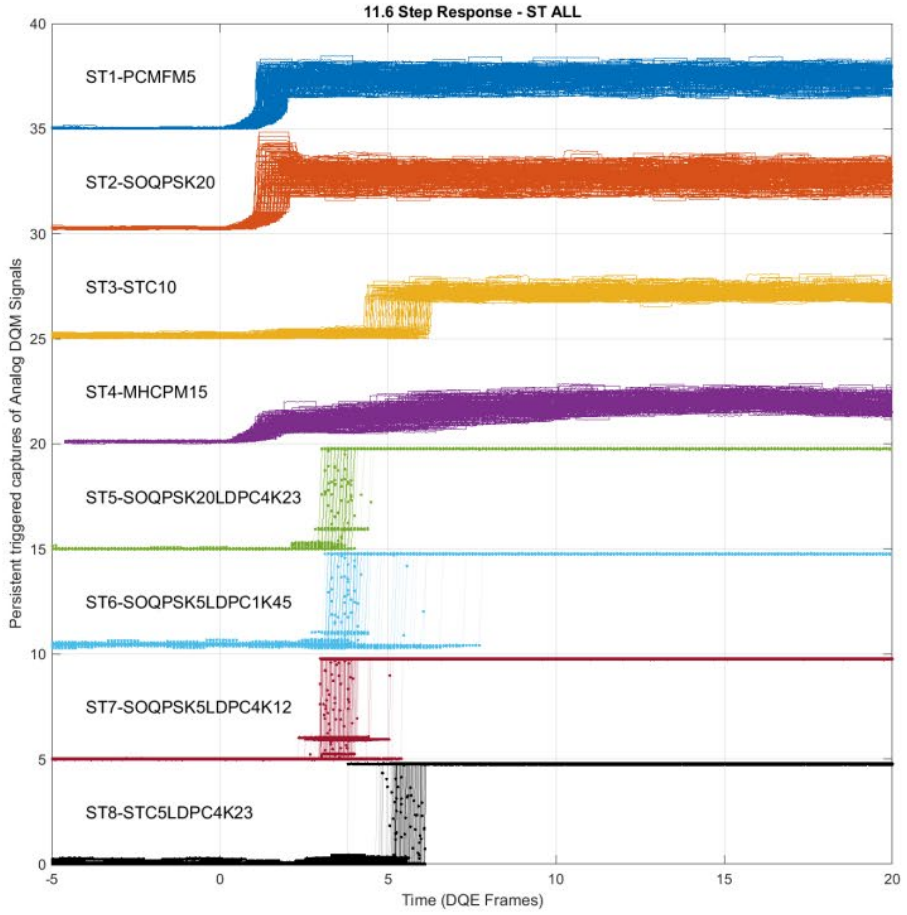
11.4 & 11.5 (Multipath) Report

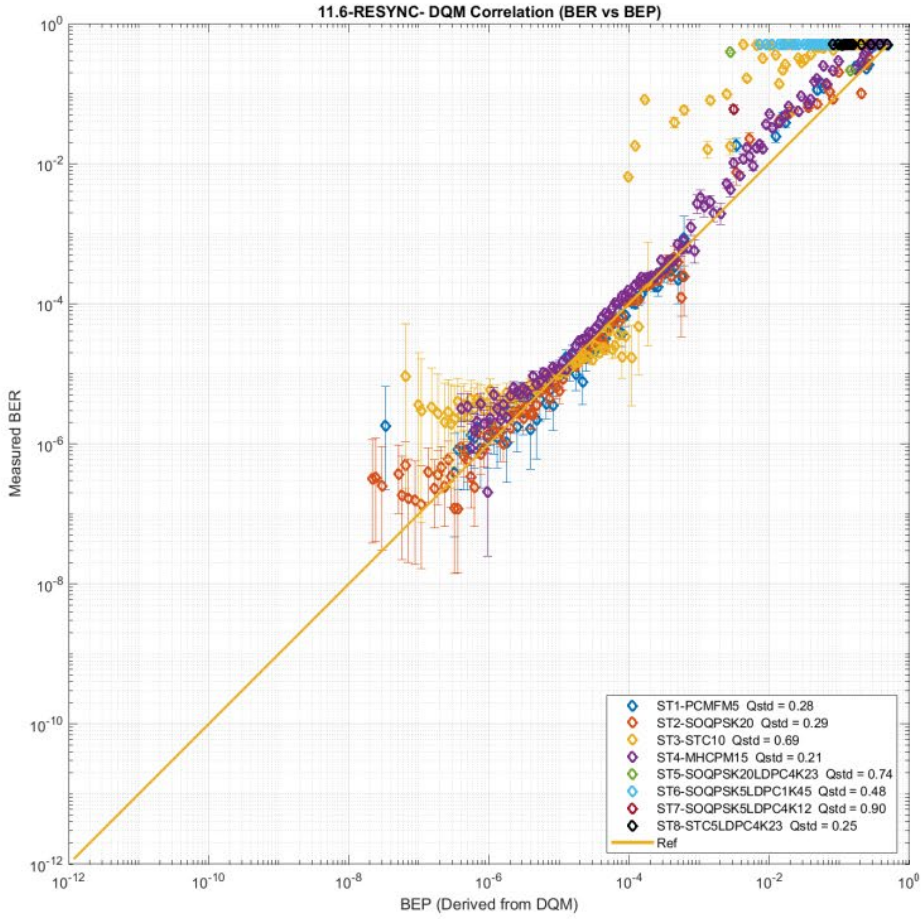




Terry Hill - thill@quasonix.com

11.6 (Resync) Report



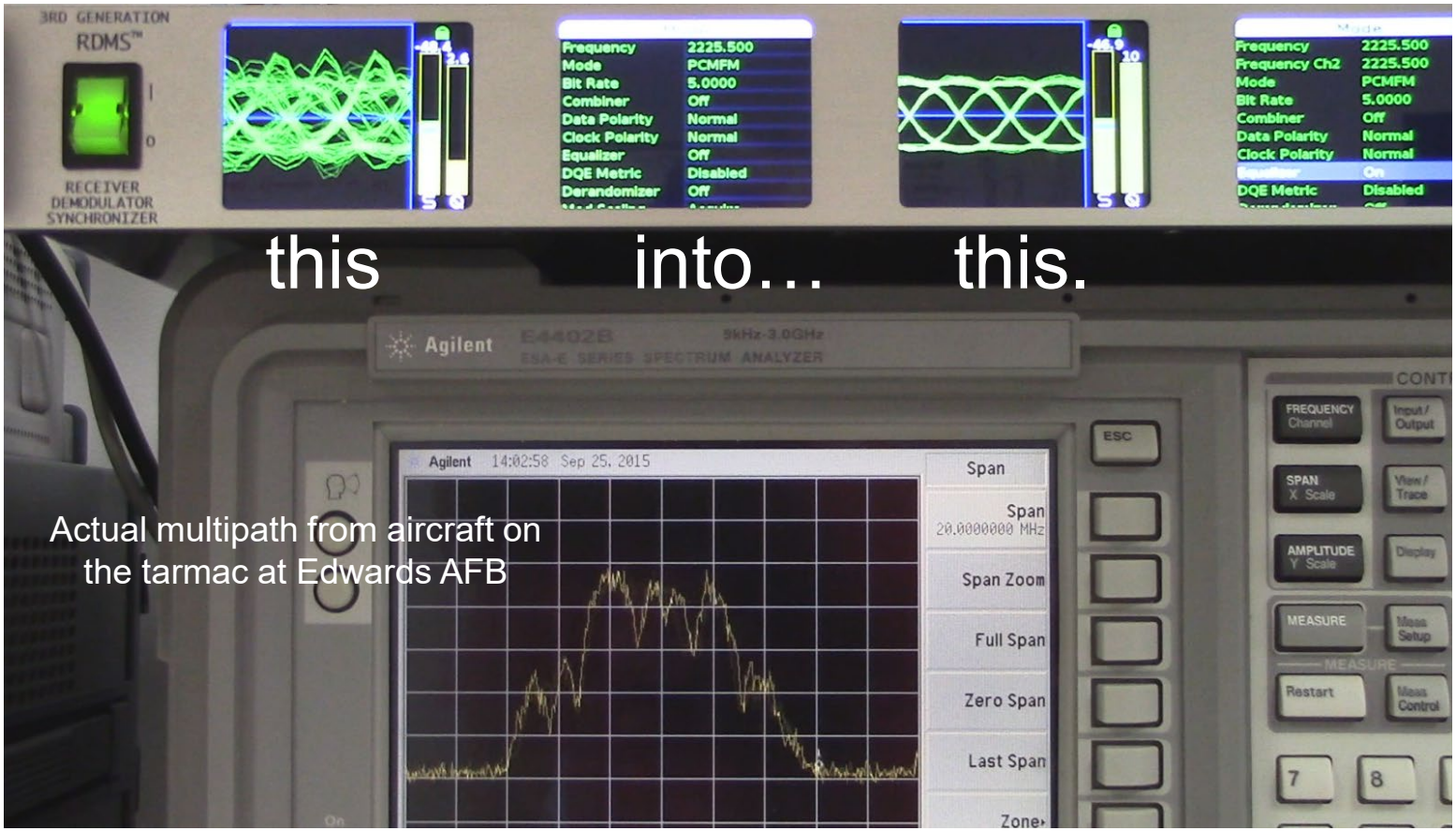


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Adaptive Equalization

Multipath is Ugly

- Equalization can turn
- this into… this.

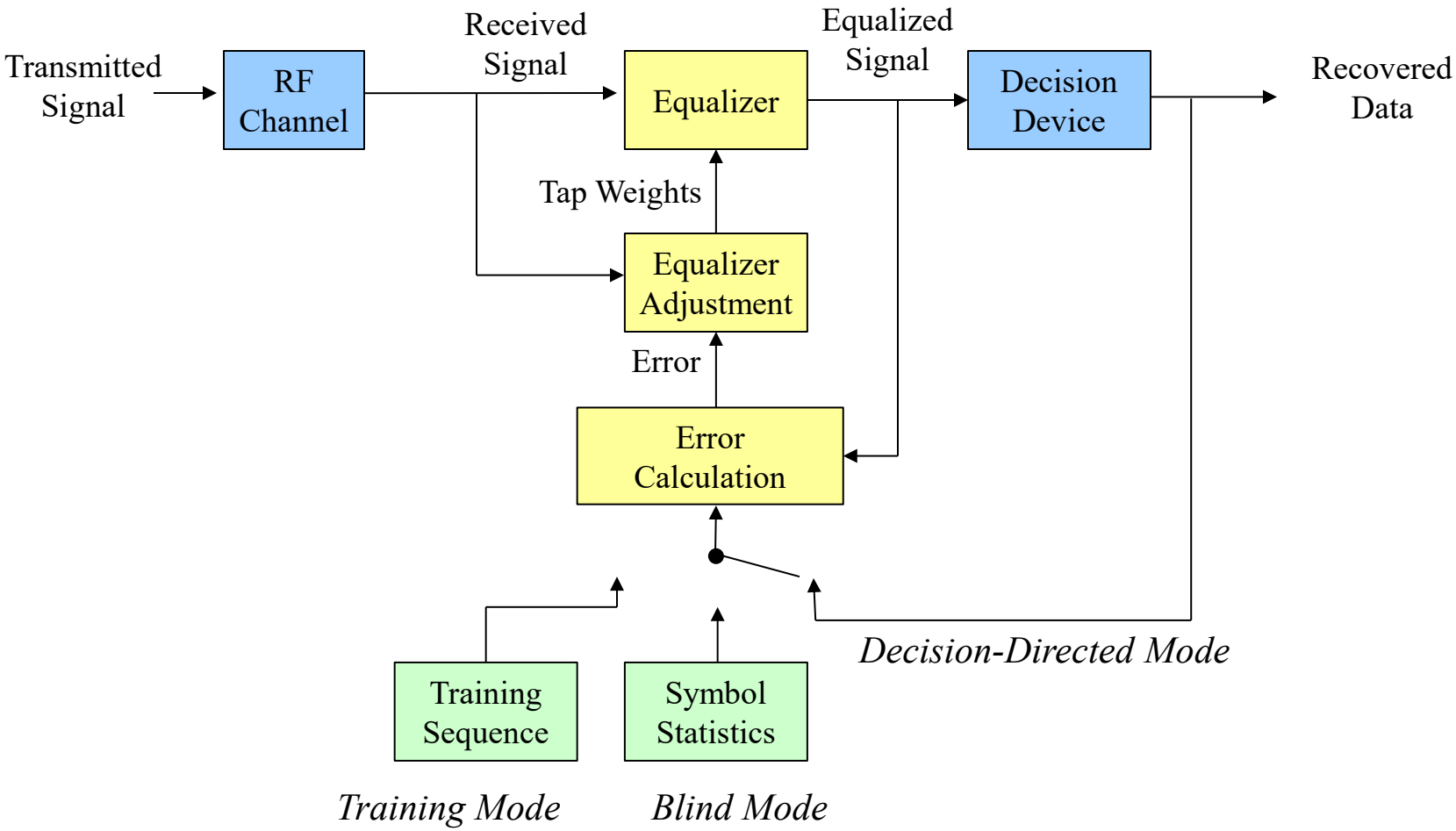


Actual multipath from aircraft on the tarmac at Edwards AFB

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

Generic Adaptive Equalizer



Adaptive Equalization, PCM/FM



Adaptive Equalization, SOQPSK



Adaptive Equalizer Summary

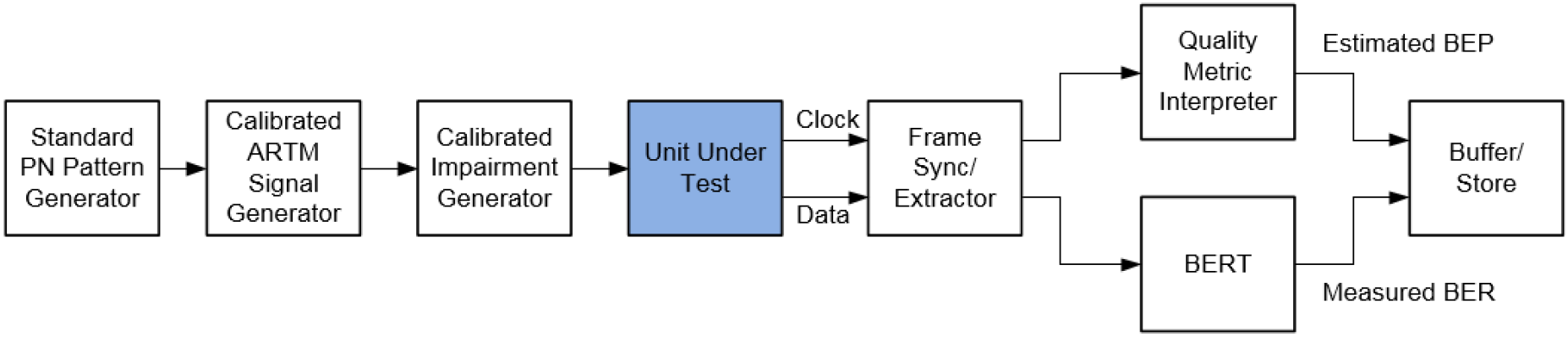
- Adaptive equalizer can “undo” multipath distortion
- Requires no changes at the transmit end
  - If available, a training sequence can be helpful
- Effectiveness of equalizer depends on the severity of the multipath
- Well-designed equalizers monitor their own performance, and disengage when they are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

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Performance Evaluation of Adaptive Equalizers

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 frame-by-frame basis



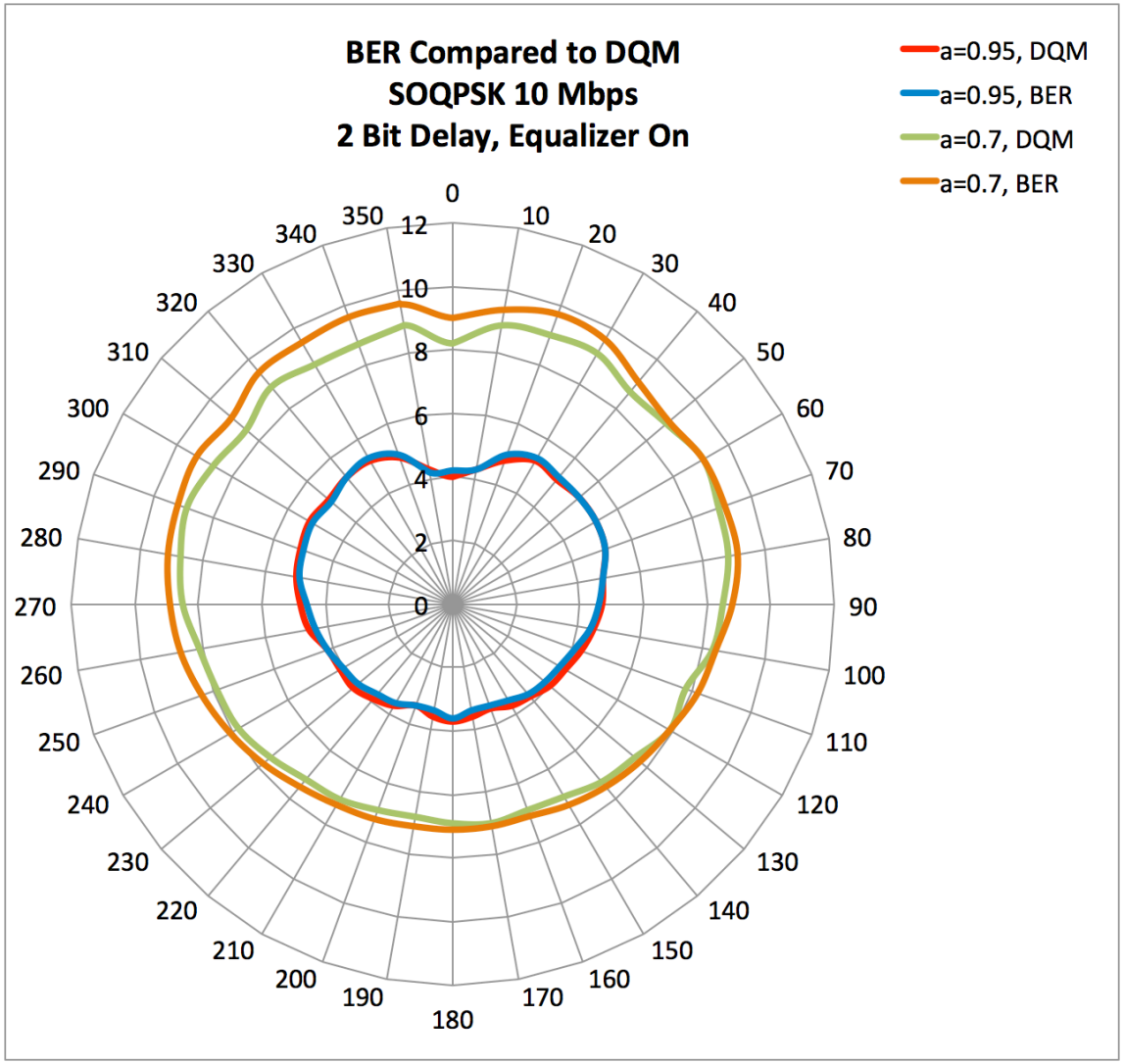
Test Procedure

- Set frequency, modulation, and bit rate
- Turn the equalizer off
- Set E_b/N_0 to 20 dB
- Set direct path to delay 0, amplitude 1, angle 0
- Enable multipath
- Set reflected path delay and amplitude
- Loop through delayed path phase
  - 0 degrees to 360 degrees in 10 degree steps
  - Record DQM at each step, or record BER and calculate DQM
  - Plot DQM versus phase in polar form
- Turn equalizer on and repeat
  - If two test units are available, test EQ on and EQ off at the same time

Grading the Tests

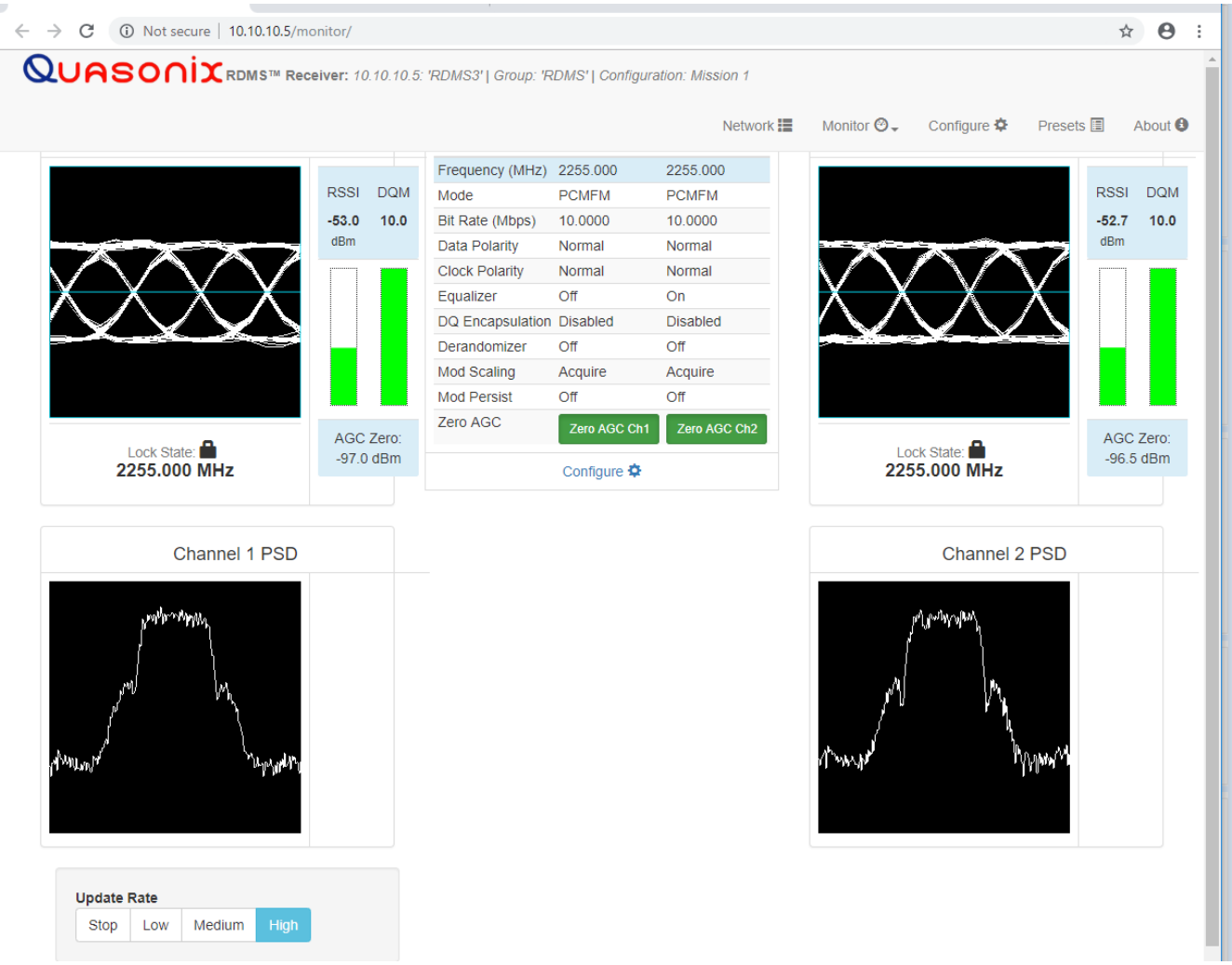
- Measure BER with EQ on and off, then compute DQM
  - If your DQM is well calibrated, measure DQM directly
- Plot DQM vs. delay path phase, in polar form
  - Radius = DQM
  - Angle = phase of delayed path
- Result will be a distorted “hoop”
  - Bigger radius is better
  - Some angles will be worse than others
- Compute the area of each “hoop” for EQ on and off
- “Equalizer Benefit” = $Area_{on} – Area_{off}$
  - Since the radius is (essentially) the logarithm of the BER, the difference is the number of orders of magnitude improvement in BER

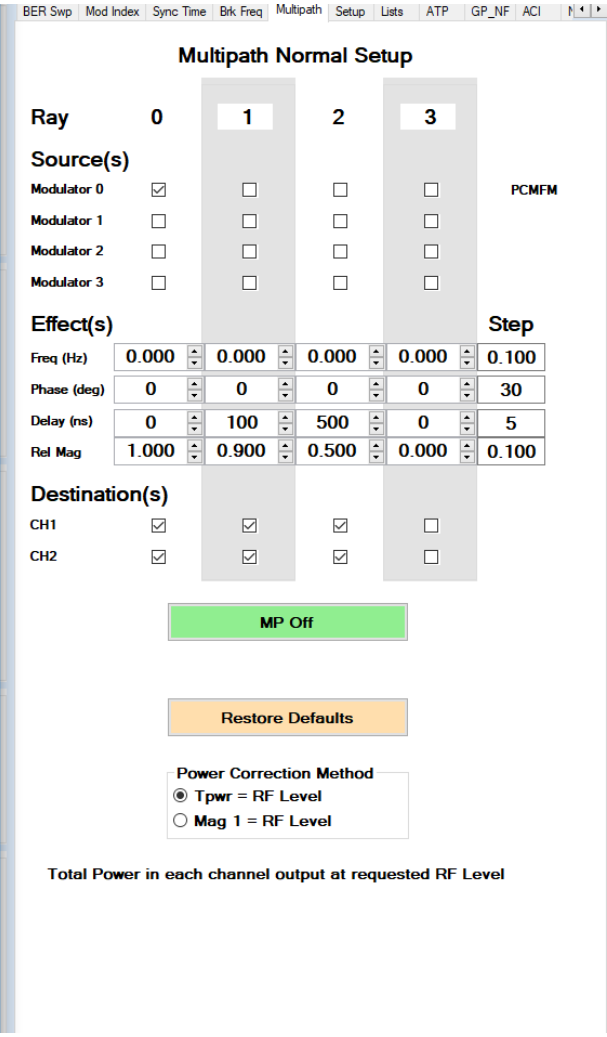
DQM Calibration



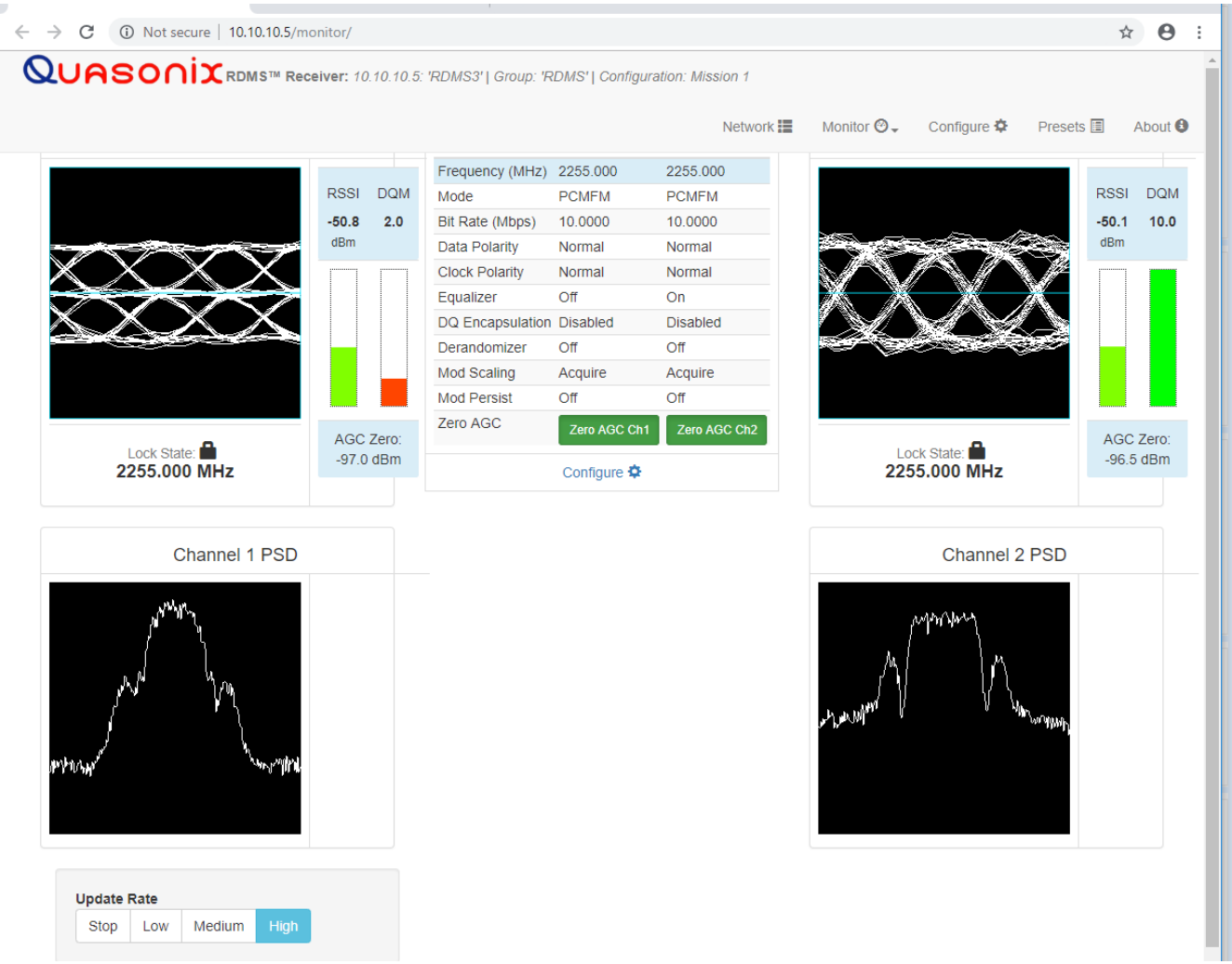
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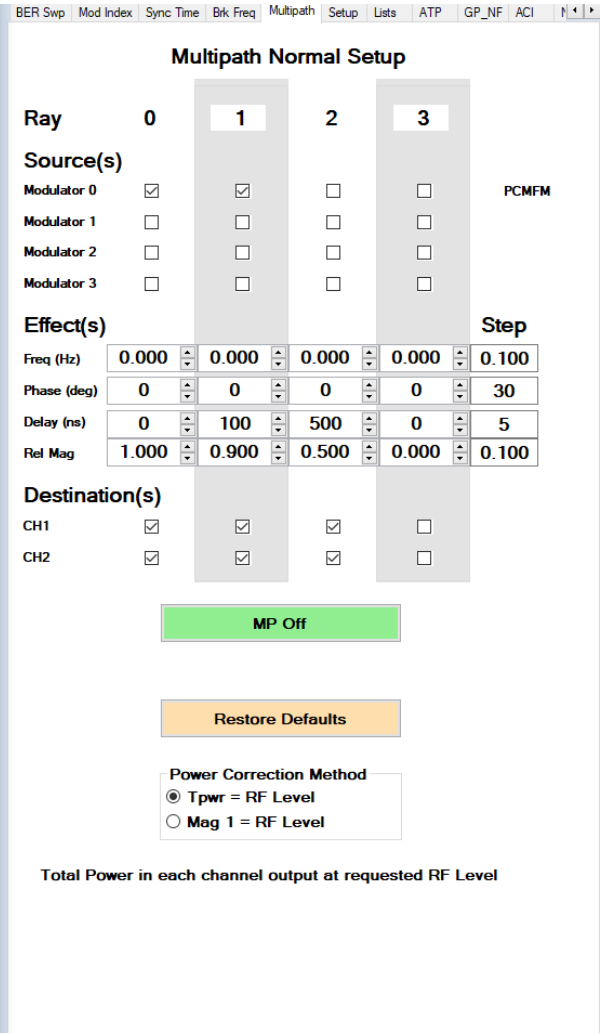
No Multipath, No Problem



