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Advanced Modulation Techniques for Telemetry

A Short Course at the
International Telemetering Conference
Glendale, AZ • 24 October 2022

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

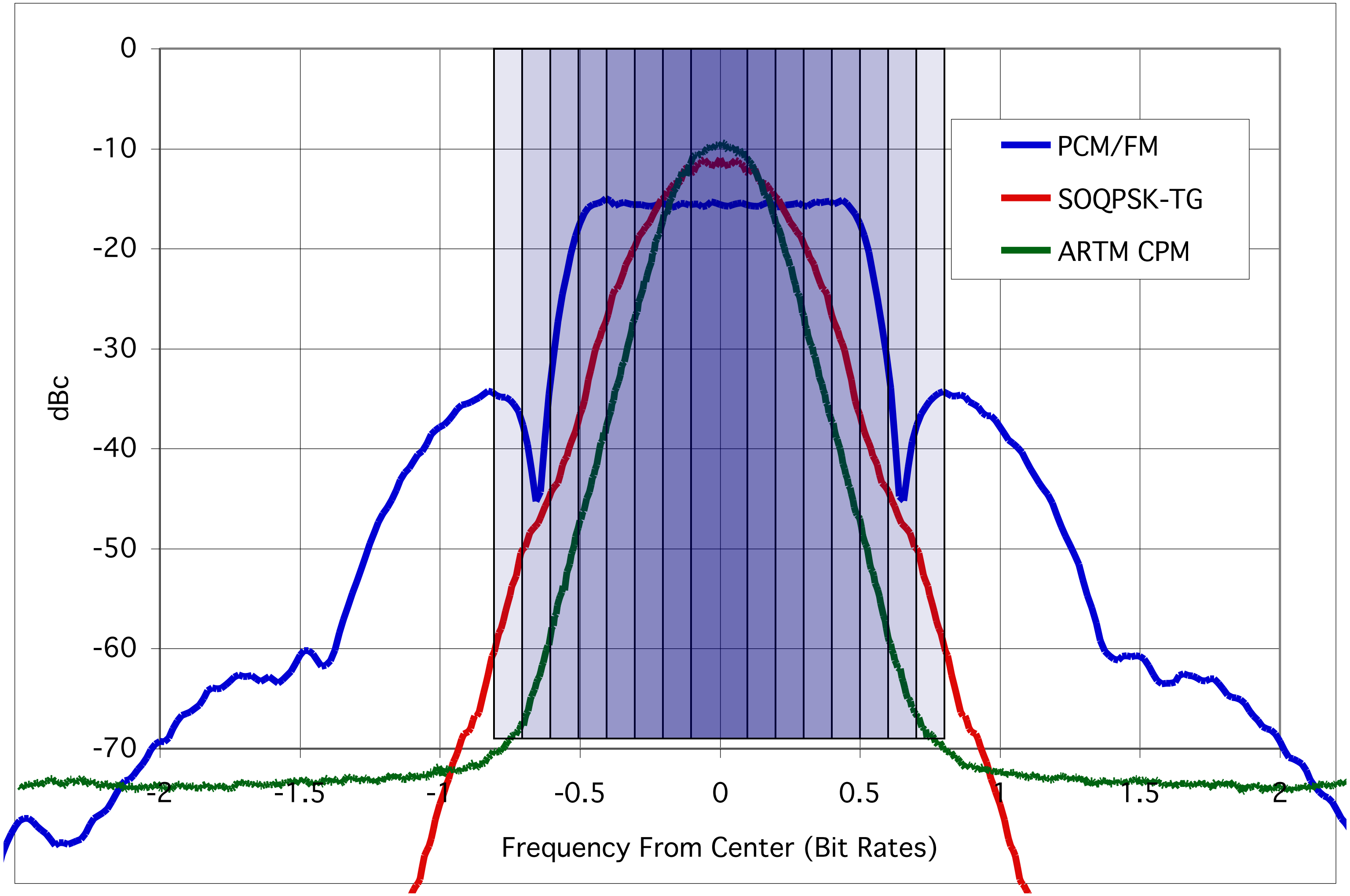
Bandwidth Efficiency

- 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

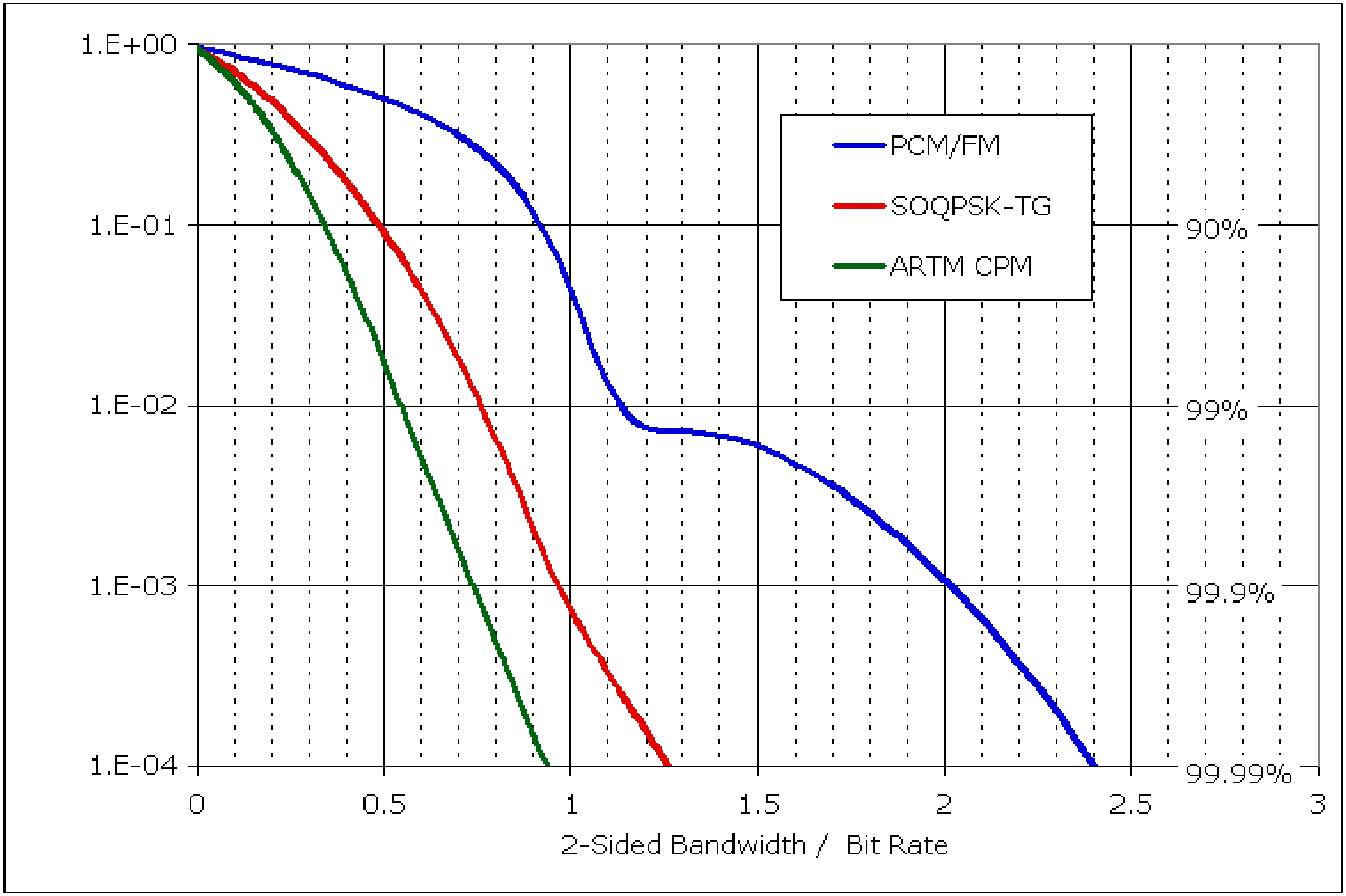
Which Bandwidth?

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

Power Spectral Density (PSD)



Fractional Out-of-band Power



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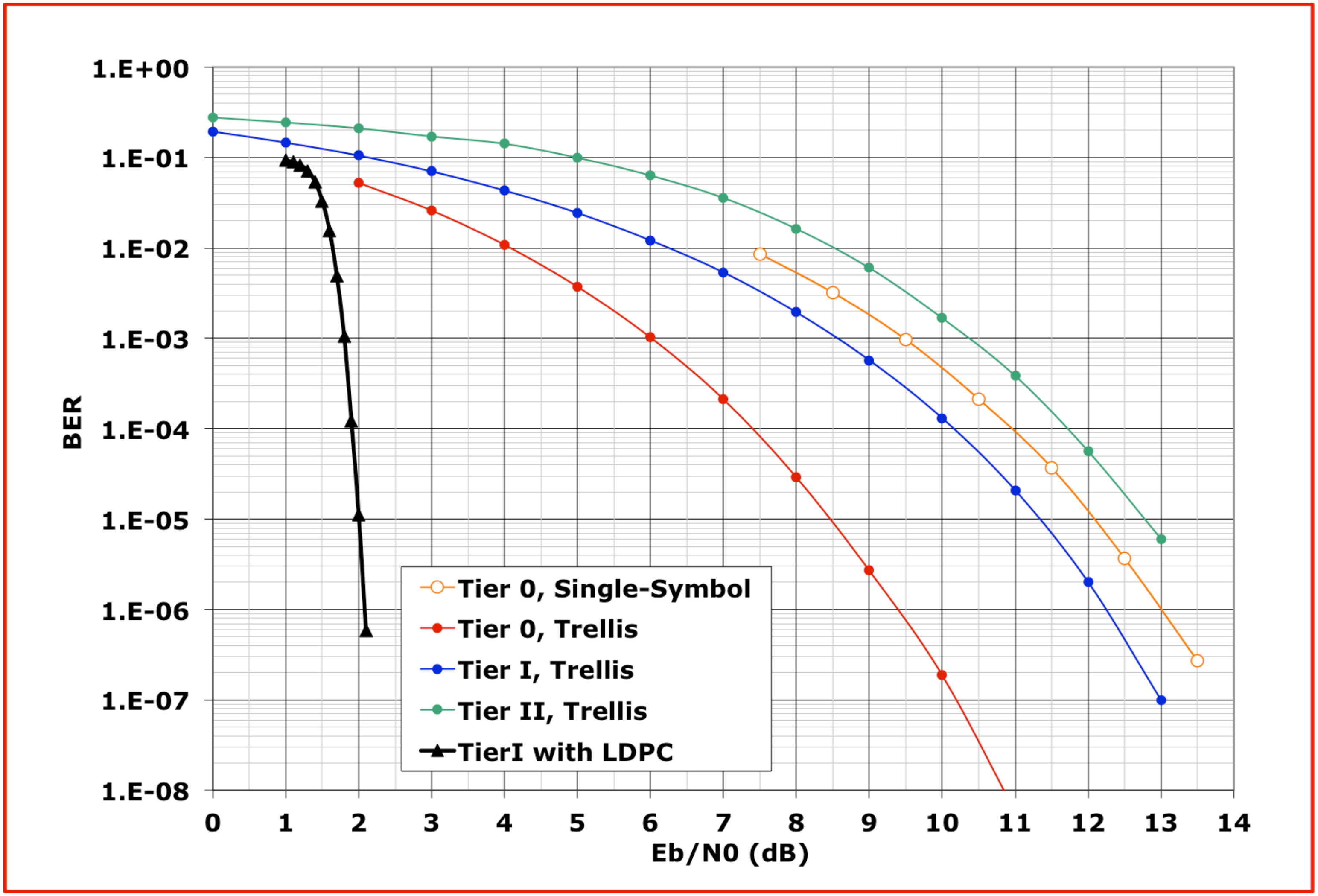
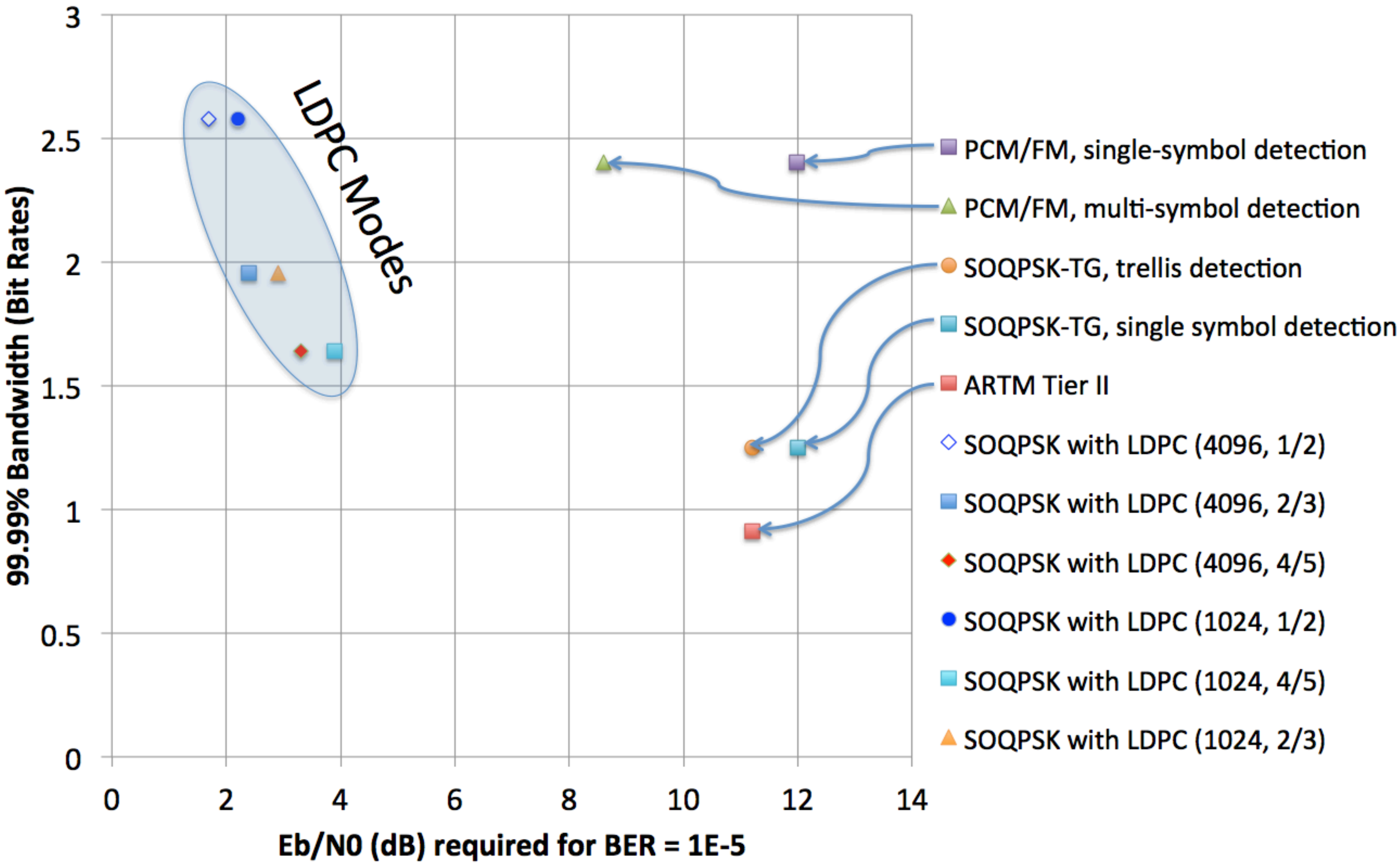
Information Fidelity

- 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



Today's Modulation Tour



Continuous Phase Modulation

The Modulation Universe

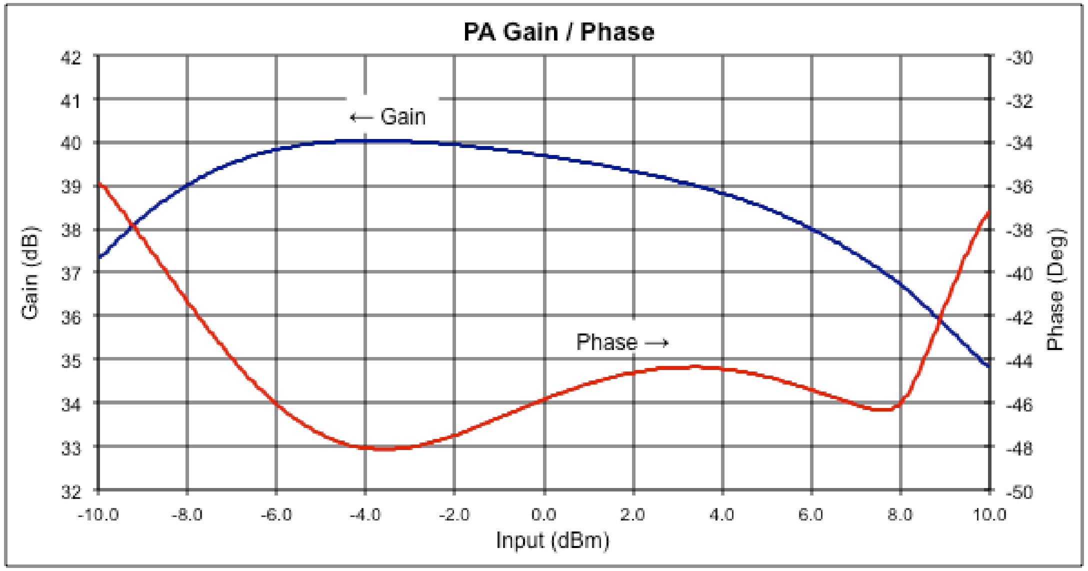
- Analog, Digital
- Amplitude modulation
- Quadrature amplitude modulation
- Angle modulations
  - Frequency modulation
  - Phase modulation
- Amplitude/Phase Shift Keying (APSK)

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.

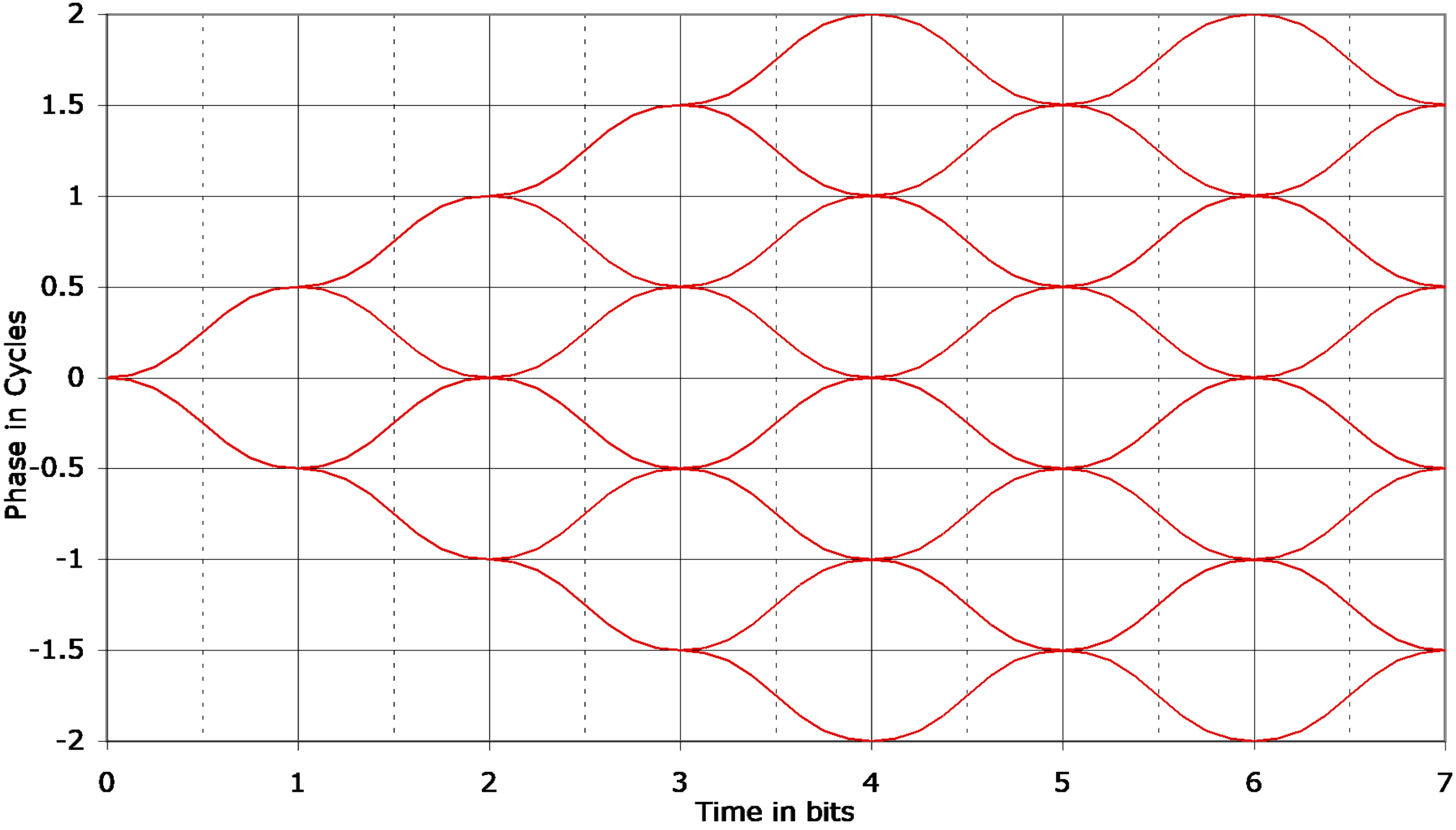
Key Parameters of CPM

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

CPM Characteristics

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

Phase Tree Representation



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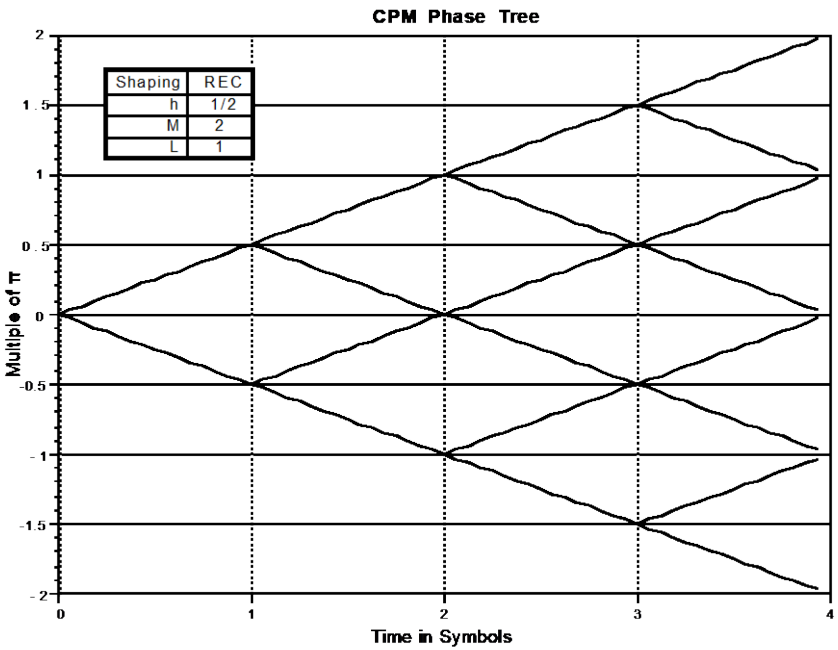
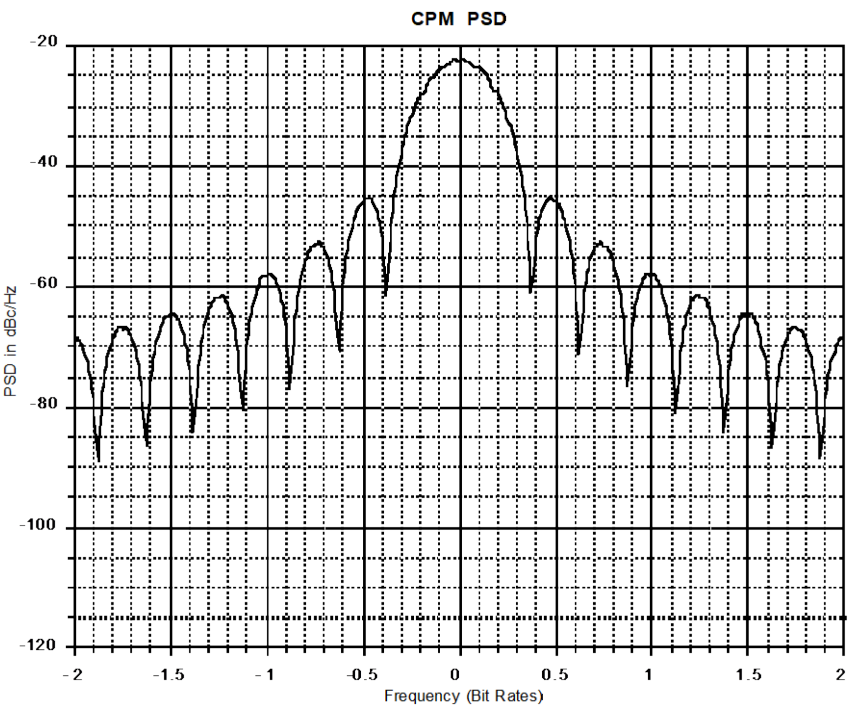
M=2, h=1/2, 1REC (MSK)