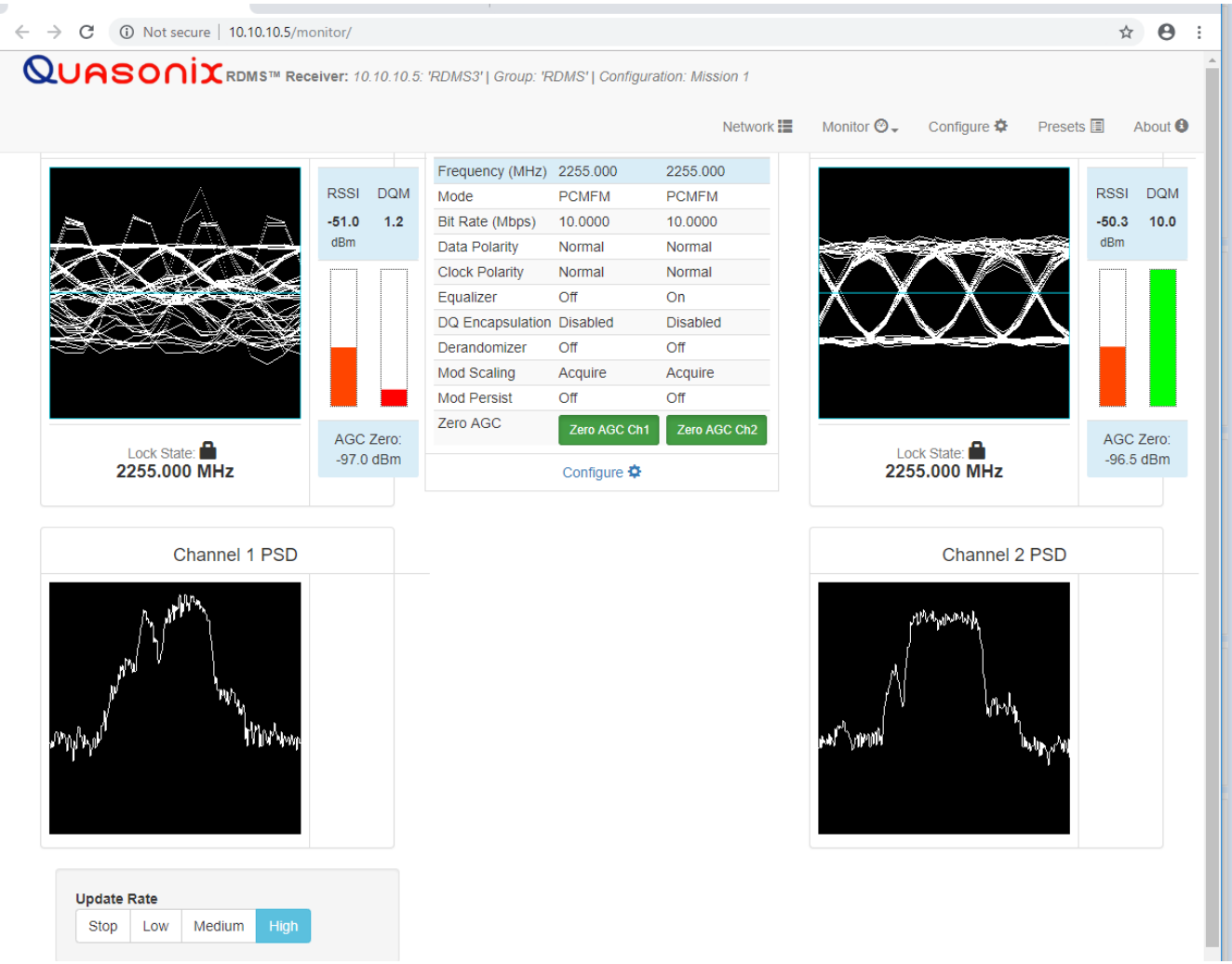


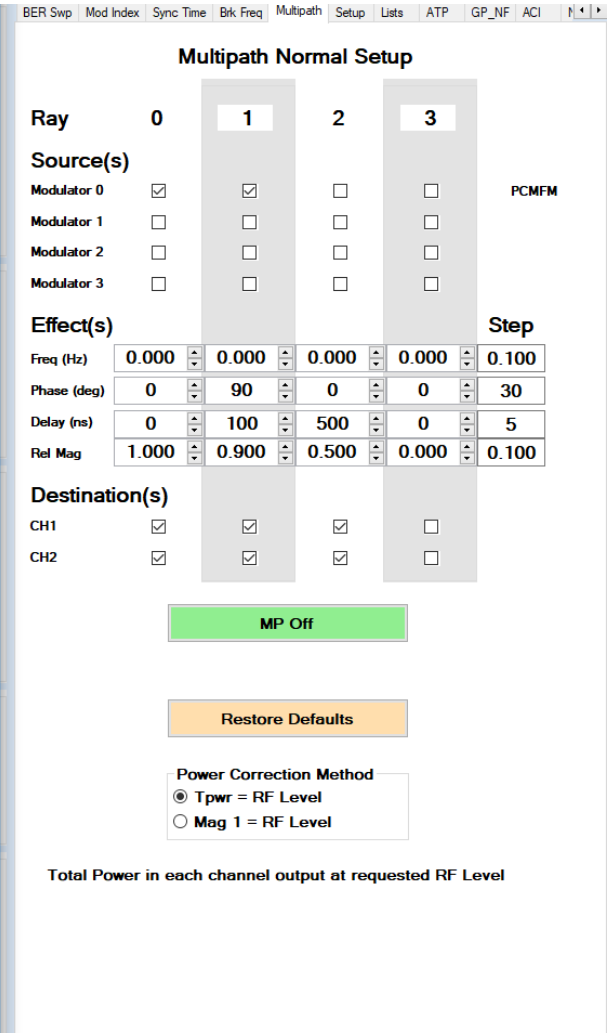
0-100-0.9


Not secure | 10.10.10.5/monitor/
Quasonix RDMS™ Receiver: 10.10.10.5: 'RDMS3' | Group: 'RDMS' | Configuration: Mission 1
Network
Monitor
Configure
Presets
About
RSSI
DQM
-50.8
dBm
2.0
Lock State:
2255.000 MHz
AGC Zero:
-97.0 dBm
Frequency (MHz) 2255.000 2255.000
Mode PCMFM PCMFM
Bit Rate (Mbps) 10.0000 10.0000
Data Polarity Normal Normal
Clock Polarity Normal Normal
Equalizer Off On
DQ Encapsulation Disabled Disabled
Derandomizer Off Off
Mod Scaling Acquire Acquire
Mod Persist Off Off
Zero AGC
Zero AGC Ch1
Zero AGC Ch2
Configure
RSSI
DQM
-50.1
dBm
10.0
Lock State:
2255.000 MHz
AGC Zero:
-96.5 dBm
Channel 1 PSD
Channel 2 PSD
Update Rate
Stop
Low
Medium
High


BER Swp
Mod Index
Sync Time
Brk Freq
Multipath
Setup
Lists
ATP
GP_NF
ACI
Multipath Normal Setup
Ray 0 1 2 3
Source(s)
Modulator 0
Modulator 1
Modulator 2
Modulator 3
PCMFM
Effect(s)
Step
Freq (Hz) 0.000 0.000 0.000 0.000 0.100
Phase (deg) 0 0 0 0 30
Delay (ns) 0 100 500 0 5
Rel Mag 1.000 0.900 0.500 0.000 0.100
Destination(s)
CH1
CH2
MP Off
Restore Defaults
Power Correction Method
Tpwr = RF Level
Mag 1 = RF Level
Total Power in each channel output at requested RF Level

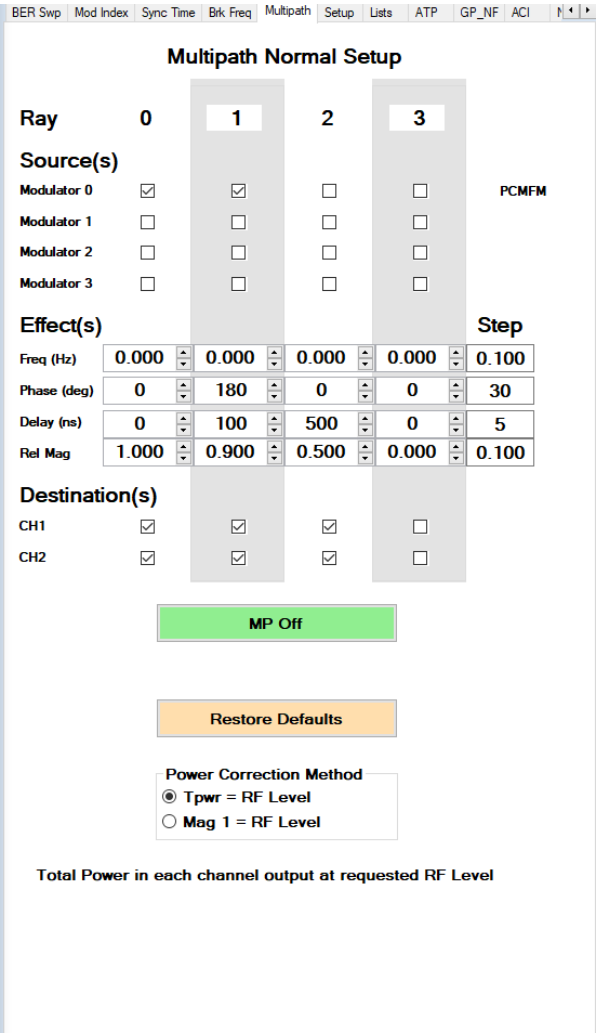
90-100-0.9


Not secure | 10.10.10.5/monitor/
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Network
Monitor
Configure
Presets
About
RSSI DQM
-51.0 1.2
dBm
Lock State:
2255.000 MHz
AGC Zero:
-97.0 dBm
Frequency (MHz) 2255.000 2255.000
Mode PCMFM PCMFM
Bit Rate (Mbps) 10.0000 10.0000
Data Polarity Normal Normal
Clock Polarity Normal Normal
Equalizer Off On
DQ Encapsulation Disabled Disabled
Derandomizer Off Off
Mod Scaling Acquire Acquire
Mod Persist Off Off
Zero AGC
Zero AGC Ch1
Zero AGC Ch2
Configure
RSSI DQM
-50.3 10.0
dBm
Lock State:
2255.000 MHz
AGC Zero:
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Channel 1 PSD
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BER Swp
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Step
Freq (Hz) 0.000 0.000 0.000 0.000 0.100
Phase (deg) 0 90 0 0 30
Delay (ns) 0 100 500 0 5
Rel Mag 1.000 0.900 0.500 0.000 0.100
Destination(s)
CH1
CH2
MP Off
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Power Correction Method
Tpwr = RF Level
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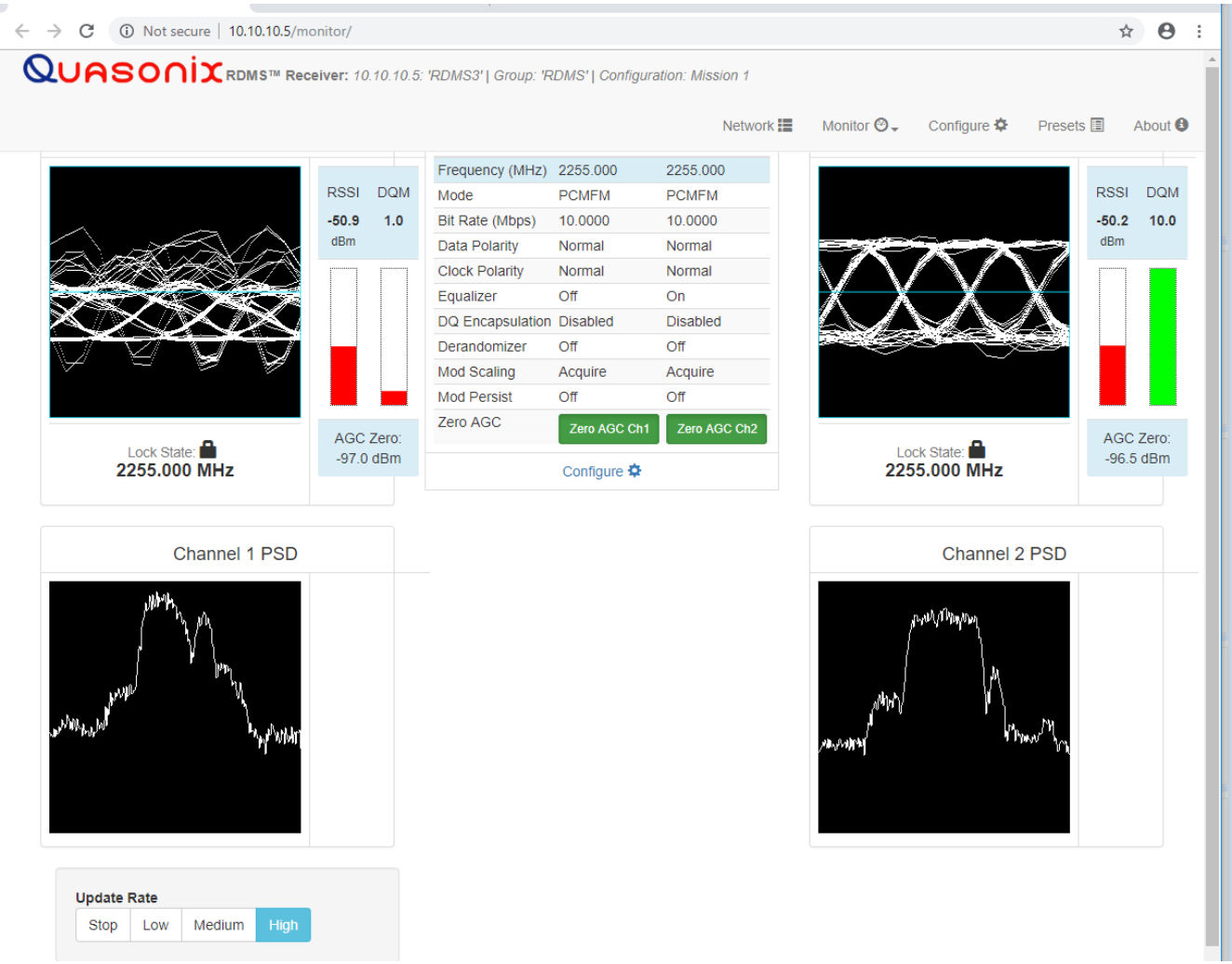
180-100-0.9

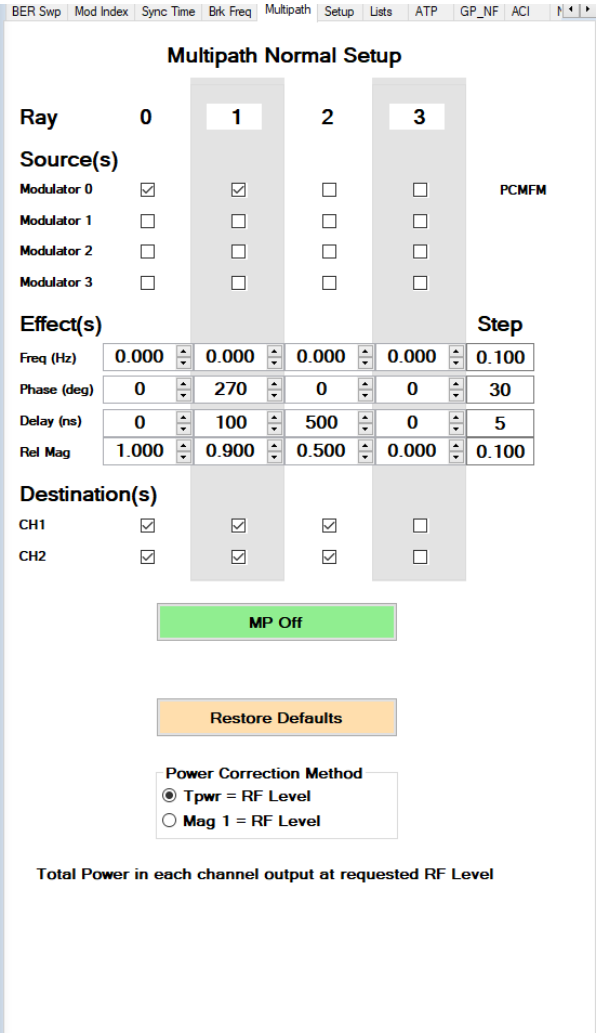




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270-100-0.9

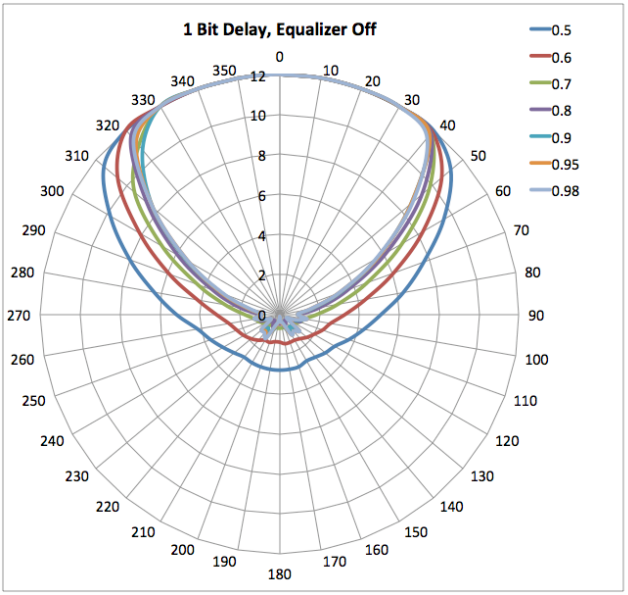

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RSSI
DQM
-50.9
dBm
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Lock State:
2255.000 MHz
AGC Zero:
-97.0 dBm
Frequency (MHz) 2255.000 2255.000
Mode PCMFM PCMFM
Bit Rate (Mbps) 10.0000 10.0000
Data Polarity Normal Normal
Clock Polarity Normal Normal
Equalizer Off On
DQ Encapsulation Disabled Disabled
Derandomizer Off Off
Mod Scaling Acquire Acquire
Mod Persist Off Off
Zero AGC
Zero AGC Ch1
Zero AGC Ch2
Configure
RSSI
DQM
-50.2
dBm
10.0
Lock State:
2255.000 MHz
AGC Zero:
-96.5 dBm
Channel 1 PSD
Channel 2 PSD
Update Rate
Stop
Low
Medium
High

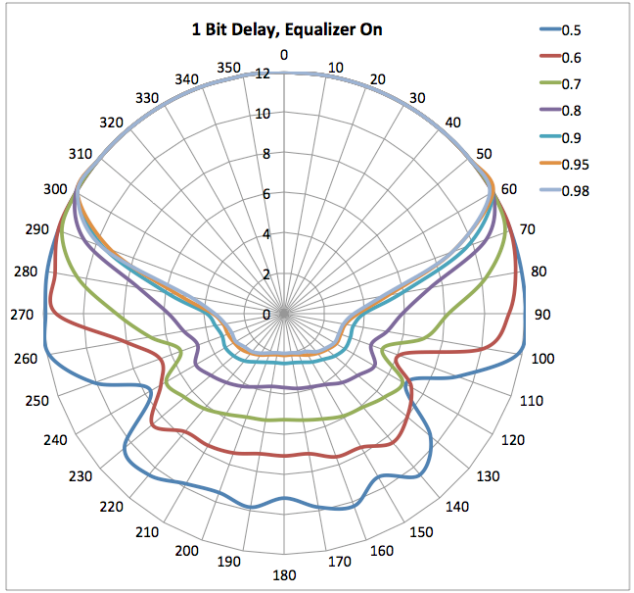

BER Swp
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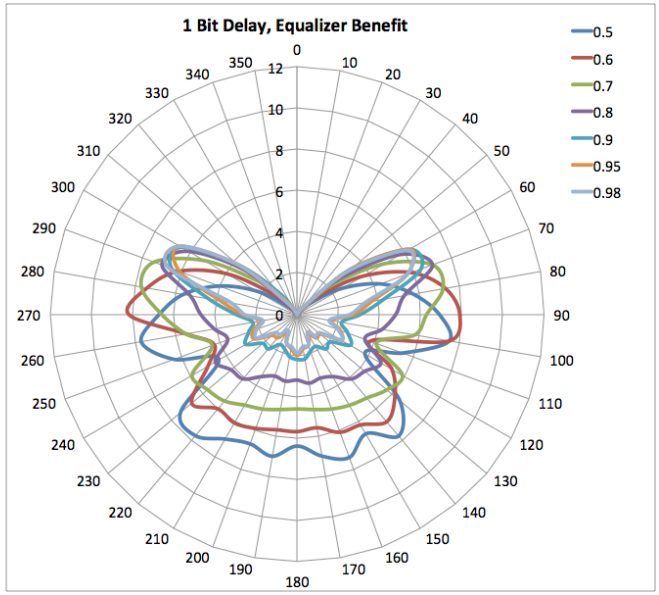
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Test Results Examples