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





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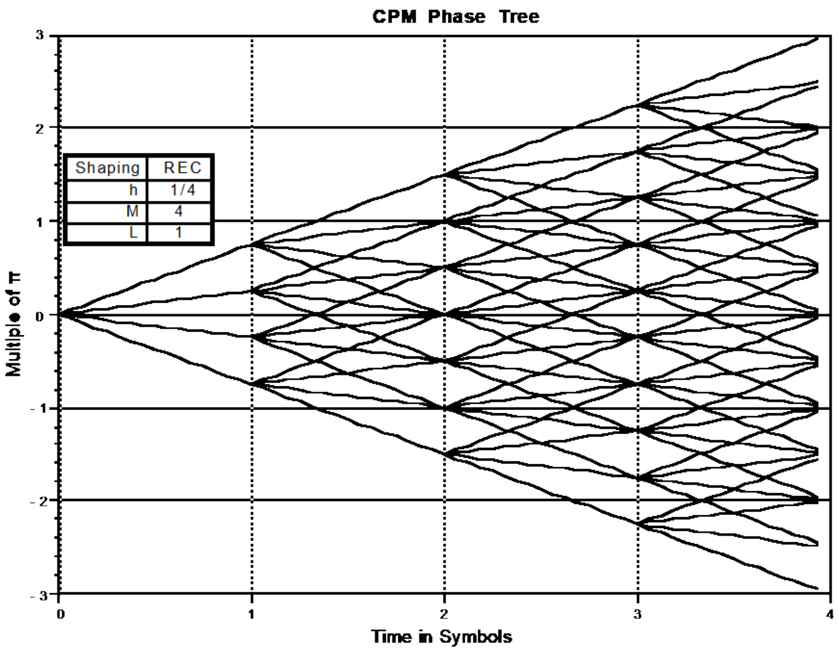
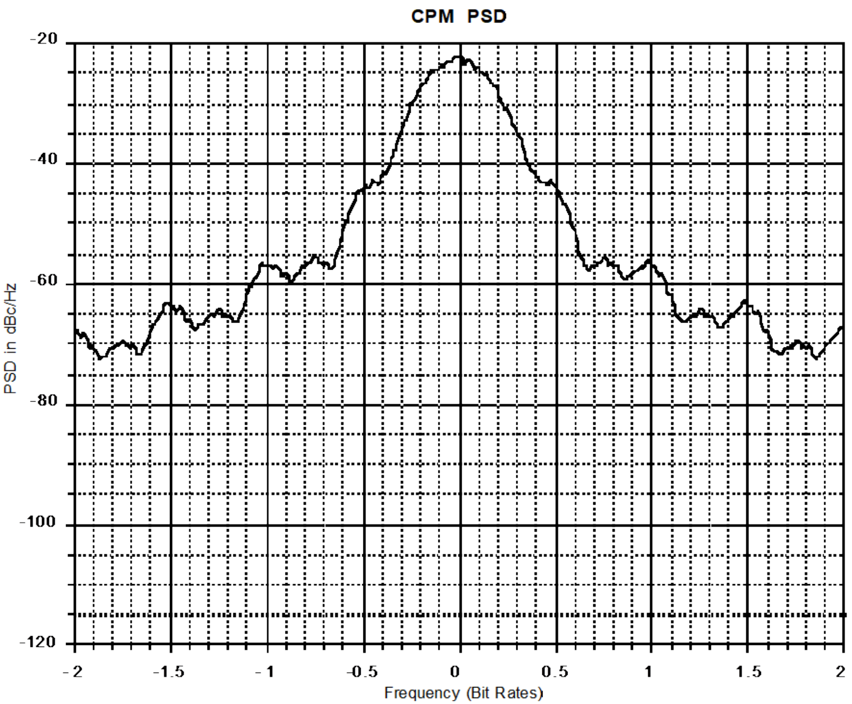
M=4, h=1/4, 1REC

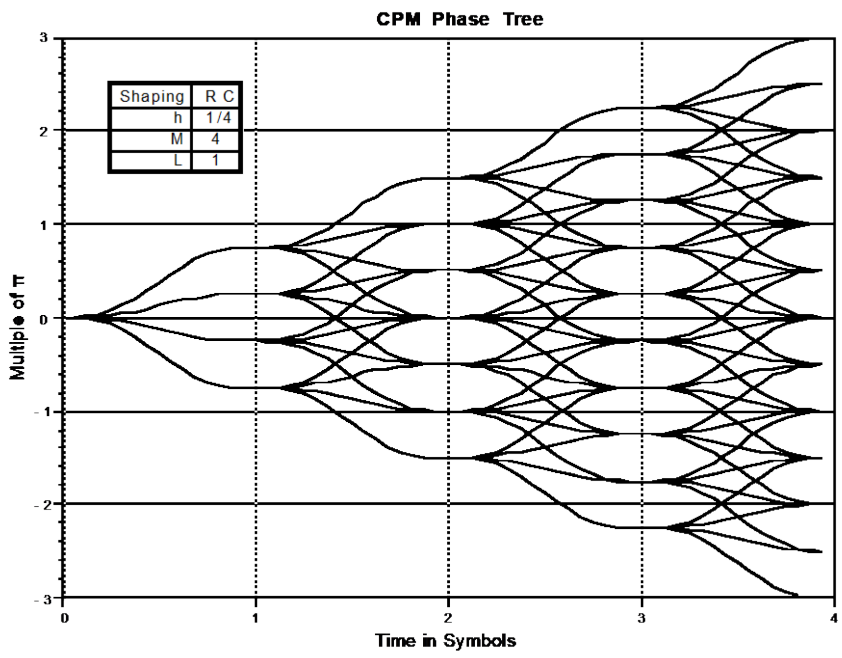
PSD vertical axis is dBc per FFT bin
1 FFT bin = 1/64 * symbol rate

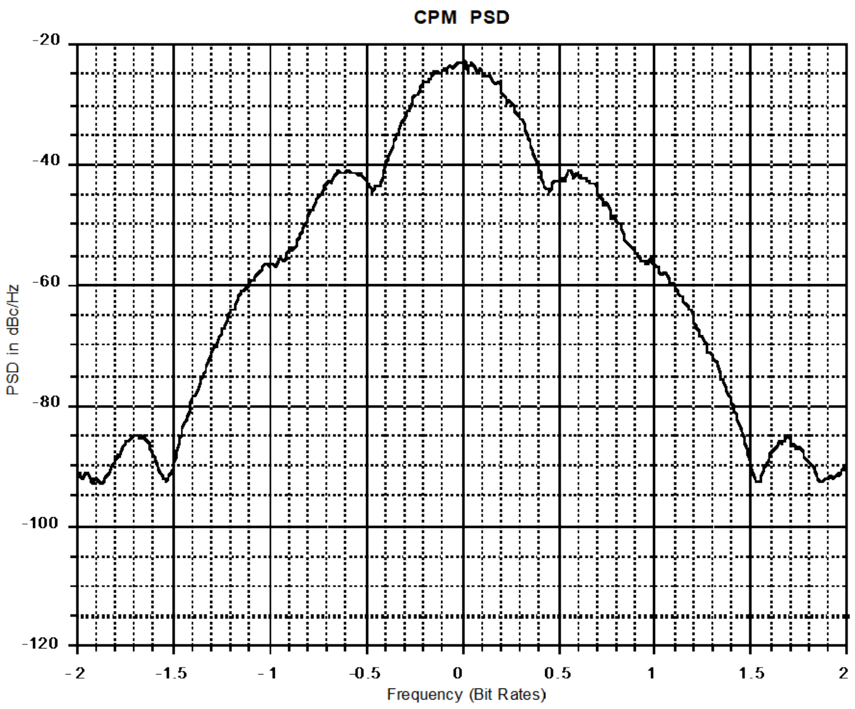




M=4, h=1/4, 1RC

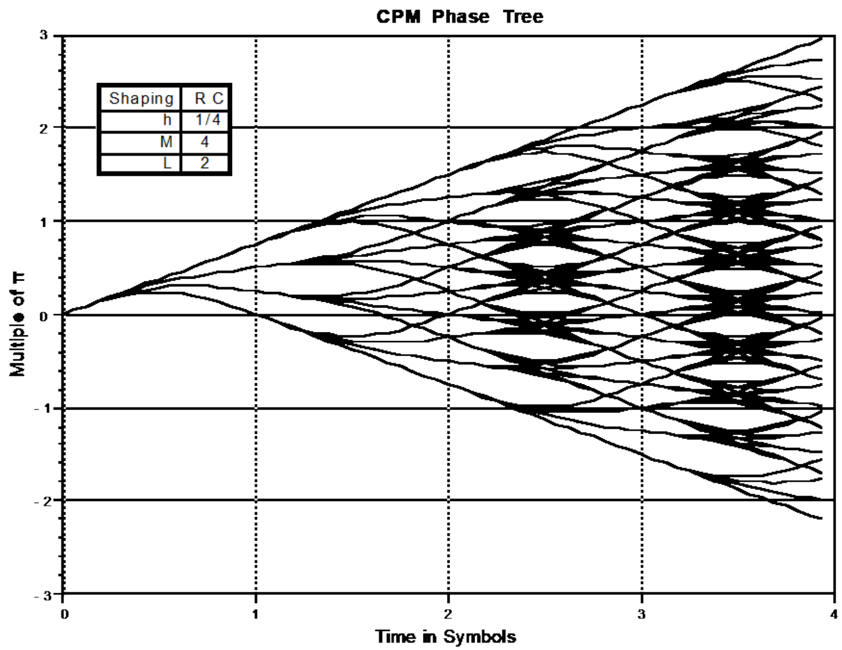
PSD vertical axis is dBc per FFT bin
1 FFT bin = 1/64 * symbol rate

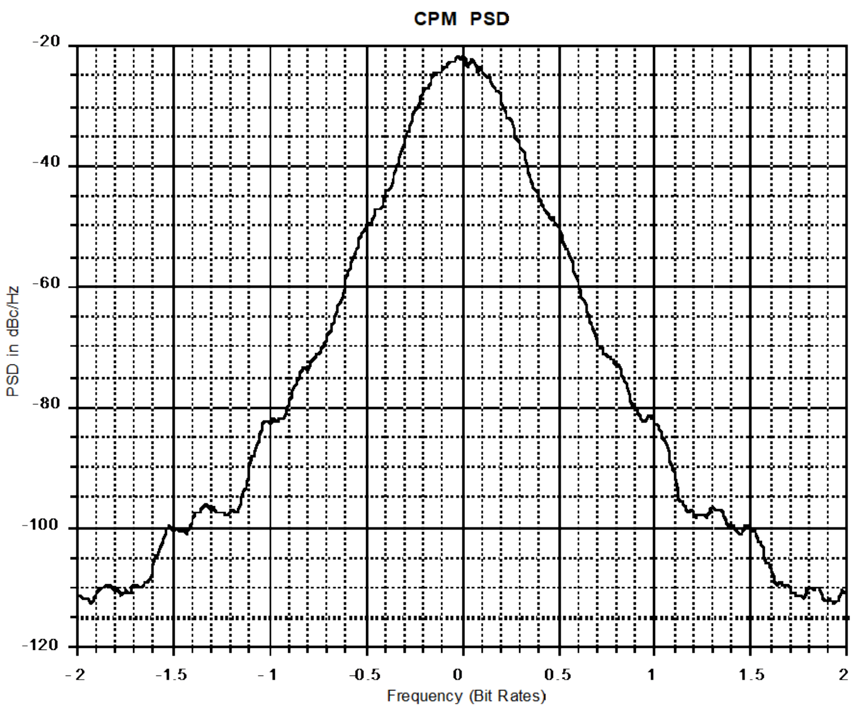




M=4, h=1/4, 2RC

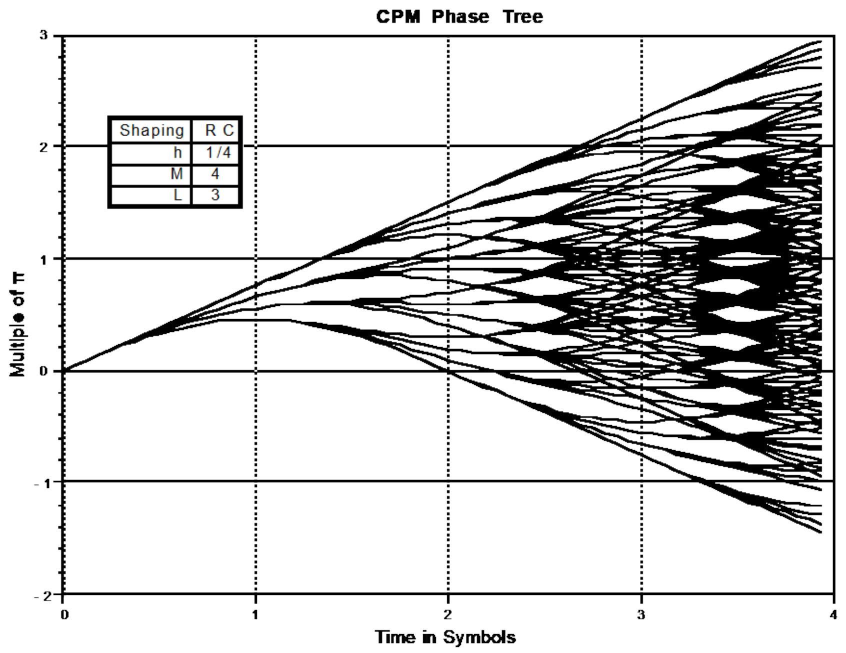
PSD vertical axis is dBc per FFT bin
1 FFT bin = 1/64 * symbol rate

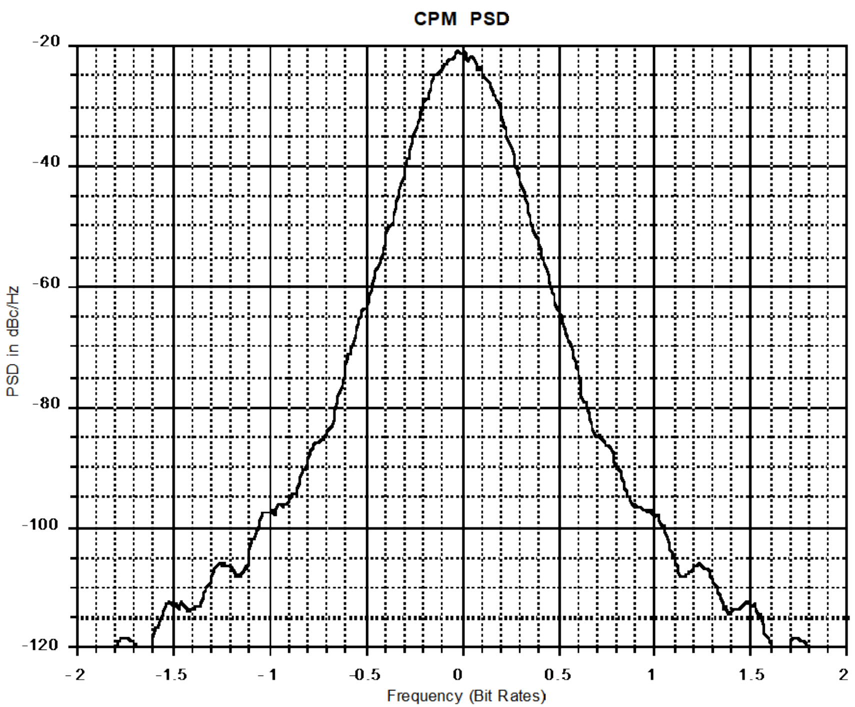




M=4, h=1/4, 3RC

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





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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

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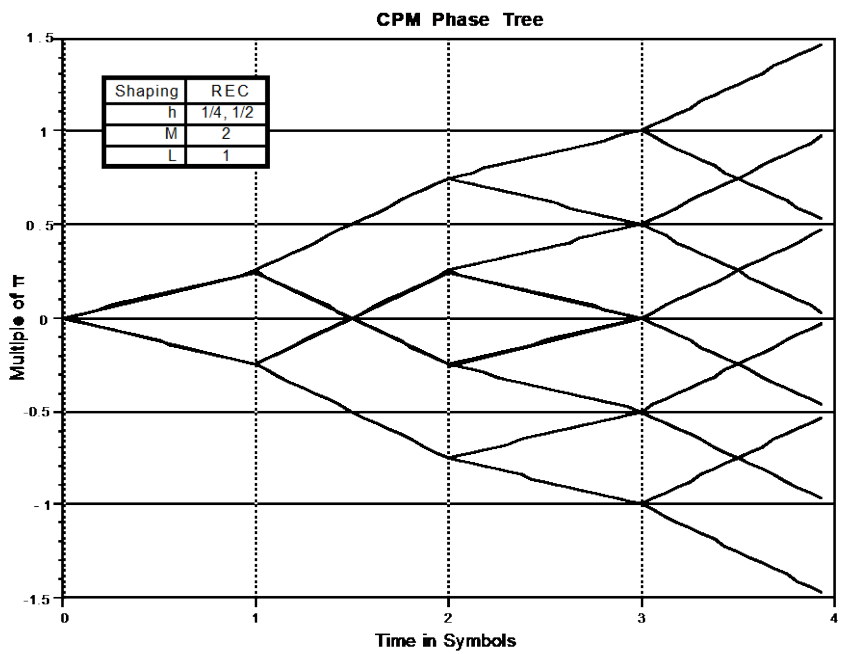
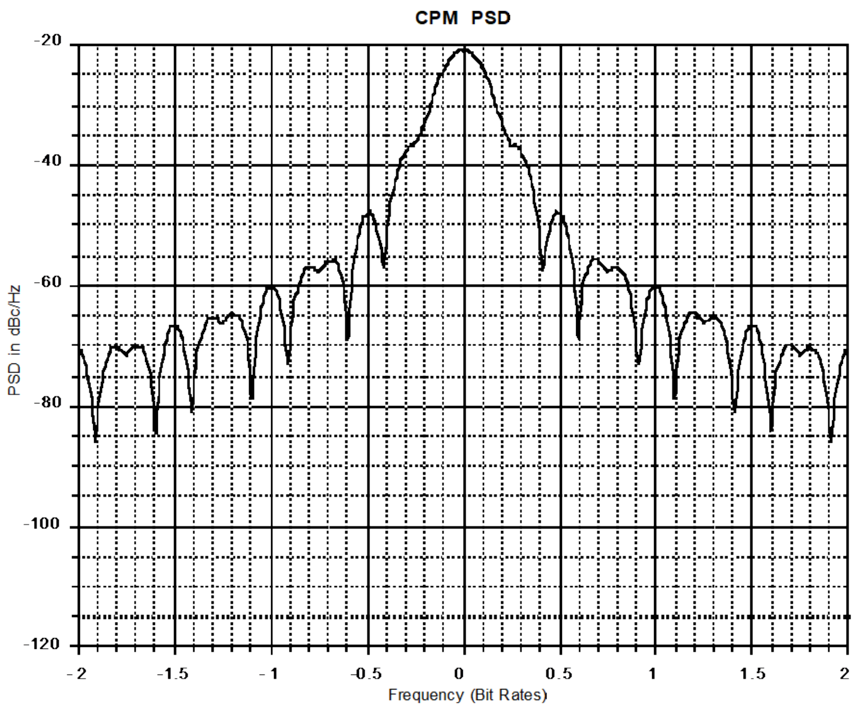
M=2, h_1=1/4, h_2=1/2, 1REC

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





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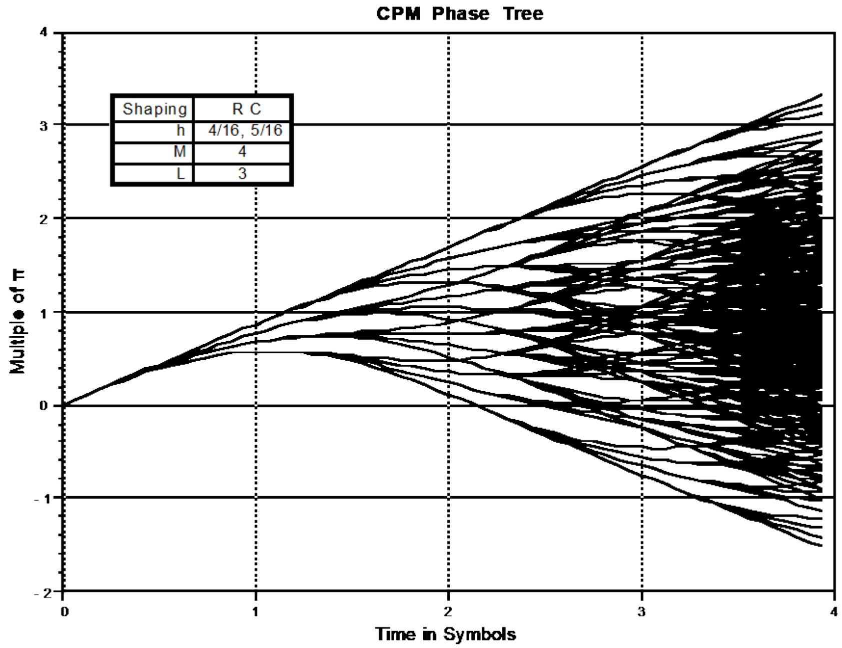
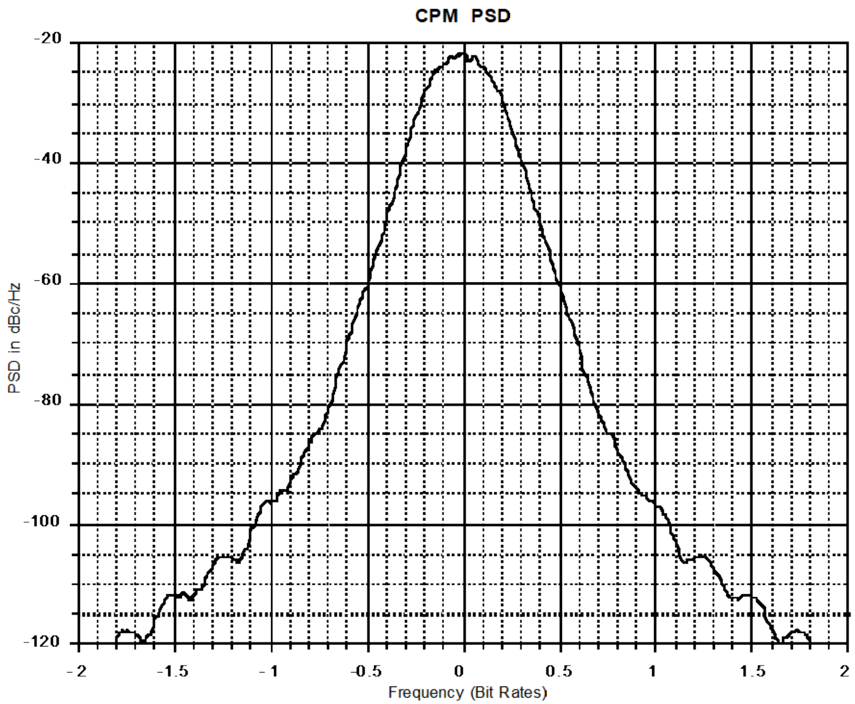
M=4, h_1=4/16, h_2=5/16, 3RC

ARTM Tier II Waveform

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



Shaping	R C
h	4/16, 5/16
M	4
L	3



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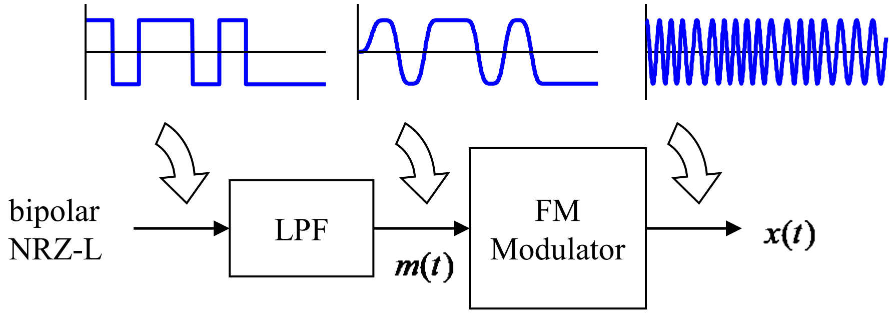
CPM Summary

- 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.

ARTM Tier 0 (PCM/FM) (CPFSK)

The way things were

PCM/FM (Tier 0)



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

time-varying phase

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

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

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

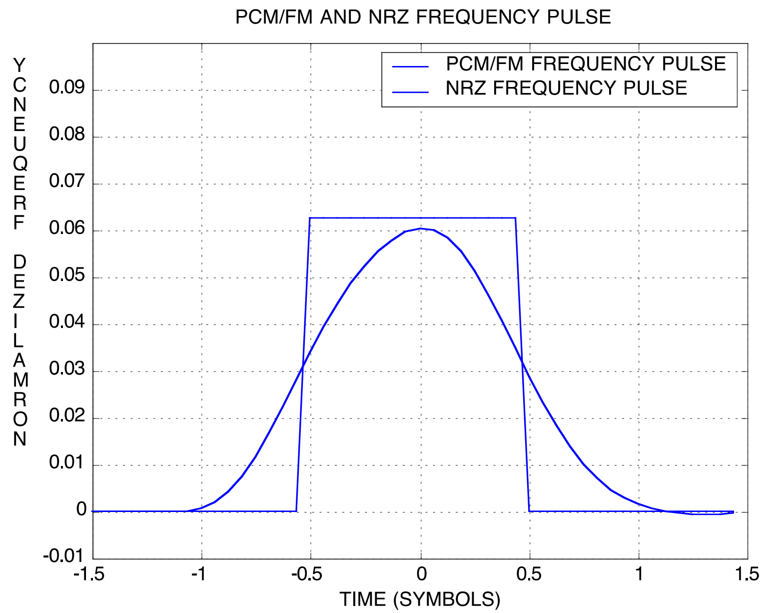
Tier 0 in CPM Notation

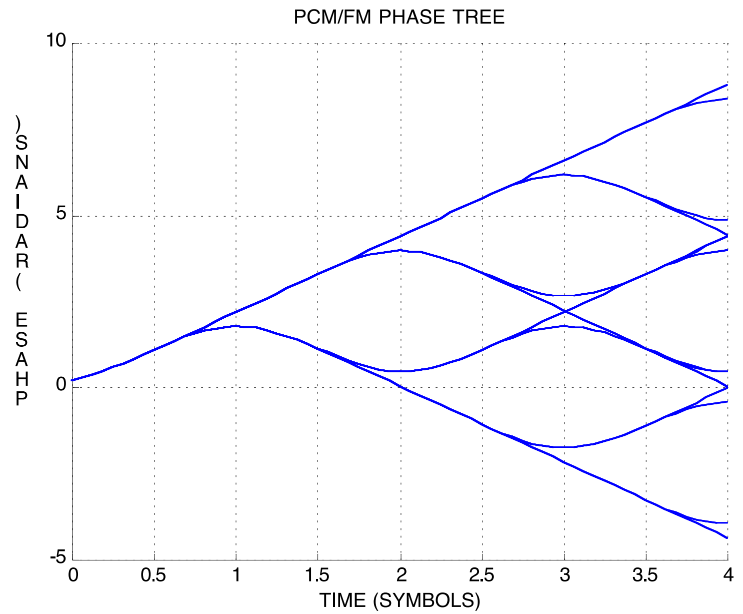
$$s(t) = \sqrt{2E/T}\cos[2\pi f_o t + \phi(t,\overline{\alpha}) + \phi_o]$$

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

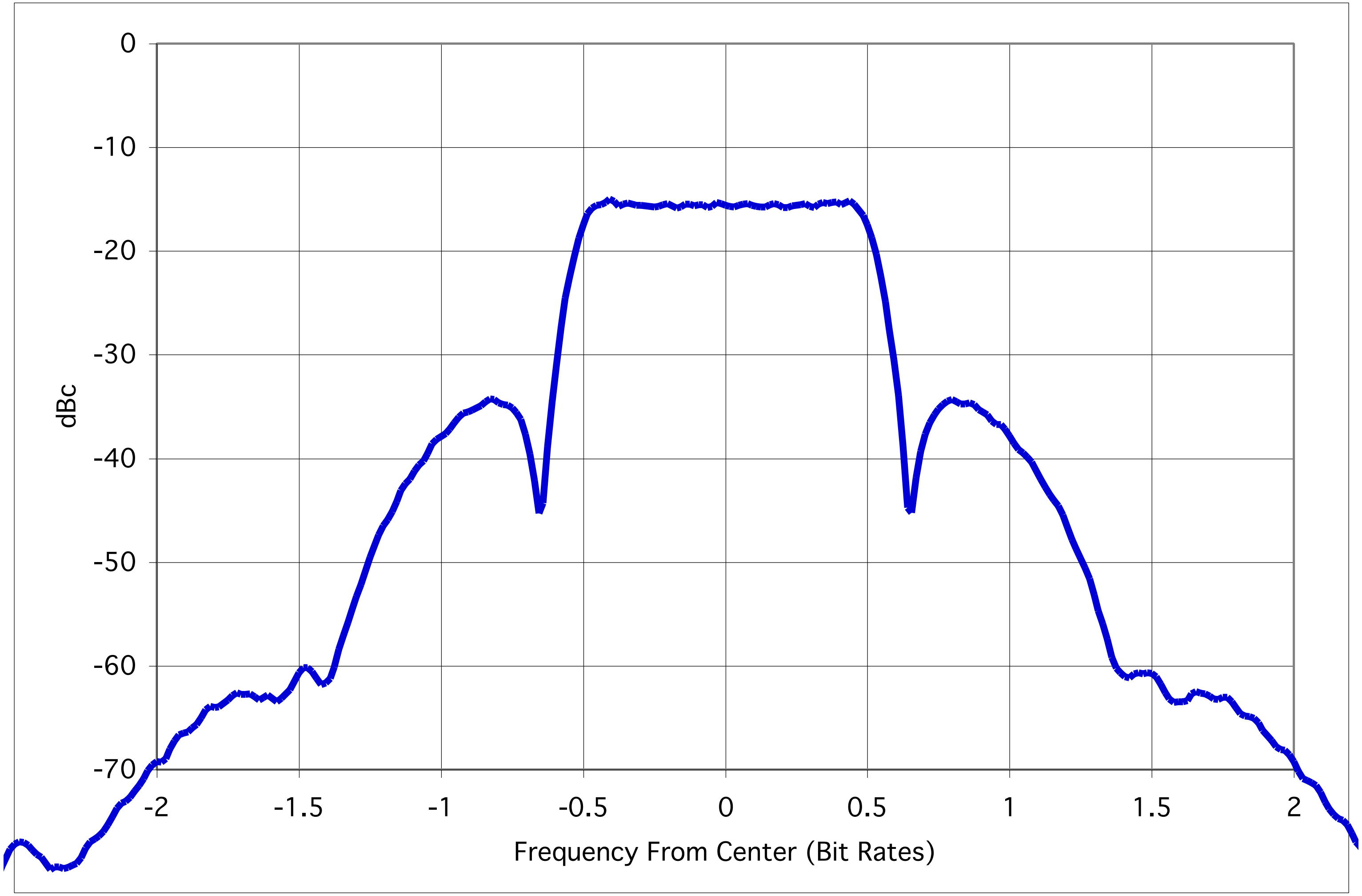
- M = 2 (binary)
- $\alpha_i = 2d_i - 1$
  - $d_i = \{0, 1\}$, $\alpha_i = \{-1, +1\}$
- h = 0.7
- g(t) is the normalized impulse response of a high order Bessel filter with 3 dB bandwidth = 0.7 * bit rate
  - Normalized such that the integral over all time = 1/2

PCM/FM as a Phase Modulation

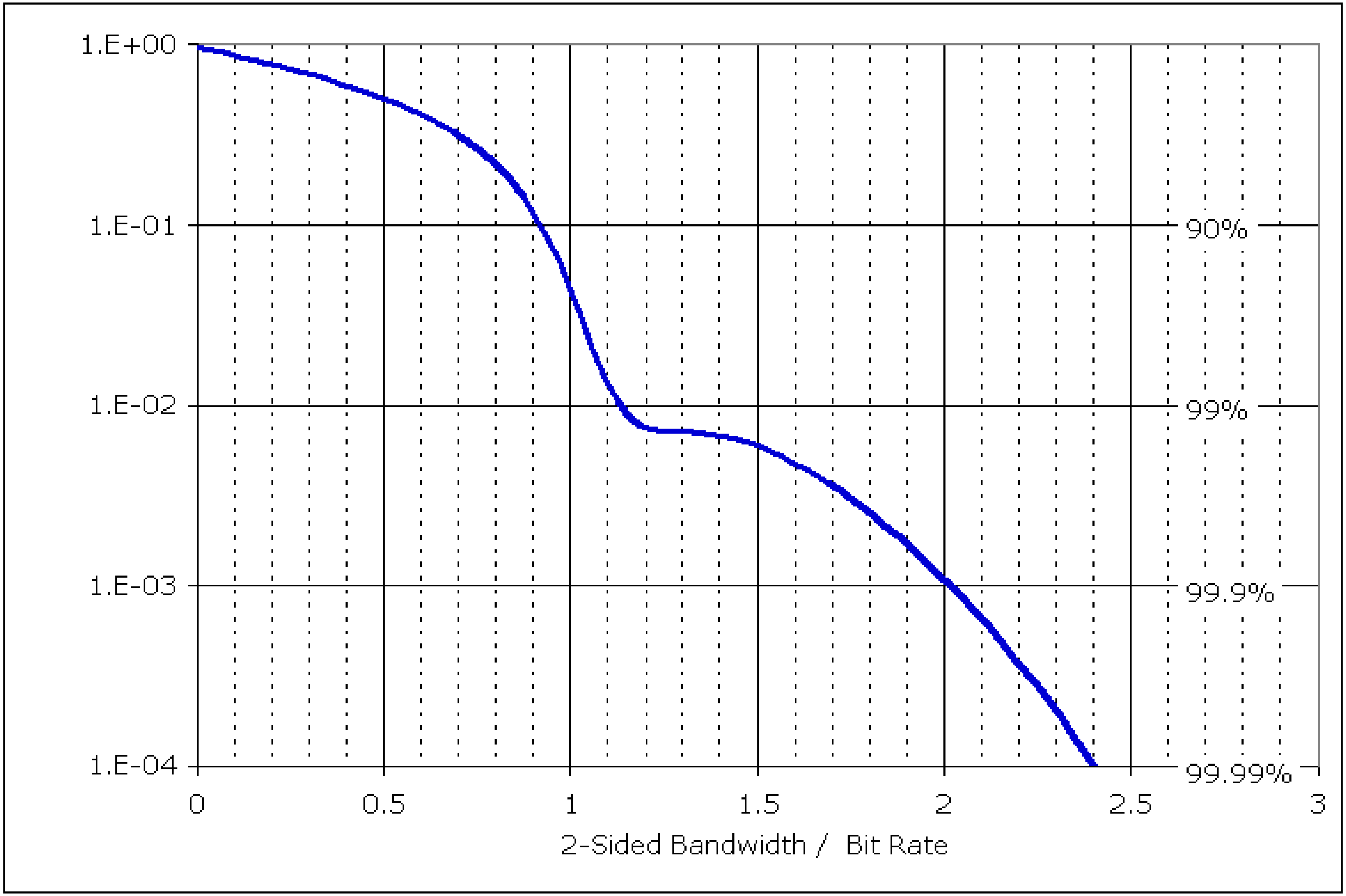




Power Spectral Density (PSD)



Fractional Out-of-band Power



PCM/FM Summary

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

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

ARTM Tier I (SOQPSK-TG)

The way things are

Tier I Overview

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

SOQPSK in CPM Notation

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

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

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

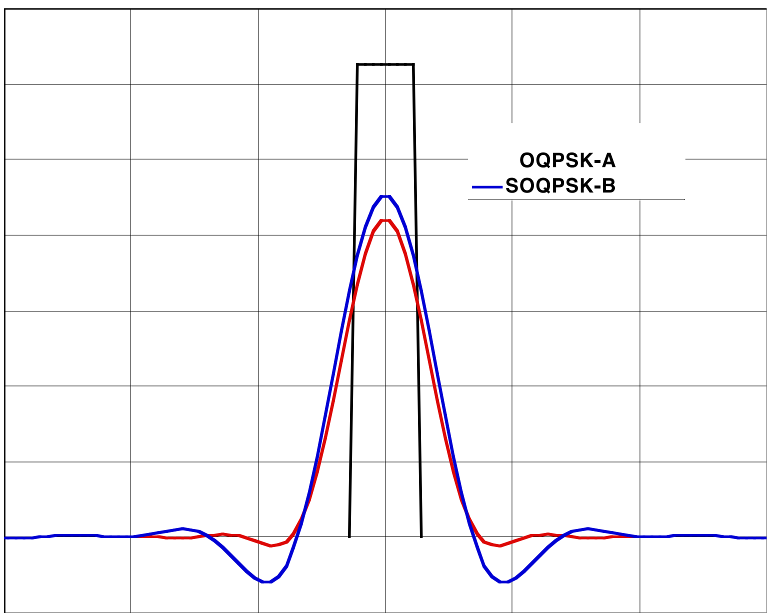
Definition of SOQPSK Pulse

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

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

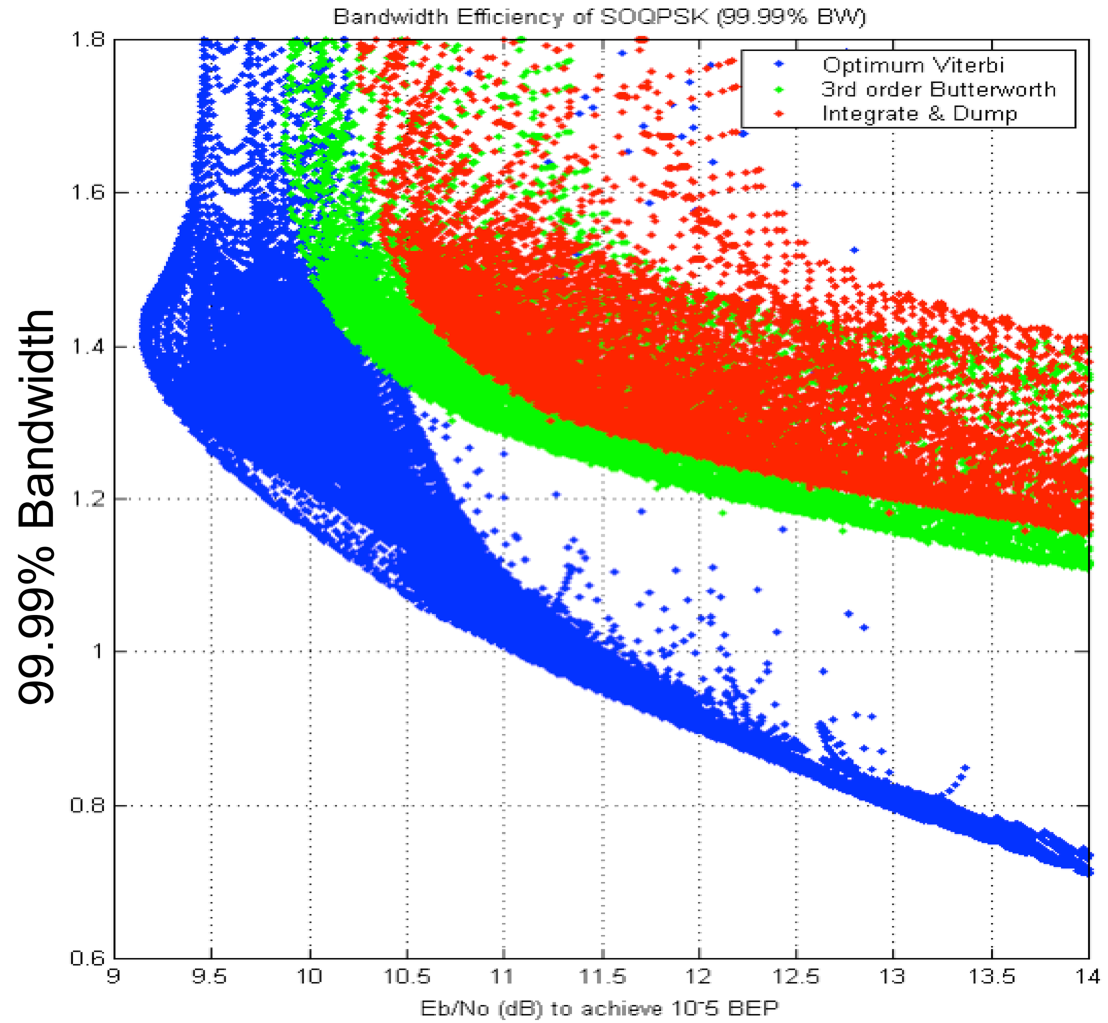
$$w(t) = \begin{cases} 1, & for \quad |t/T| < T_1 \\ \frac{1}{2} + \frac{1}{2}\cos\frac{\pi(|t/T| - T_1)}{T_2}, & for \quad T_1 < |t/T| < T_1 + T_2 \\ 0, & for \quad |t/T| > T_1 + T_2 \end{cases}$$

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



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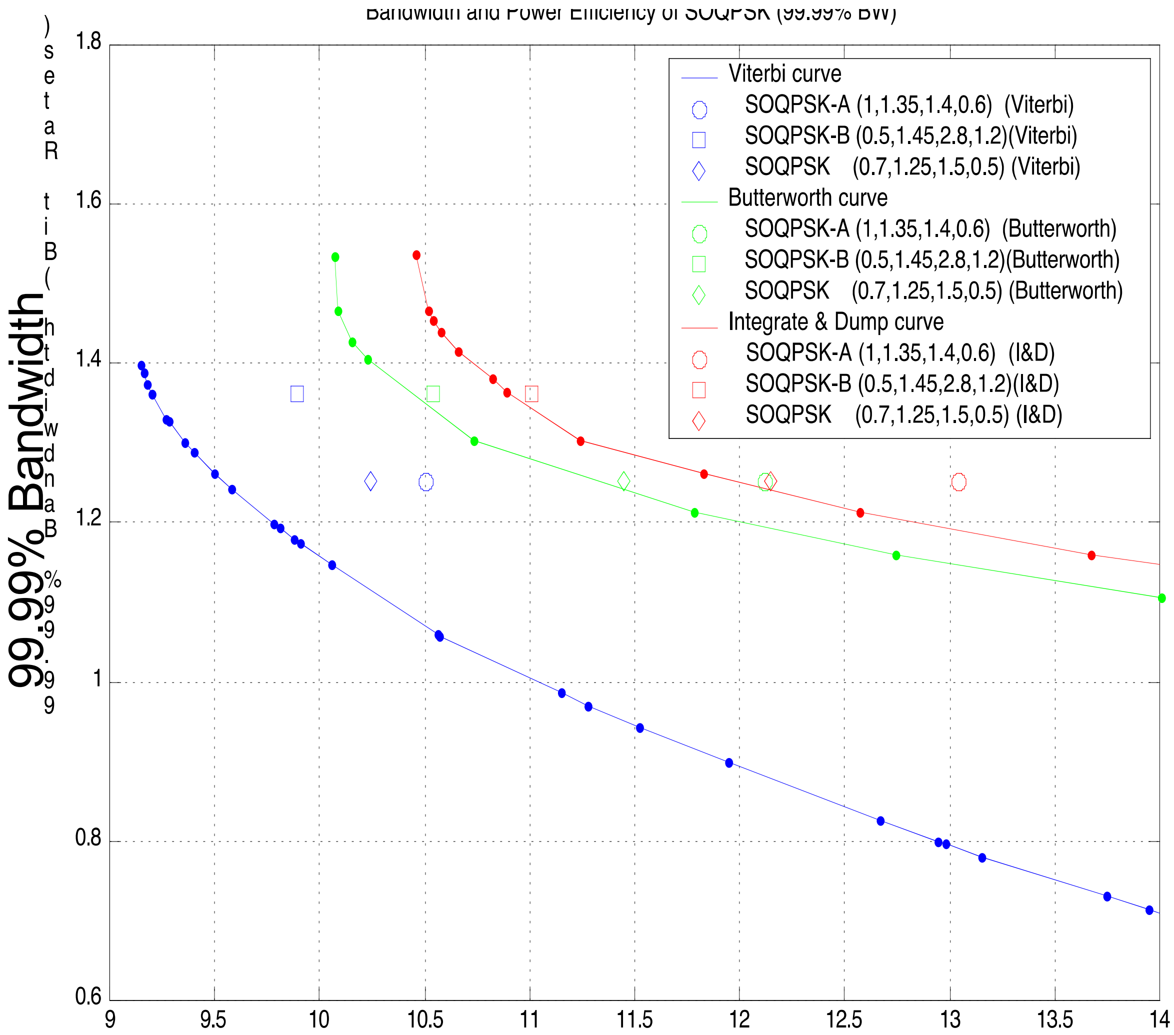
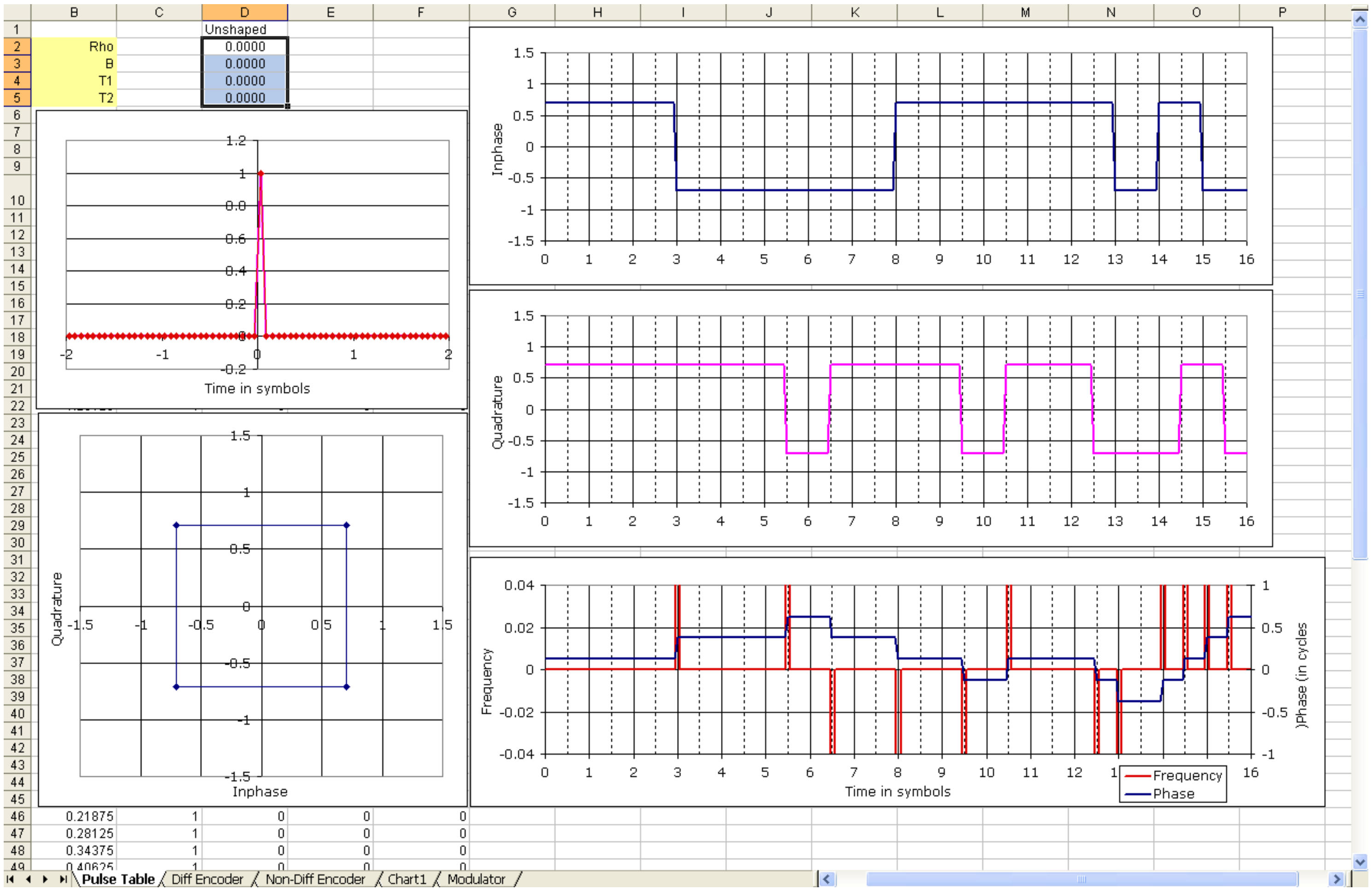
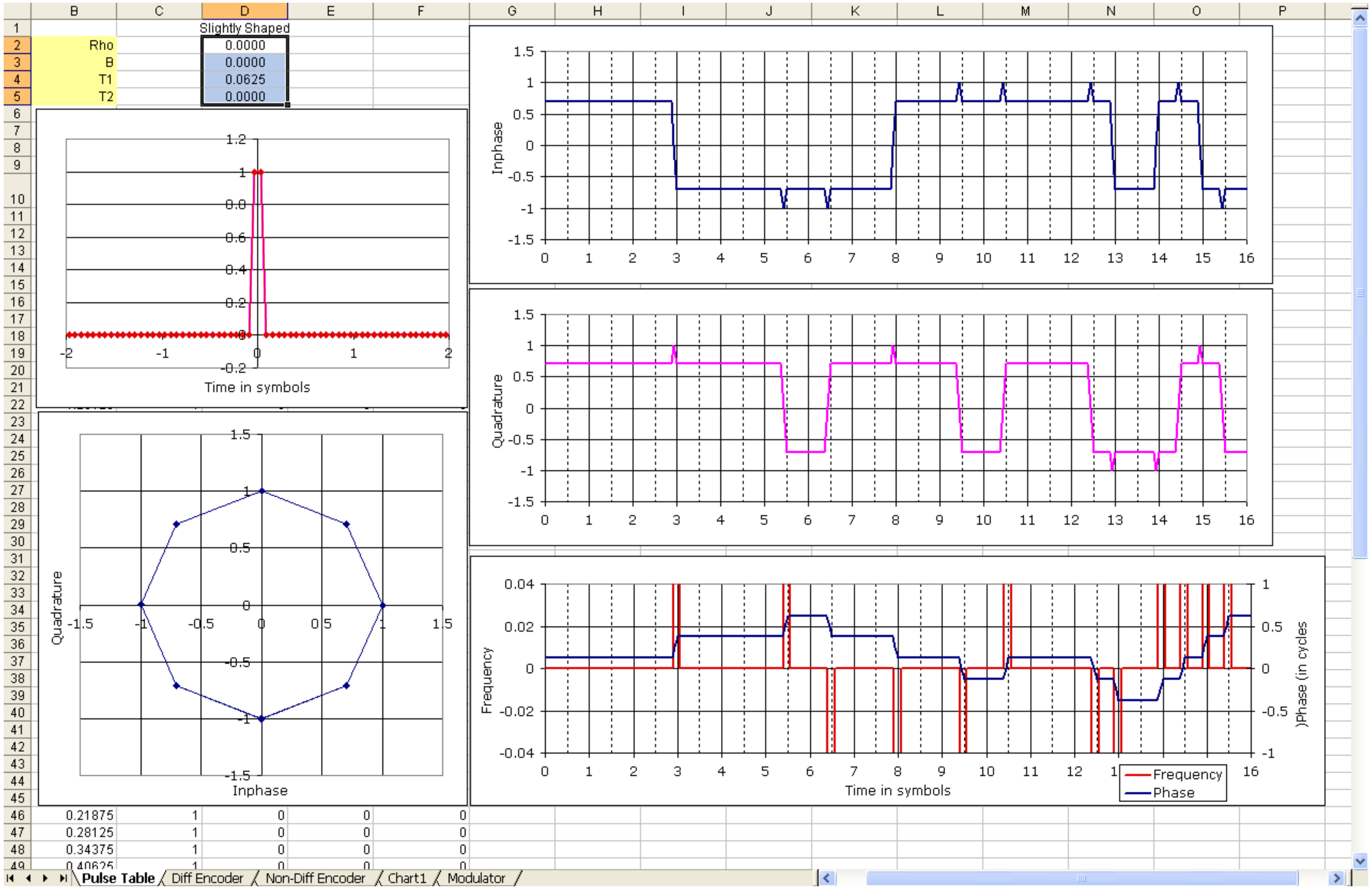
Optimal SOQPSK Variants