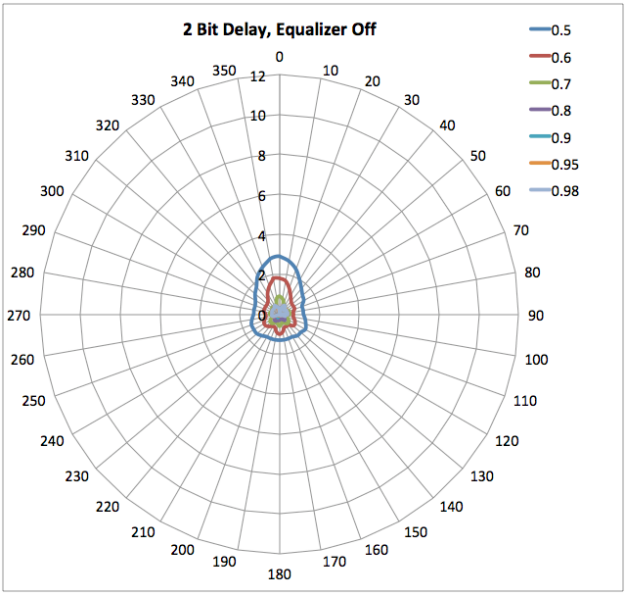
10 Mbps SOQPSK, 1 bit Delay

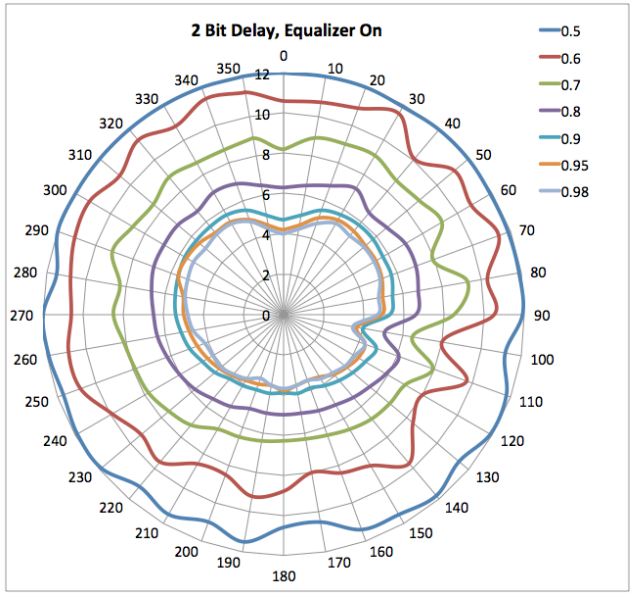


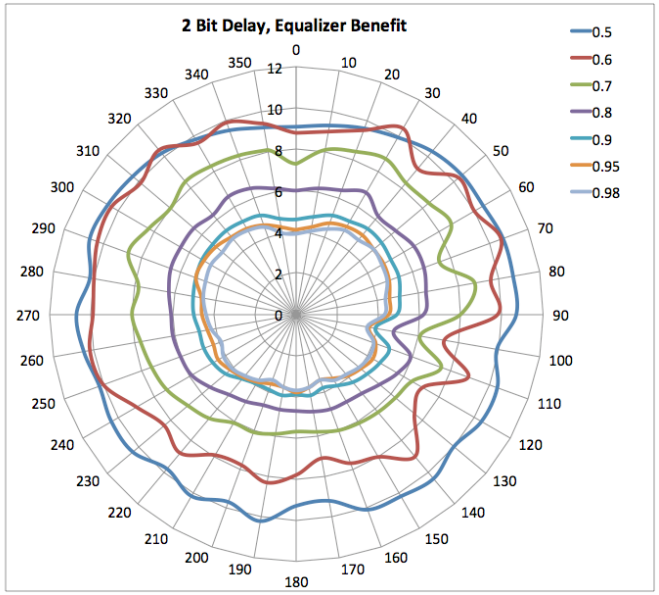




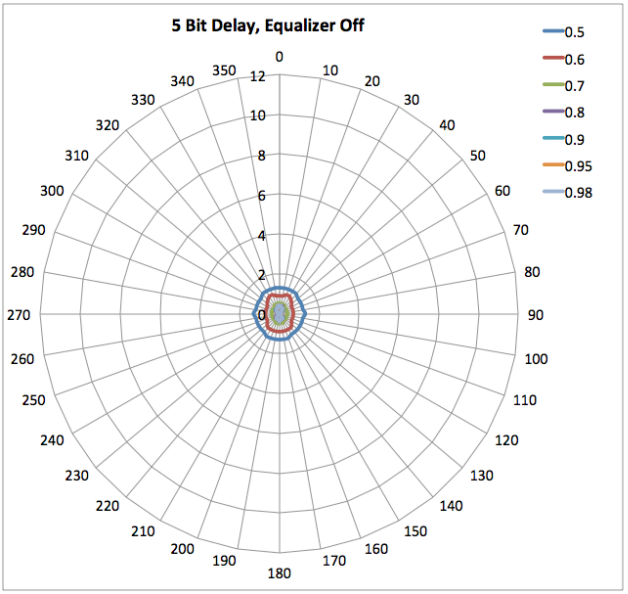
10 Mbps SOQPSK, 2 Bits Delay

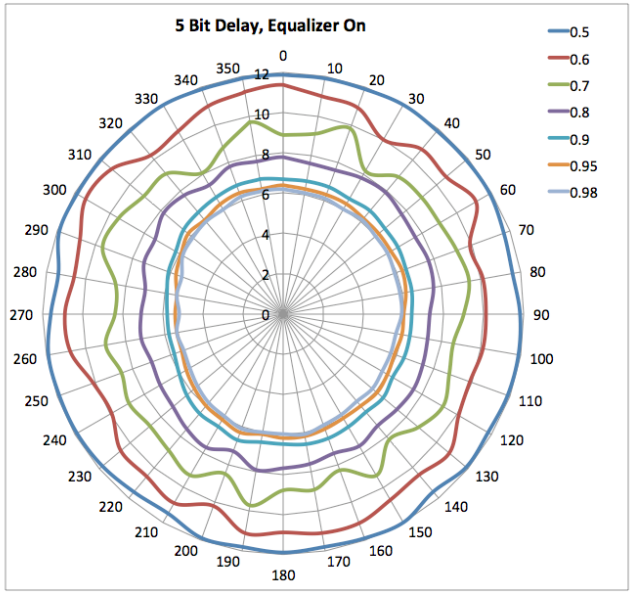


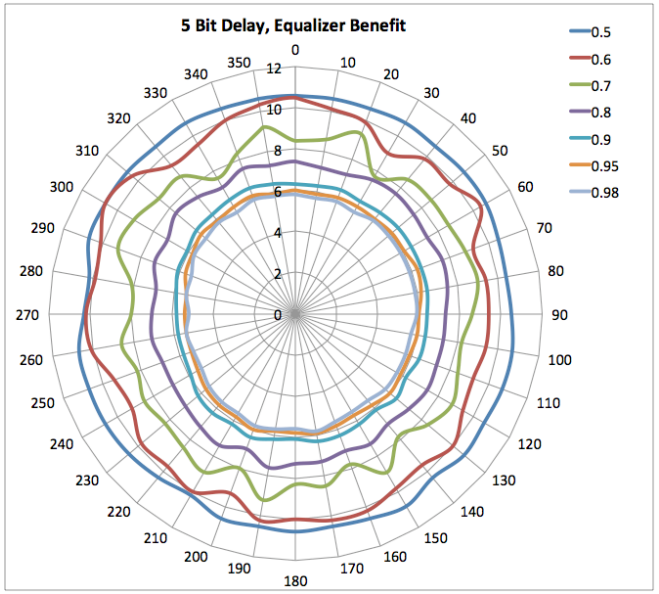




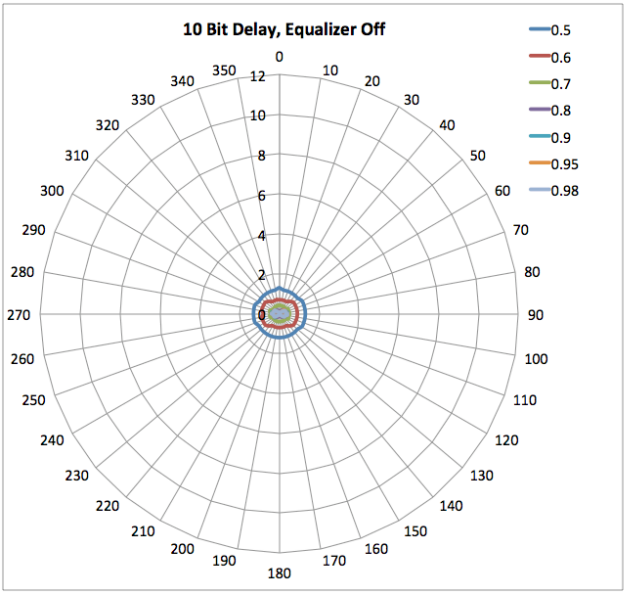
10 Mbps SOQPSK, 5 Bits Delay

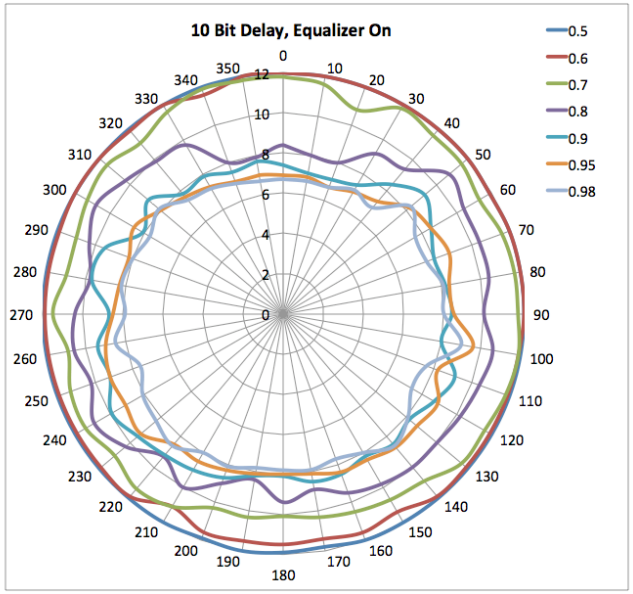


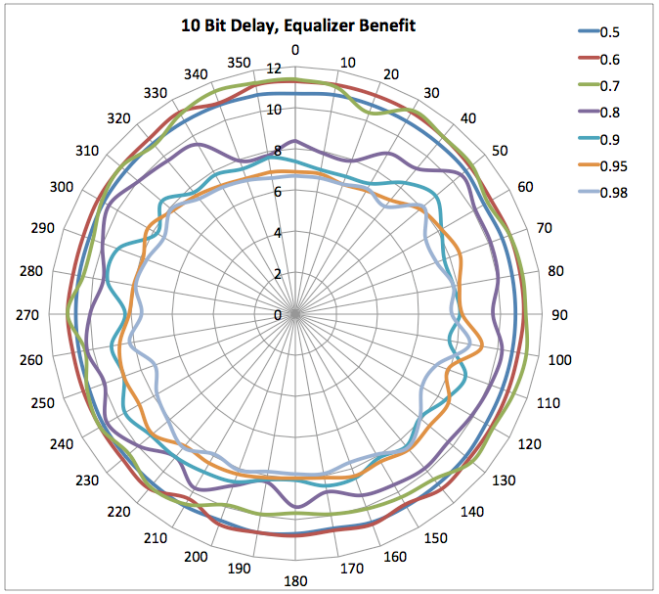




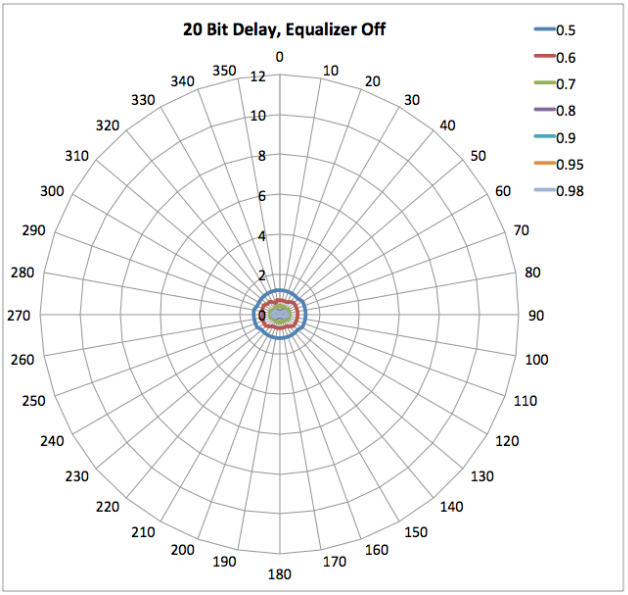
10 Mbps SOQPSK, 10 Bits Delay

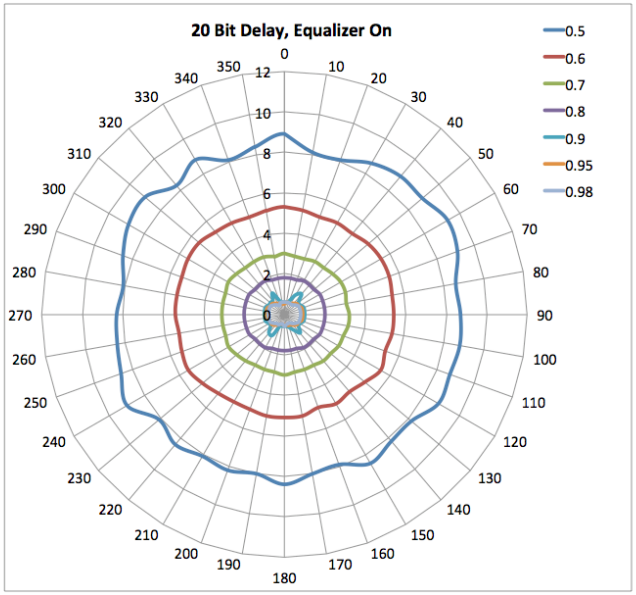


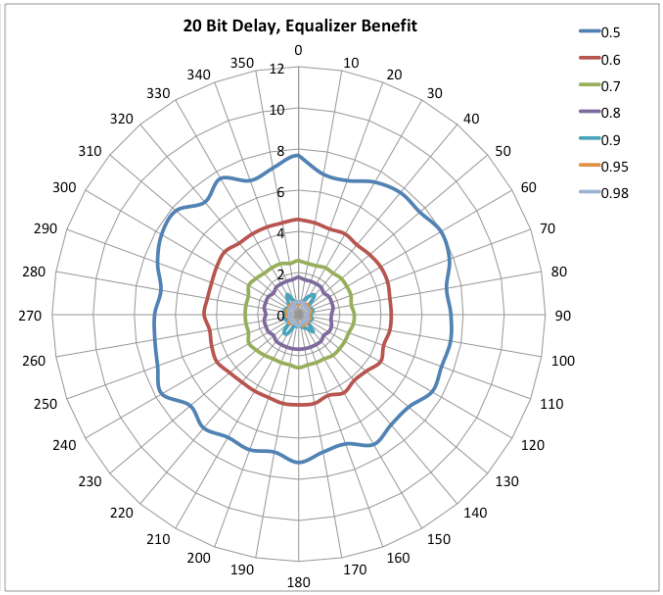




10 Mbps SOQPSK, 20 Bits Delay







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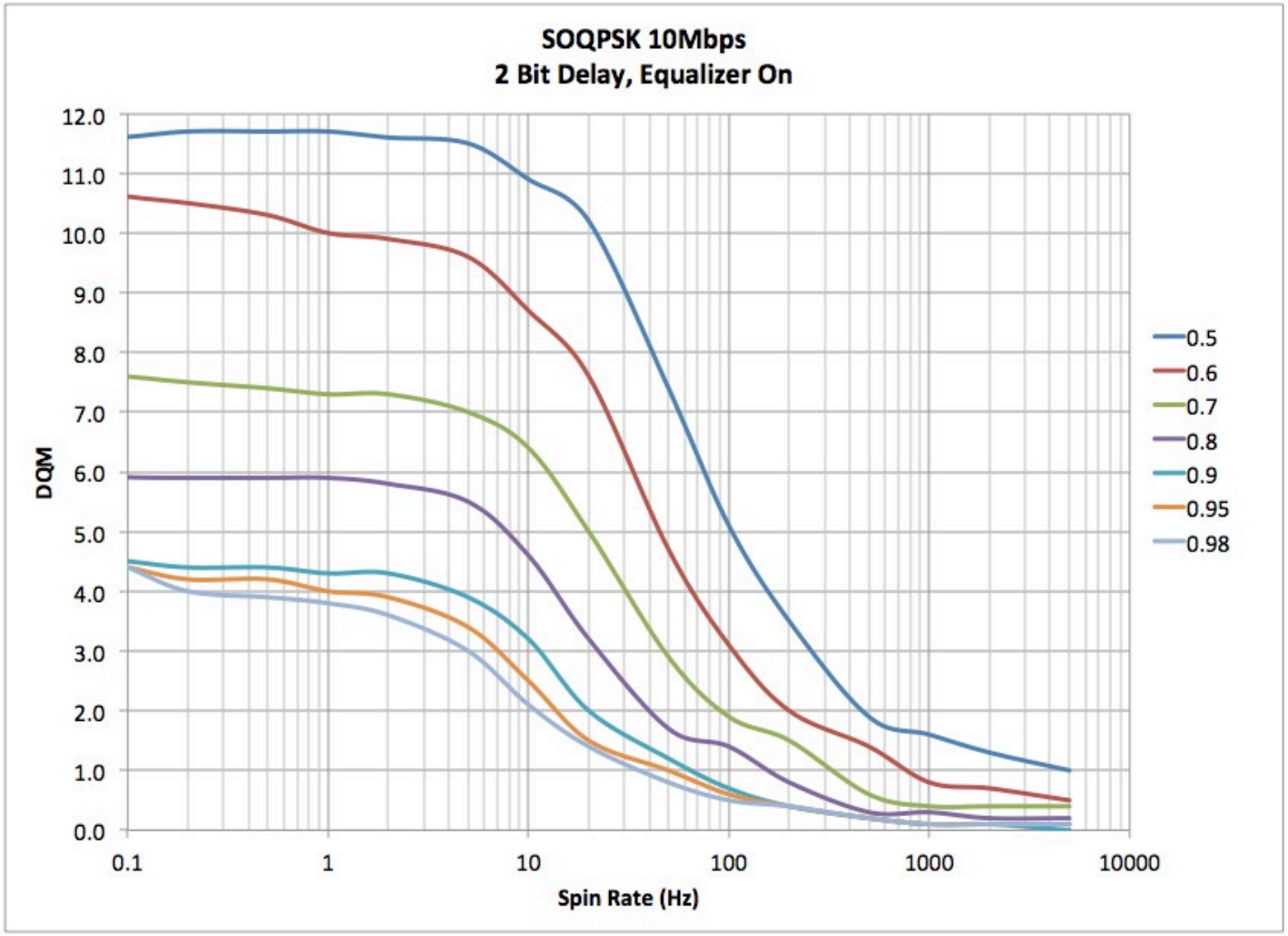
What About Dynamics?

- Most pronounced effect of target motion is variation in phase of the reflected path
  - Manifests as spectral nulls sweeping through spectrum
- Proposal:
  - Stress the equalizer by sweeping the null faster and faster, until the EQ benefit starts to drop.
  - Similar to the Break Frequency test for combiners
- Figure of merit becomes the “Break Frequency” of the equalizer

What Can we Measure?

- Measure the BER, averaged over all phases
  - Correlates with moving test article
  - Convert to DQM
  - Or measure DQM, but average it correctly (see next slide)
- For consistency with the static plots, plot DQM versus “spin rate”
- Plot multiple delay path amplitudes on one chart
- Separate charts for each delay value

Equalizer Break Frequency

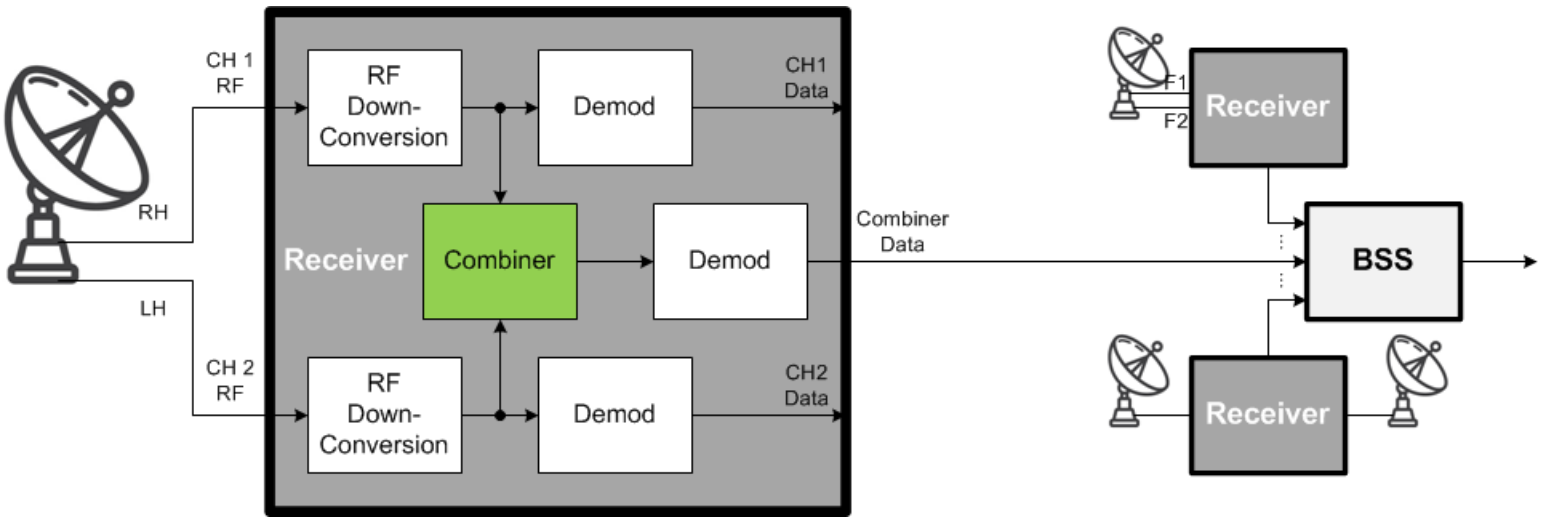


Quasonix

Best Channel Selector (BCS)

Handling the “Un-Combinable” Signals

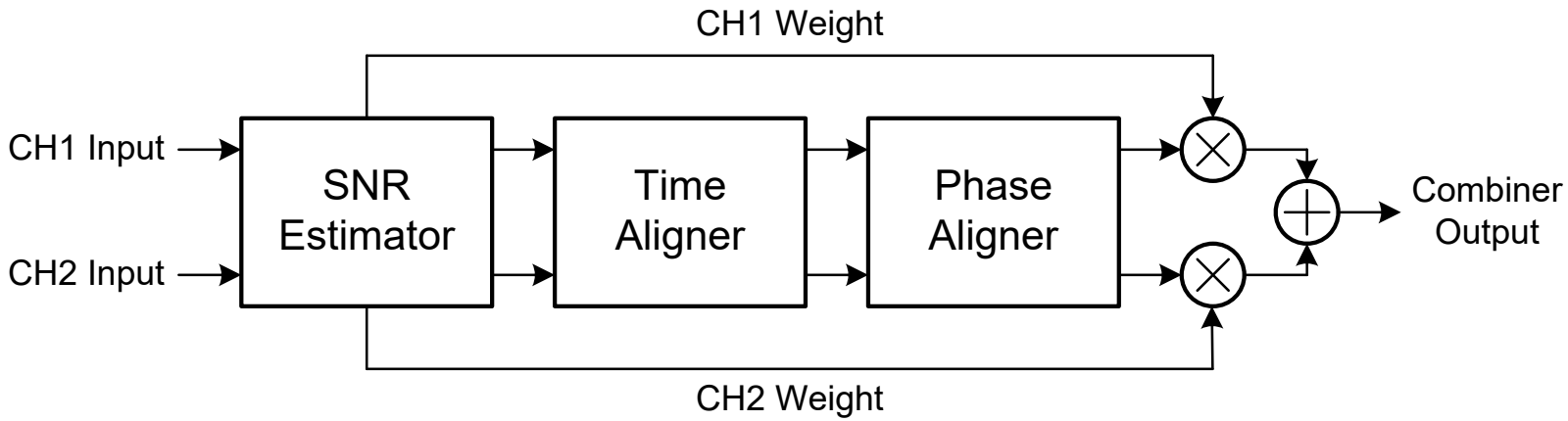
Receive Diversity – Combiner



- Polarization, frequency, or short-range spatial diversity
- Maximal Ratio Combiner sums input channels proportional to their SNR
  - Optimal in additive white Gaussian noise (AWGN) – up to 3 dB gain
  - Use as only receiver output?

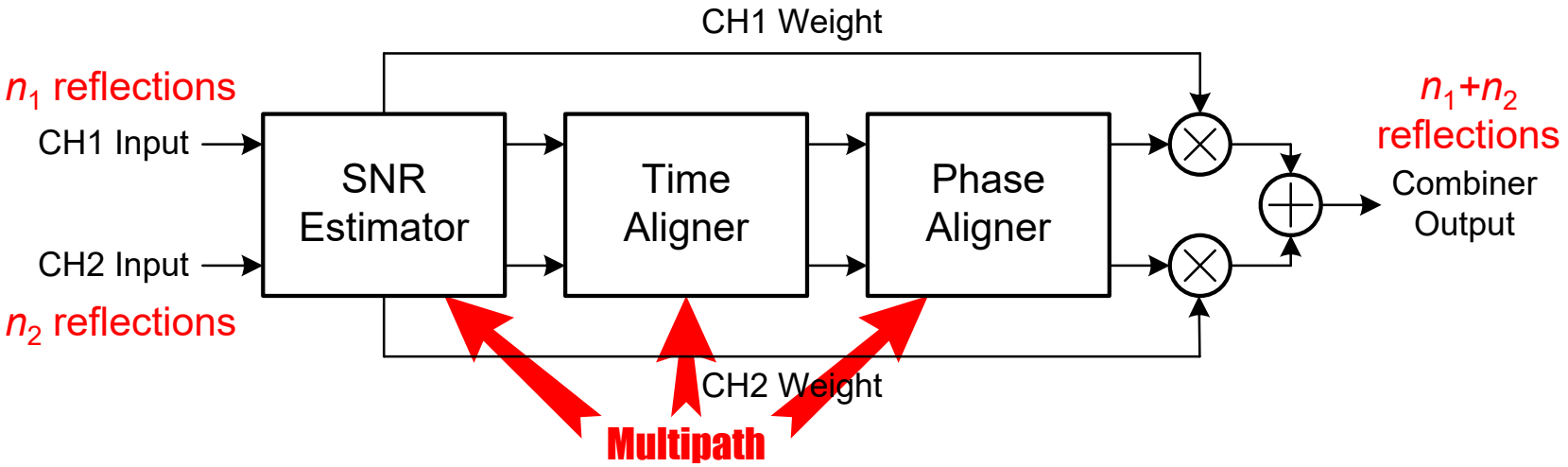
Combiner Structure

- Maximal ratio combining



Combiner Performance

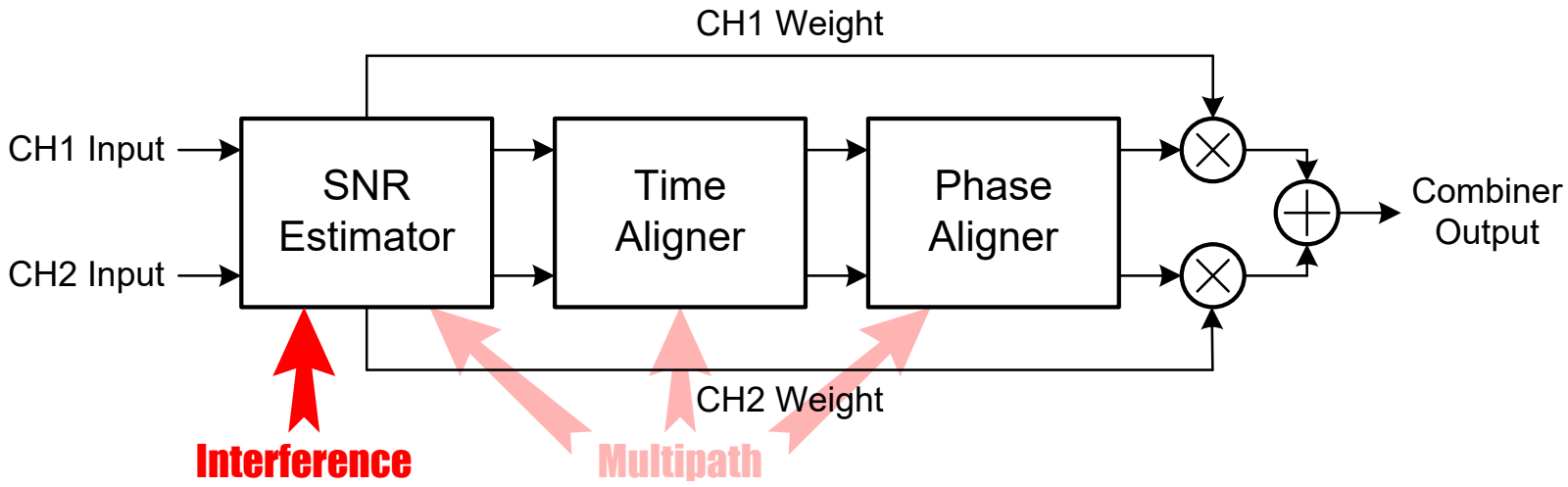
- Maximal ratio combining issues



- Inaccurate SNR estimation: multiple signal copies, little or no noise
- Degraded time and phase alignment
- *Downstream demodulator must deal with **all** received reflections*

Combiner Performance

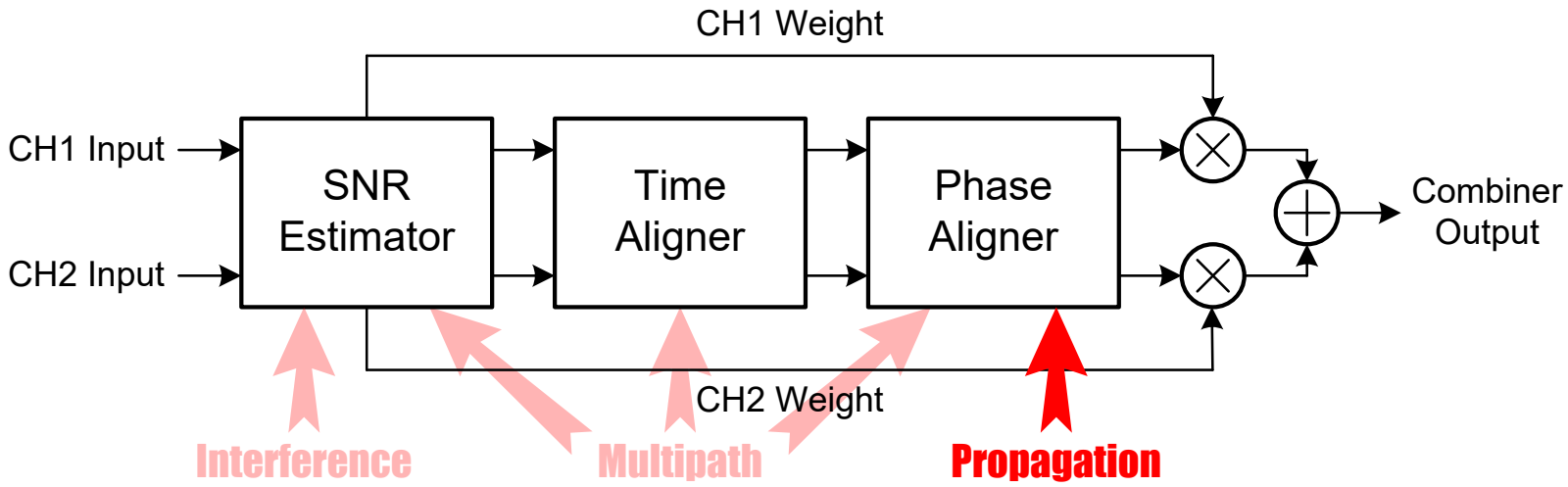
- Maximal ratio combining issues



  - Inaccurate SNR estimation: overwhelm estimator with strong *undesired* signal

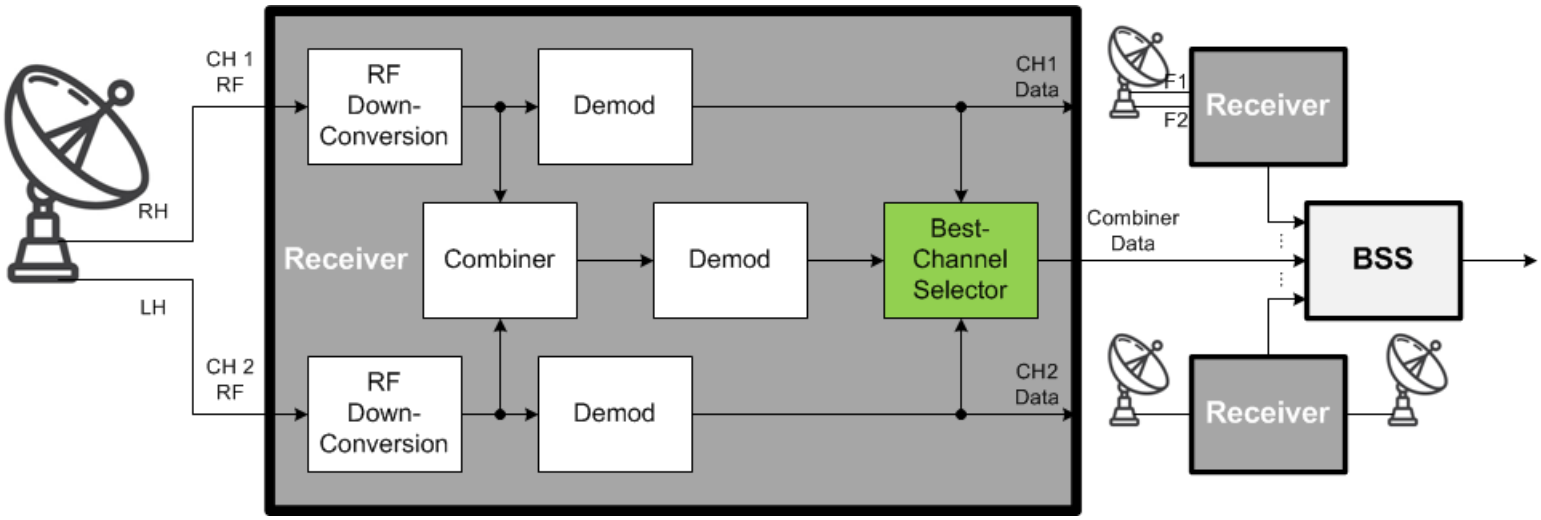
Combiner Performance

- Maximal ratio combining issues



  - Propagation effects may result in non-combinable signals

Receive Diversity – BCS

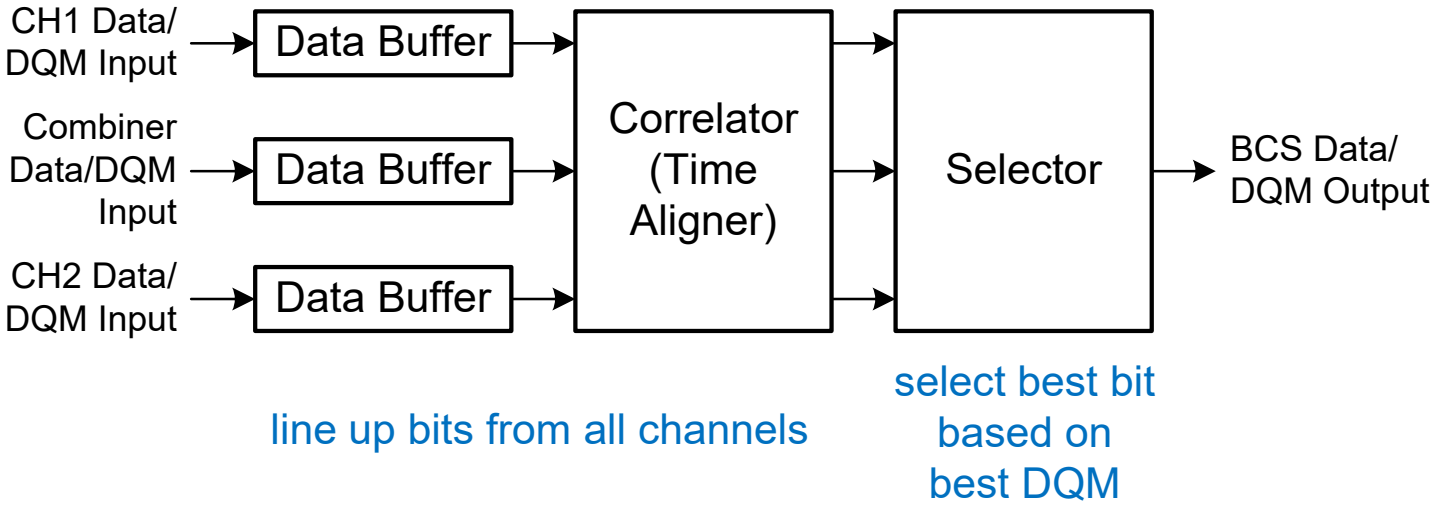


- Like a mini-BSS *inside the receiver*
- Selects and outputs best data from just three sources (Channel 1, Channel 2, and Combiner)
- Optimized for this narrowly scoped role