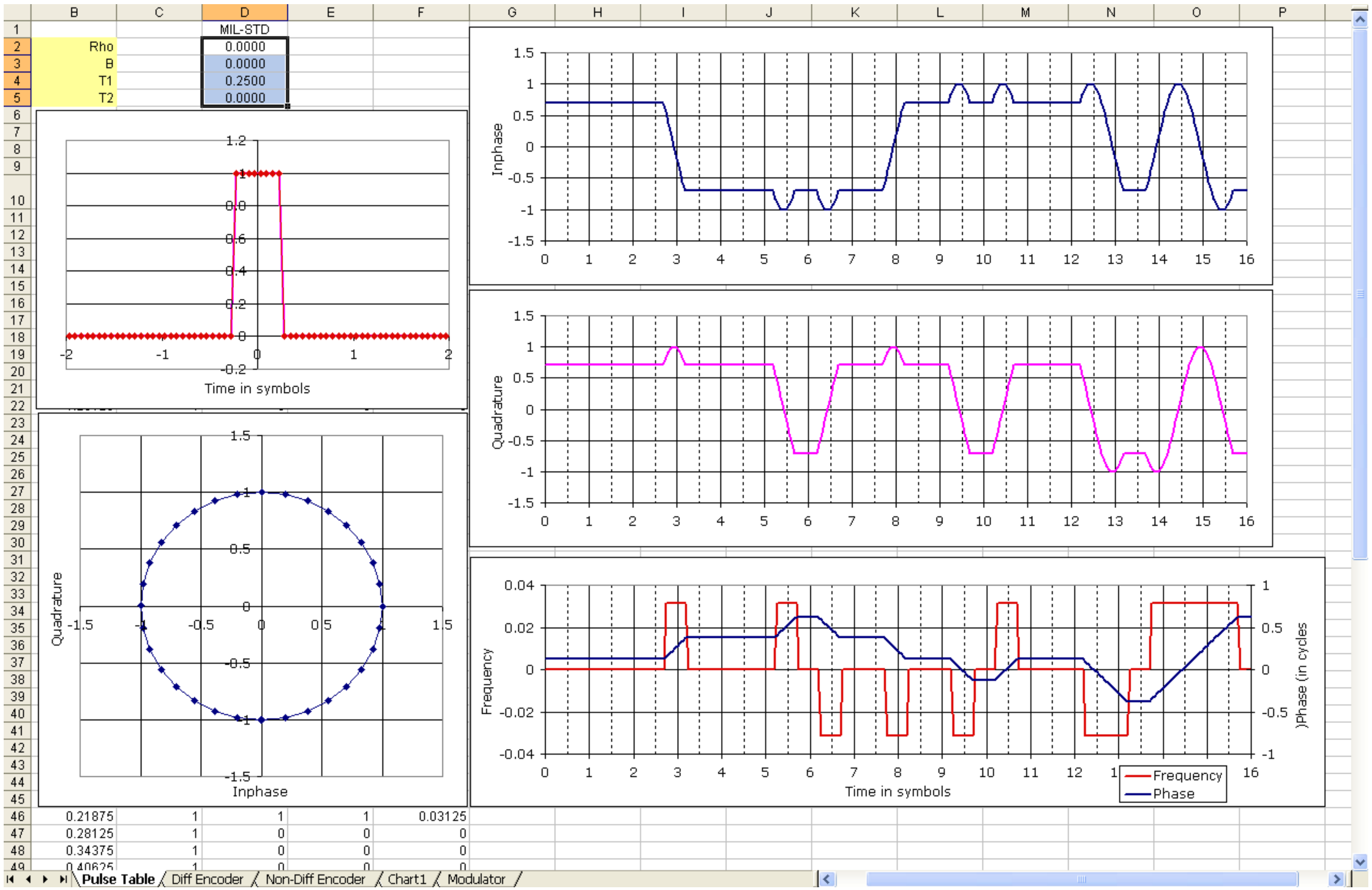
Unshaped Offset QPSK



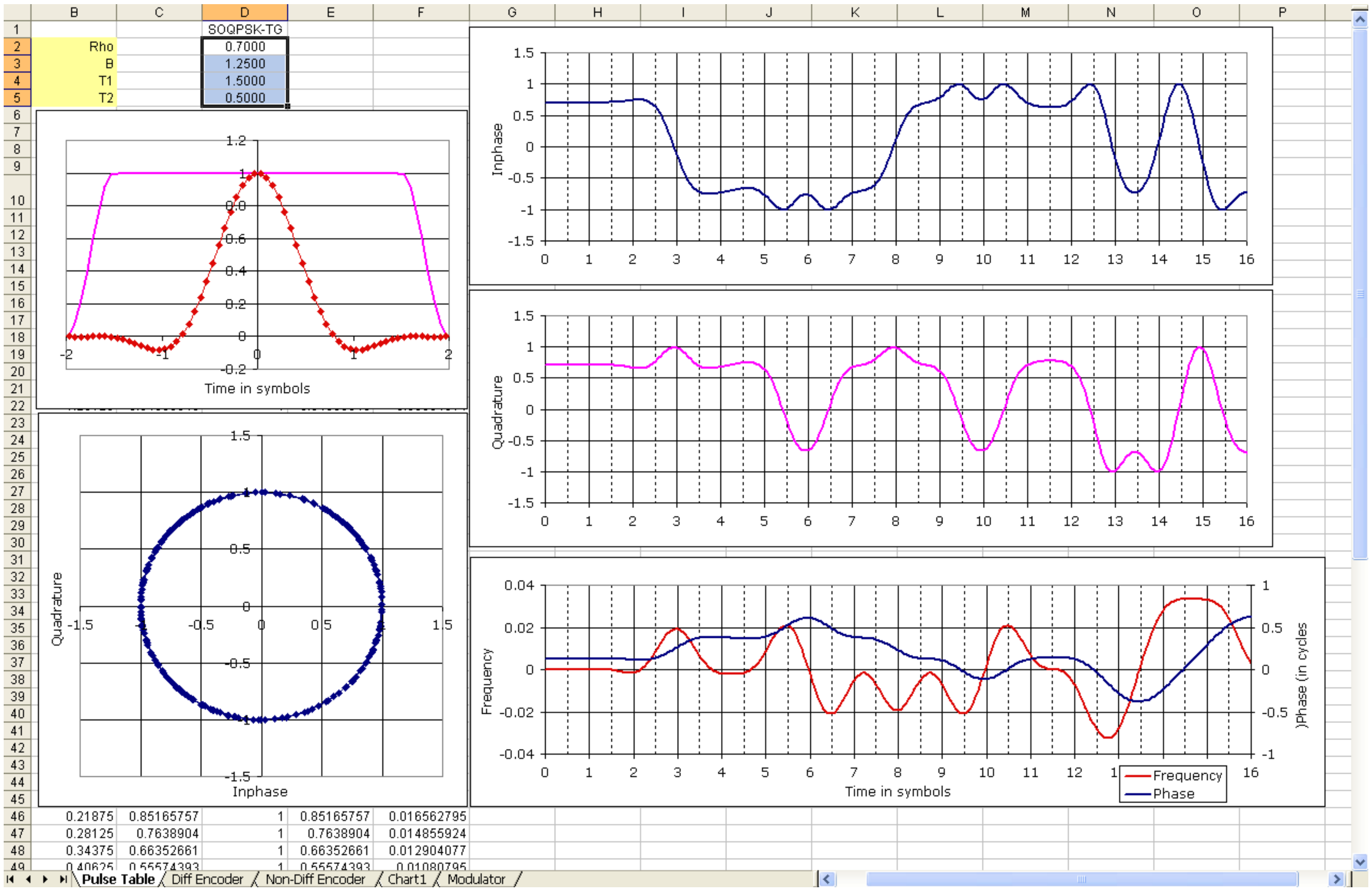
Slightly Shaped OQPSK



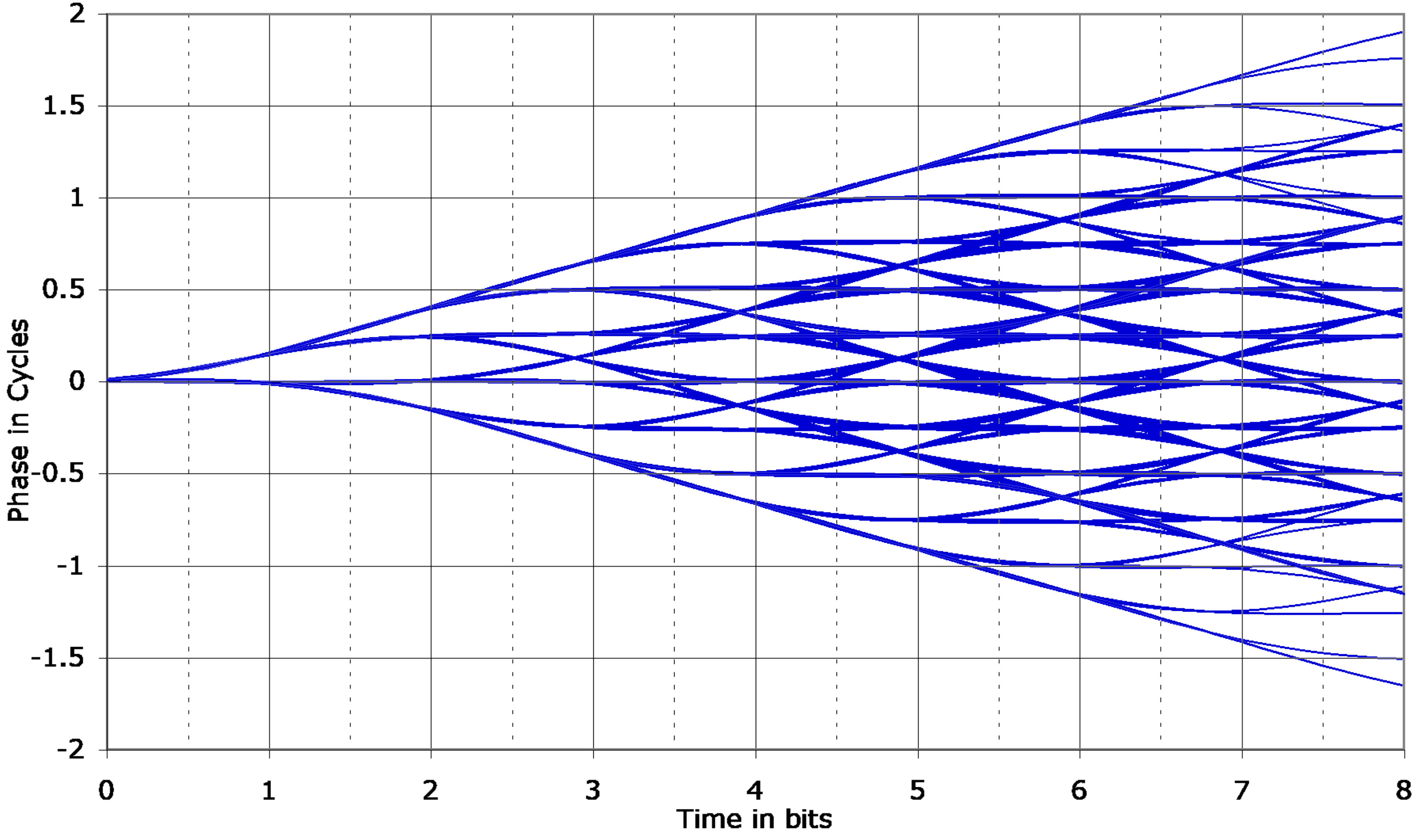
MIL-STD SOQSPK



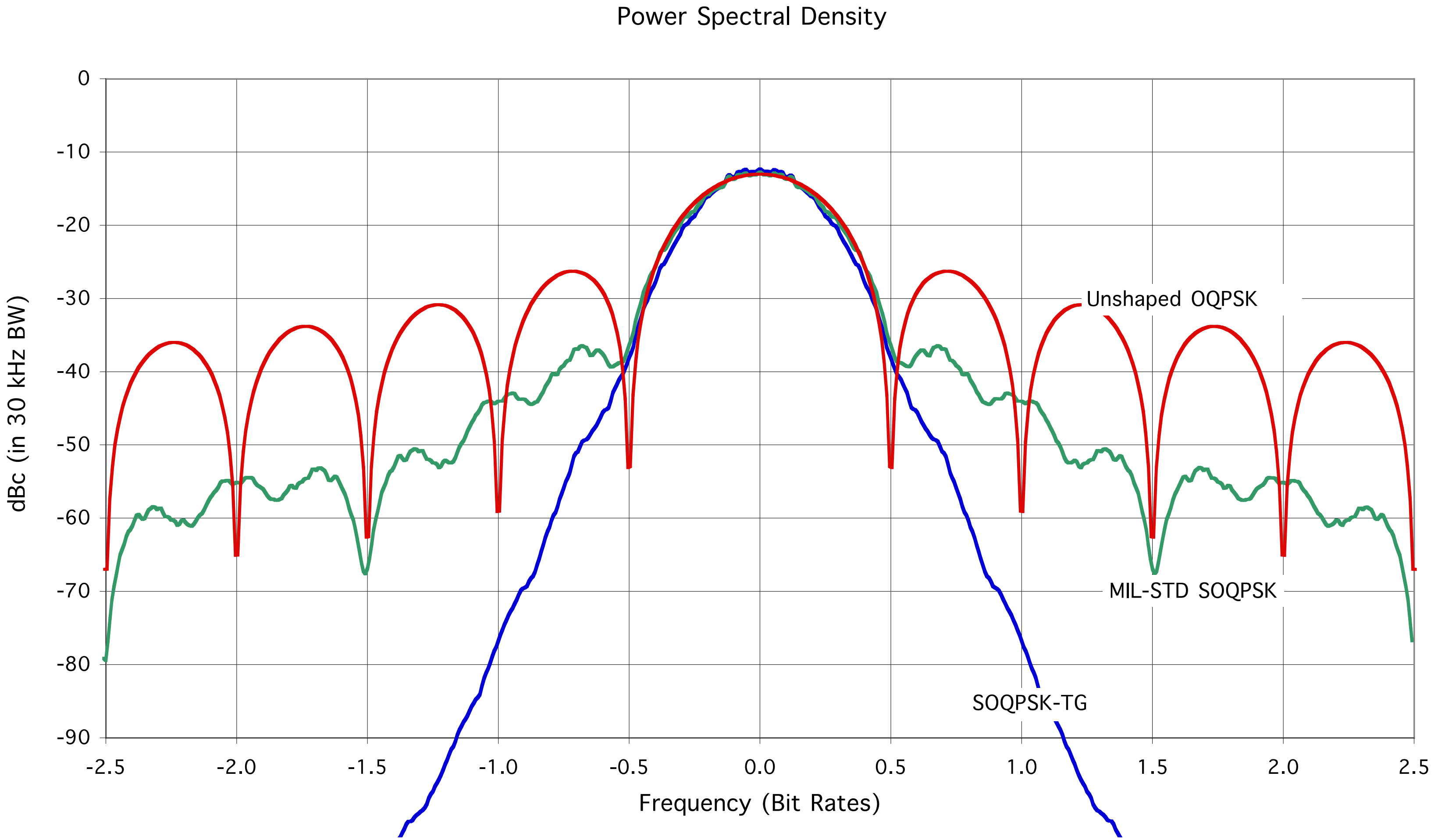
SOQPSK-TG


SOQPSK-TG
Rho 0.7000
B 1.2500
T1 1.5000
T2 0.5000
Time in symbols
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

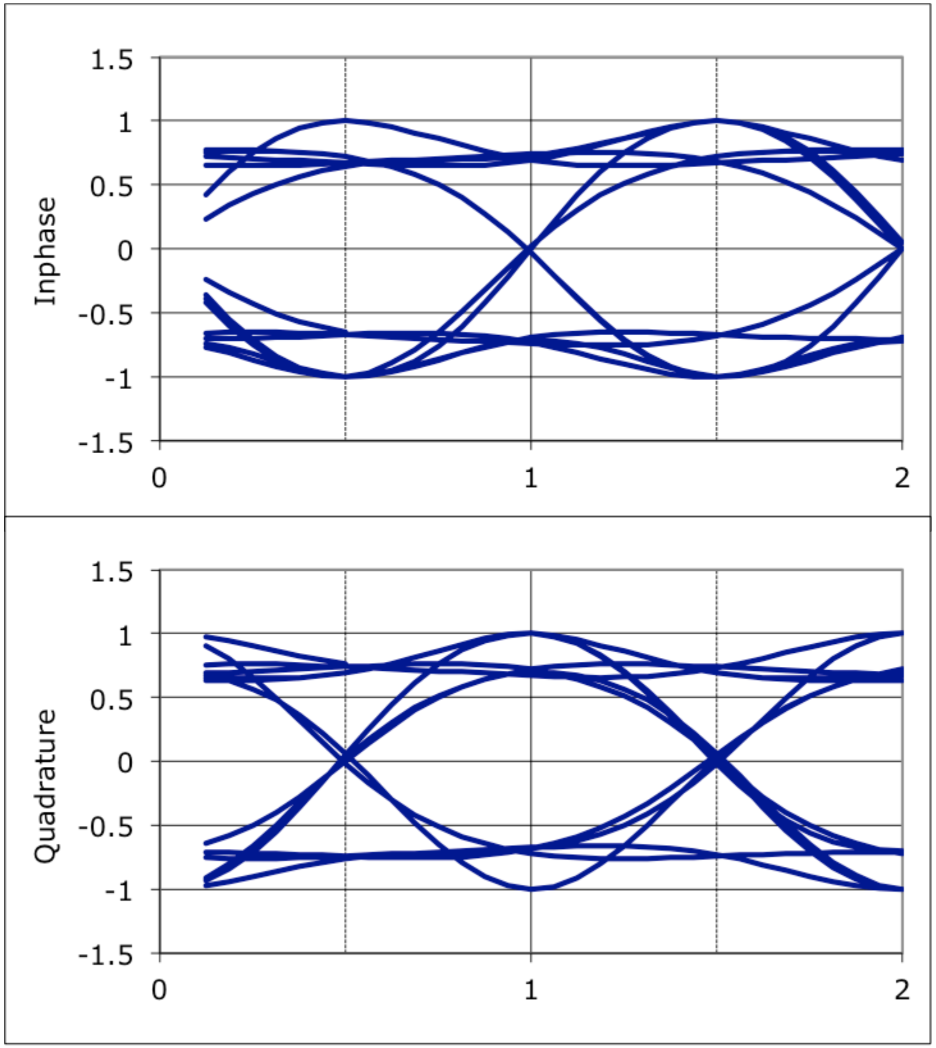
SOQPSK-TG Phase Tree



Power Spectral Density

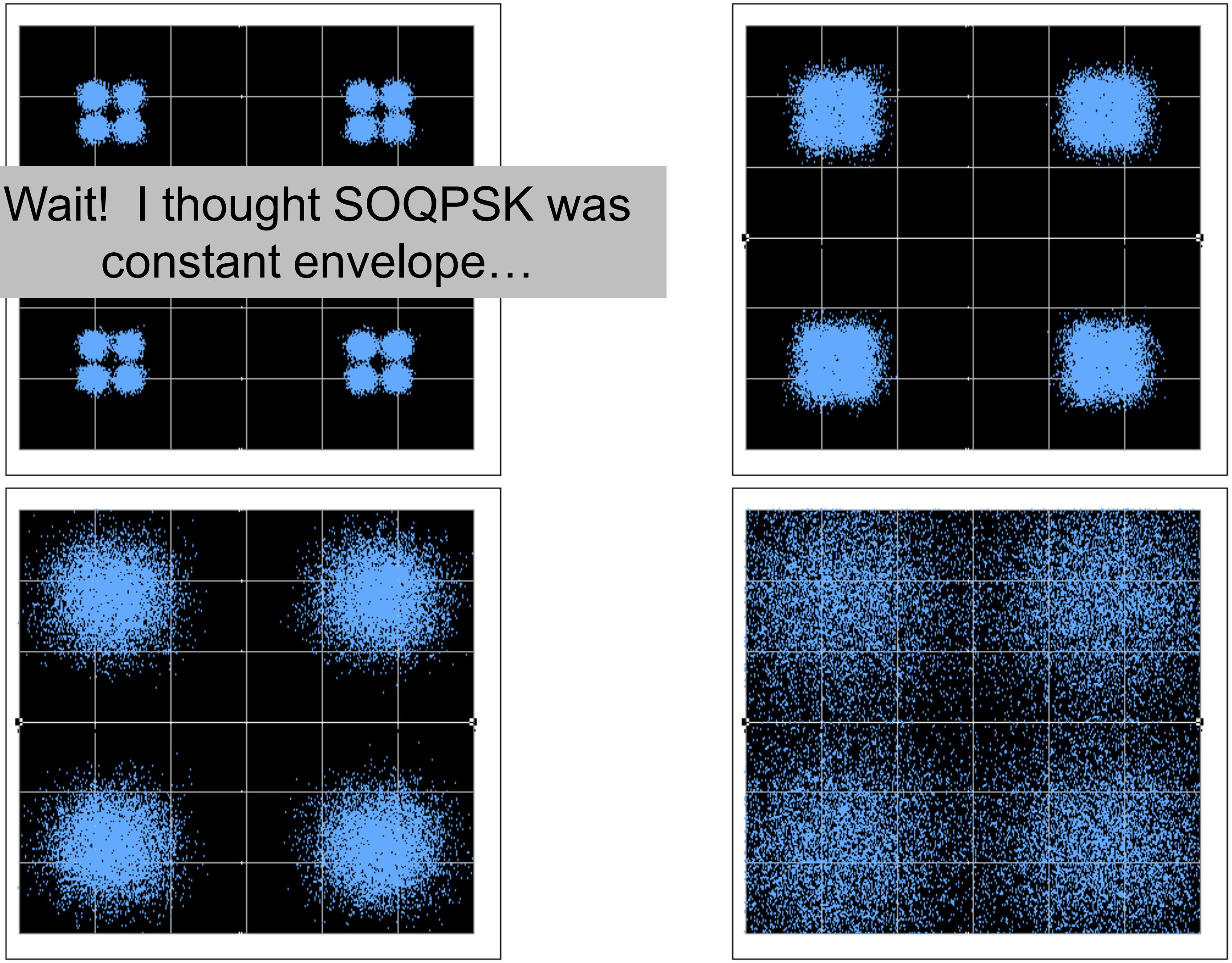


SOQPSK-TG Eye Patterns

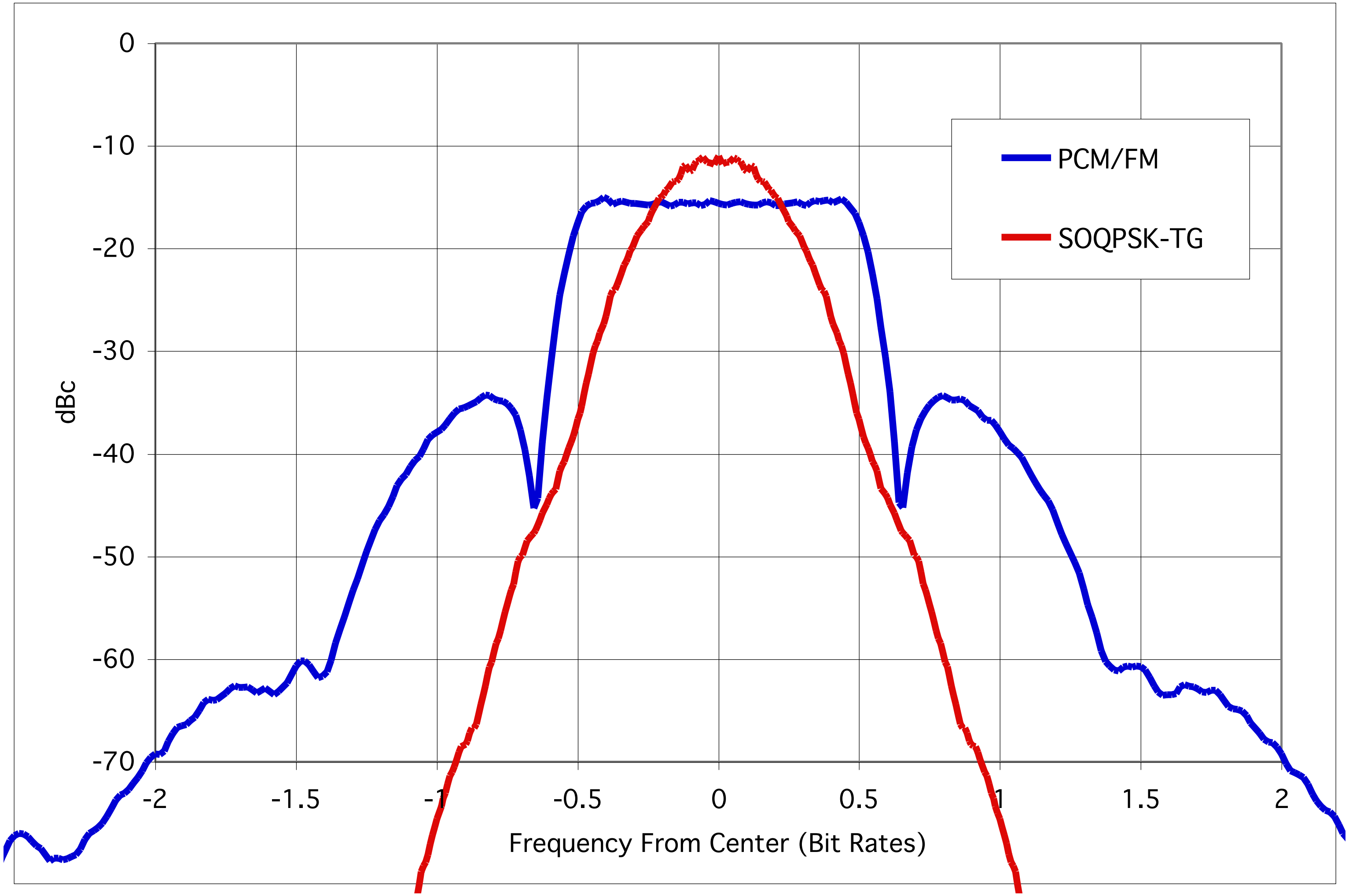


- Single-symbol detection is sub-optimal, but practical

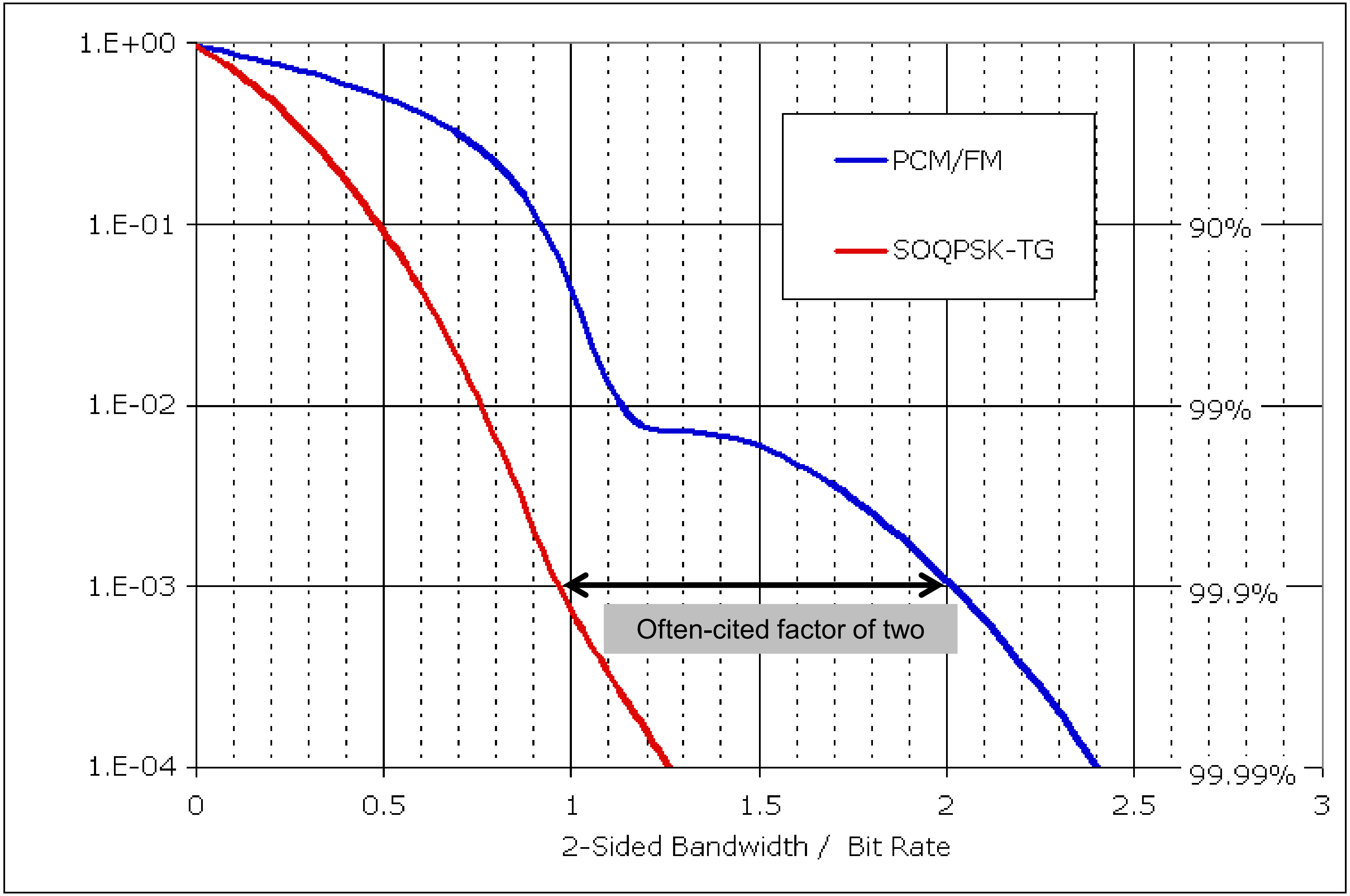
SOQPSK Constellations



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

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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.

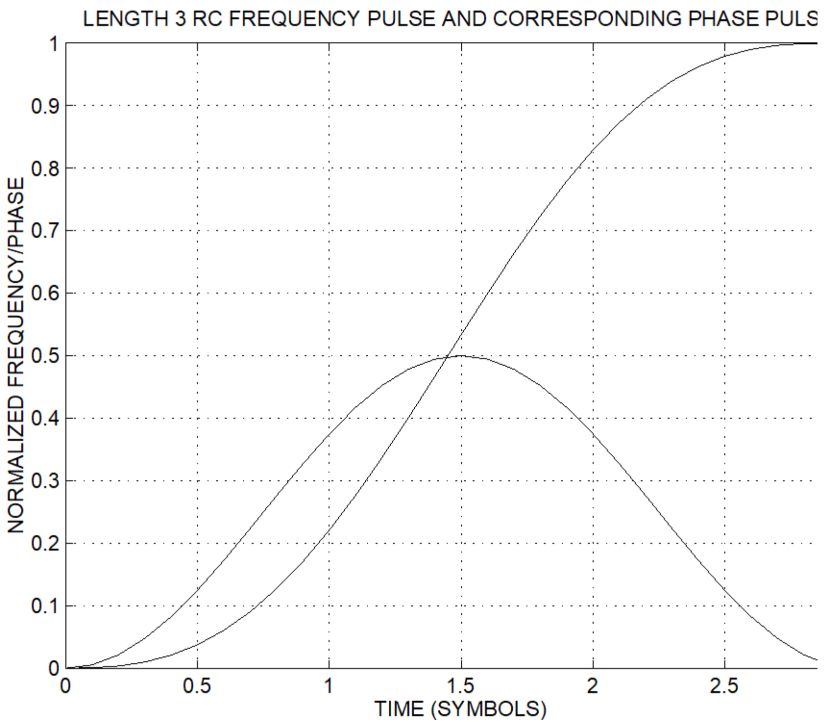
ARTM Tier II in CPM Notation

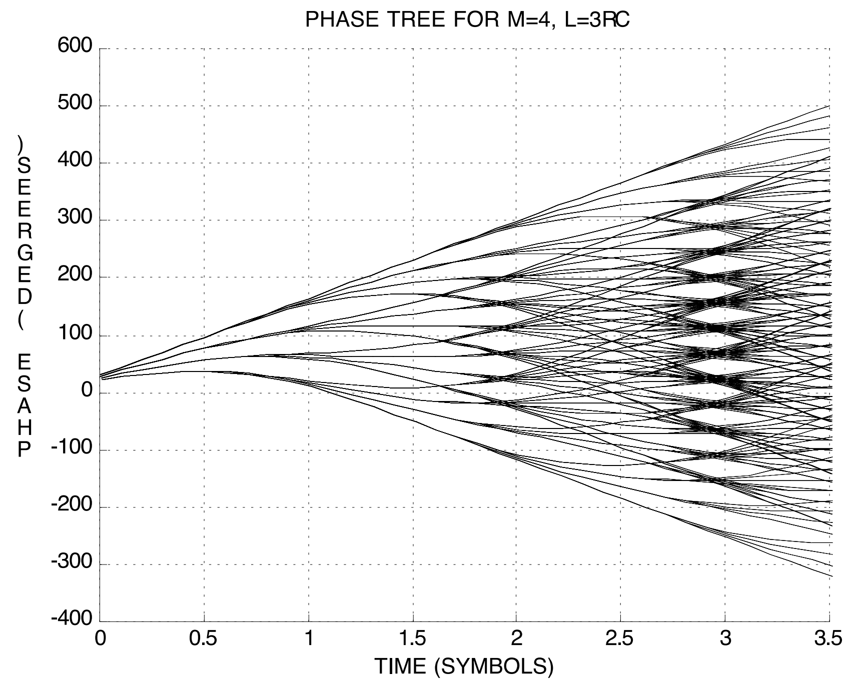
$$s(t) = \sqrt{2E/T}\cos[2\pi f_o t + \phi(t,\overline{\alpha}) + \phi_o]$$

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

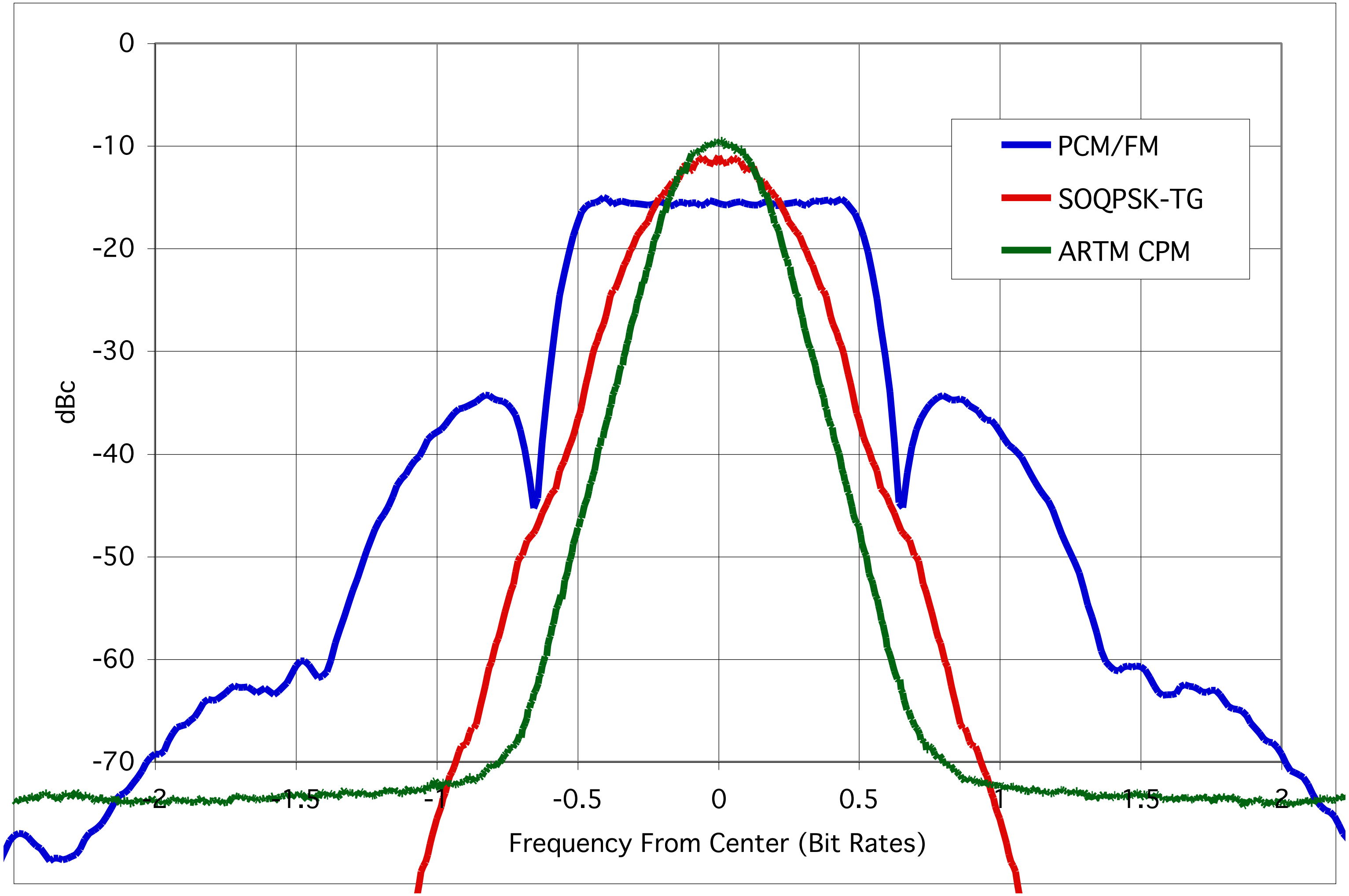
- M = 4 (quaternary)
- $\alpha_i = 2\,[2d_{1i} + d_{0i}] - 3$
  - $\alpha_i = \{-3, -1, +1, +3\}$
  - $d_i = \{0, 1\}$
- h = {4/16, 5/16}, alternating
- g(t) = raised cosine, 3 symbols (6 bits) in duration
  - Normalized such that the integral over all time = 1/2

Frequency Pulse & Phase Tree





PSD (Tier 0, I, & II)



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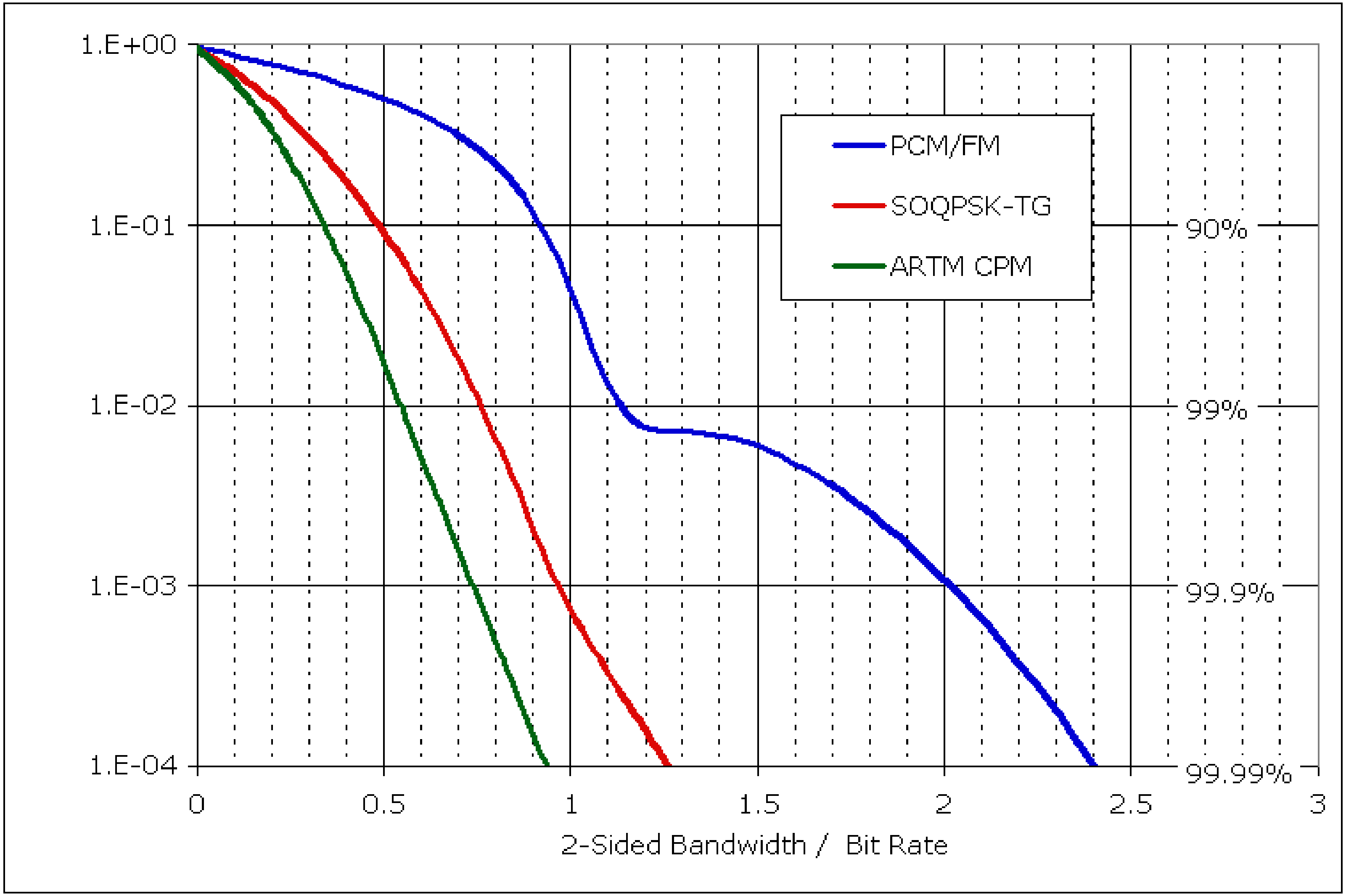
Fractional Out-of-band Power



Tier II Multi-h CPM Summary

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

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

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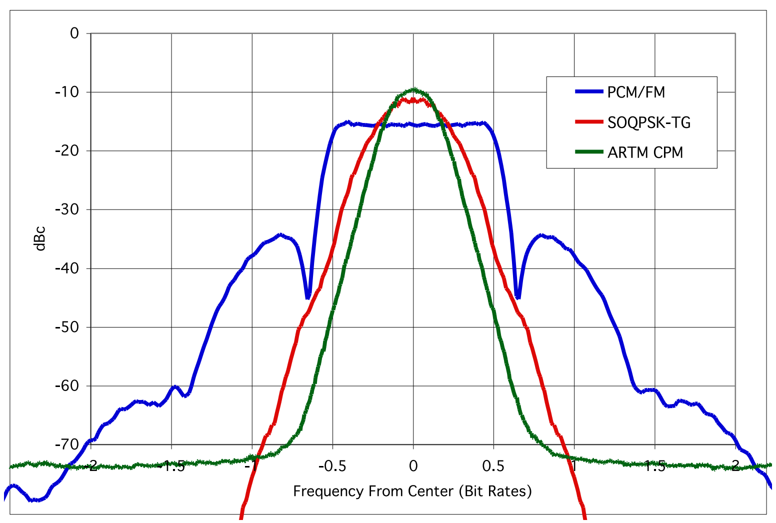
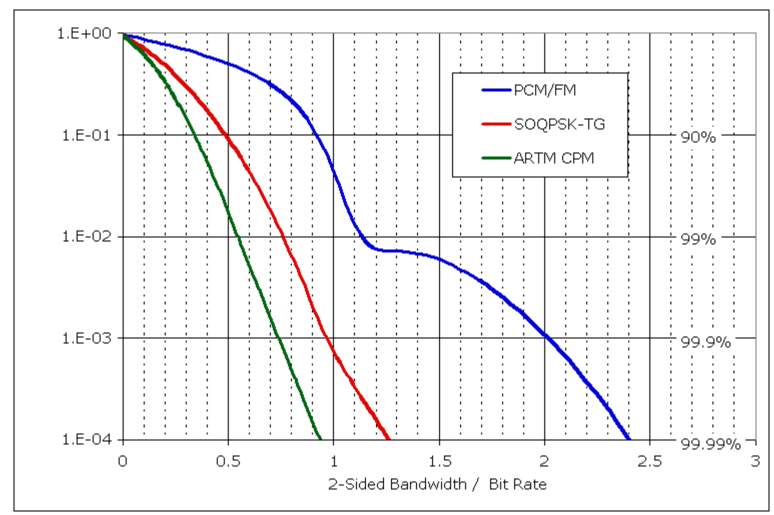
Side by Side Summary

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





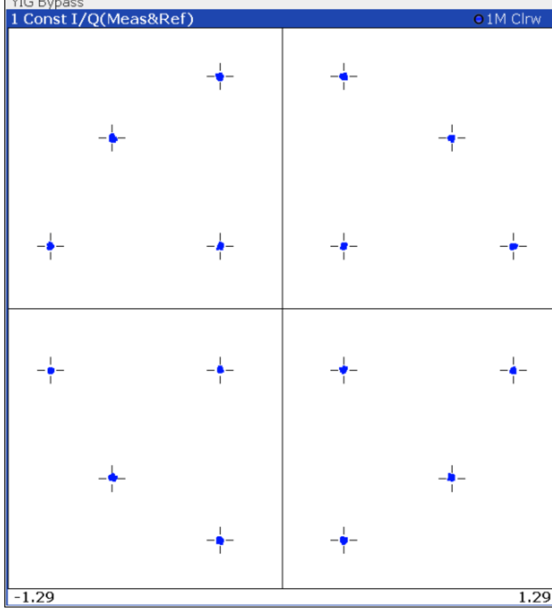
Amplitude/Phase Shift Keying (APSK)

Things to come?