BCS Structure

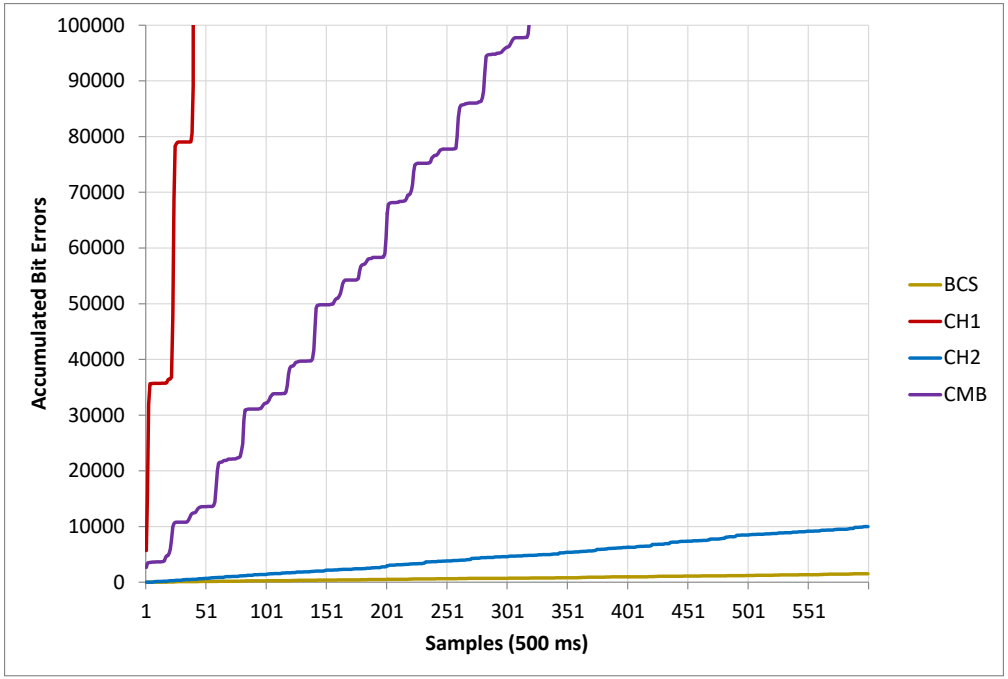
- 3-channel correlating selection

"hit-less" – no dropped or duplicated bits

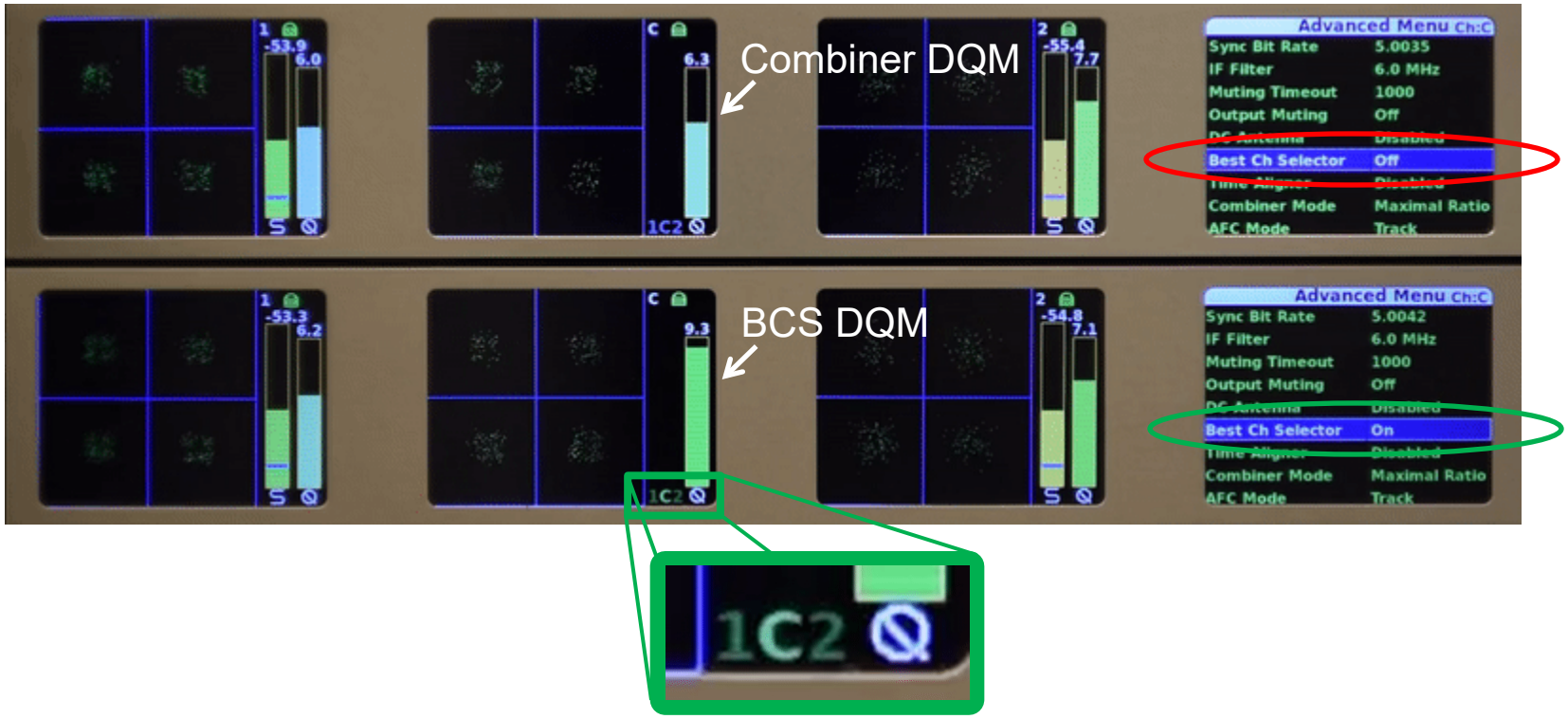


BCS Test – Multipath

- Apply severe multipath, engage adaptive equalization
- BCS outperforms all channels



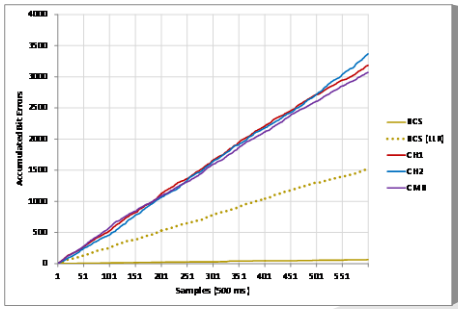
BCS Test – Multipath



- DQM reduction of 1 = BER increase of 10x (!)
- BCS selection > 1000x faster than display

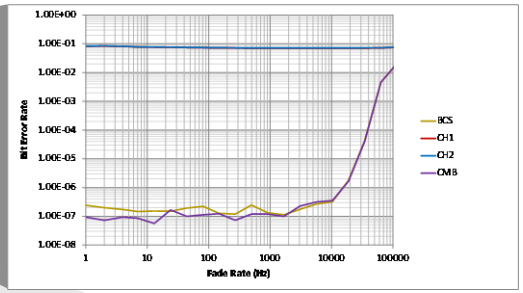
BCS Test – Summary

- Uniformly equals or exceeds best channel's performance

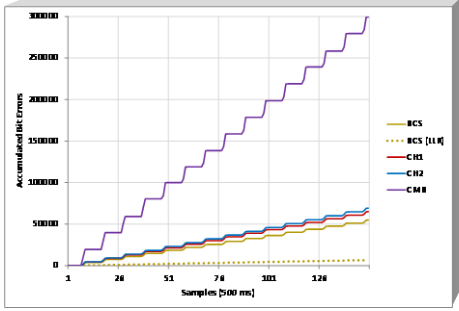


AWGN

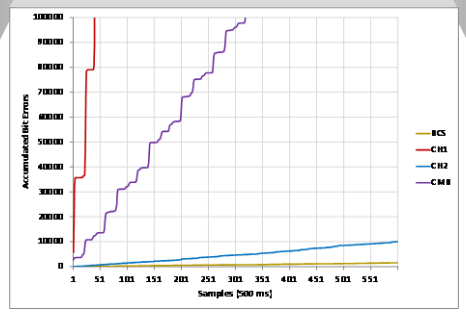
BCS



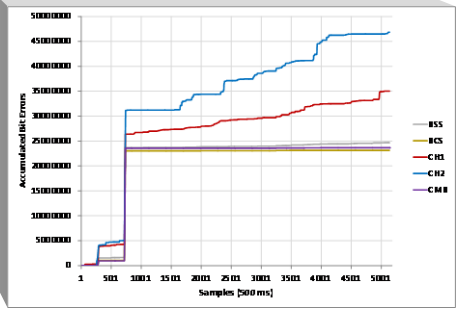
Break Frequency



STC polarization



Multipath



Flight Recording

Conclusions

- Combiner best most of the time, but not always
- BCS mitigates cases where Combiner falls short
  - Uses DQM to form reliable selection criterion
  - Dynamically selects best data from Channel 1, Channel 2, or Combiner
    - Preserves combiner gain in AWGN
    - Supplements combiner in multipath, interference, etc.
  - Generates output with accurate composite DQM
  - **Provides single output from dual-channel receiver that reliably supplies data superior to best channel, including Combiner**
- BCS does not replace BSS
  - BCS has great performance local to one receiver
  - BSS extends performance range-wide with multiple receive sites

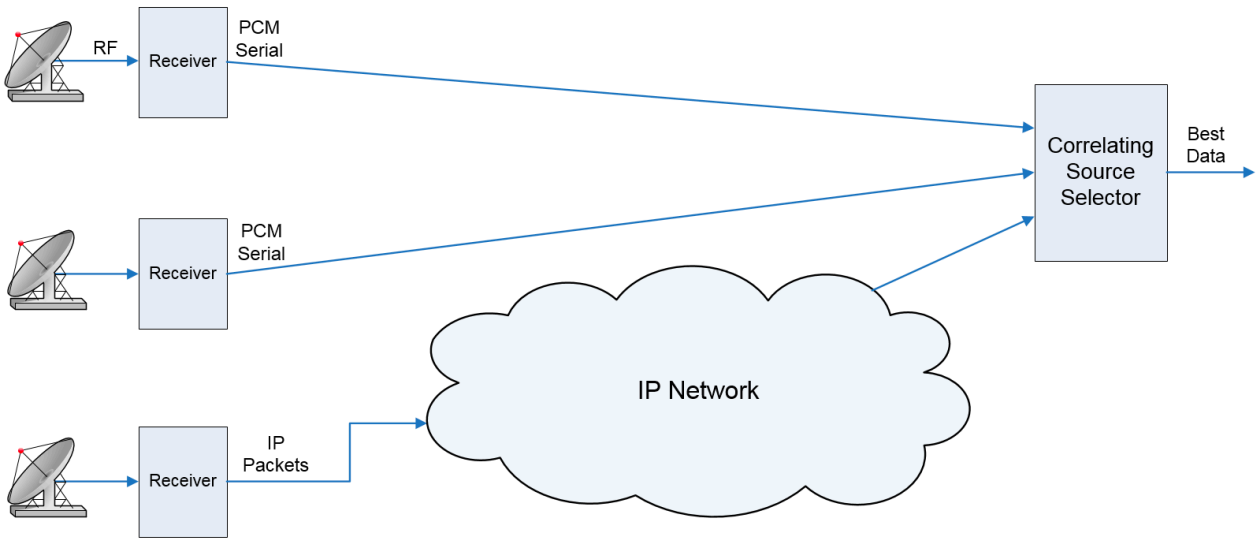
Quasonix

Best Source Selection

Short Break

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



Selection Algorithms

- Best Source
  - Based on “side information”
  - Never better than the best source
- Majority vote
  - Reasonably effective with three or more sources
  - Reduces to guesswork with only two sources
  - Sub-optimal for any number of sources
  - Can be *worse* than Best Source
- Maximum Likelihood Bit Detection (MLBD)
  - Uses 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.

Best Source Algorithm

- As the name implies, just pick the “best”, using…
- DQM
  - Best option if DQM is available and accurate
- PCM frame header accuracy
  - Uses only a small fraction of the bits to make an estimate
  - Poor resolution (BER is typically measured as Number of errors ÷ 32)
  - Useless with encrypted data
- Signal strength
  - Assumes “louder” is better
- SNR
  - May be more useful than signal strength
  - Requires significant DSP for accuracy
- Never better than the best available source

Majority Vote Algorithm

- Assumes all voters are equally “well informed”
  - All sources are equally weighted
- Relatively simple to implement
- Not useful with only two sources
- Suboptimal for any number of sources
- Benefits from “voter screening”
  - Exclude sources that are not “good enough”
- Can yield *worse* data than Best Source if some sources are poor
  - Equivalent to letting uninformed voters go to the polls

Max Likelihood Bit Detection

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

$$\hat{x} = 0 \iff \prod_{n\in\mathcal{N}_0} p(y_n|x=0) \prod_{n\in\mathcal{N}_1} p(y_n|x=0) > \prod_{n\in\mathcal{N}_0} p(y_n|x=1) \prod_{n\in\mathcal{N}_1} p(y_n|x=1)$$

$$\iff \prod_{n\in\mathcal{N}_0} (1-p_n) \prod_{n\in\mathcal{N}_1} p_n > \prod_{n\in\mathcal{N}_0} p_n \prod_{n\in\mathcal{N}_1} (1-p_n)$$

$$\iff \log\left(\prod_{n\in\mathcal{N}_0} (1-p_n) \prod_{n\in\mathcal{N}_1} p_n\right) > \log\left(\prod_{n\in\mathcal{N}_0} p_n \prod_{n\in\mathcal{N}_1} (1-p_n)\right)$$

$$\iff \sum_{n\in\mathcal{N}_0} \log(1-p_n) + \sum_{n\in\mathcal{N}_1} \log(p_n) > \sum_{n\in\mathcal{N}_0} \log(p_n) + \sum_{n\in\mathcal{N}_1} \log(1-p_n)$$

$$\iff \sum_{n\in\mathcal{N}_0} \log(1-p_n) - \sum_{n\in\mathcal{N}_0} \log(p_n) > \sum_{n\in\mathcal{N}_1} \log(1-p_n) - \sum_{n\in\mathcal{N}_1} \log(p_n)$$

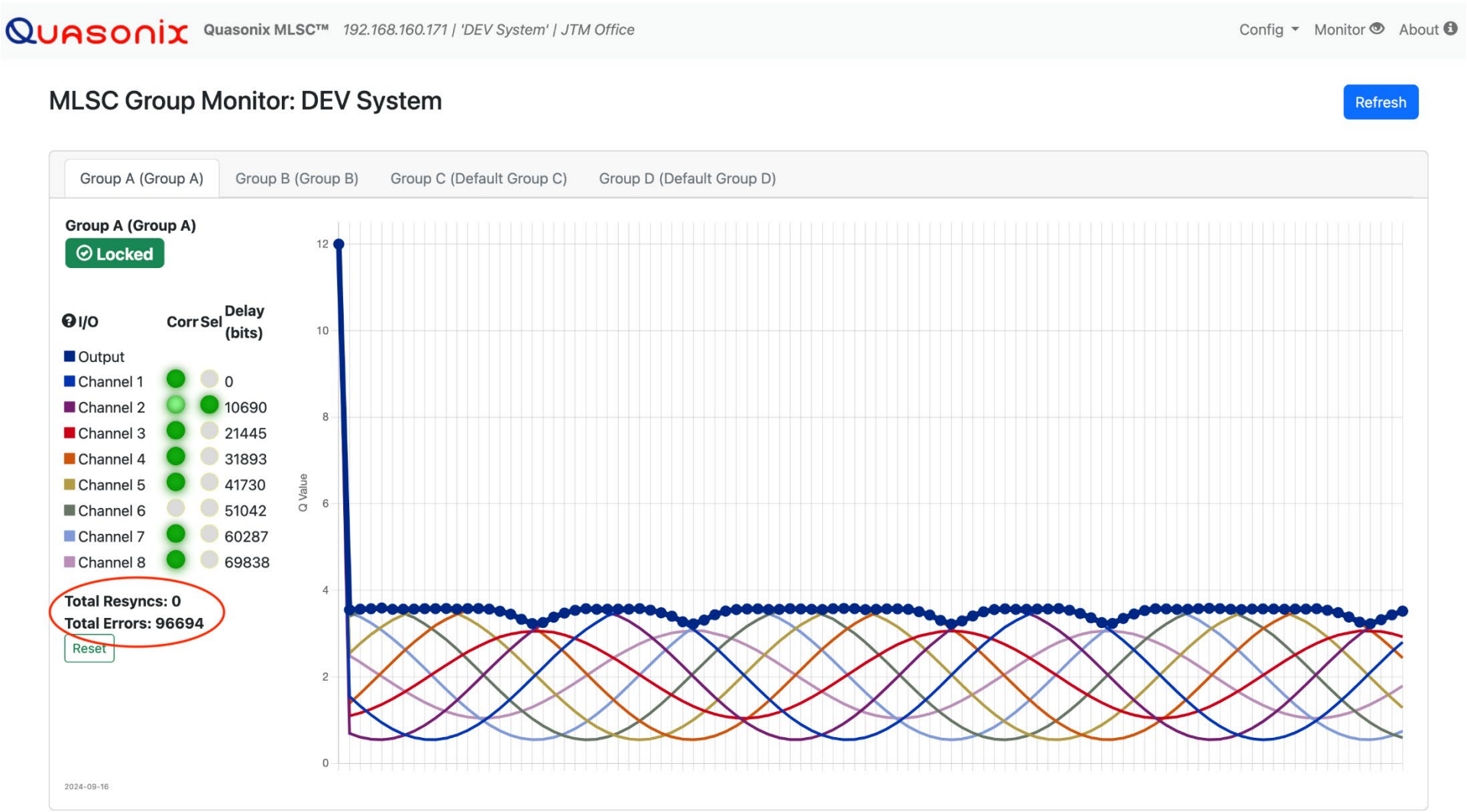
$$\iff \sum_{n\in\mathcal{N}_0} \log\left(\frac{1-p_n}{p_n}\right) > \sum_{n\in\mathcal{N}_1} \log\left(\frac{1-p_n}{p_n}\right).$$

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

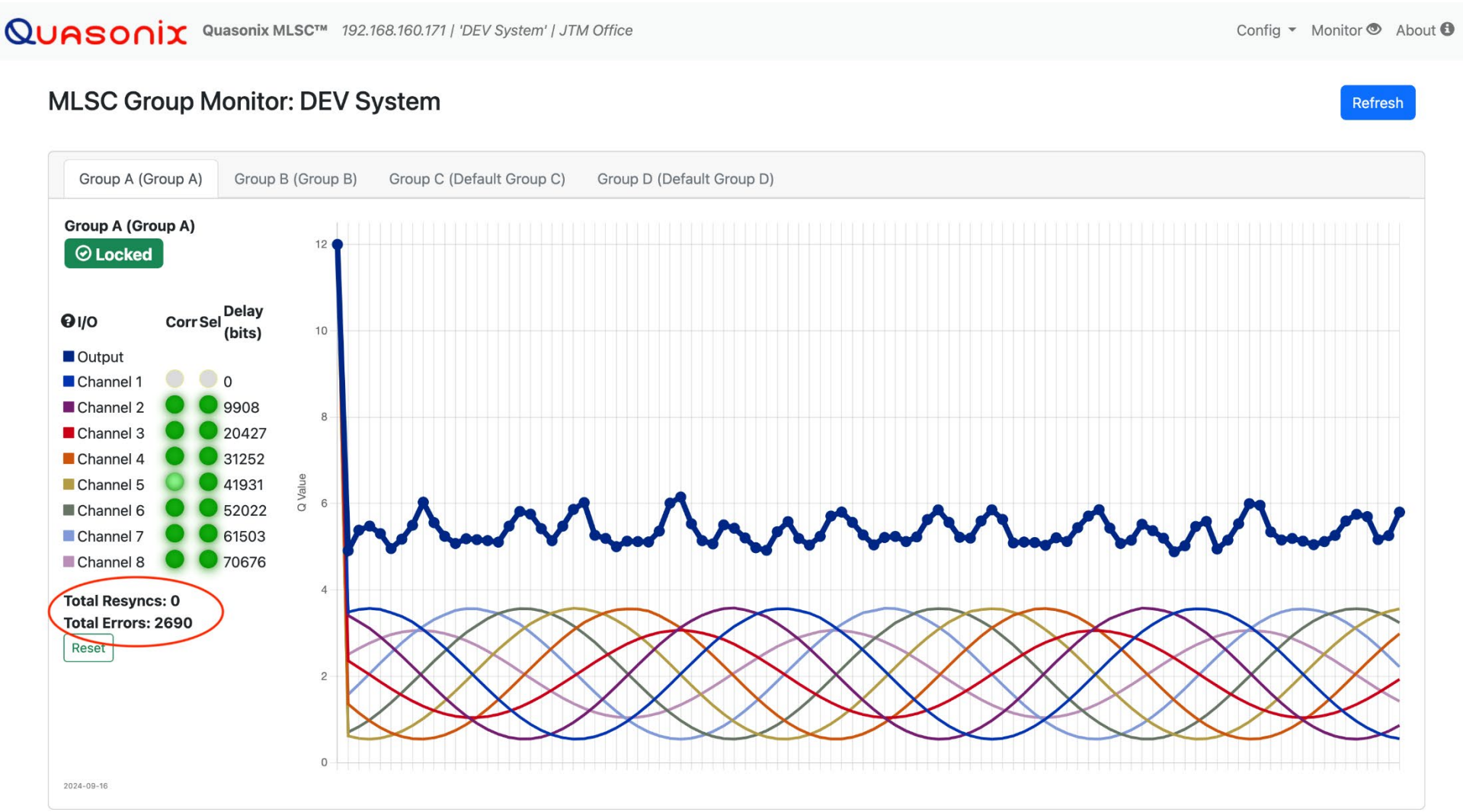
Data Quality Encapsulation

- 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
  - RCC standard as of IRIG 106-17, Chapter 2, appendix G
- Includes test procedures to evaluate DQM accuracy

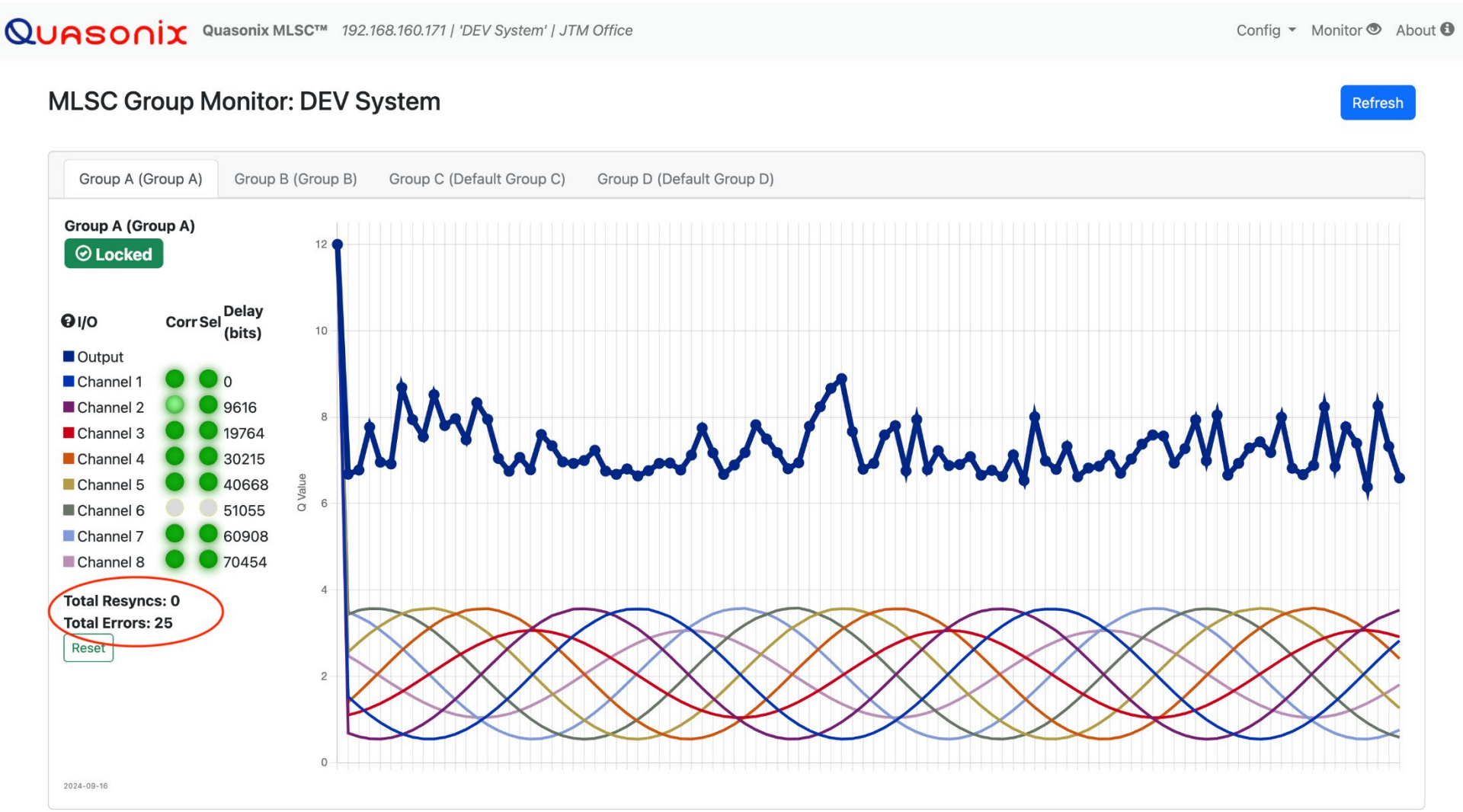
Best Source Selection



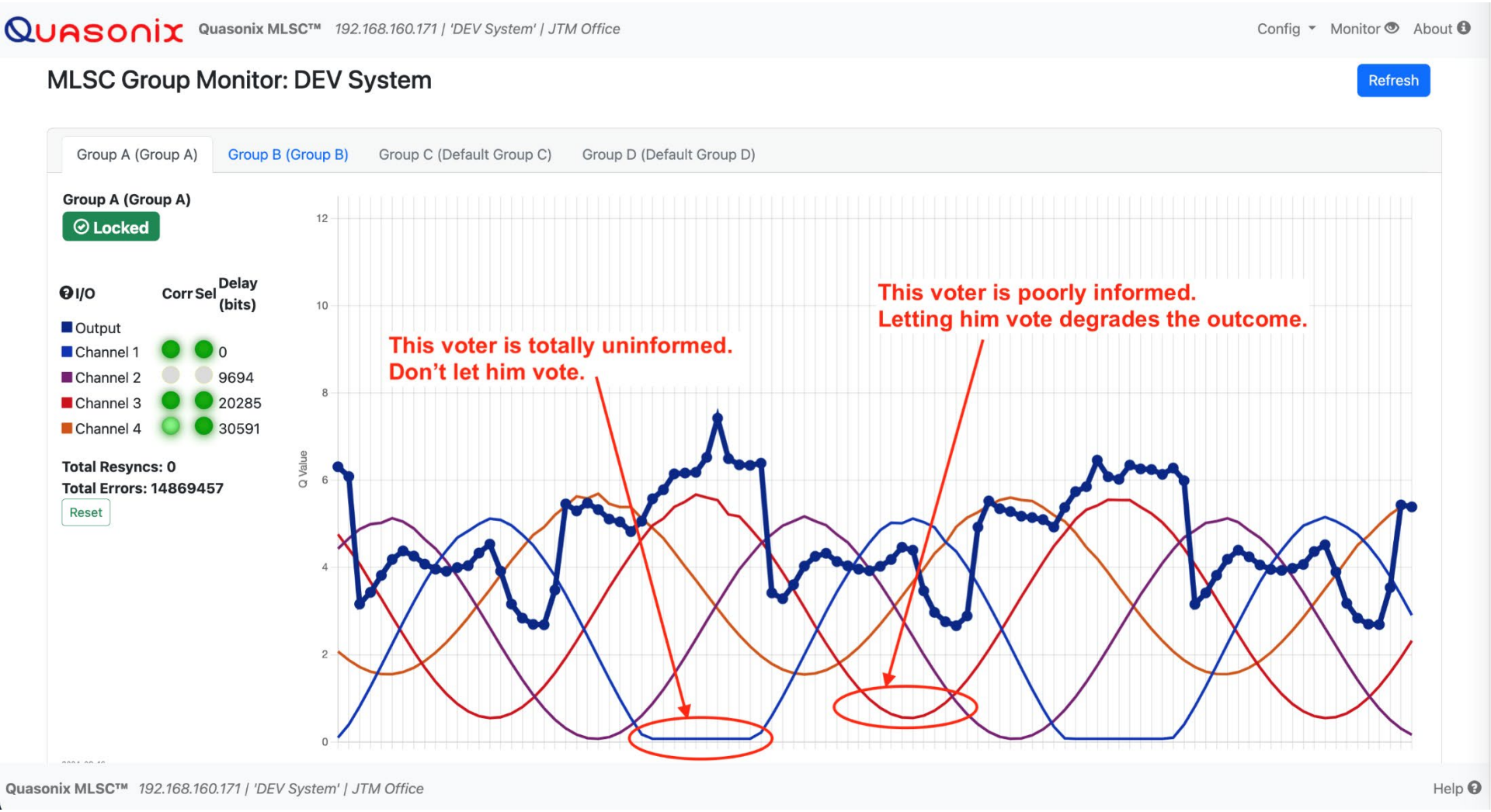
Majority Vote



Max Likelihood Bit Detection



Majority Vote with Dumb Voter



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
- **Accurate DQM with Max Likelihood Bit Detection…**
- **Yields optimal results**

Rx/TX DSP Techniques

Rx/Tx DSP Techniques

- If you can choose your transmitter…
- 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

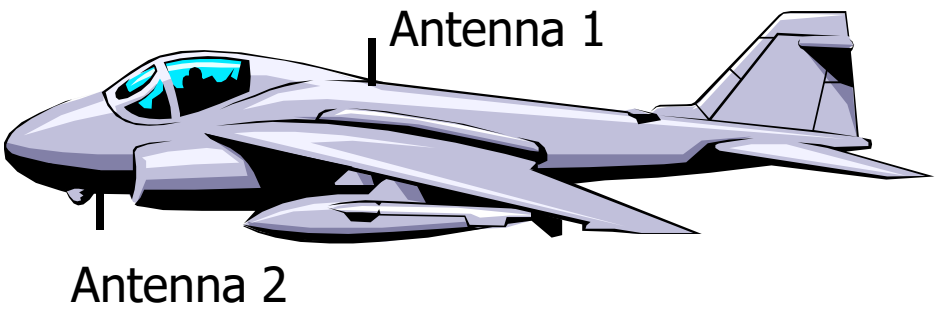
Quasonix

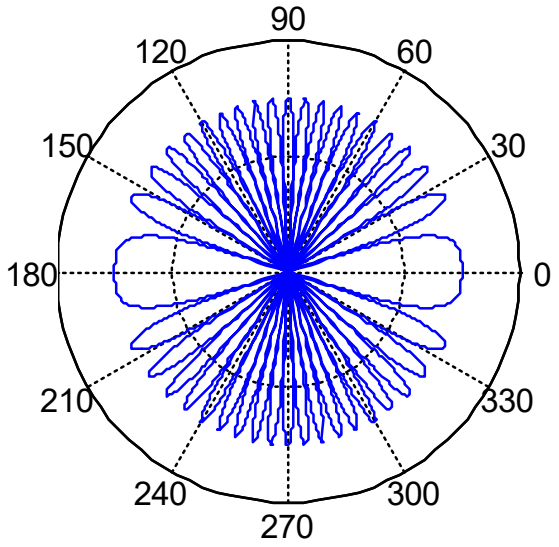
Space-Time Coding

Eradicates Porcupines!

Difficulties with TX Diversity

Spatially Separated Antennas Create Interference Pattern

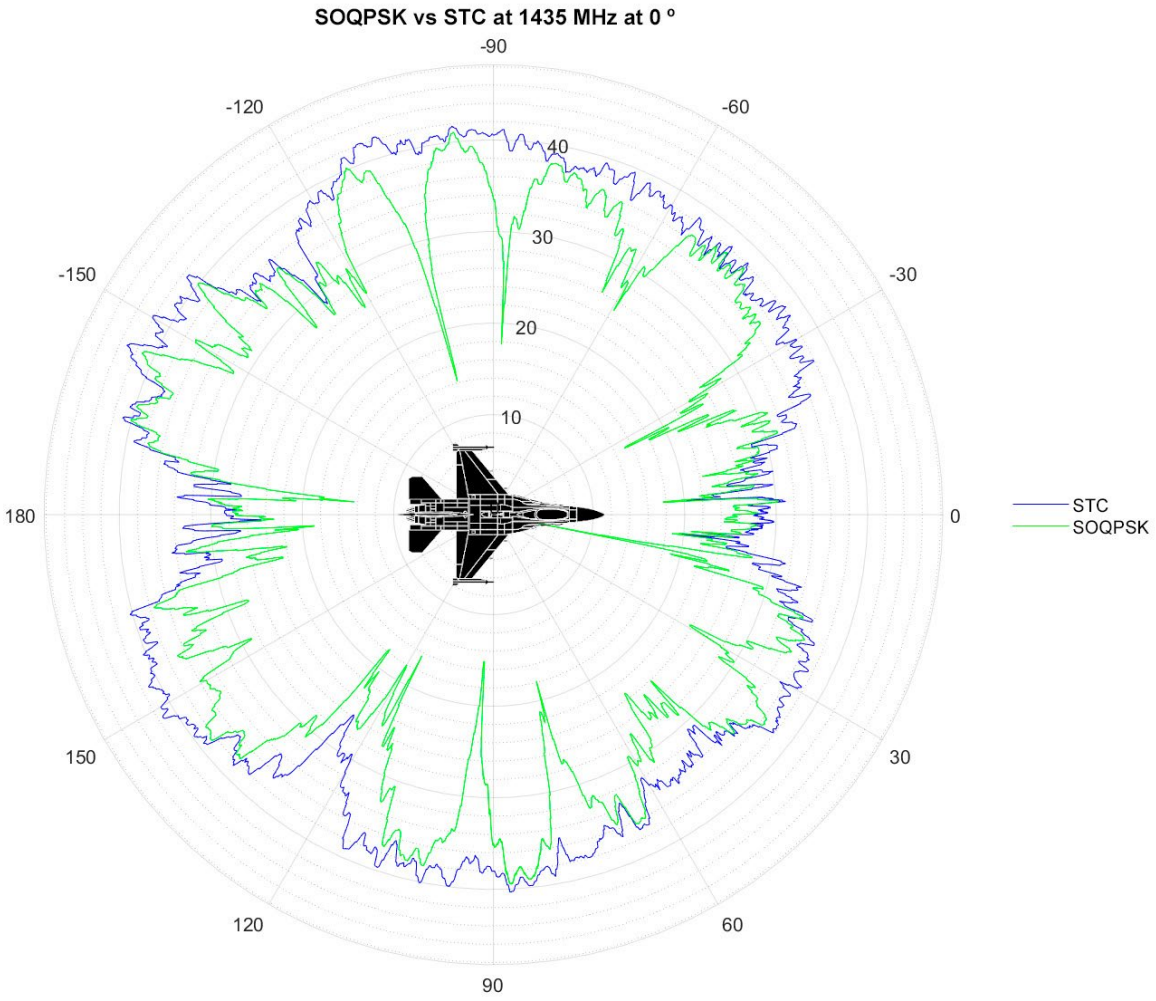




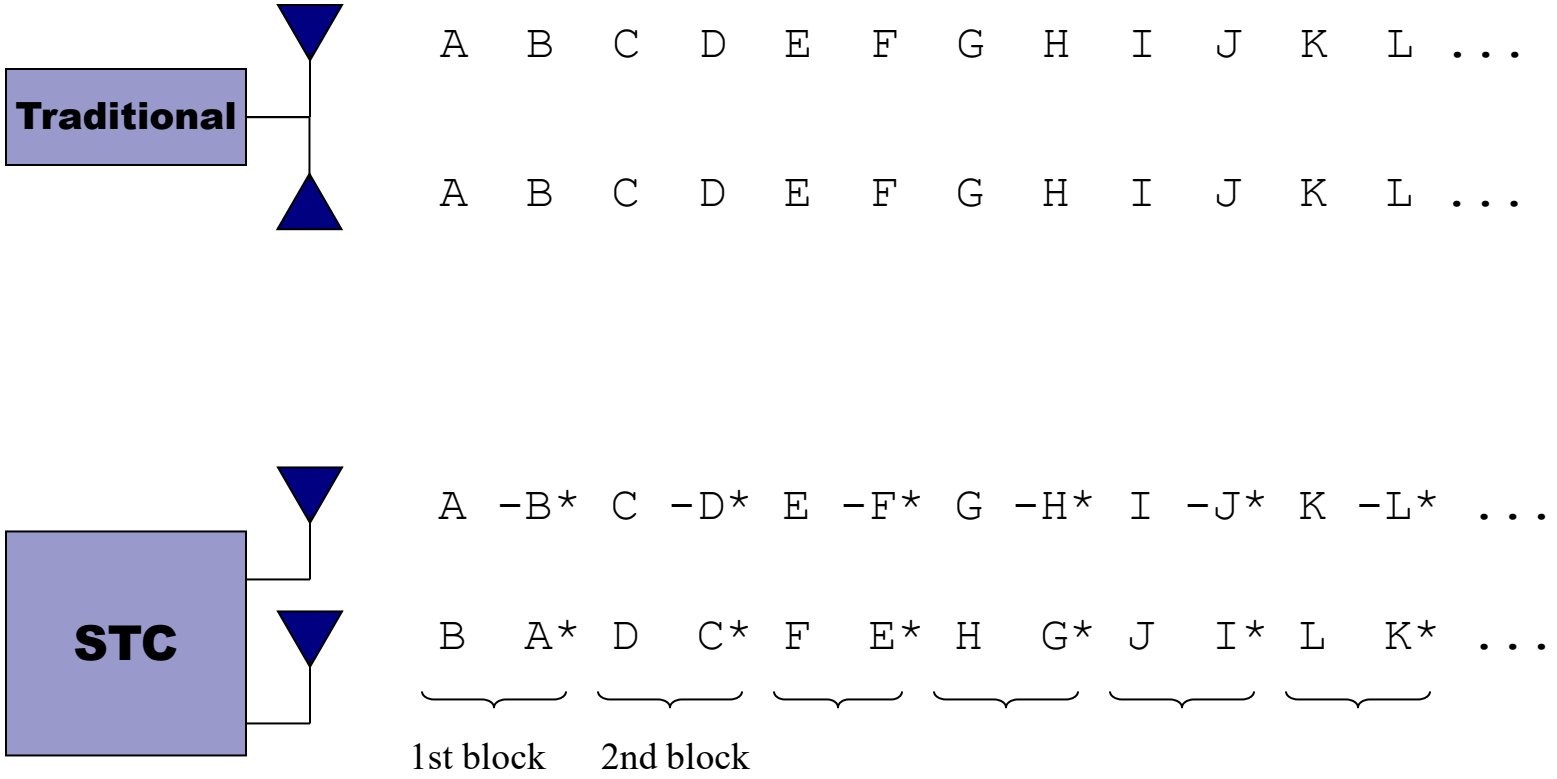
Pattern Measurement Setup



Measured Antenna Pattern



Alamouti Space-Time Coding (STC)



Symbol Error Rate - QPSK

Traditional signaling

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

Addition of transfer functions leads to reduction in effective SNR

For Alamouti signaling

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

Only magnitudes of transfer functions used in sum

Antenna Pattern Interpretation

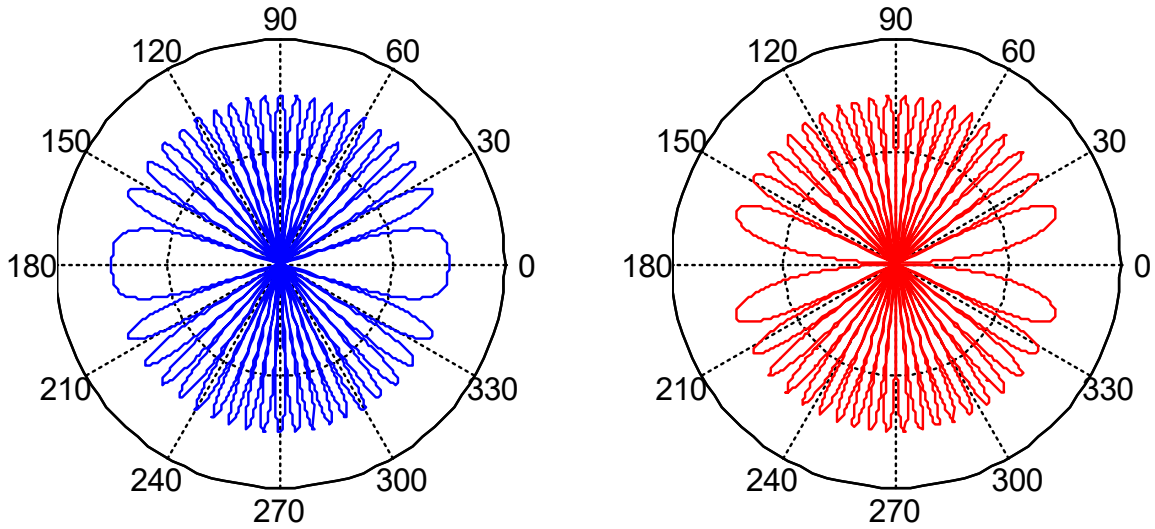
Consider BPSK Signaling and Assume $s_1 = s_2 = 1$

Time Slot 1:

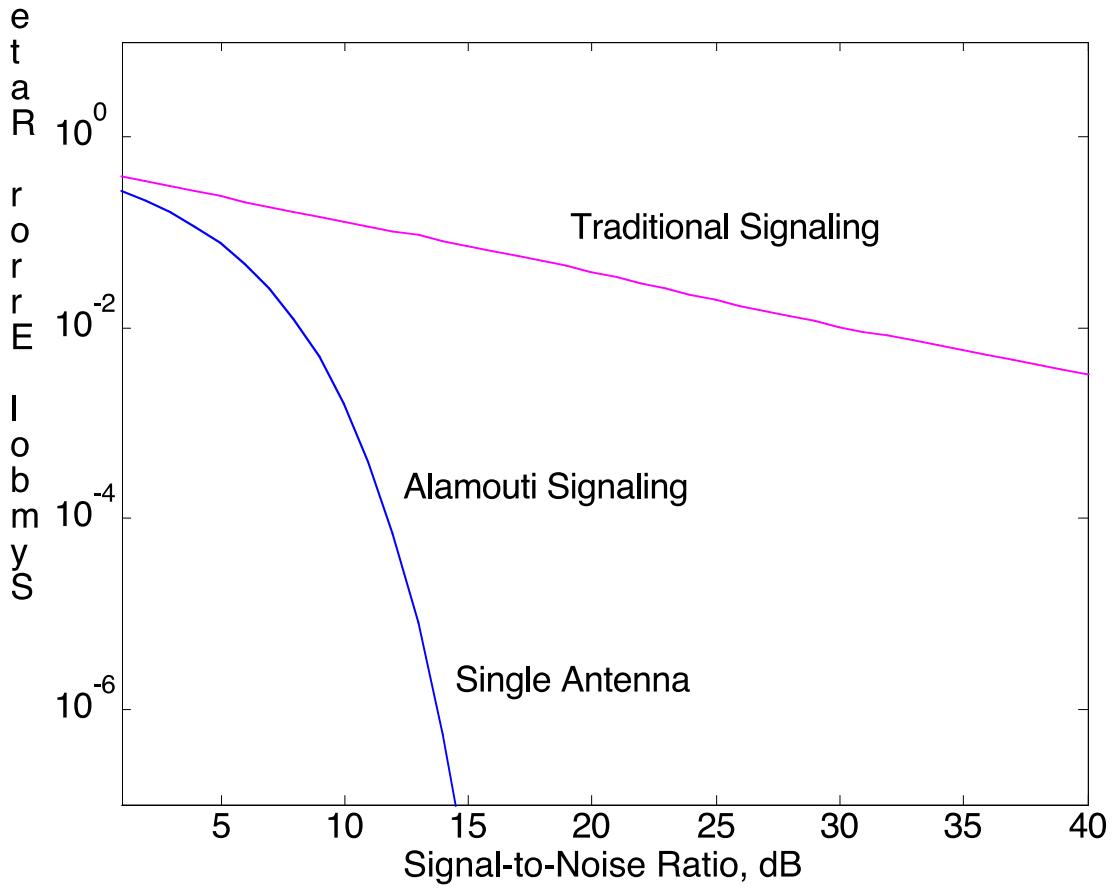
Gain Pattern: $G_{t1}(\phi) = 2\cos^2\left[\frac{kd}{2}\cos\phi\right]$

Time Slot 2:

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



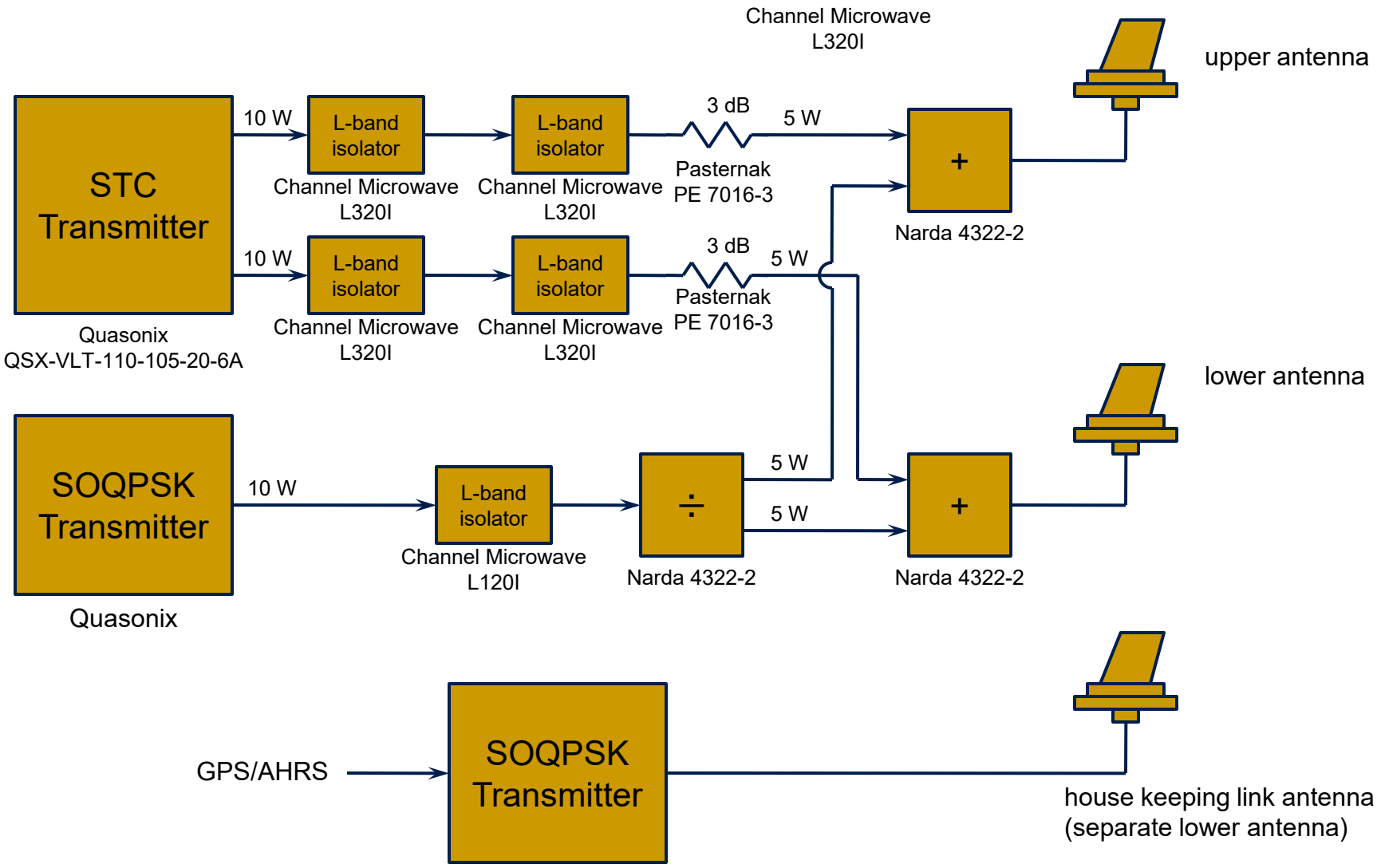
SER Simulations



Circular Polarization Diversity Reception

Results Identical to Single Receive Antenna System

Flight Tests: Airborne Configuration

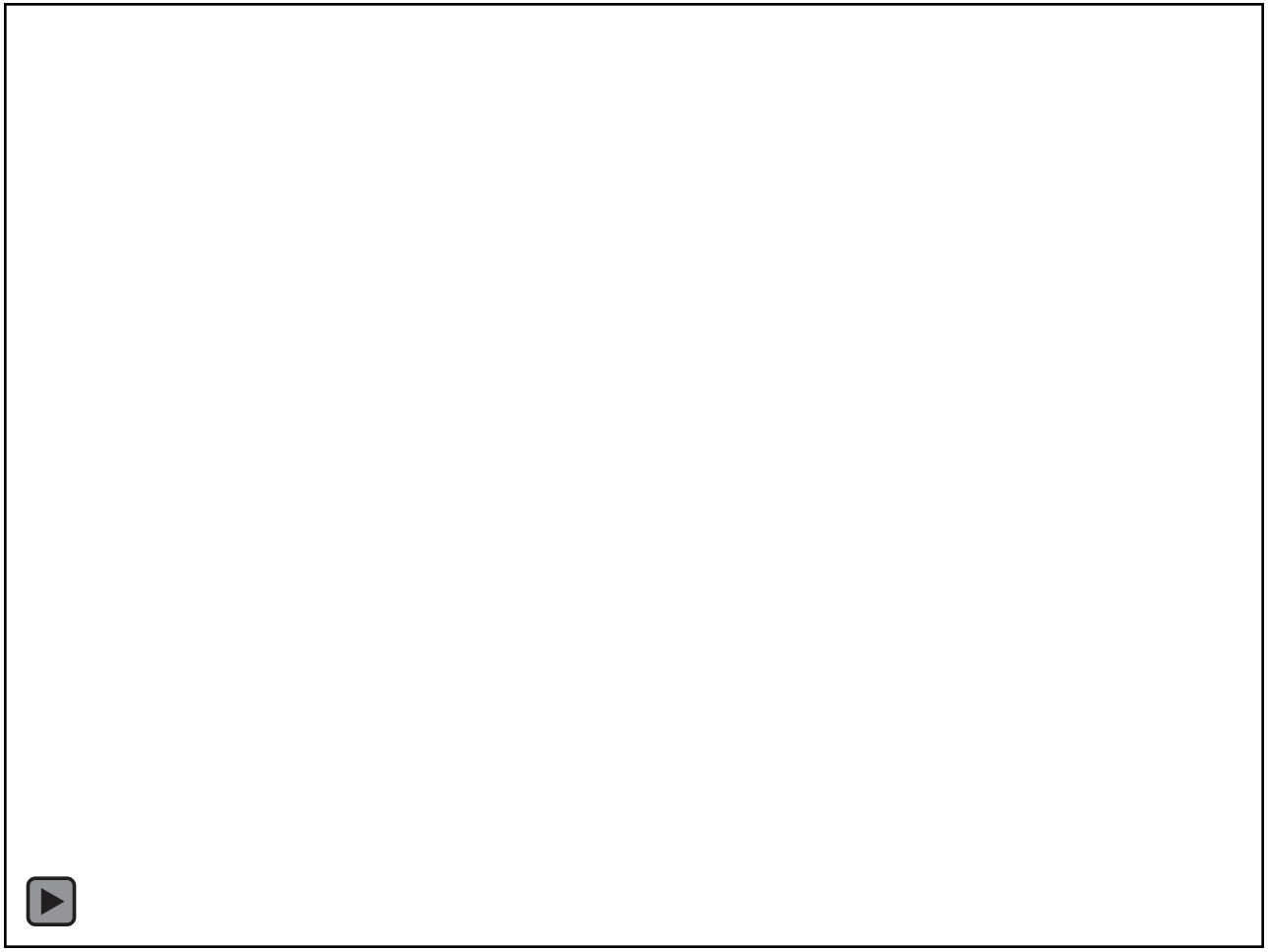


C-12 Beechcraft: Airborne Platform

BYU



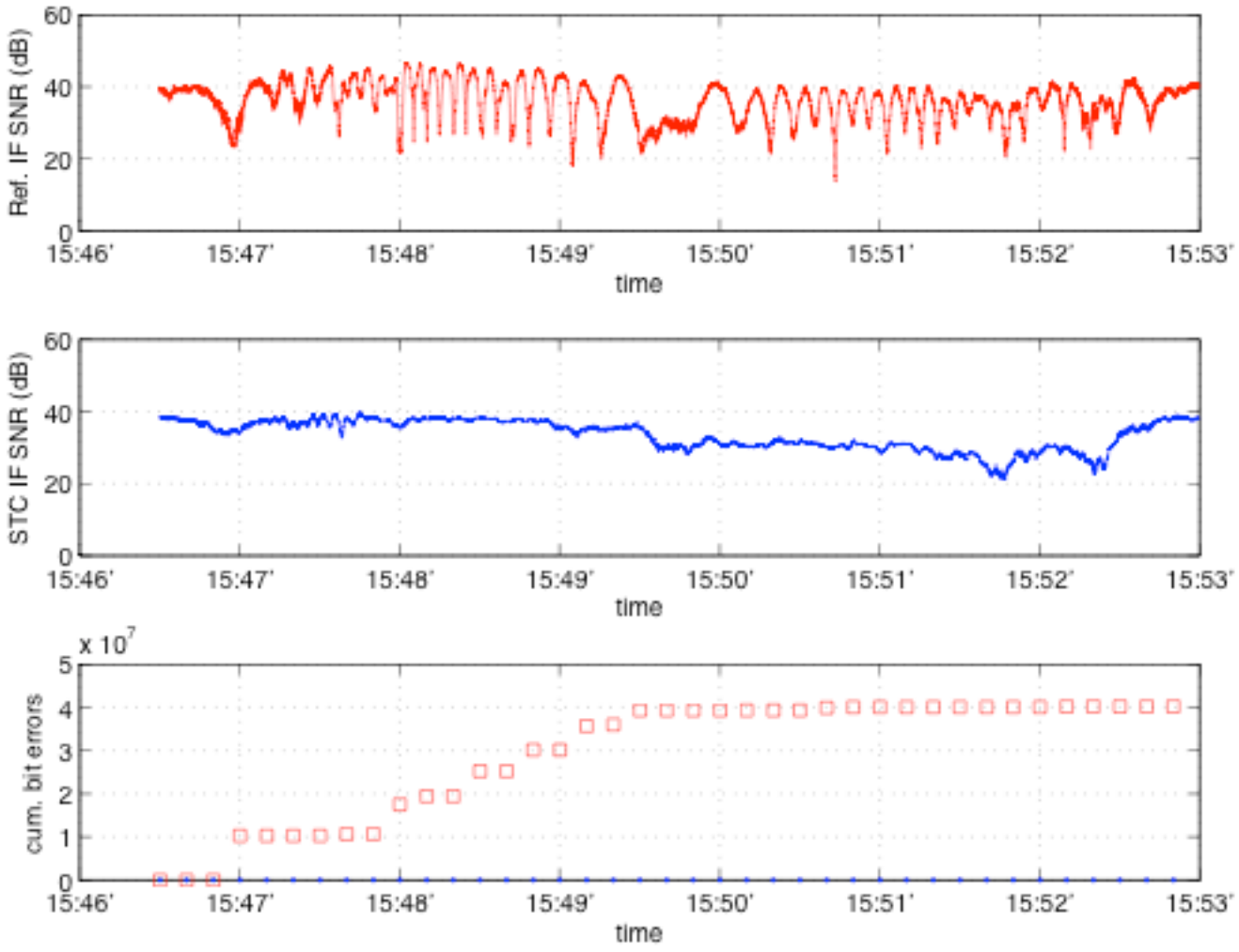
STC Video Clip



STC Summary

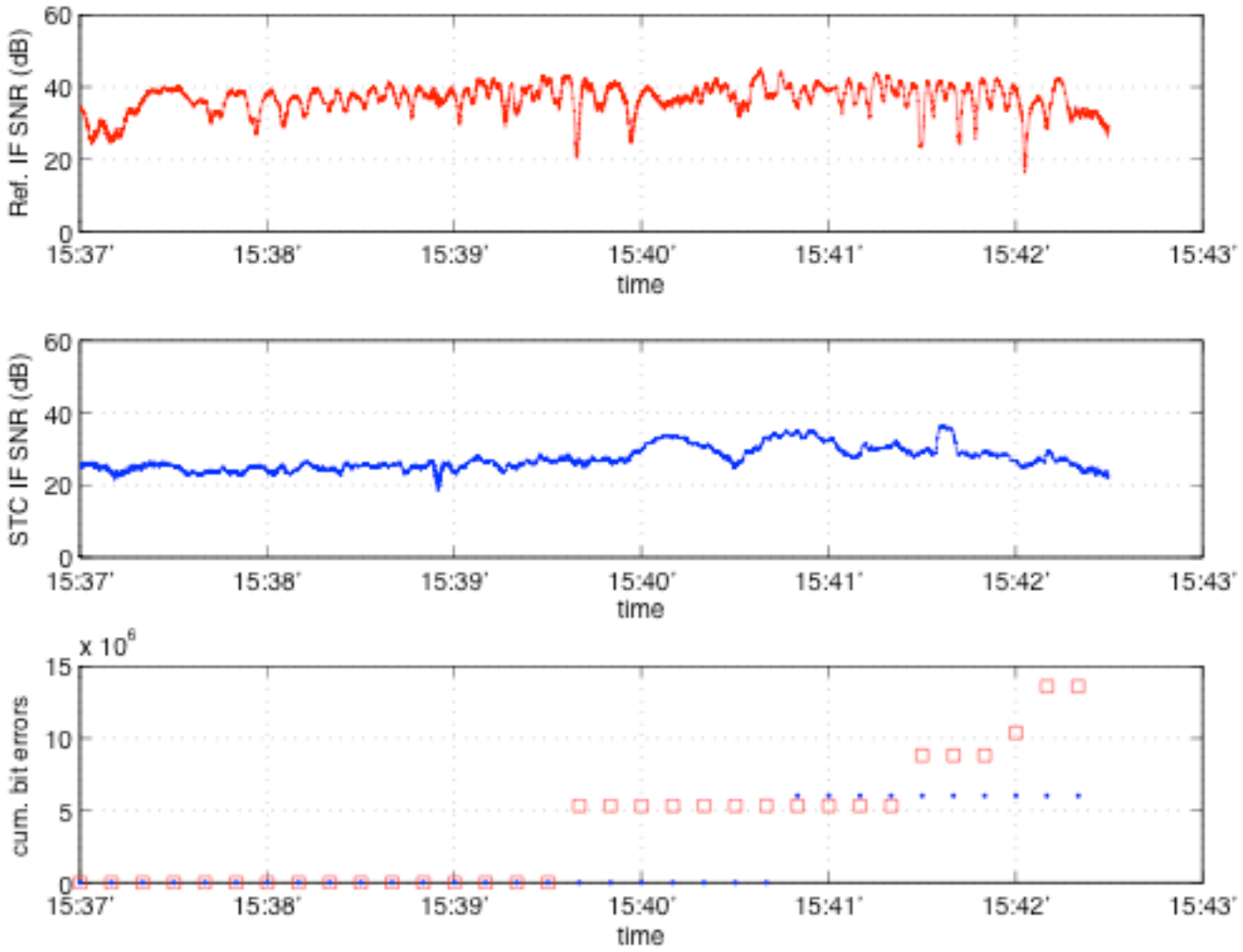
- Dual-Antenna Diversity Scheme
- Removes dropouts created by multiple transmit antennas
  - SNR equivalent to single antenna transmission
  - Multi-antenna scheme alleviates masking during maneuvering
  - Can be used with diversity reception
- Realtime hardware flight tested at Edwards AFB and showed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

M1: Test Results



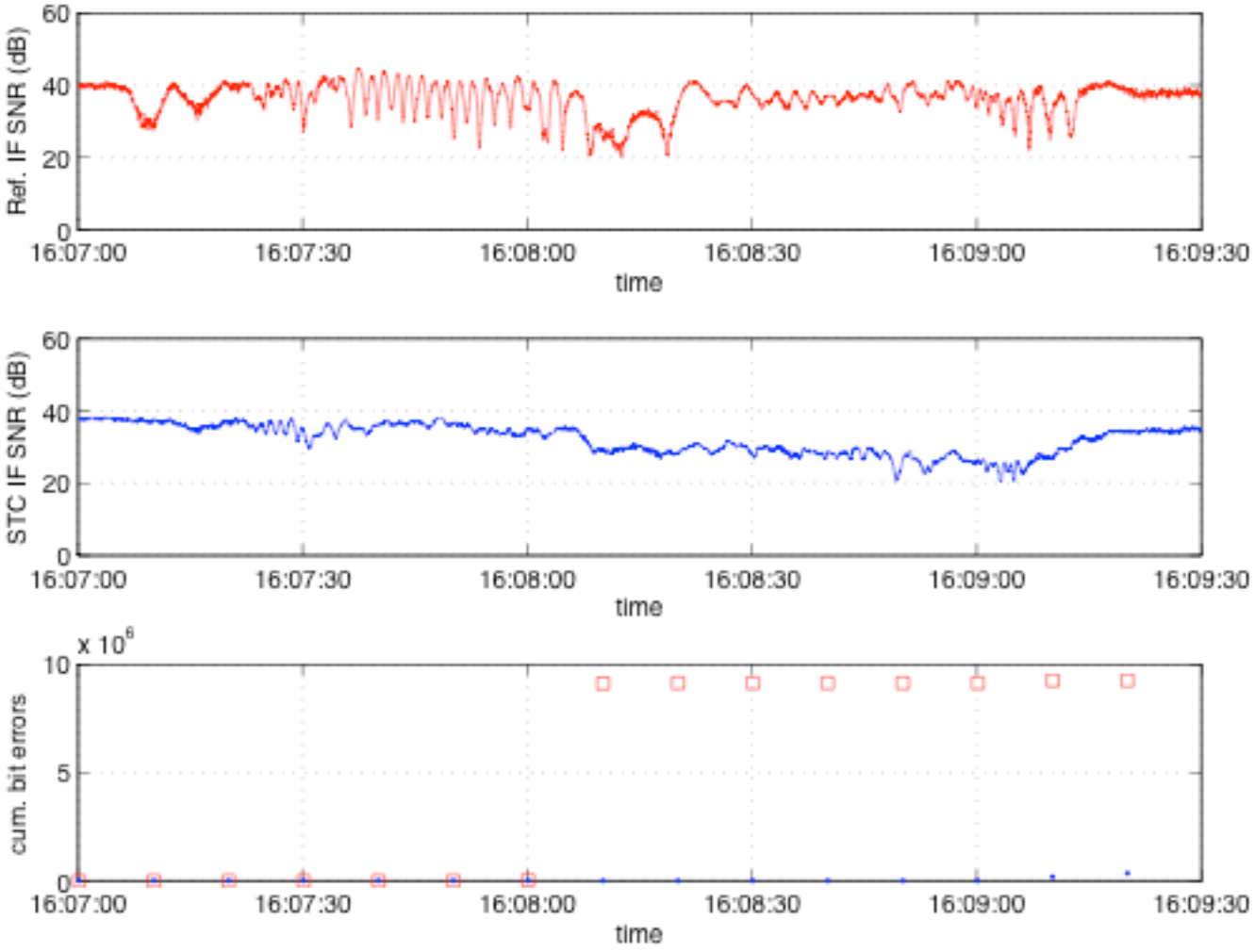
M2: Test Results

BYU



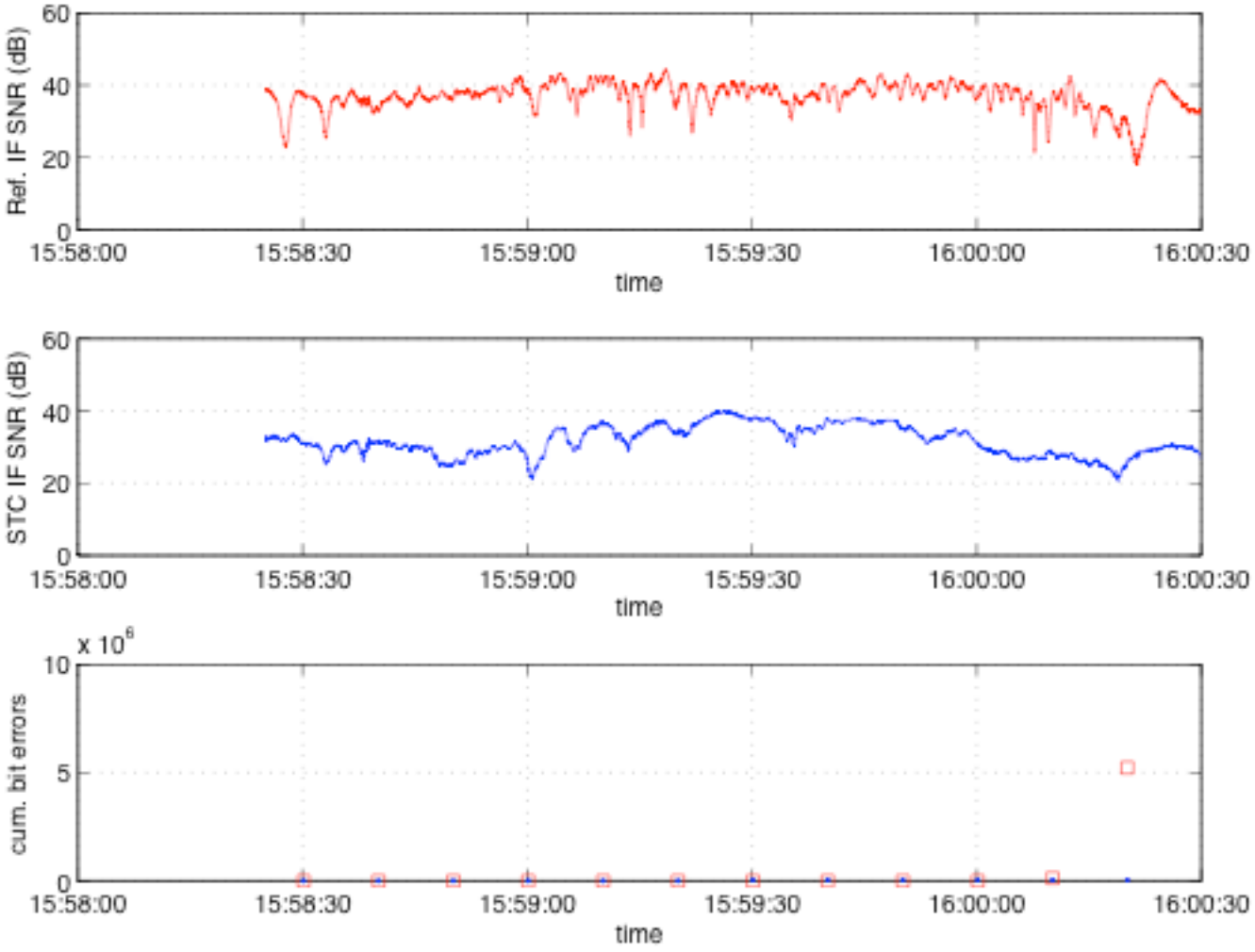
M3: Test Results

BYU



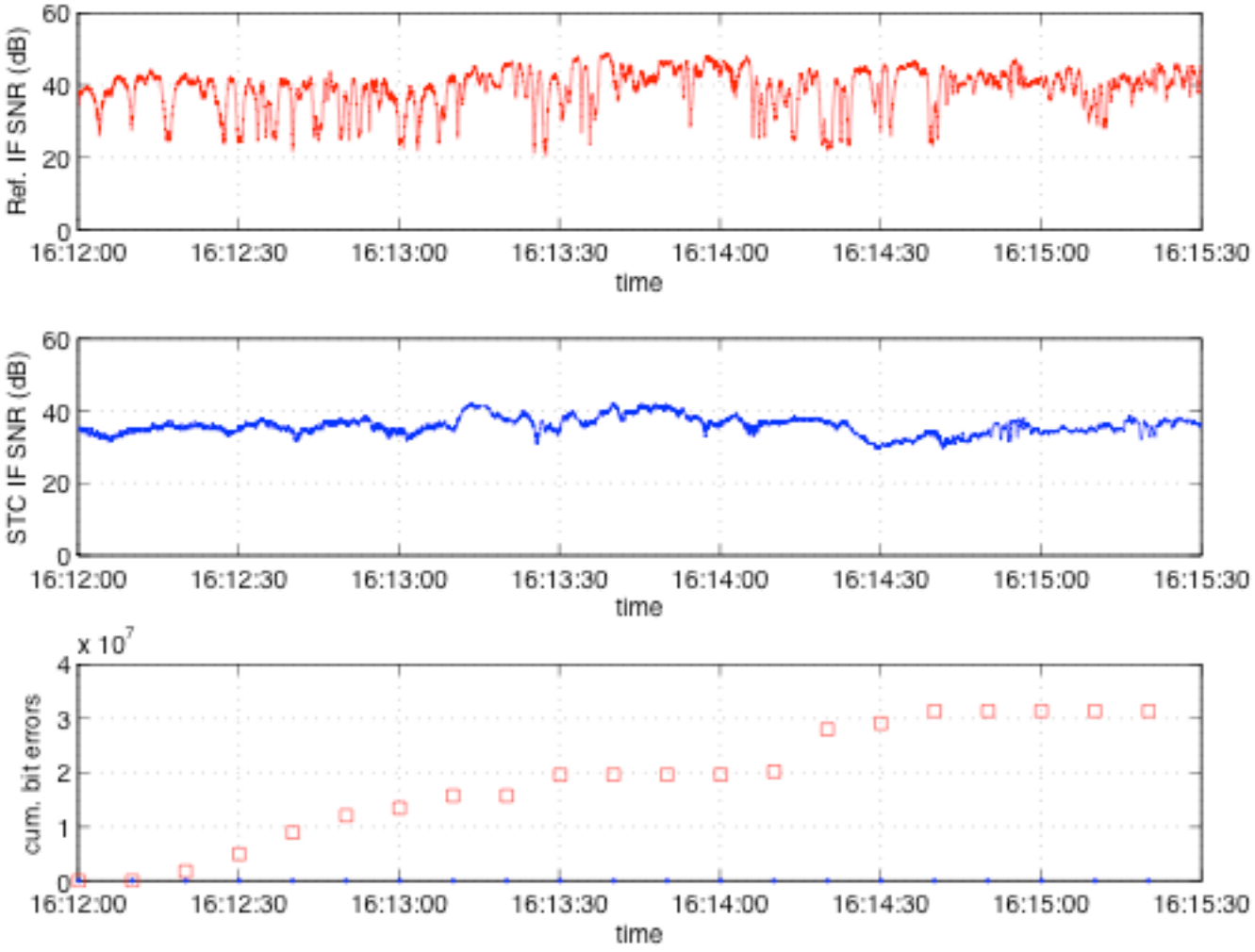
M4: Test Results

BYU



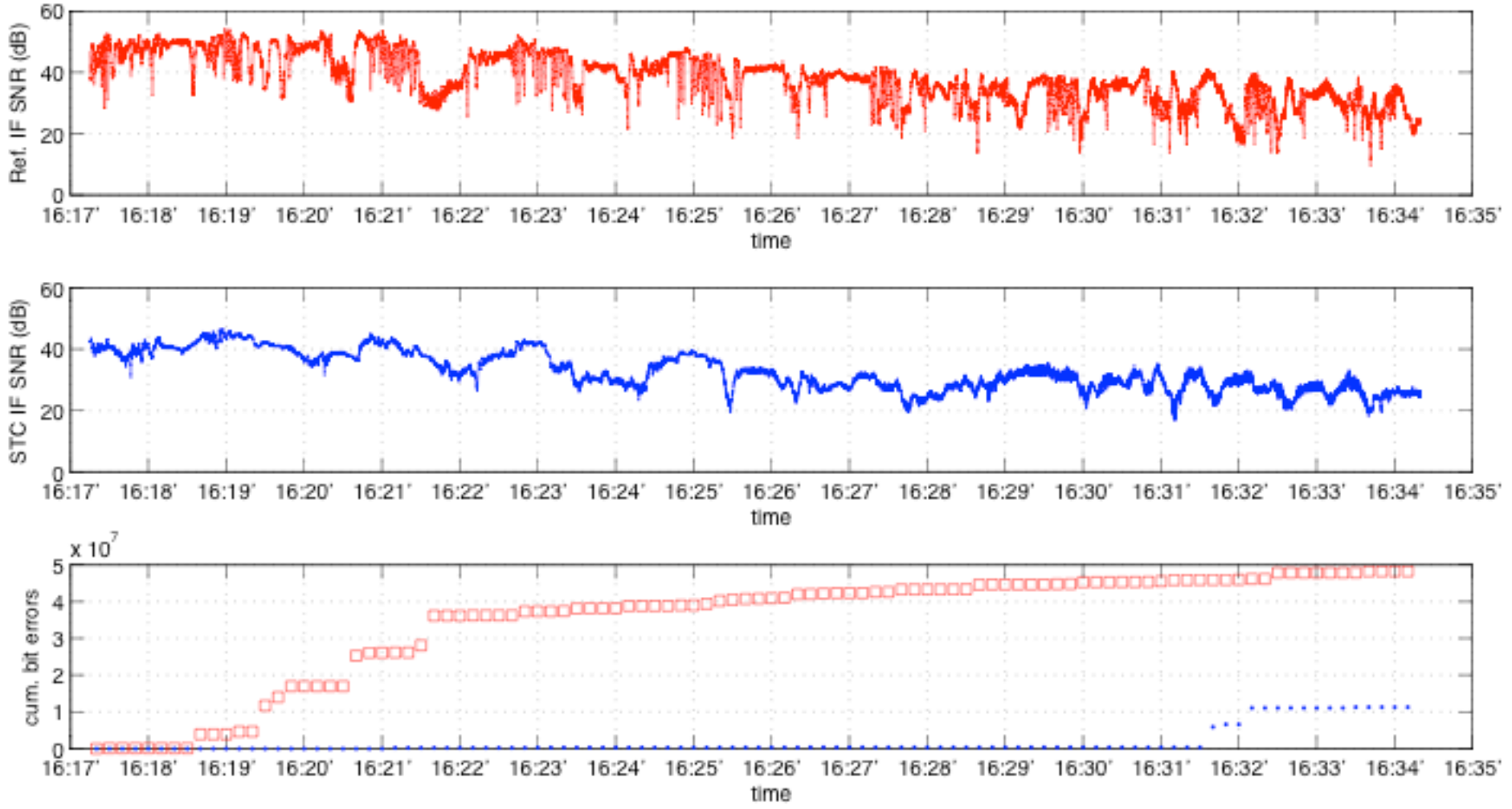
M3 to C2 Transition Test Results

BYU



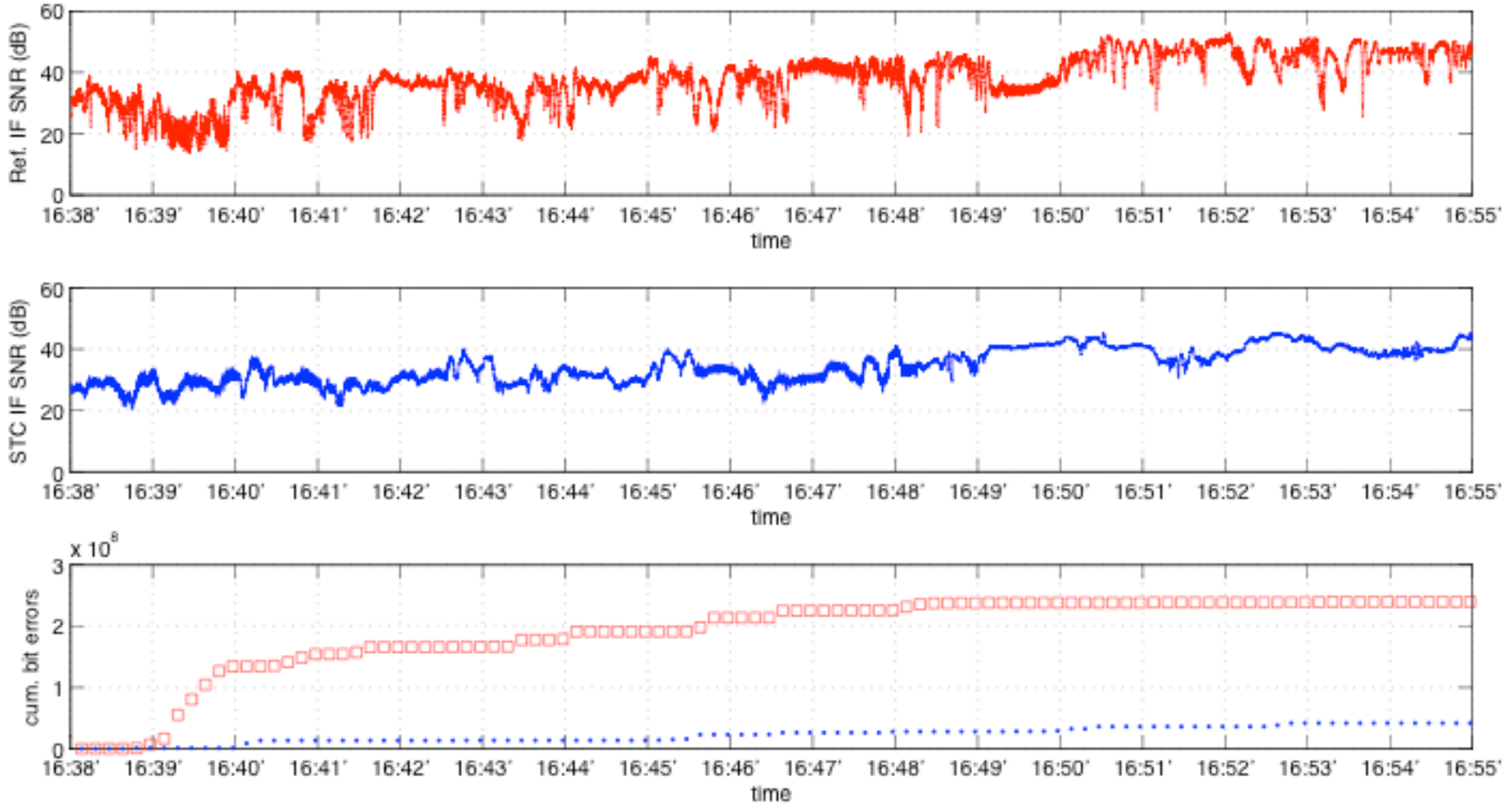
C2: Test Results

BYU



D2: Test Results

BYU



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

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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

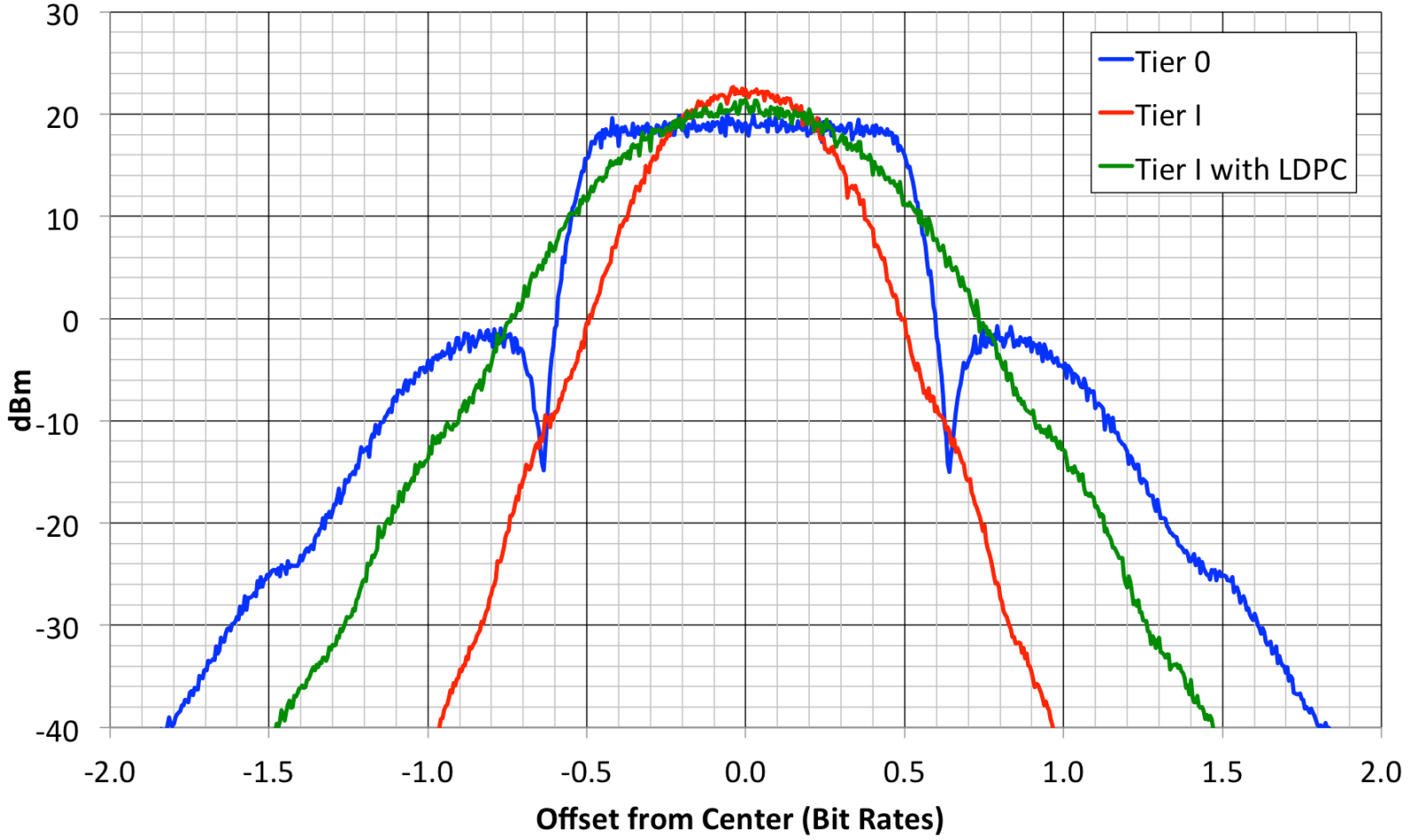
- Defines attached sync markers (ASM)
  - Specified in section 6 of CCSDS Recommended Standard CCSDS 131.0-B-1
- Present work based on the (6144, 4096) code