16-APSK Constellation - Ideal

MultiView | Spectrum | VSA 2

Ref Level 0.00 dBm | Capture Length 8000 | Modulation 16APSK | Result Length 3000
Att 20 dB | Freq 70.0 MHz | Symbol Rate 2.916666 MHz | Tx Filter User
YIG Bypass



2 Result Summary

		Current	Peak	Unit
EVM	RMS	0.82	0.95	%
	Peak	2.07	2.75	%
MER	RMS	41.71	40.46	dB
	Peak	33.67	31.22	dB
Phase Error	RMS	0.45	0.48	deg
	Peak	2.43	-2.85	deg
Magnitude Error	RMS	0.57	0.75	%
	Peak	-2.04	2.72	%
Carrier Frequency Error		0.30	0.65	Hz
Symbol Rate Error		0.33	0.47	ppm
I/Q Skew		---	---	ps
Rho		0.999 927	0.999 921	
I/Q Offset		-57.91	-57.21	dB
I/Q Imbalance		-47.05	-46.11	dB
Gain Imbalance		0.00	0.01	dB
Quadrature Error		0.51	0.57	deg
Amplitude Droop		-0.000 01	0.000 023	dB/sym
Power		-20.04	-20.00	dBm

3.5 MHz Occupied BW
(8.889 Mbps Info Rate /11.667 Mbps OTA Rate)

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

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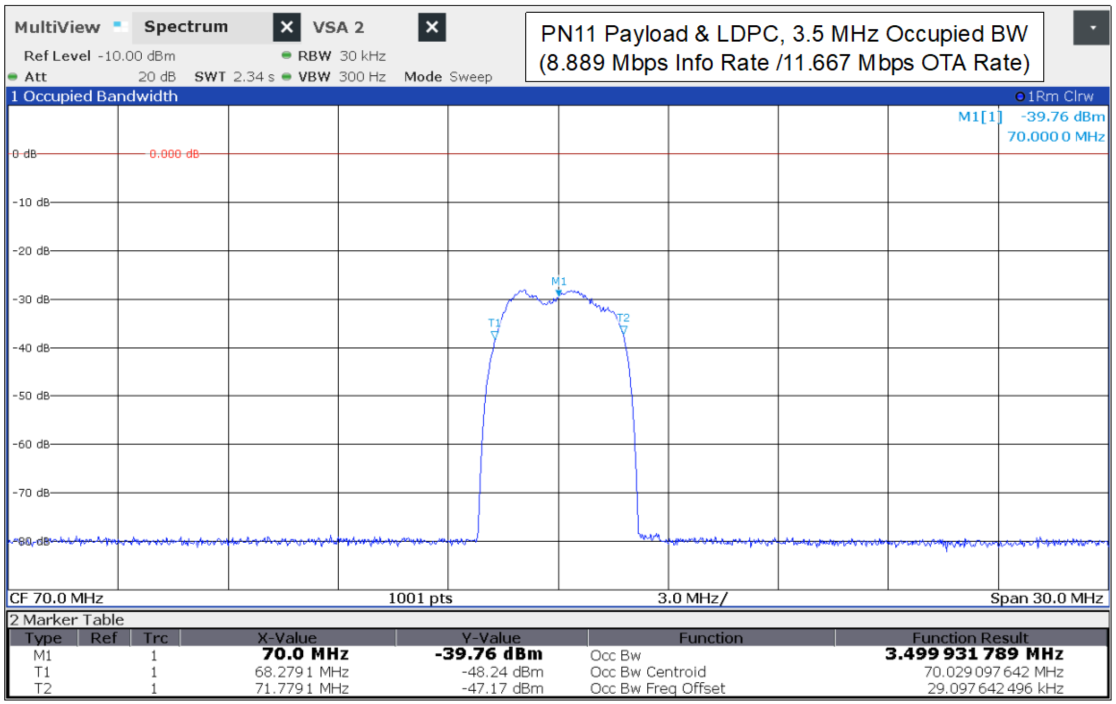
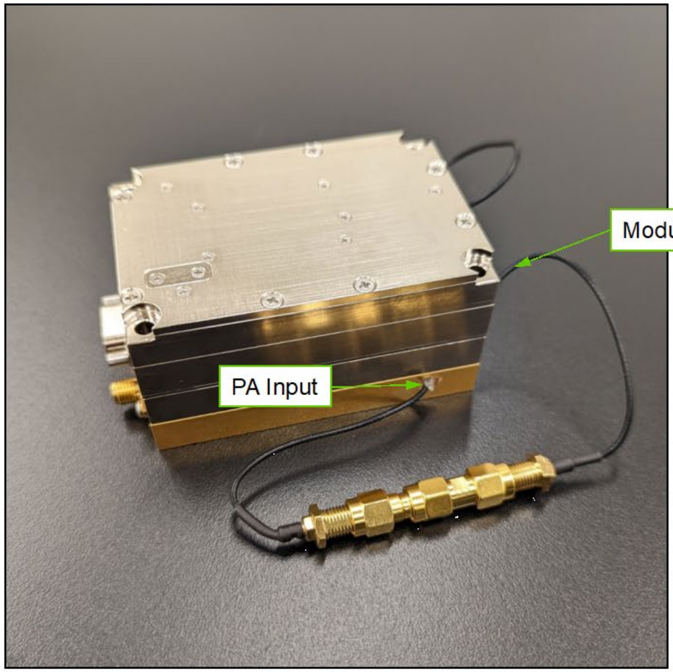
16-APSK Spectrum - Ideal



Vector Signal Generator 70 MHz 16-APSK

16-APSK Transmitter



Prototype C-Band 16-APSK Transmitter

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16-APSK TX Output

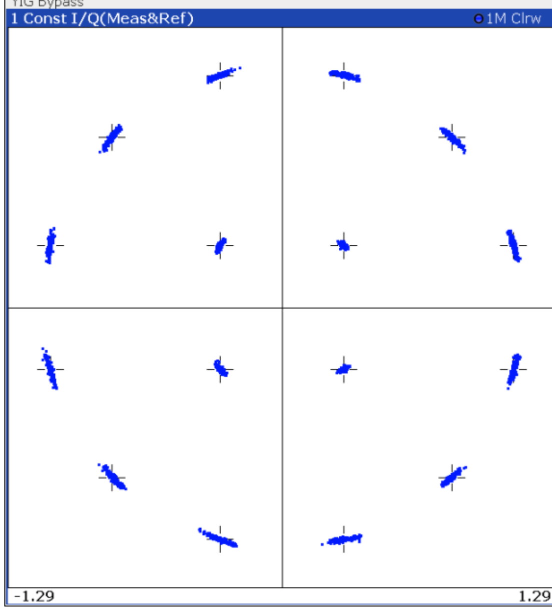
MultiView | Spectrum | VSA 2

Ref Level -20.00 dBm | Capture Length 8000 | Modulation 16APSK | Result Length 3000

Att 20 dB | Freq 4.78 GHz | Symbol Rate 2.916666 MHz | Tx Filter User

YIG Bypass

1 Const I/Q(Meas&Ref) 1M Clrw



2 Result Summary

		Current	Peak	Unit
EVM	RMS	3.02	3.98	%
	Peak	10.70	42.91	%
MER	RMS	30.40	28.01	dB
	Peak	19.41	7.35	dB
Phase Error	RMS	1.73	2.27	deg
	Peak	-5.91	22.09	deg
Magnitude Error	RMS	0.64	0.69	%
	Peak	3.19	3.37	%
Carrier Frequency Error		-835.89	-846.46	Hz
Symbol Rate Error		-99.79	-101.41	ppm
I/Q Skew		---	---	ps
Rho		0.999 083	0.998 418	
I/Q Offset		-18.50	-18.40	dB
I/Q Imbalance		-31.36	-31.22	dB
Gain Imbalance		0.20	0.22	dB
Quadrature Error		2.81	2.85	deg
Amplitude Droop		0.000 002	0.000 006	dB/sym
Power		-3.05	-3.03	dBm

PN11 Payload & LDPC, 3.5 MHz Occupied BW
(8.889 Mbps Info Rate /11.667 Mbps OTA Rate)

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

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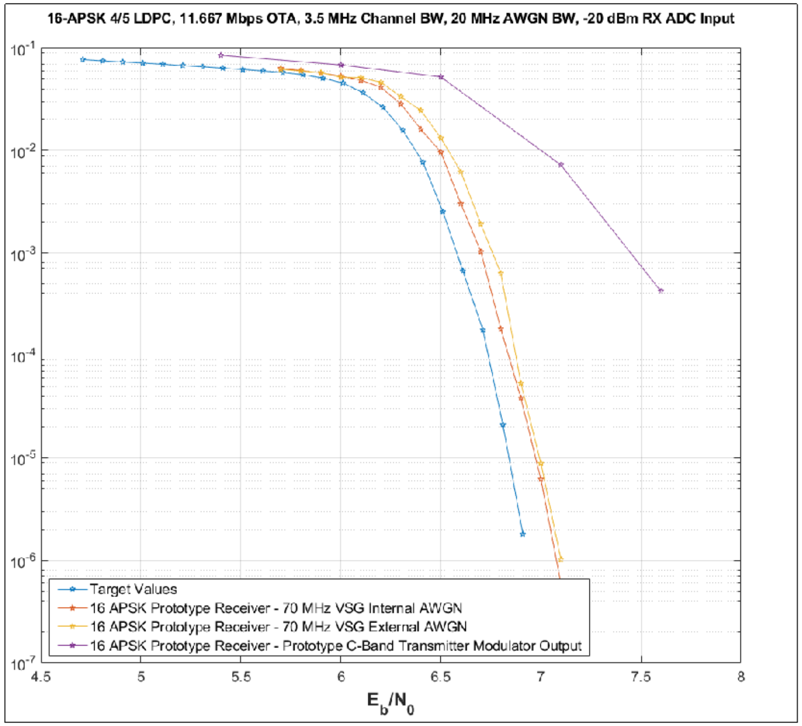
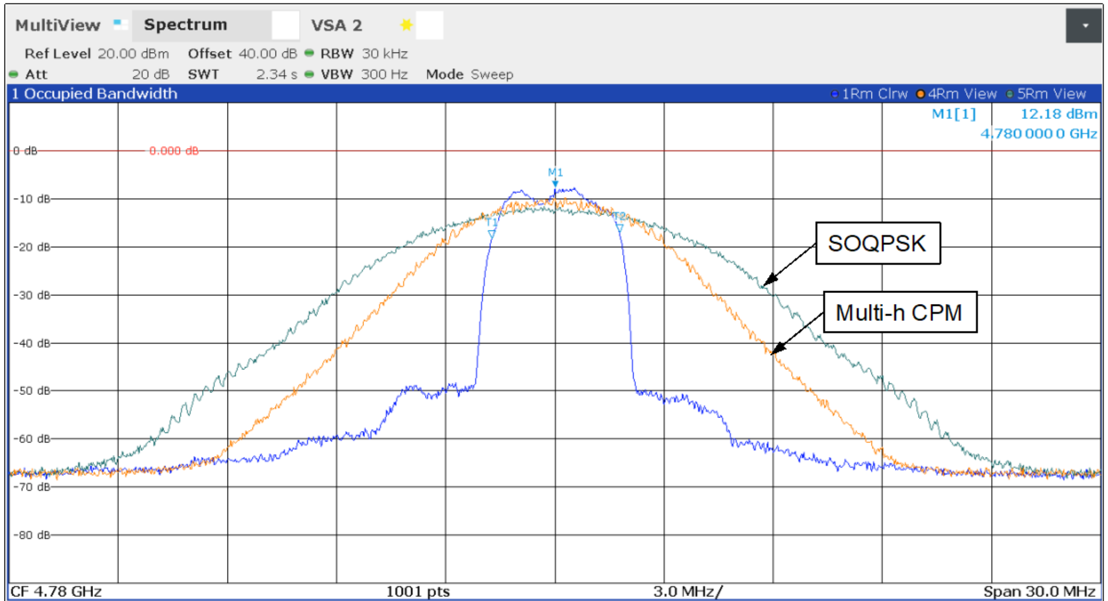
16-APSK BER



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

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



Type	Ref	Trc	X-Value	Y-Value	Function	Function Result
M1		1	**4.78 GHz**	**12.18 dBm**	Occ Bw	**3.507 027 962 MHz**
T1		1	4.778 273 3 GHz	1.71 dBm	Occ Bw Centroid	4.780 026 83 GHz
T2		1	4.781 780 3 GHz	3.02 dBm	Occ Bw Freq Offset	26.830 058 611 kHz

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

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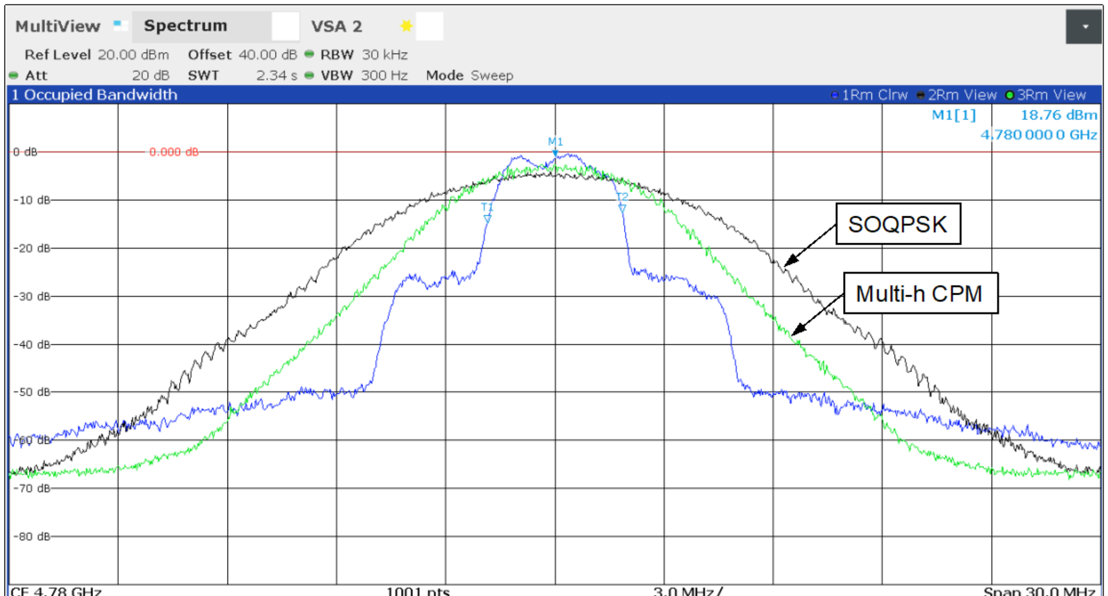
16-APSK Spectrum @ 6 Watts



2 Marker Table

Type	Ref	Trc	X-Value	Y-Value	Function	Function Result
M1		1	**4.78 GHz**	**18.76 dBm**	Occ Bw	**3.702 259 579 MHz**
T1		1	4.778 156 GHz	5.13 dBm	Occ Bw Centroid	4.780 007 118 GHz
T2		1	4.781 858 2 GHz	7.24 dBm	Occ Bw Freq Offset	7.117 768 15 kHz

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

Demodulation

Demodulation

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

Single-Symbol Demodulation

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

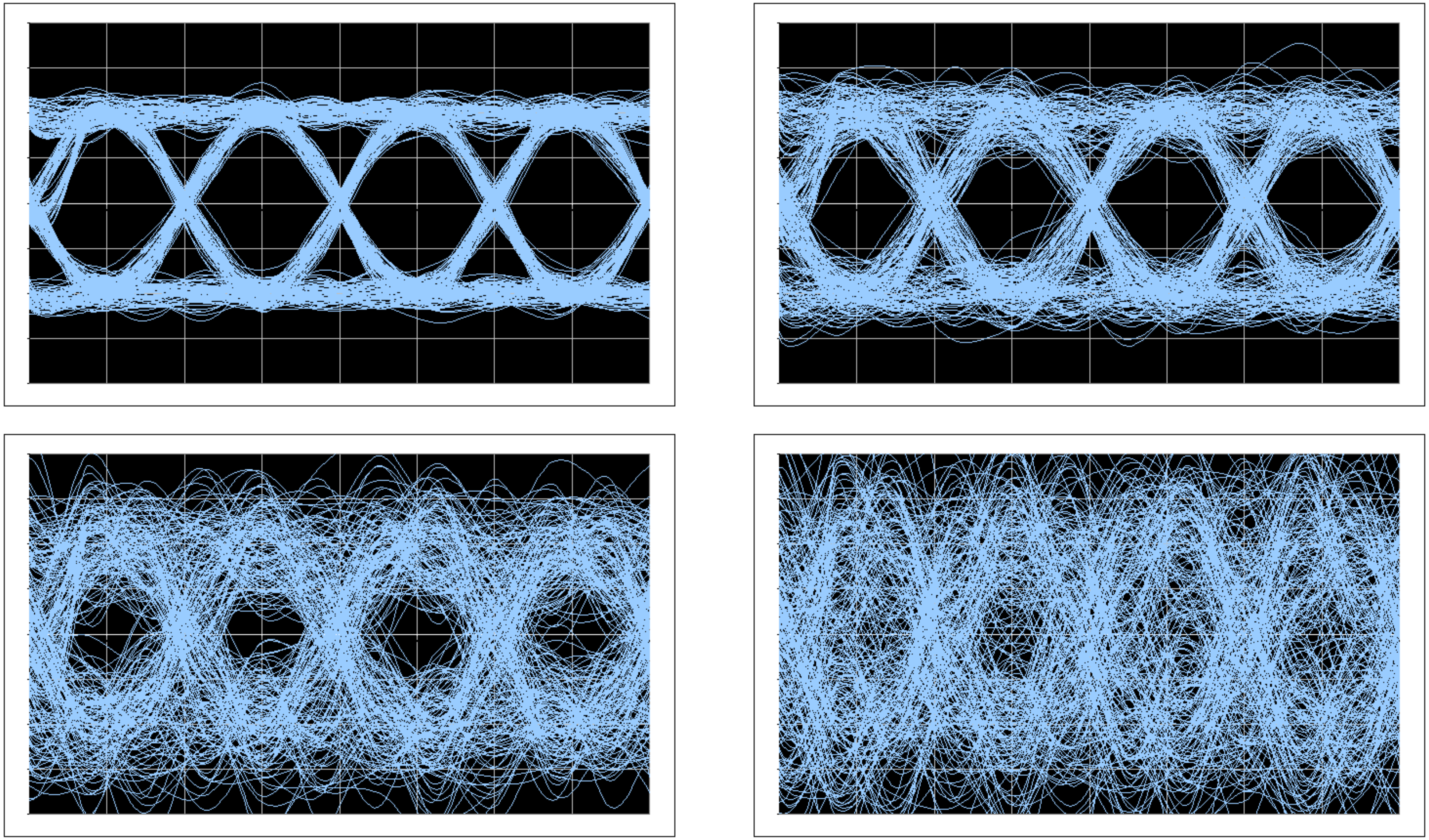
Tier 0 Single-Symbol Detection

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

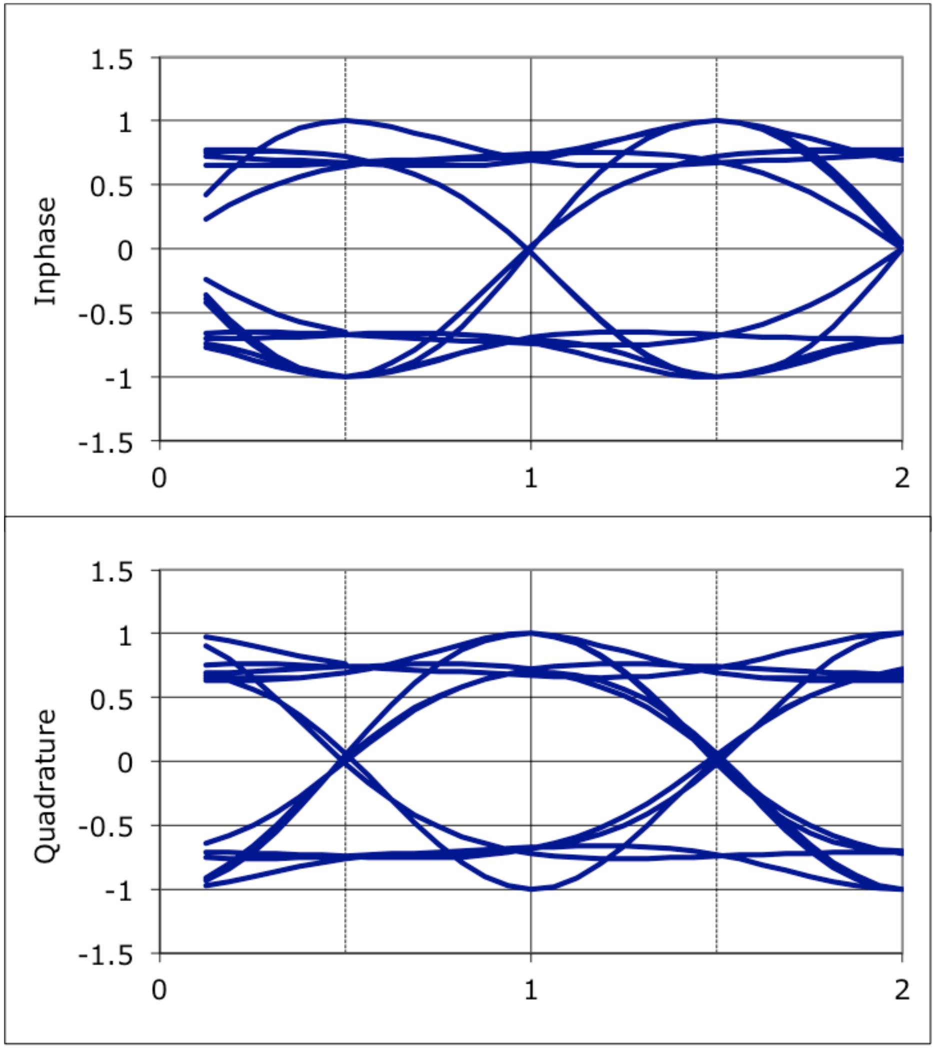
$$\phi(t,\overline{\alpha}) = 2\pi h \int_{-\infty}^{t} \sum_{i=-\infty}^{+\infty} \alpha_i g(\tau - iT)\,d\tau$$

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

Tier 0 Frequency Detection

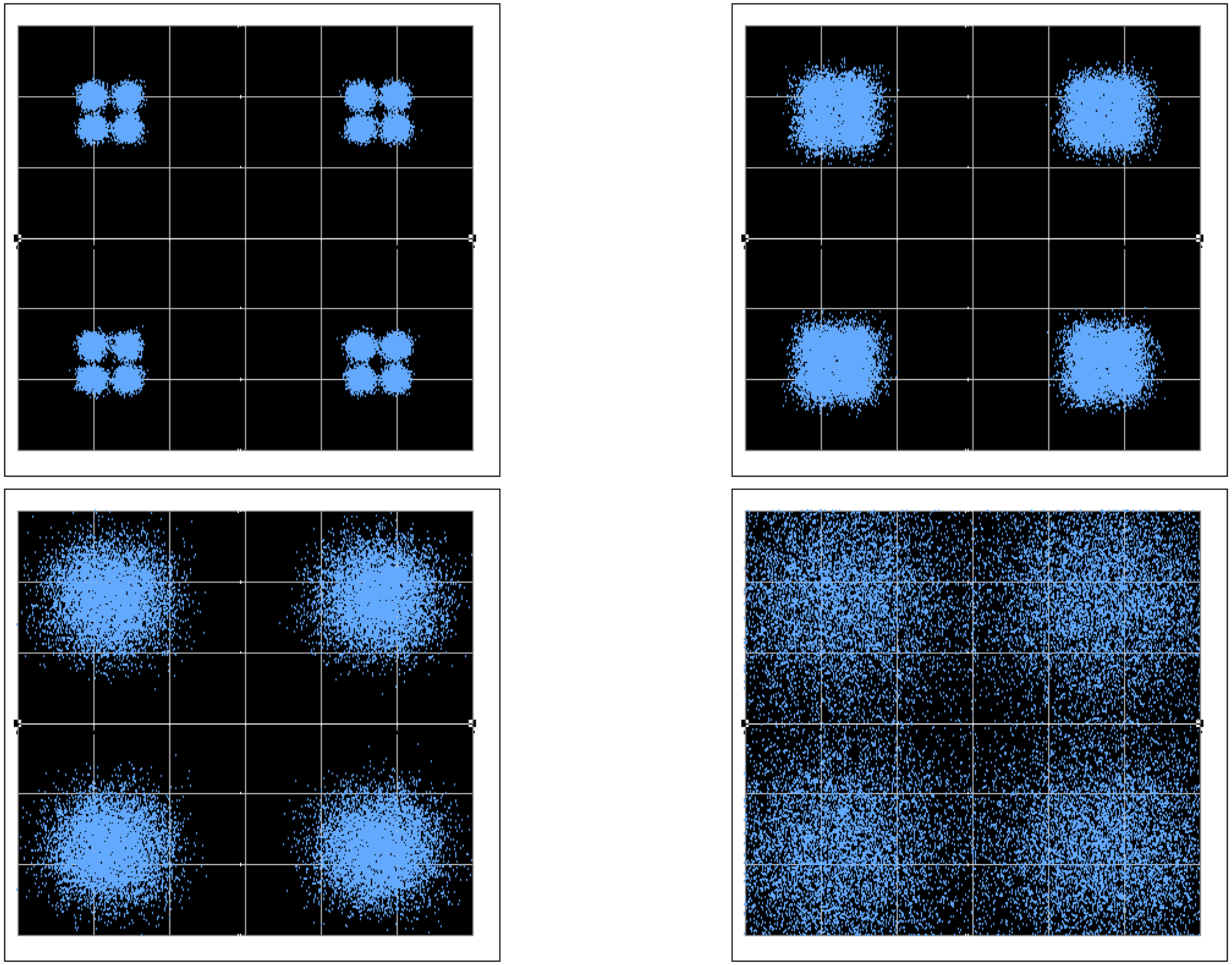


SOQPSK-TG Eye Patterns



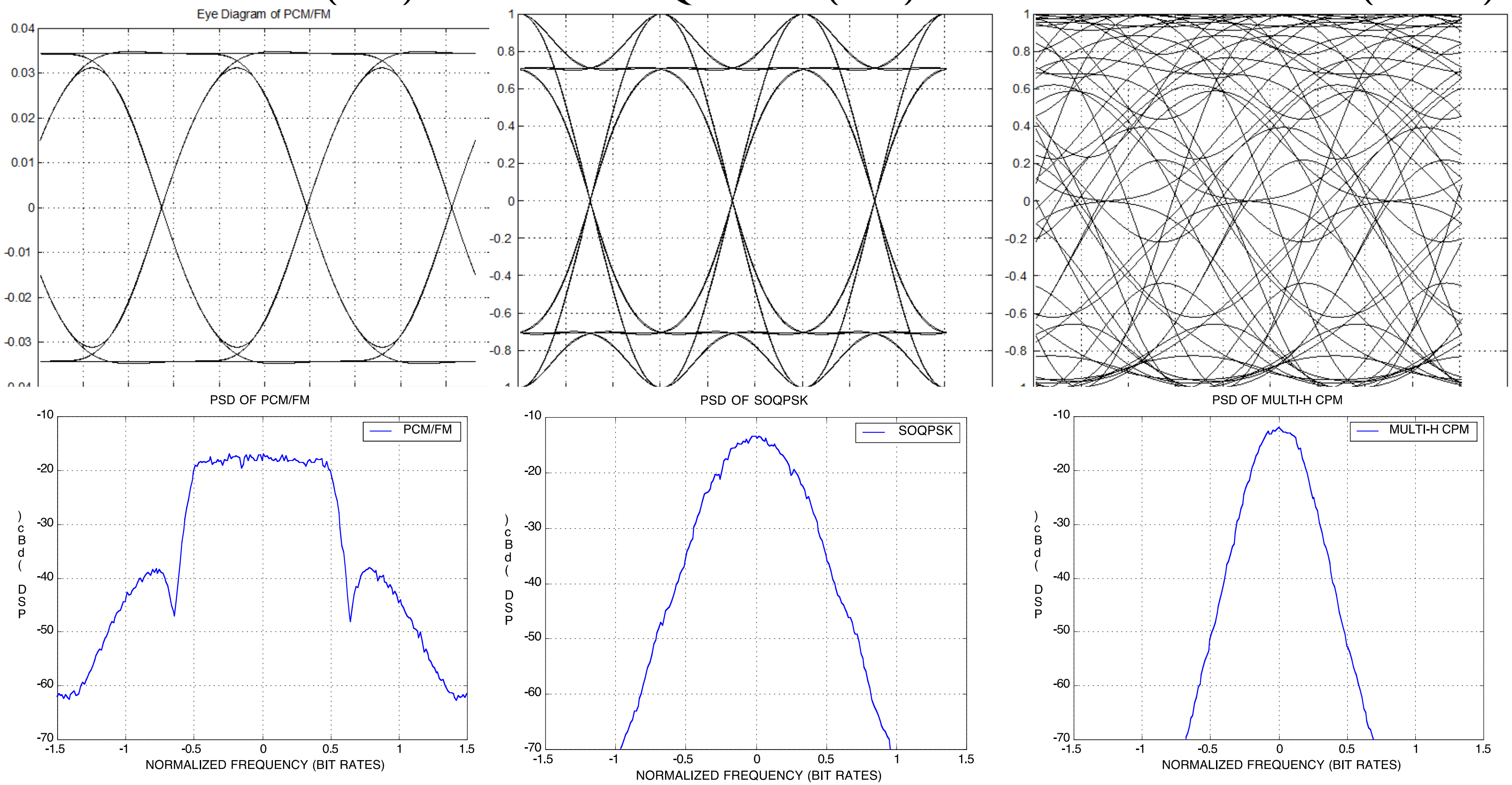
- Single-symbol detection ignores memory inherent in waveform
- Can be detected by conventional (non-shaped) offset QPSK demod
- I&D detector endures additional loss due to waveform mismatch