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

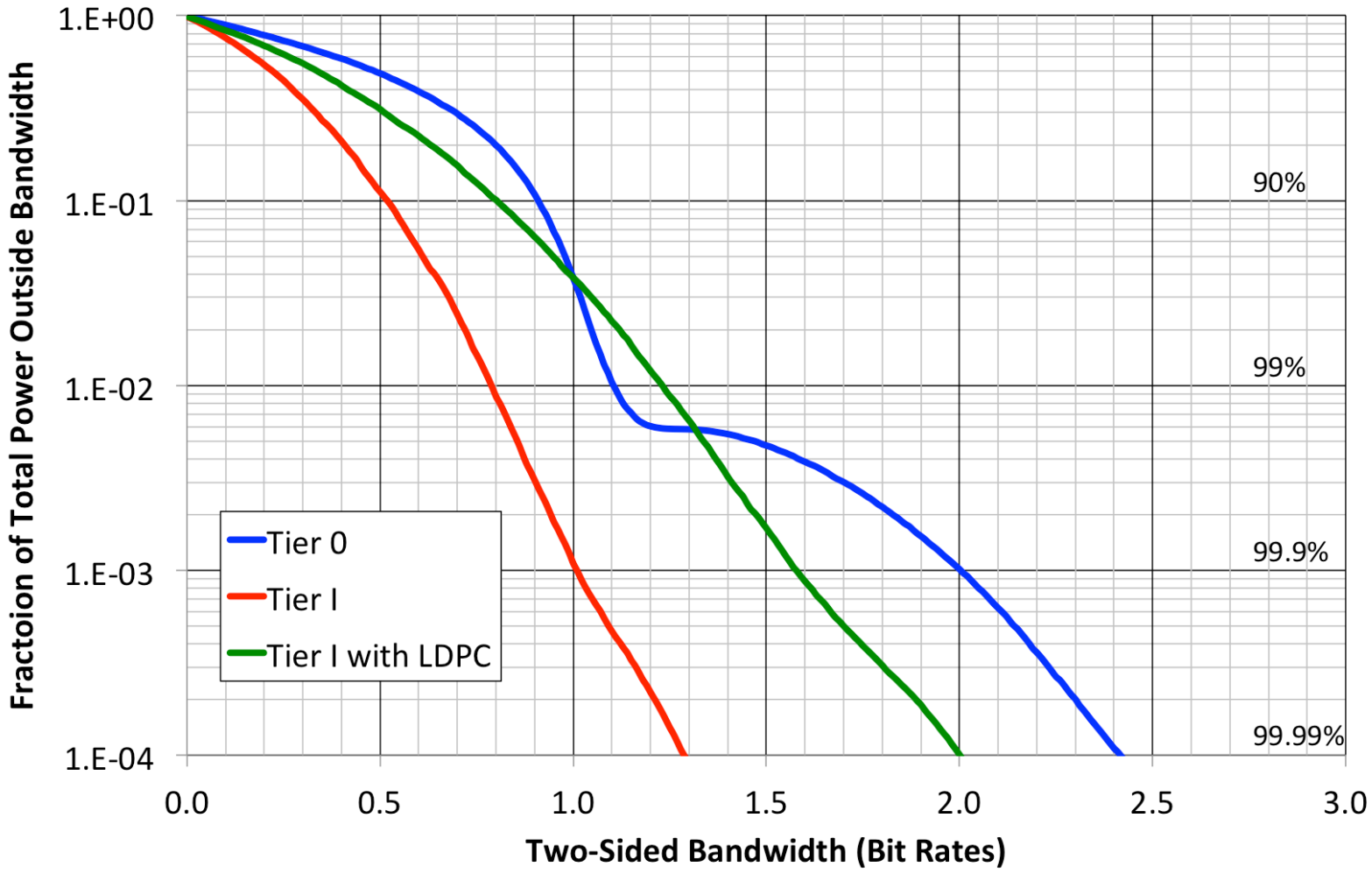


Spectral Characterization



Terry Hill - thill@quasonix.com

Fractional Out-of-Band Power

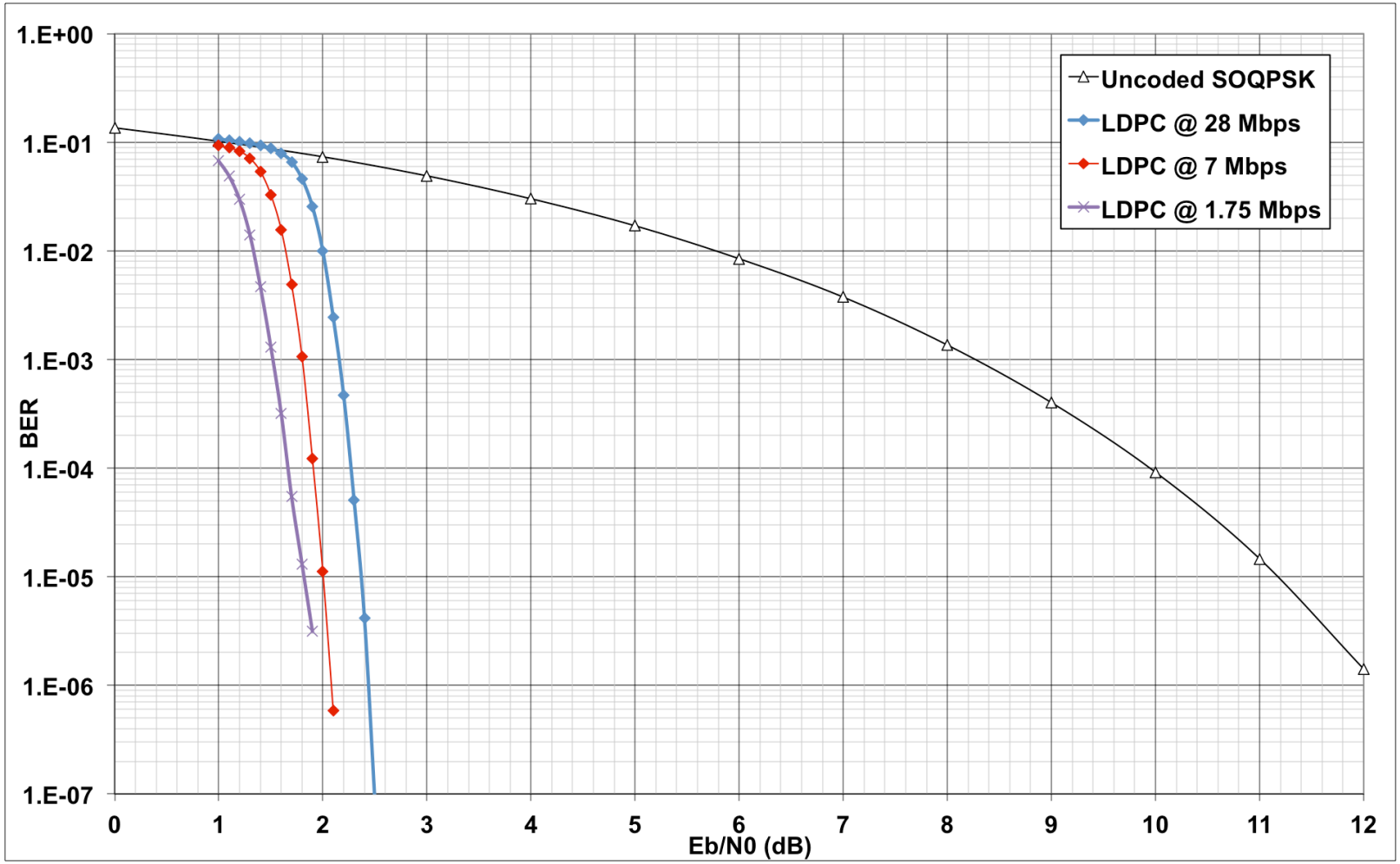


Terry Hill - thill@quasonix.com

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

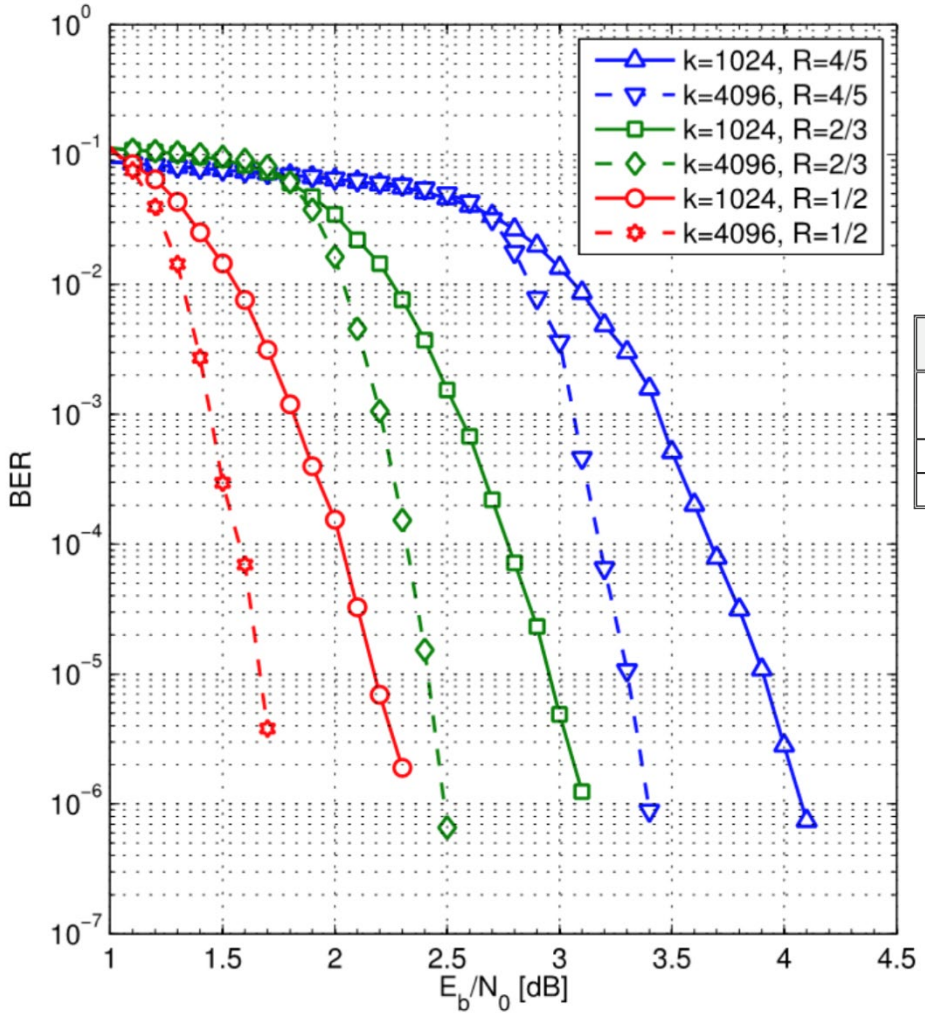
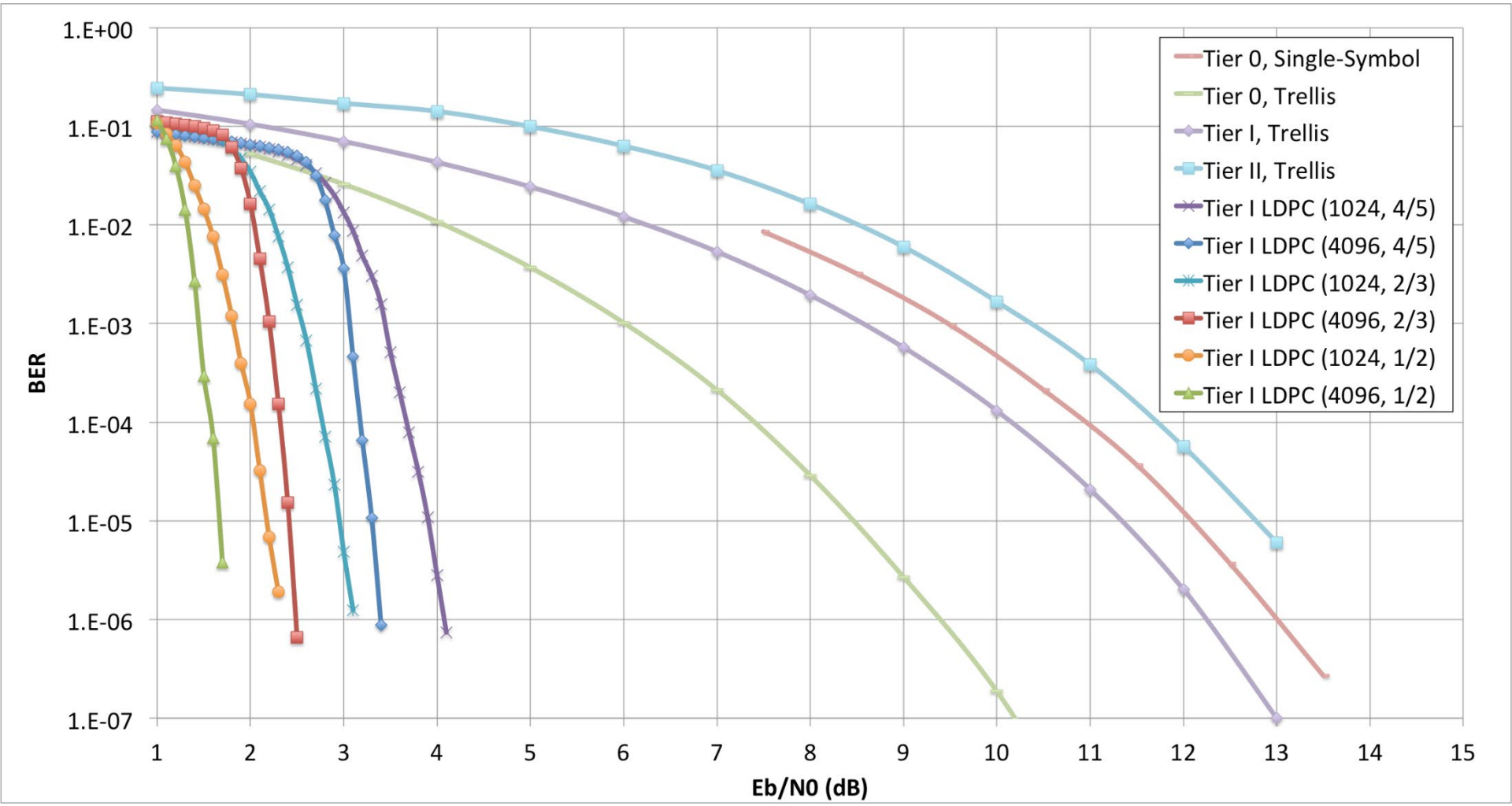


Table D-11. Bandwidth Expansion Factor

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

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How Well Does It All Work Together?

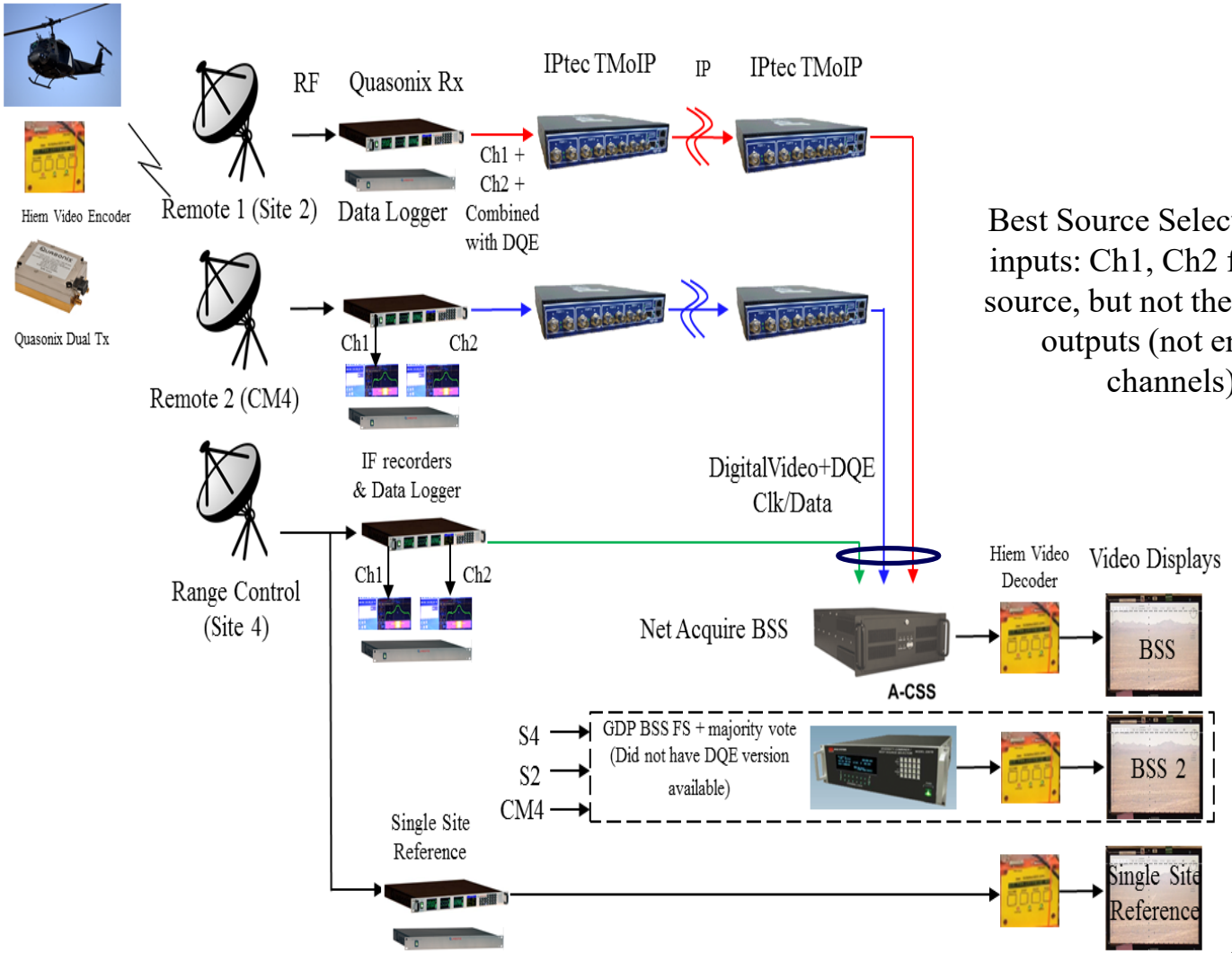
Yuma Proving Grounds, AZ

Feb 8-11, 2016

Recipe for Delivering Every Bit

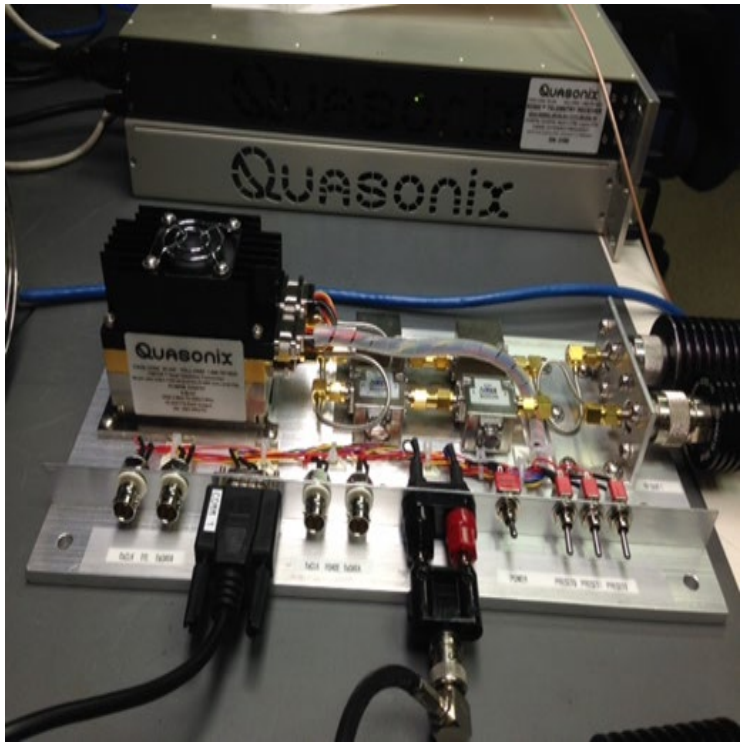
- Space Time Coding (STC)
  - Eliminates aircraft pattern nulls
- Low Density Parity Check (LDPC) coding
  - Improves margin, stops “dribbling errors”
- Adaptive Equalization (for non-STC signals)
  - Mitigates multipath
- Spatial diversity with correlating source selection
  - Eliminate coverage-based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

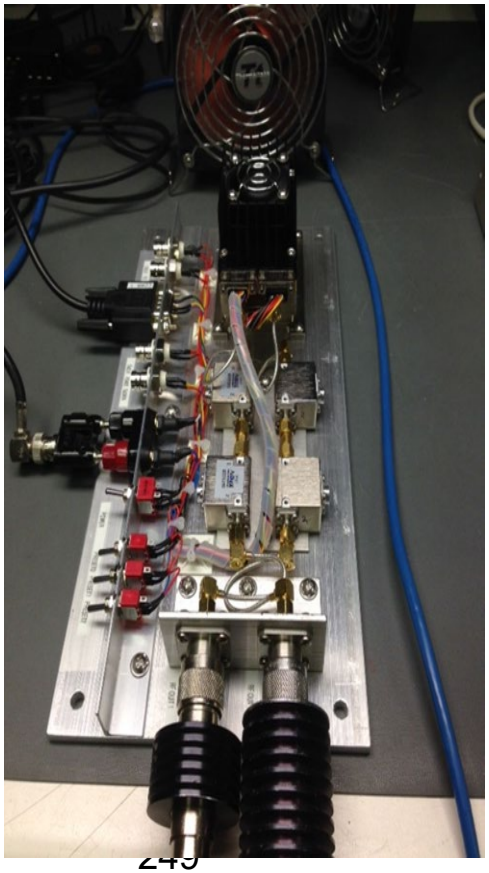
Multiple Receiving Sites



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



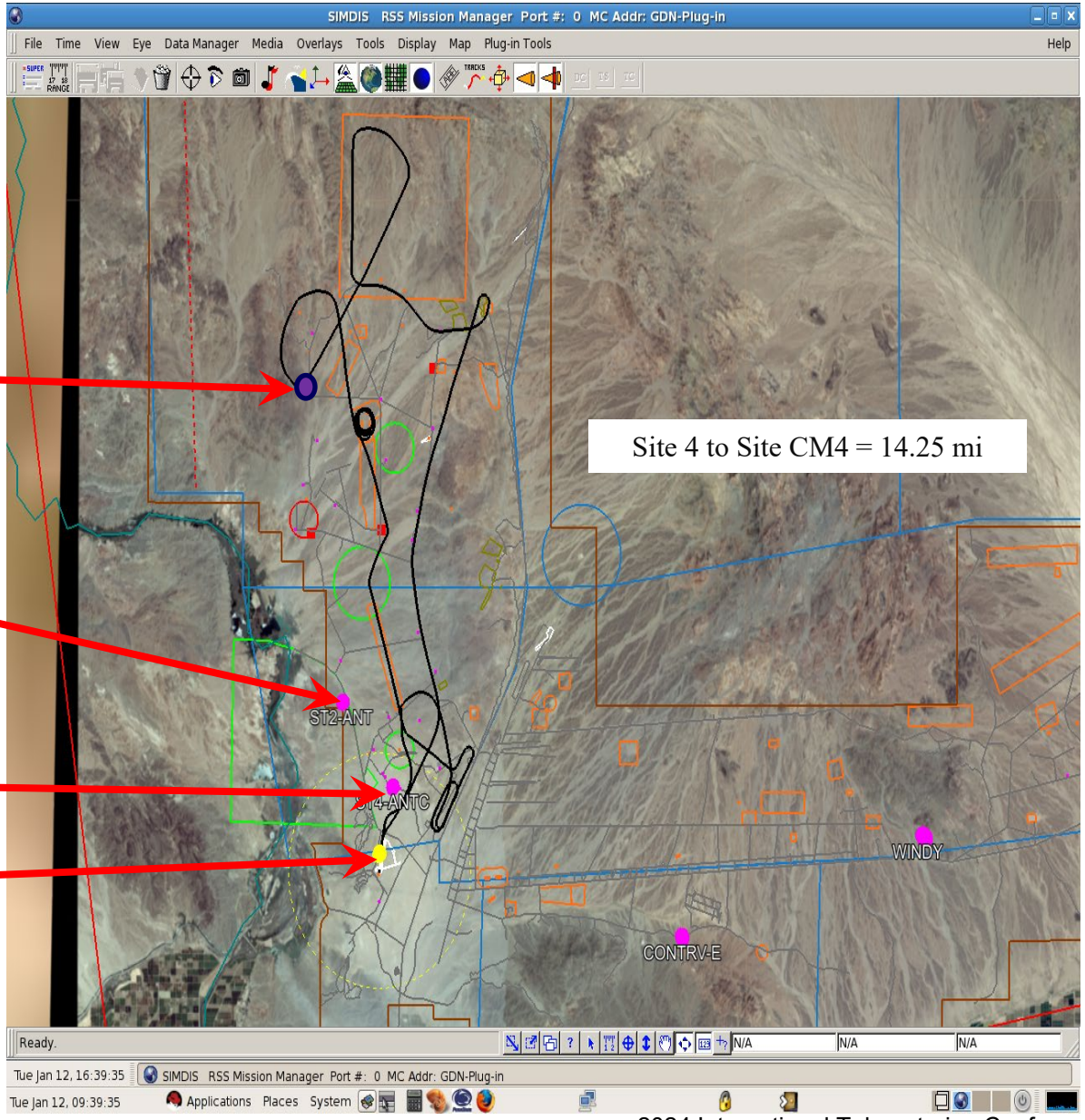
YPG Test Sites

Site CM4

Site 2

Site 4

Laguna Airfield



Analysis using Data Logs



F1 Top Antenna

F2 Bottom Antenna

Site 4

F1 Ch1

F2 Ch2

Site 2

F1 Ch1

F2 Ch2

CM4

F1 Ch1

F2 Ch2

Ch1, Ch2 DQE

Ch1, Ch2 DQE

Ch1, Ch2 DQE

A-CSS

'Best'

Receiver Analyzer BERT Log

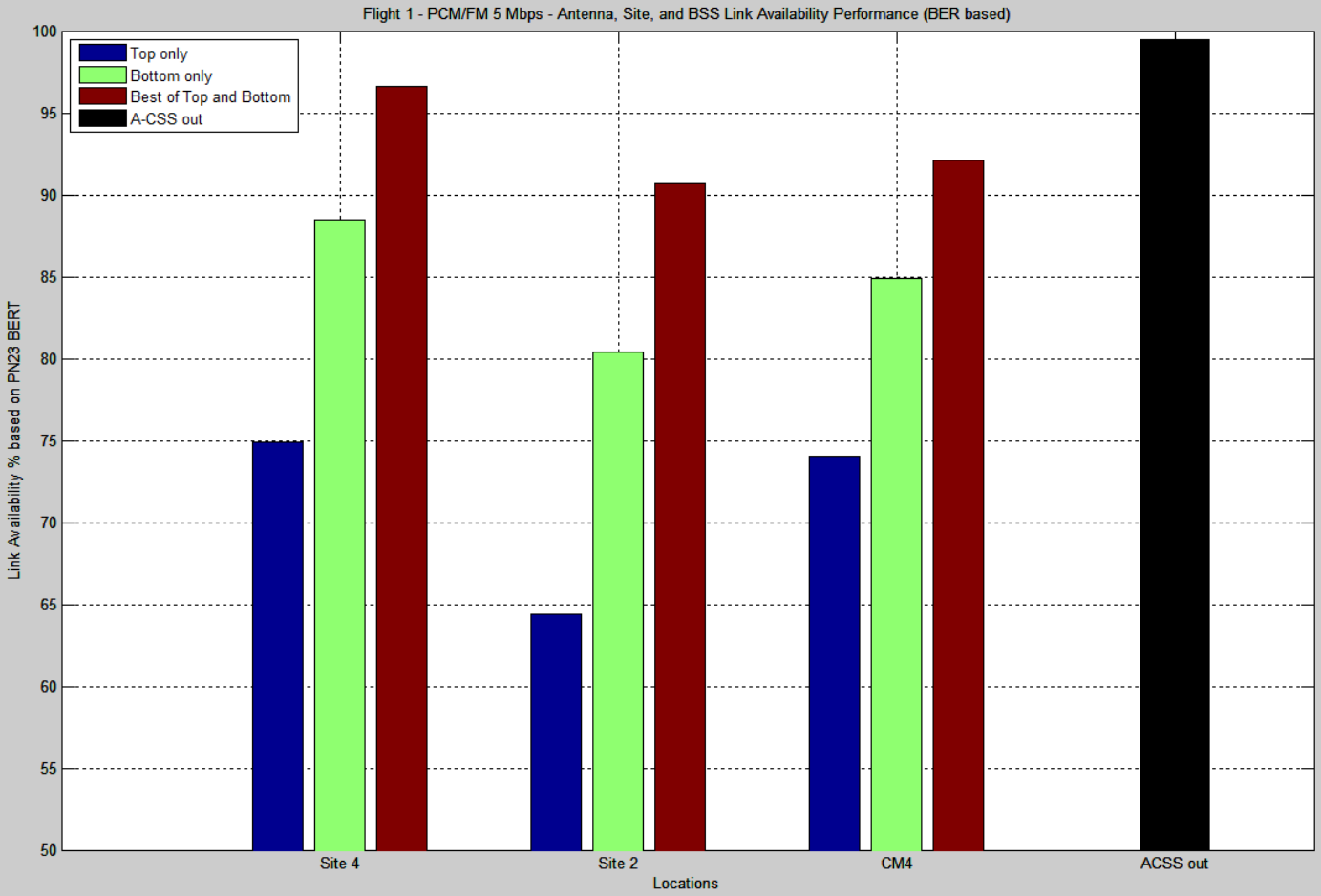
Data Log on Each Receiver (BEP, BER, RSSI,...)