SOQPSK Constellations



Waveform Comparison

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



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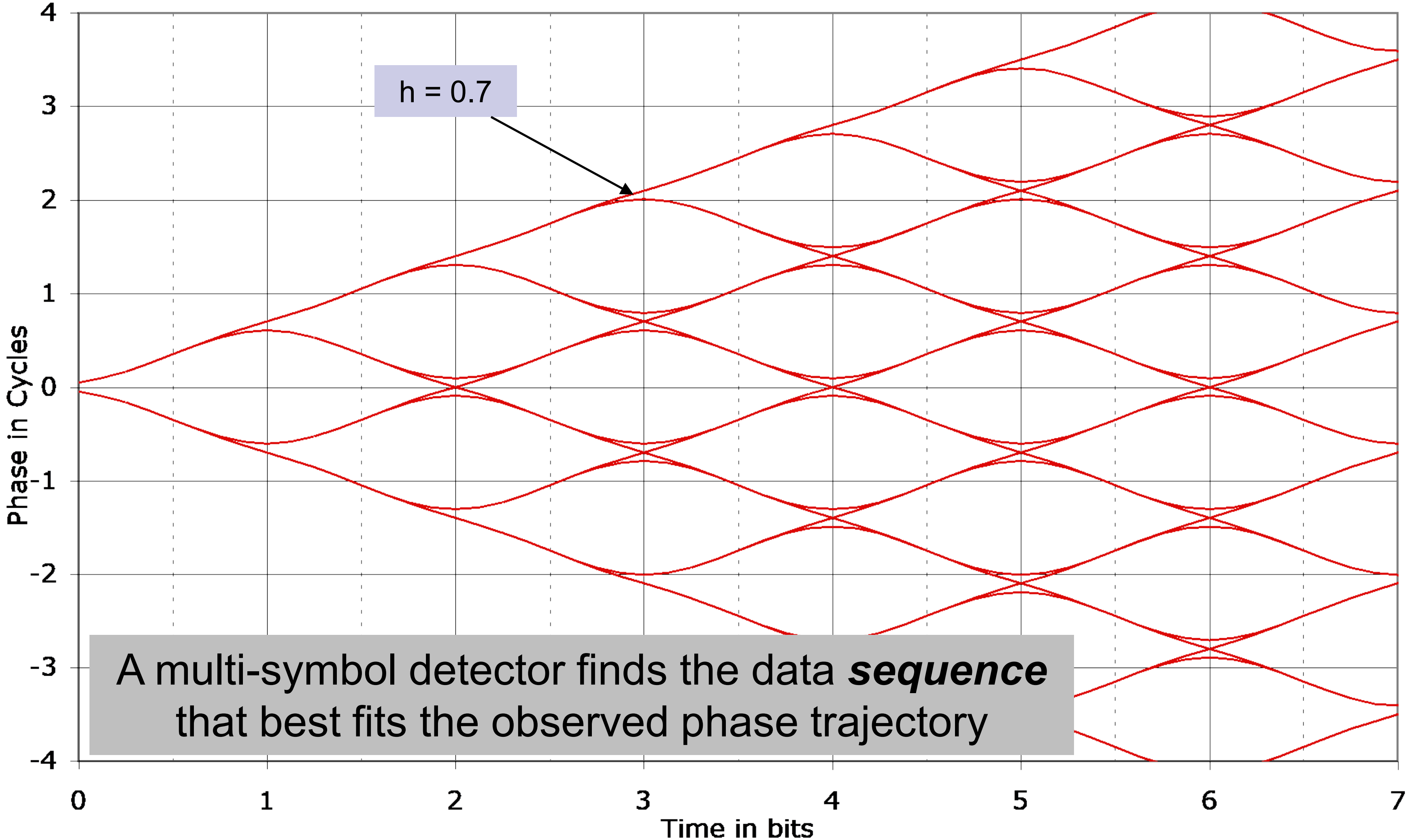
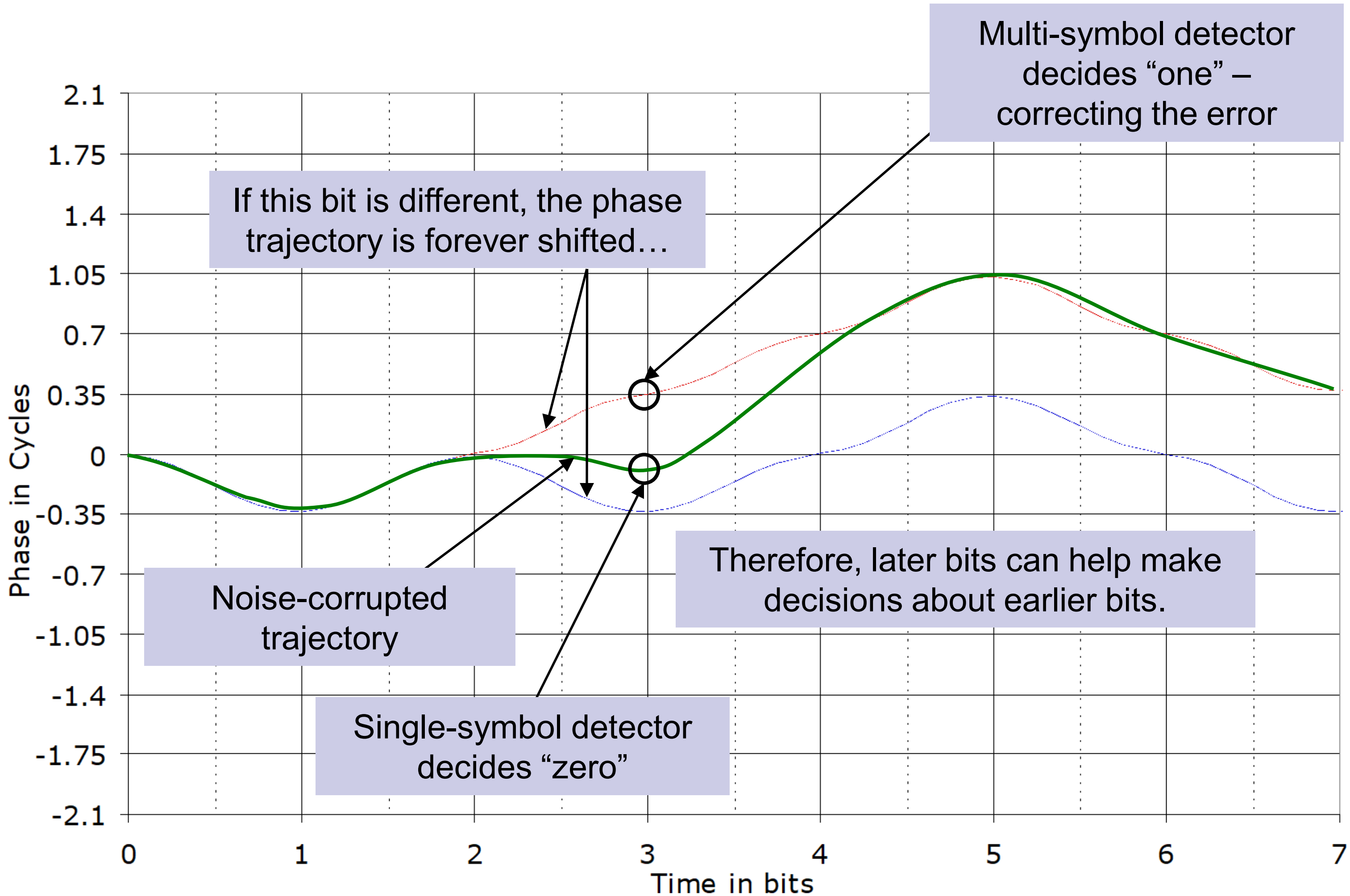
Trellis Demodulation Overview

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

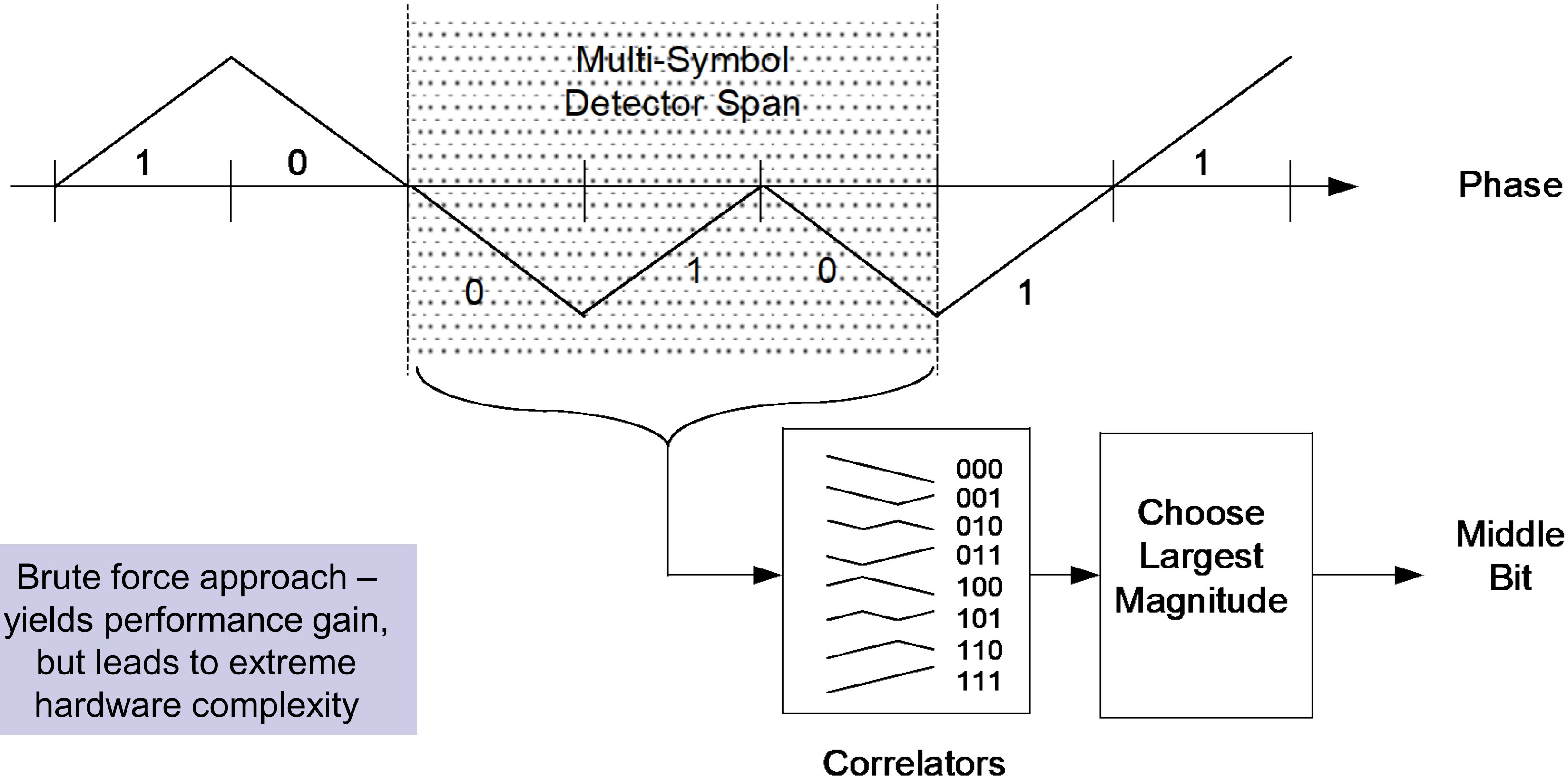
Tier 0 Phase Tree



Why Does It Matter?



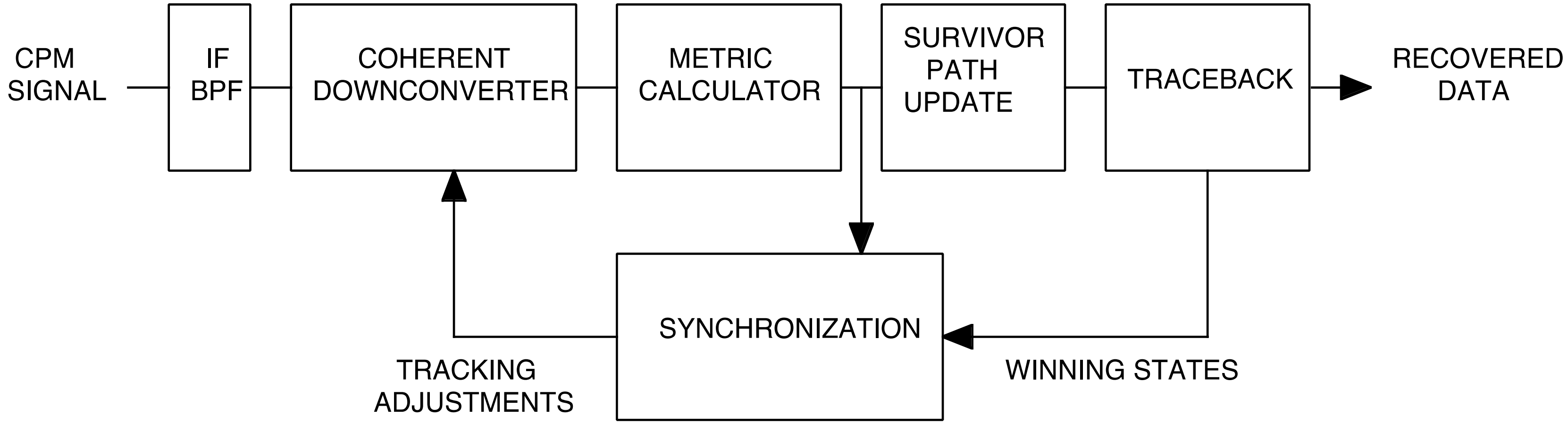
Multi-Symbol Detector Example



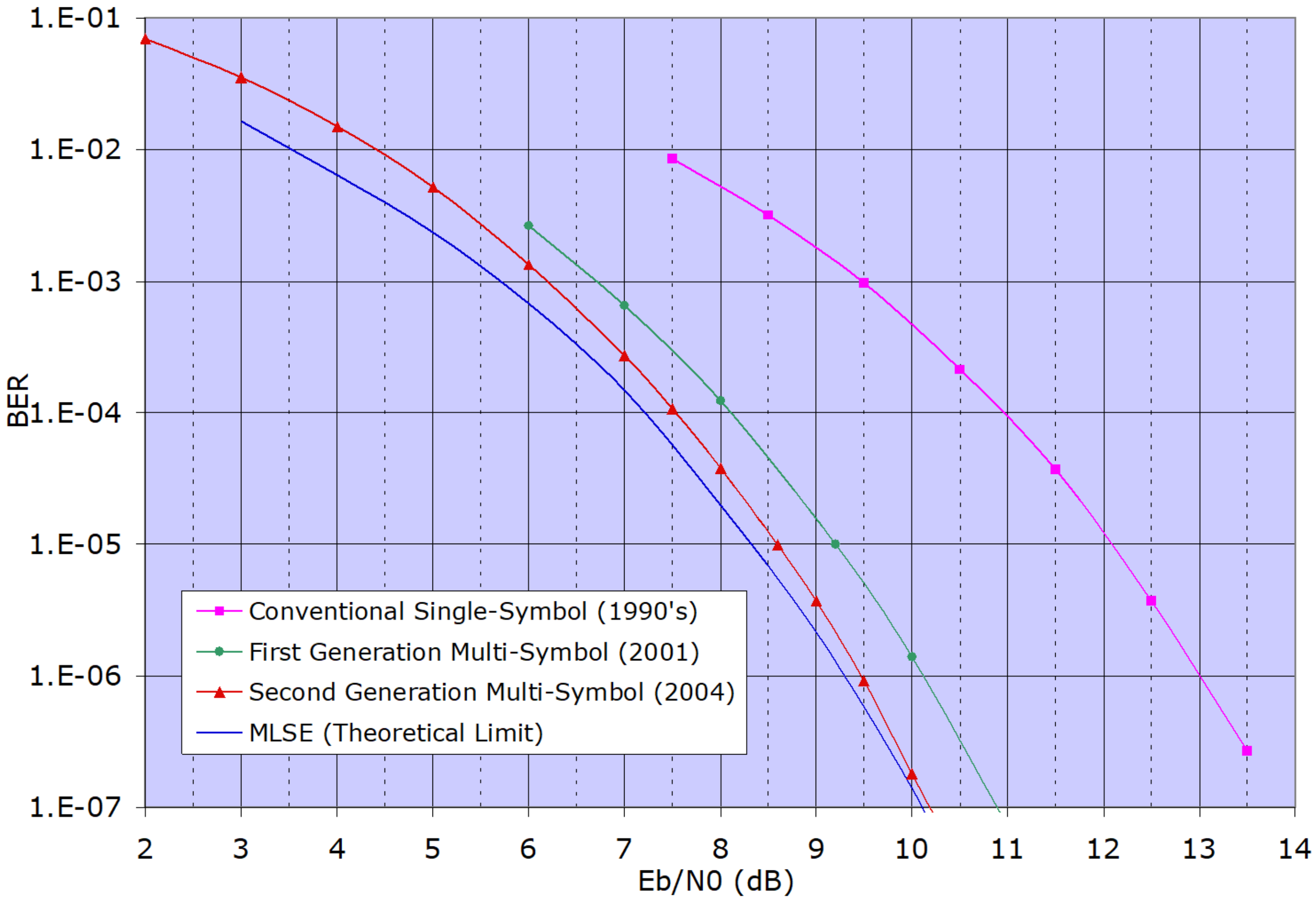
Brute force approach – yields performance gain, but leads to extreme hardware complexity

Generic Trellis Demodulator

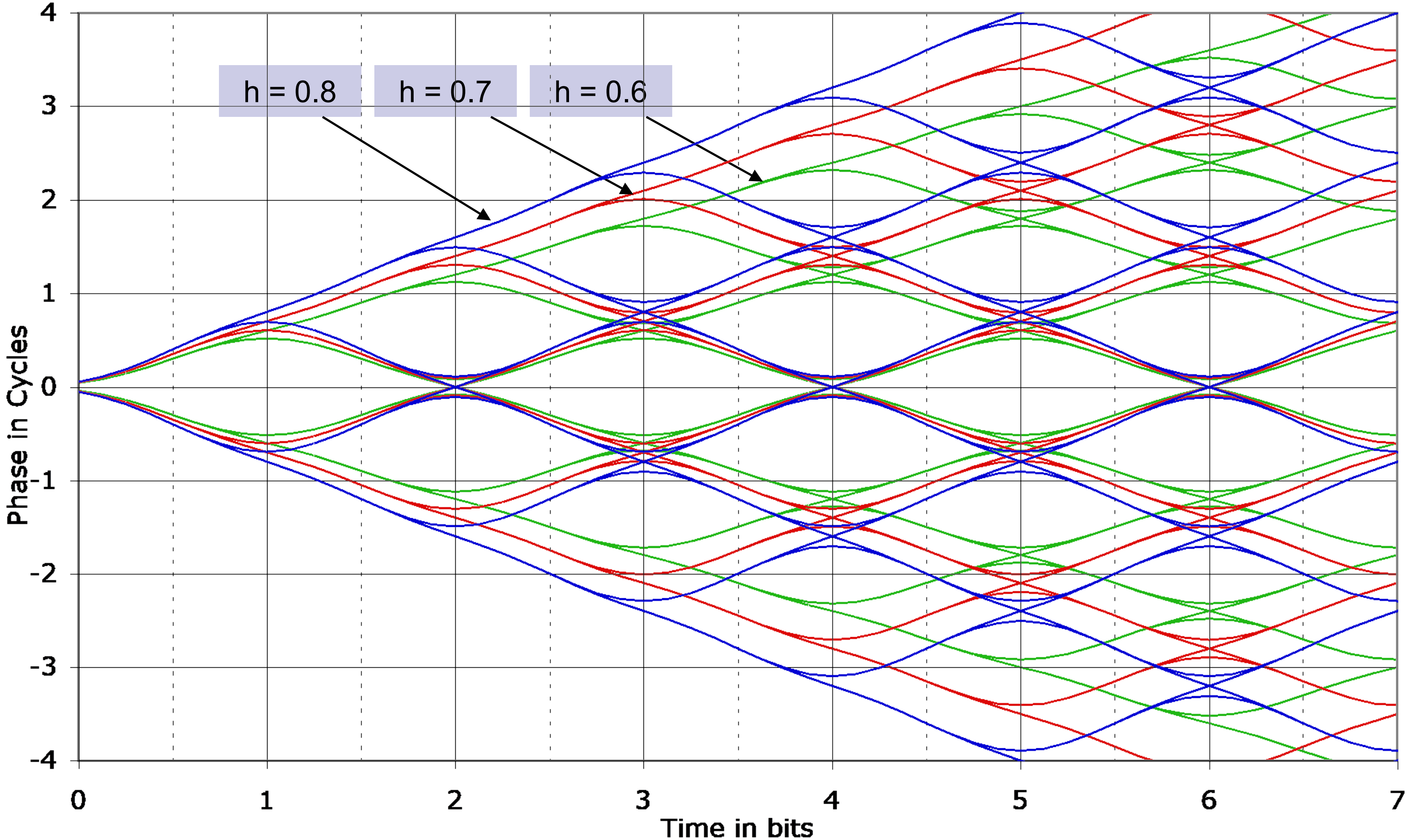
Brains over brawn – Efficient computation yields the same performance as the brute force approach, with far less hardware