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

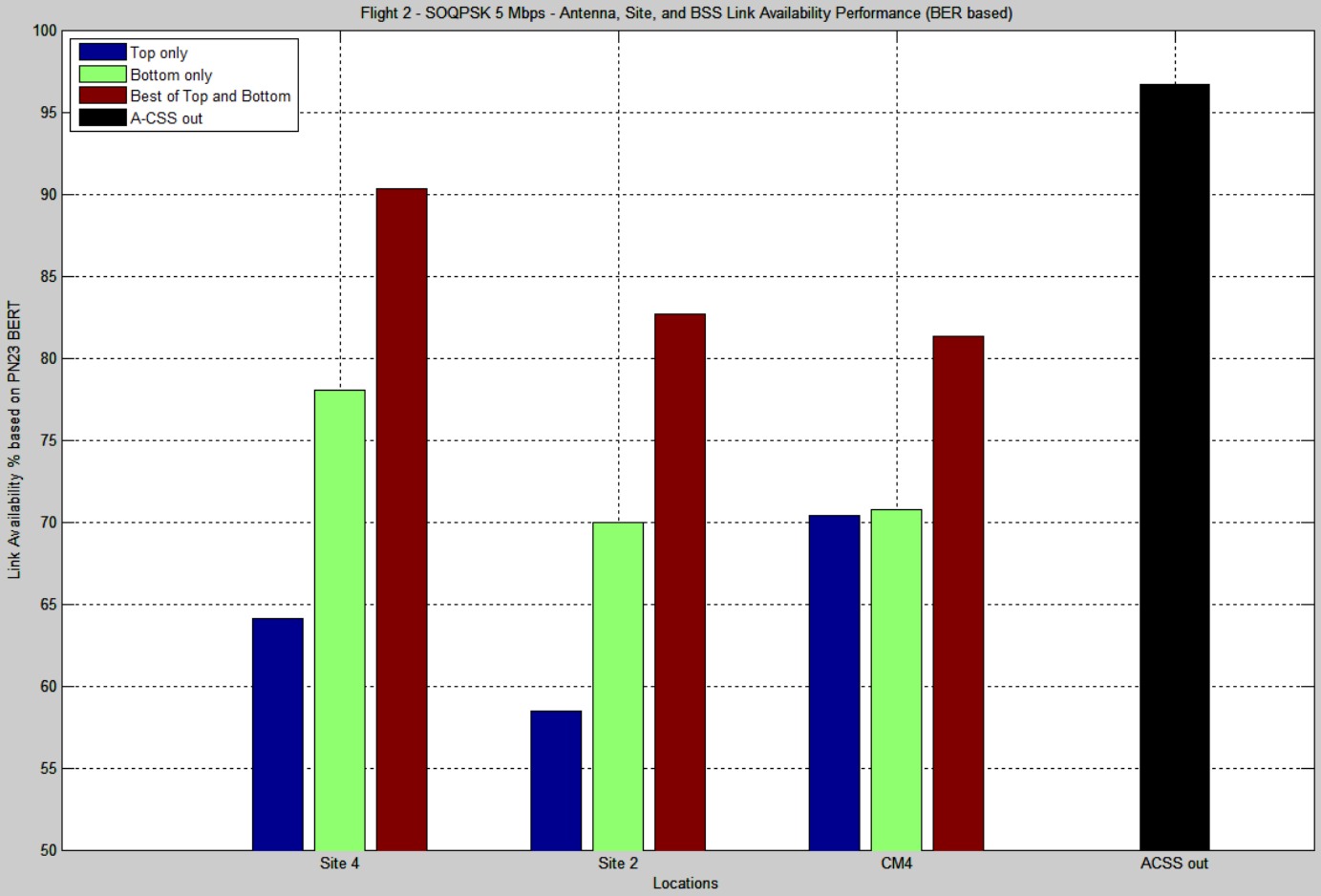
Receiver Analyzer Log (BER of A-CSS output)

- 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

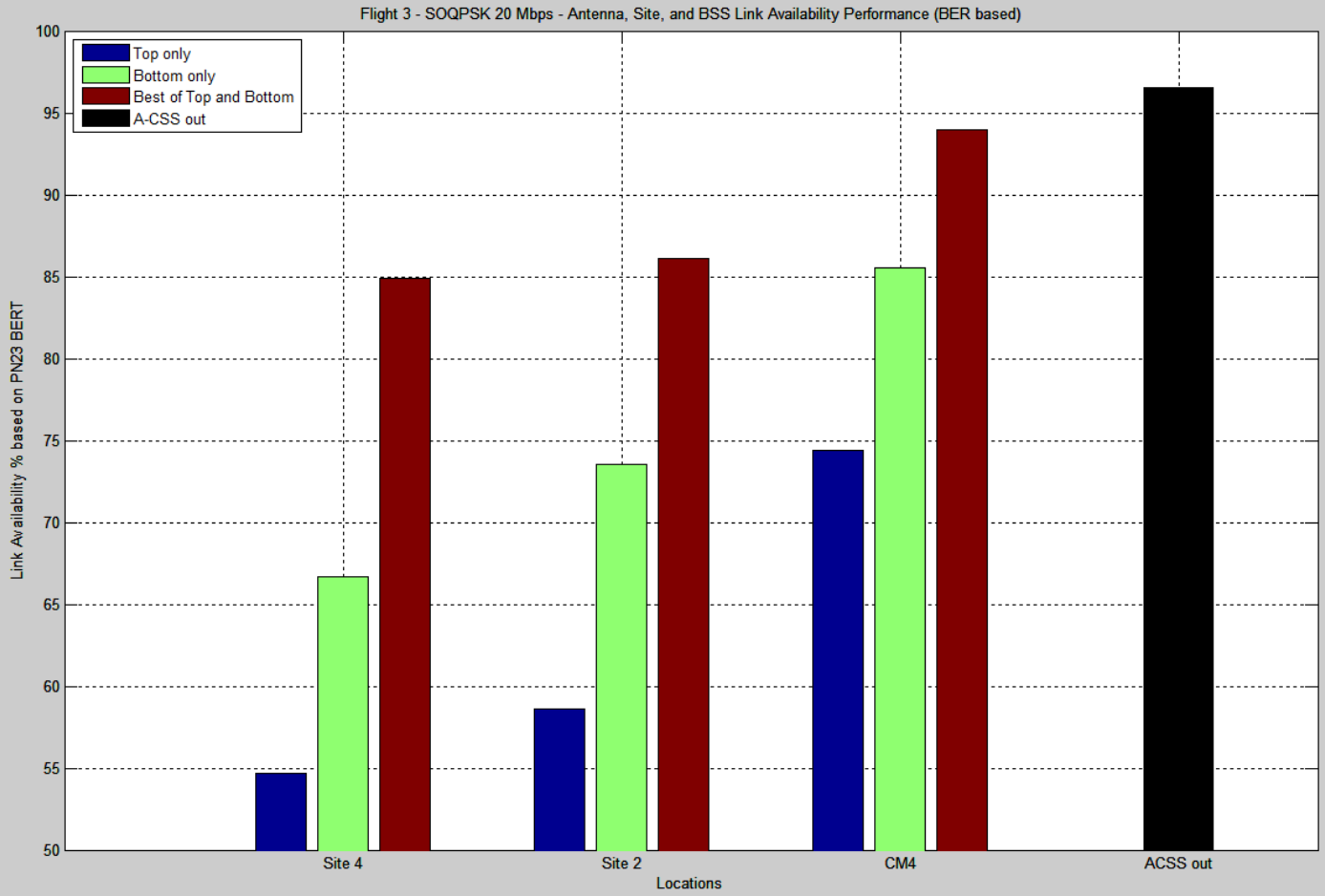
Flight 1 – PCM/FM 5 Mbps
Link Availability Summary (PN23 BER)



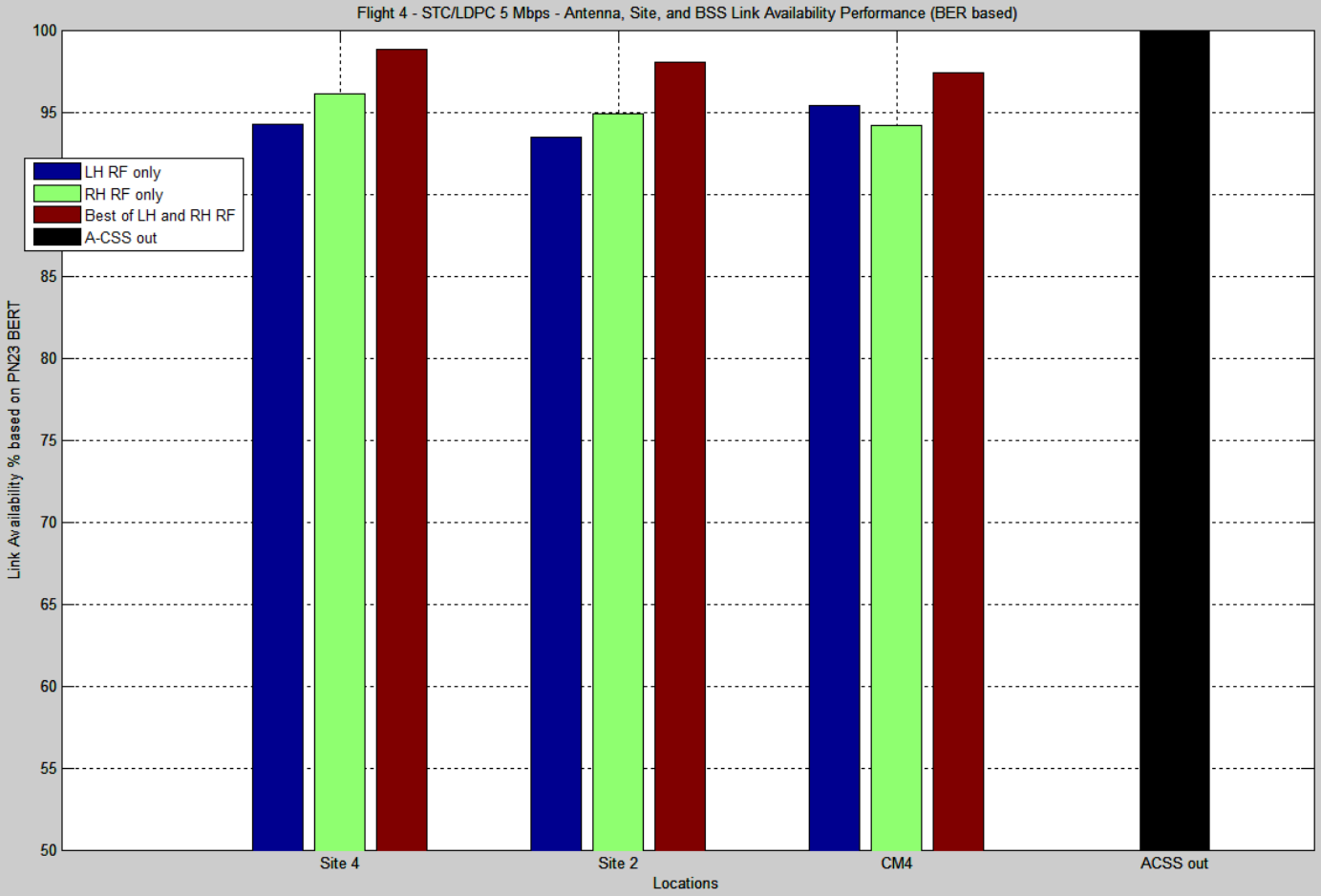
Flight 2 – SOQPSK 5 Mbps Link Availability Summary (PN23 BER)



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

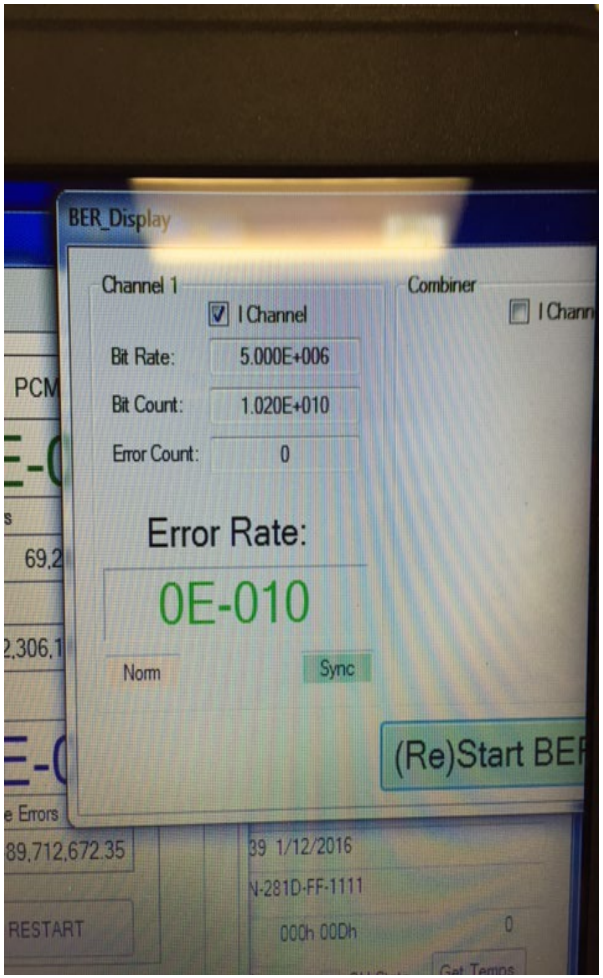


Flight 4 – STC/LDPC 5 Mbps Link Availability Summary (PN23 BER)



The elusive zero-error link…..

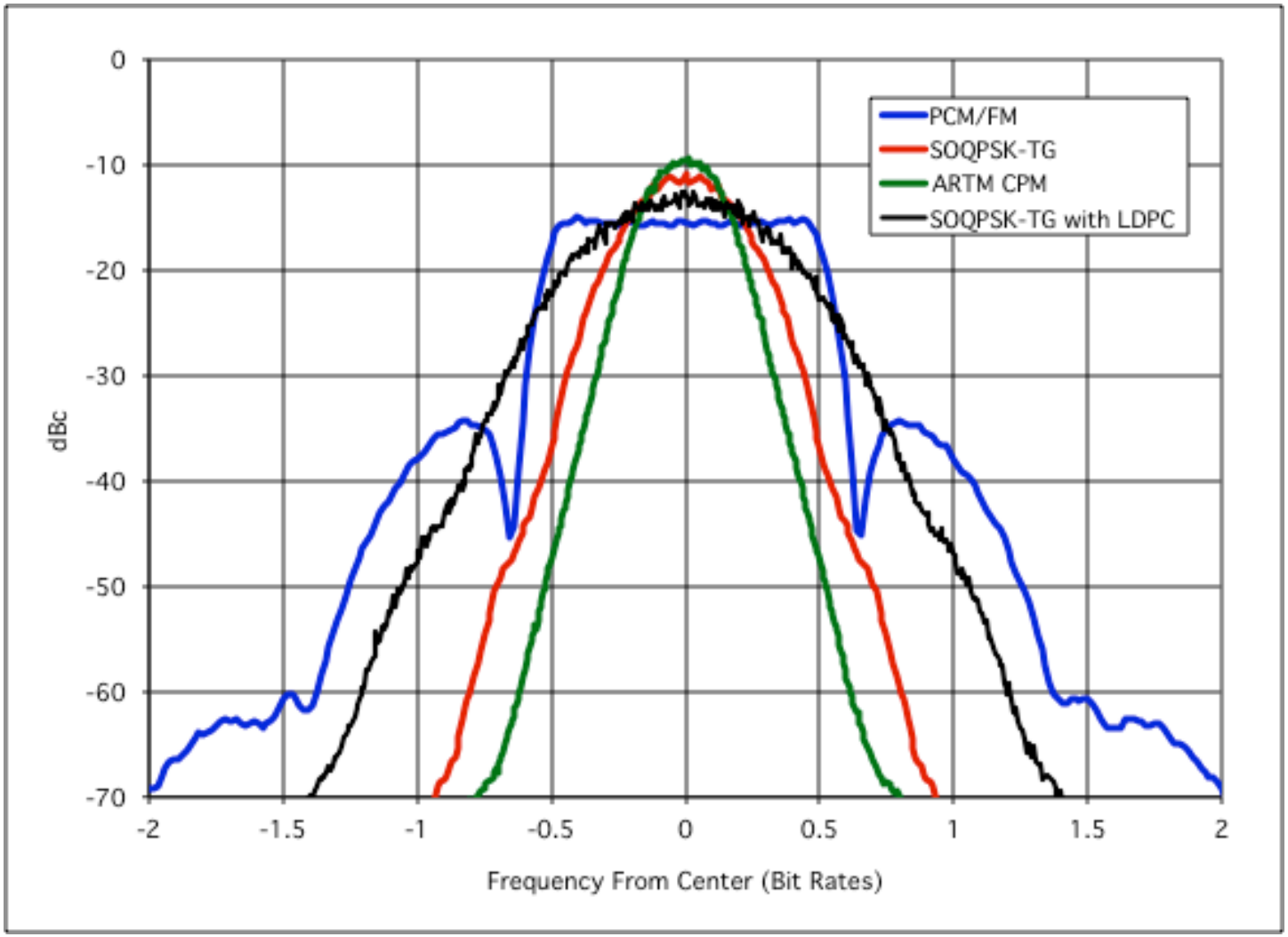
- STC/LDPC from 3 sites at 5 MBPS
- 1st pass PN23 -- 34 minutes of helicopter flight across YPG…
- Error-free!
- 2nd pass video with no freeze ups or blackouts!



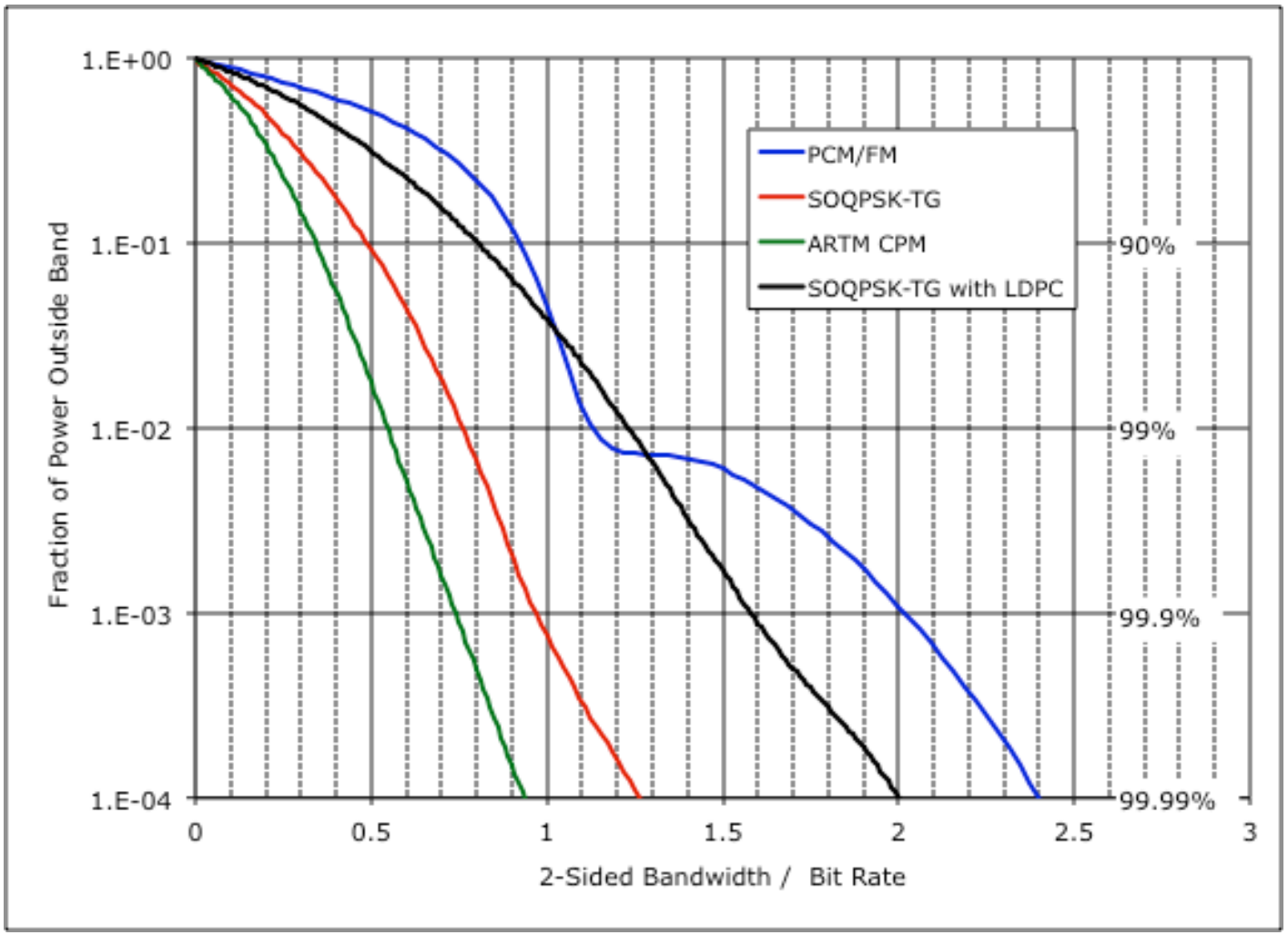
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Performance Comparison and Summary

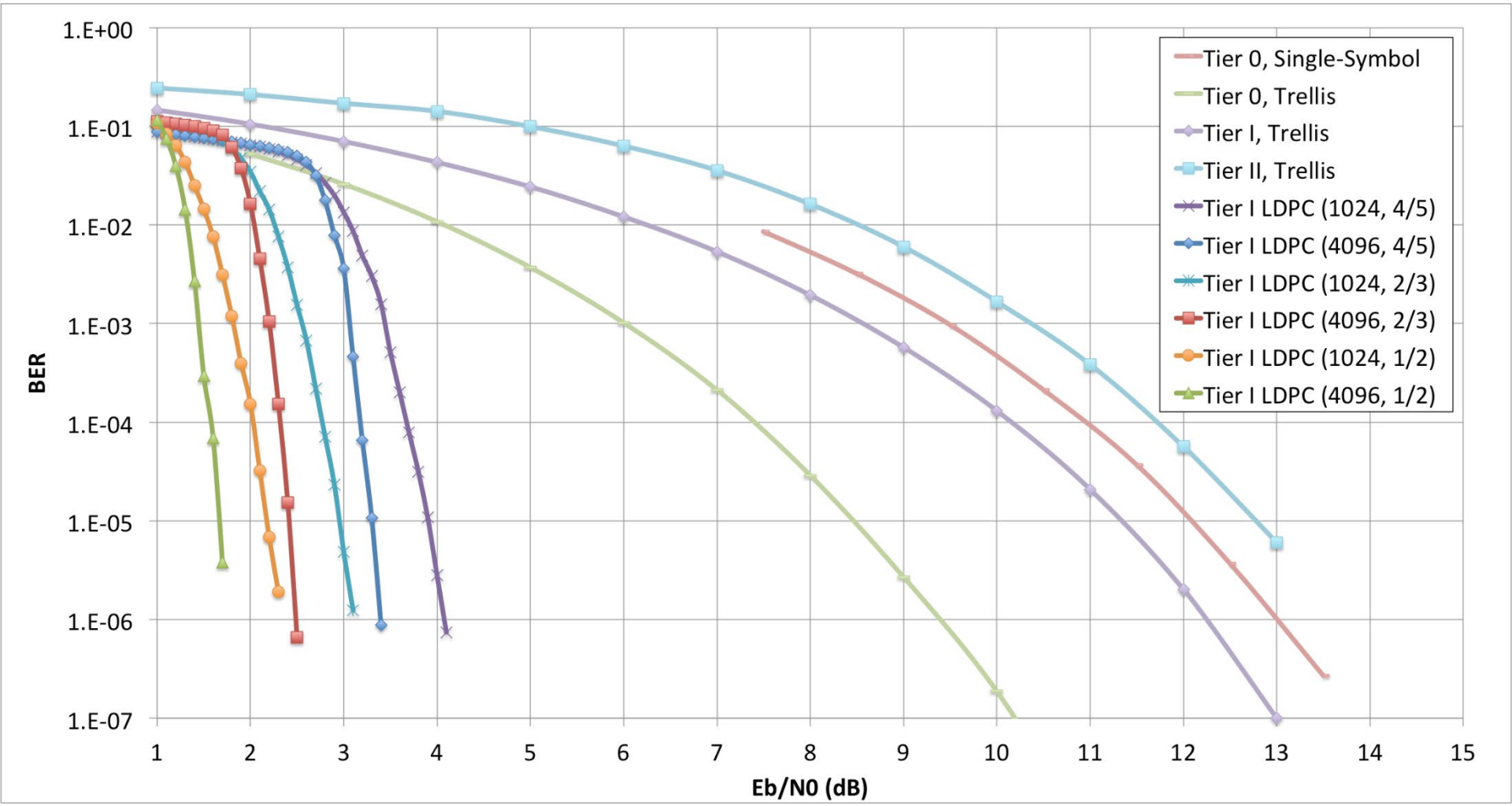
Power Spectral Densities



Out-of-Band Power

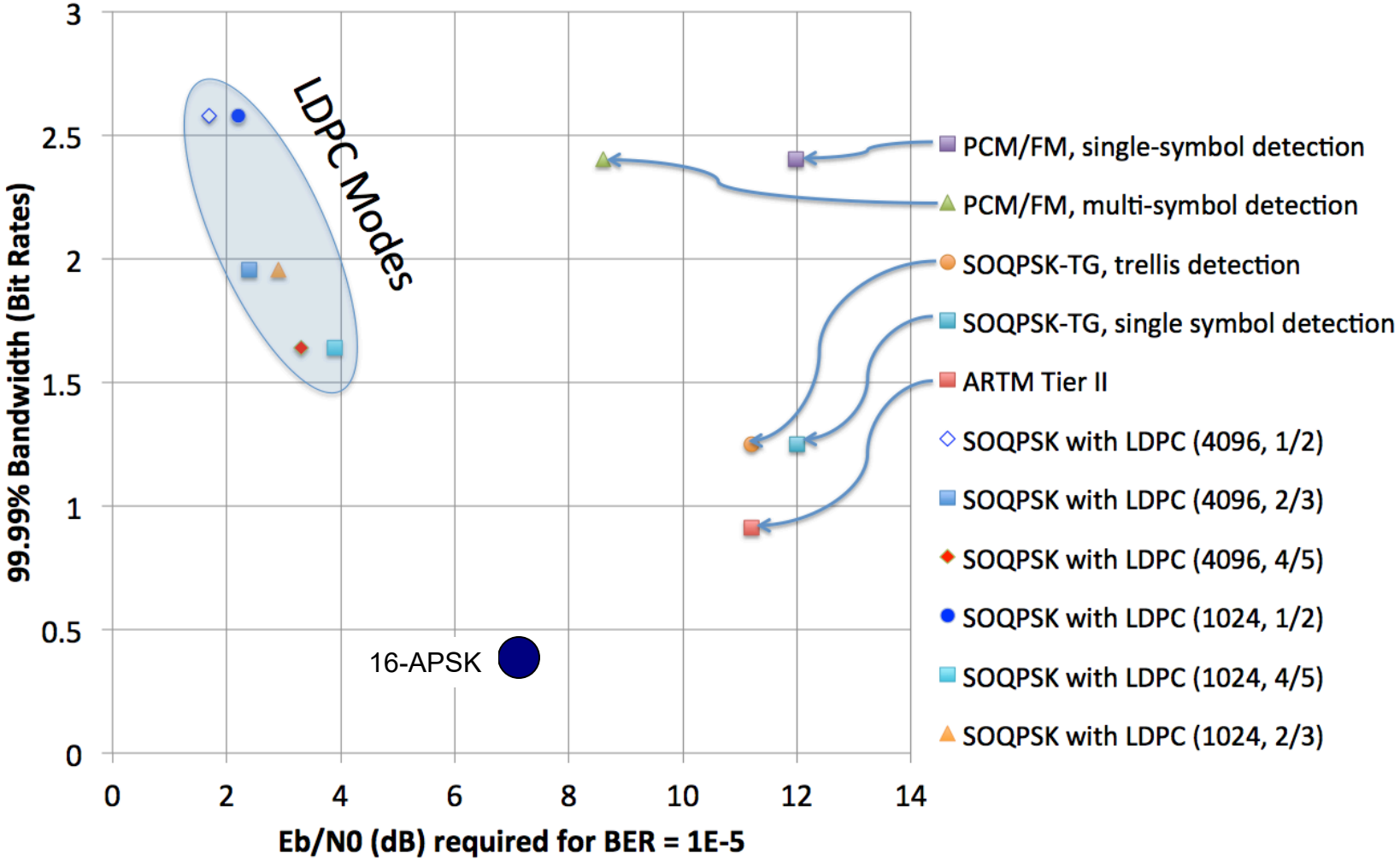


BER Performance Comparison



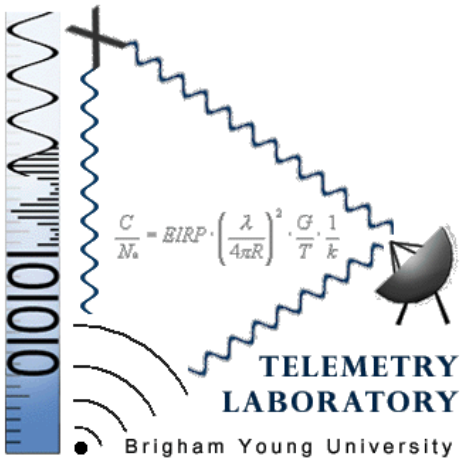
Terry Hill - thill@quasonix.com

Bandwidth-Power Plane



Terry Hill - thill@quasonix.com

Acknowledgements







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NAVAIR

Questions/Comments