Tier 0 BER Performance



Legacy PCM/FM Transmitters



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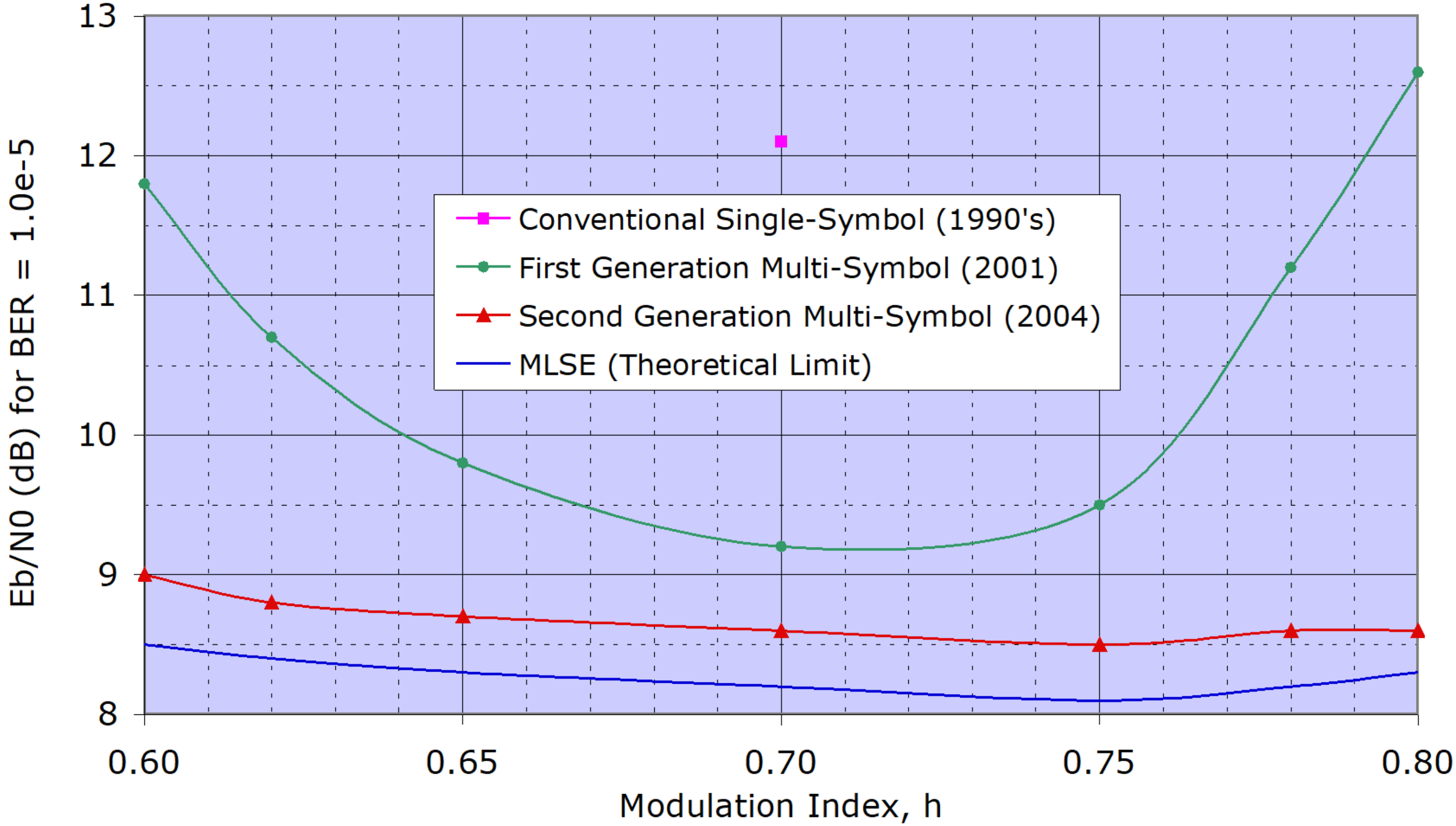
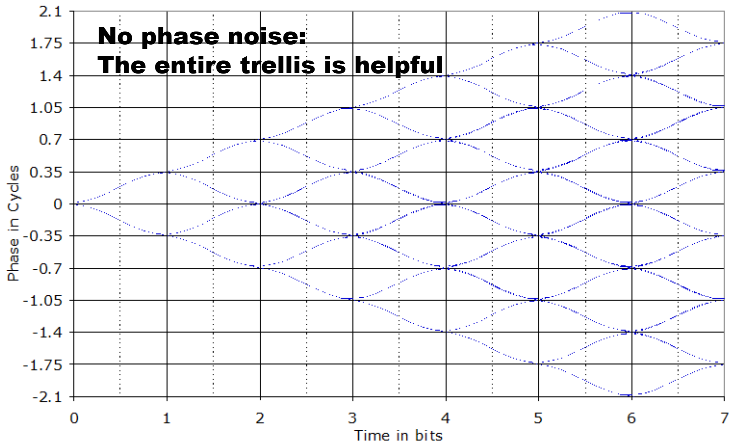
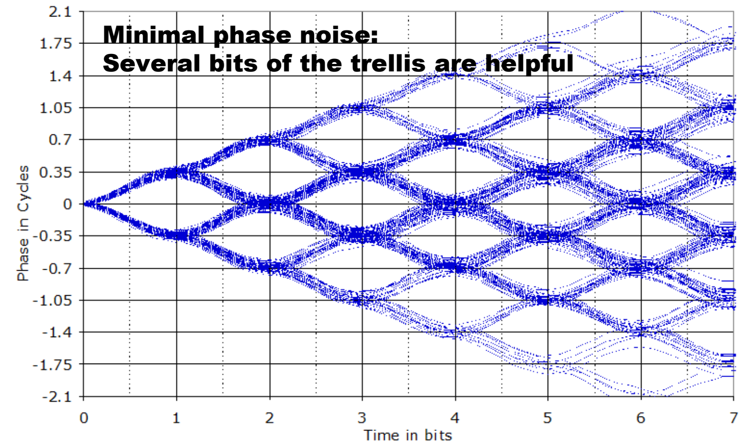
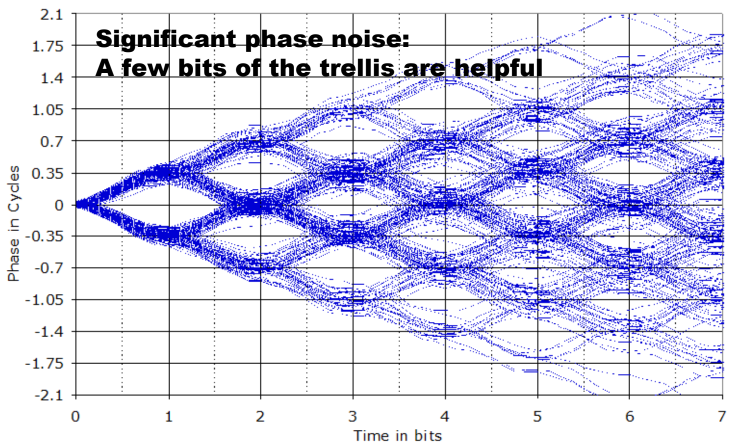
Effect of TX Deviation Error

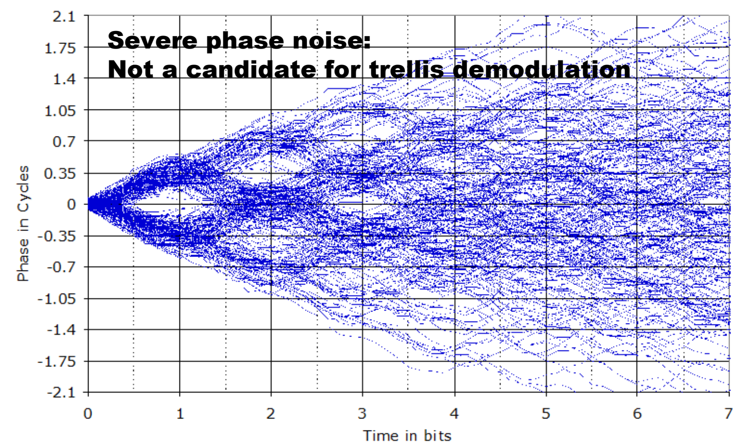


What About Phase Noise?









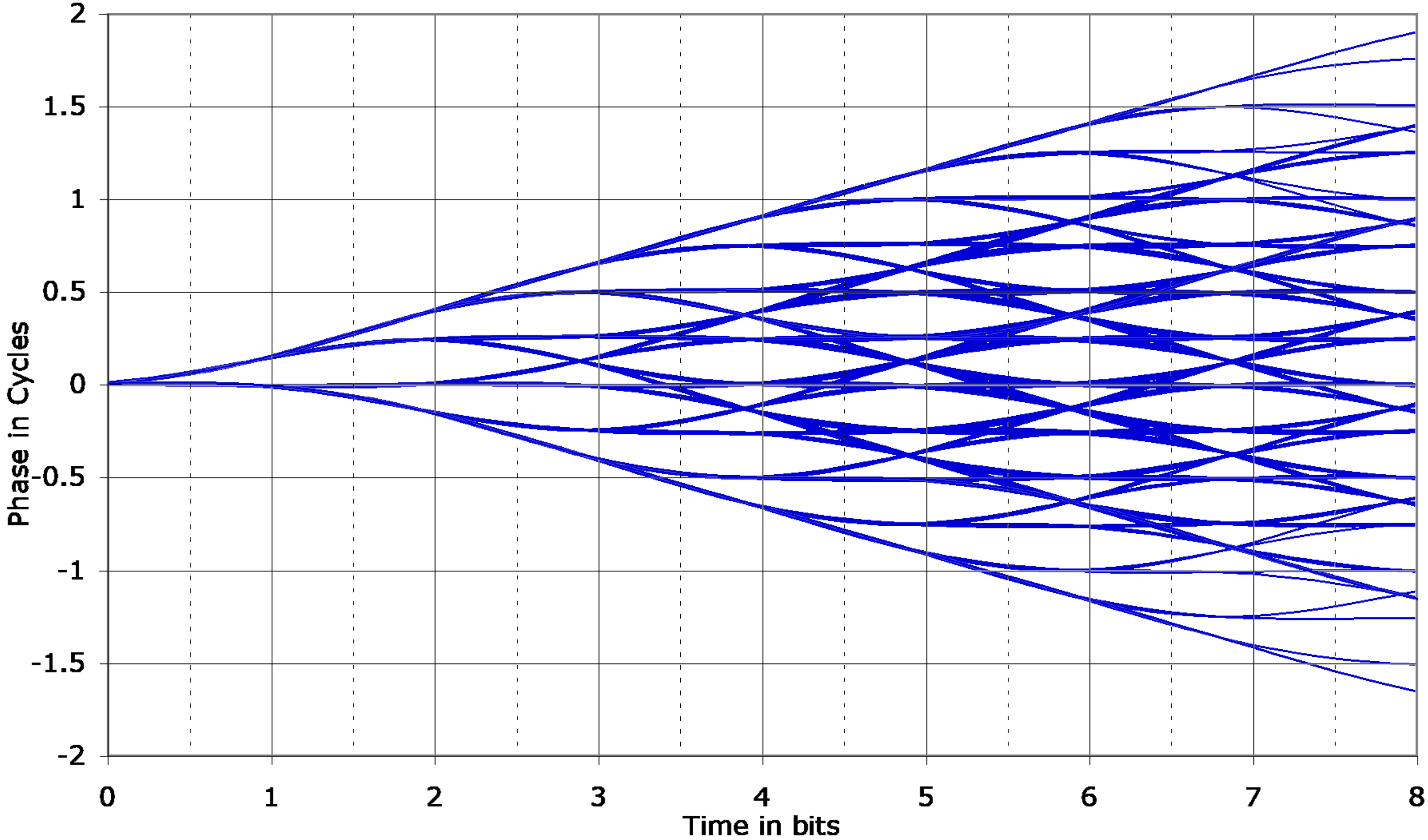
Phase Noise

- 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



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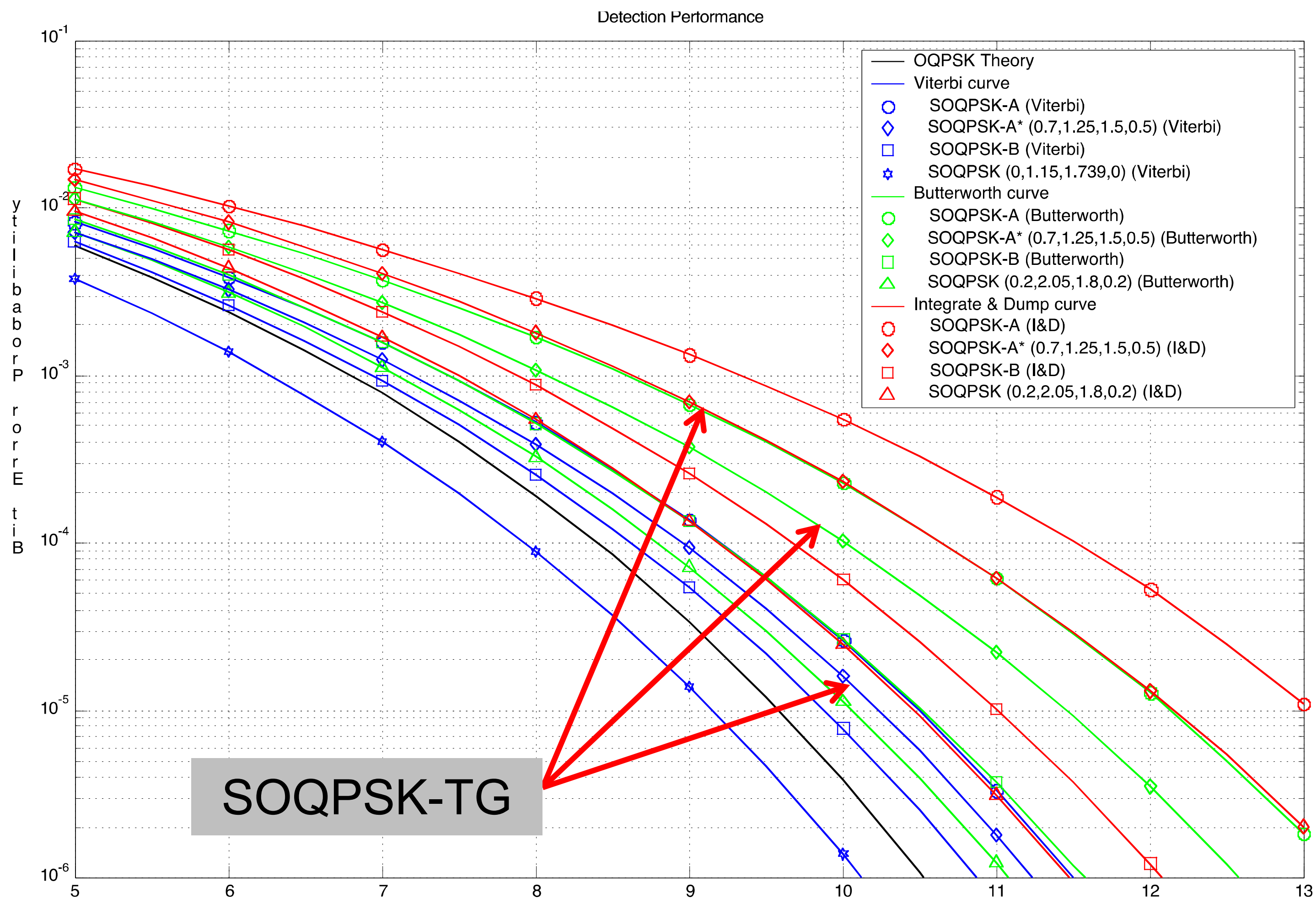
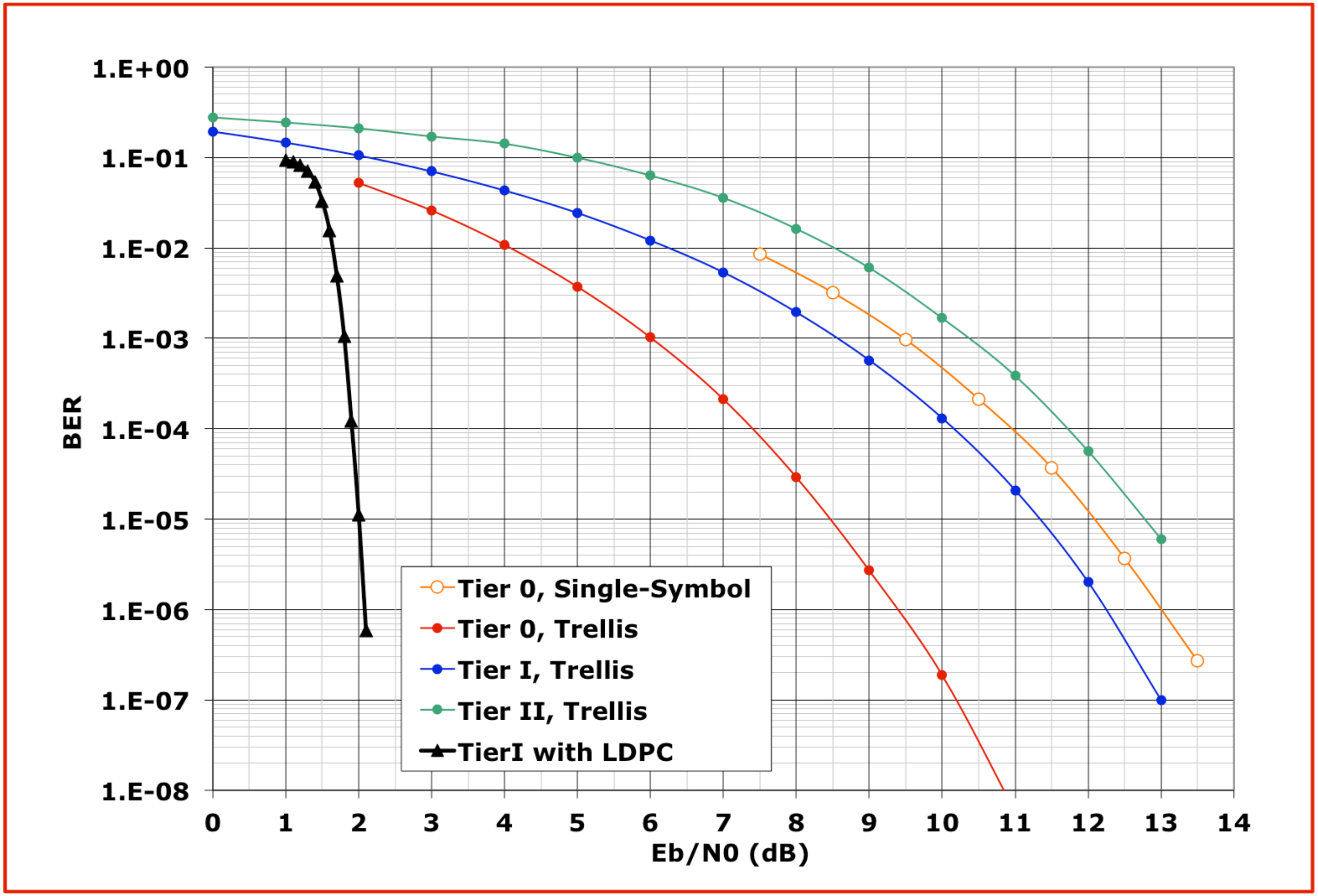
SOQPSK Detection Efficiency



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



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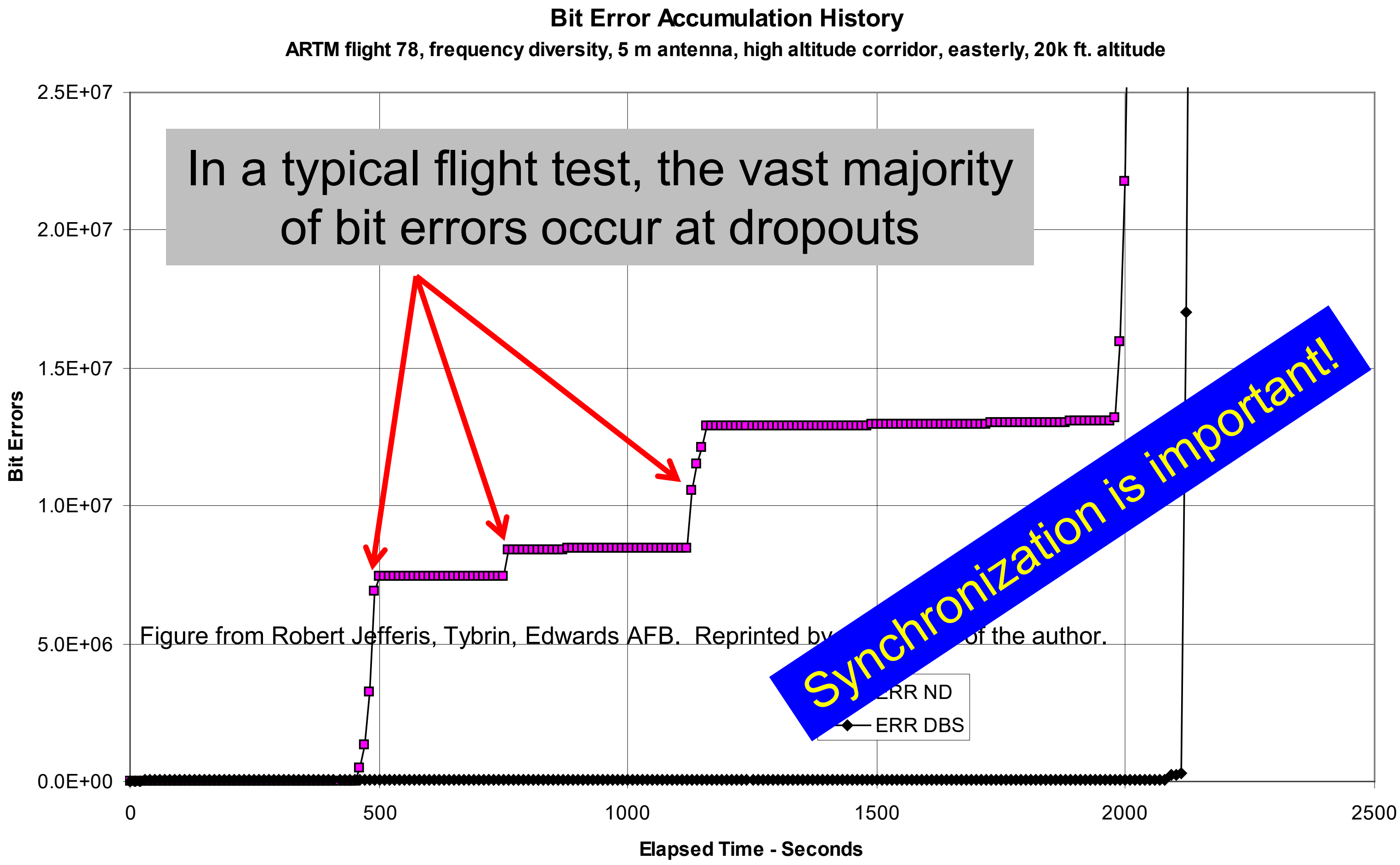
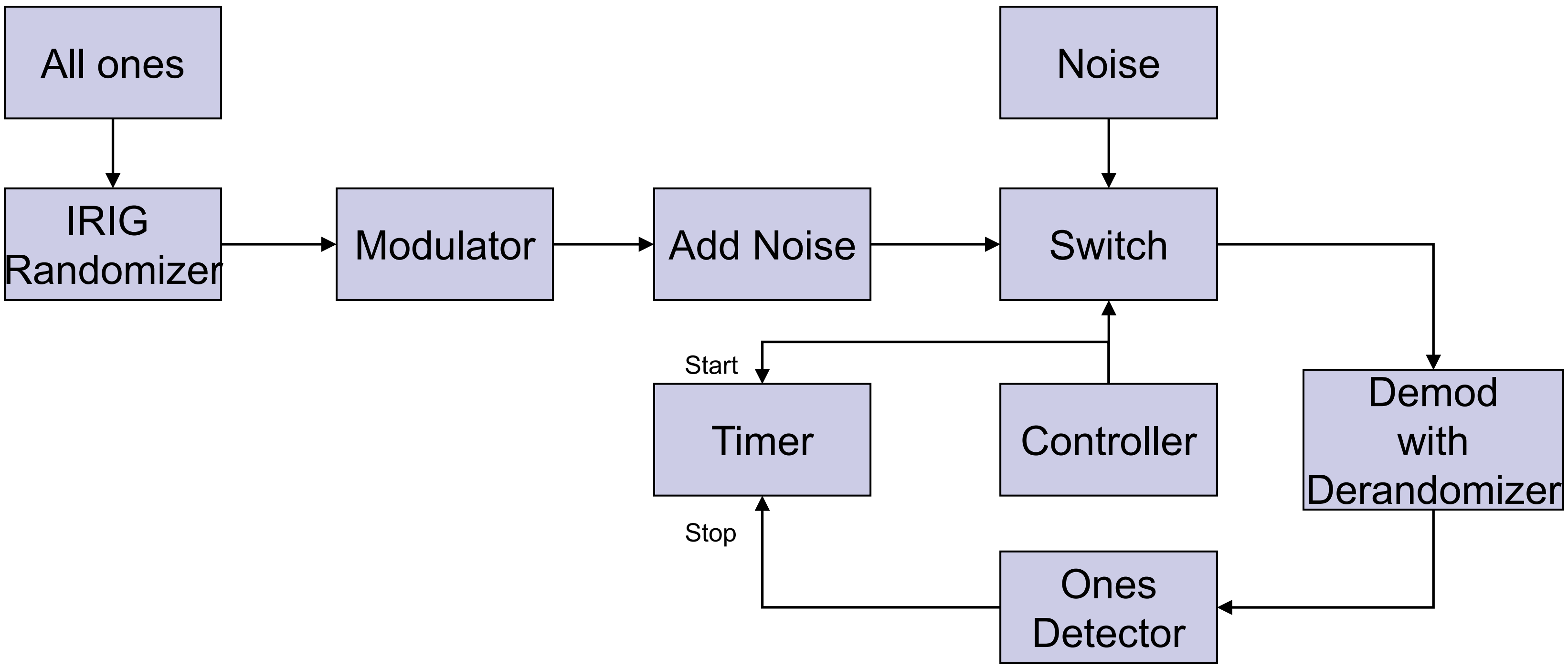
Synchronization

Telemetry Channels are Bursty



Synchronization Test

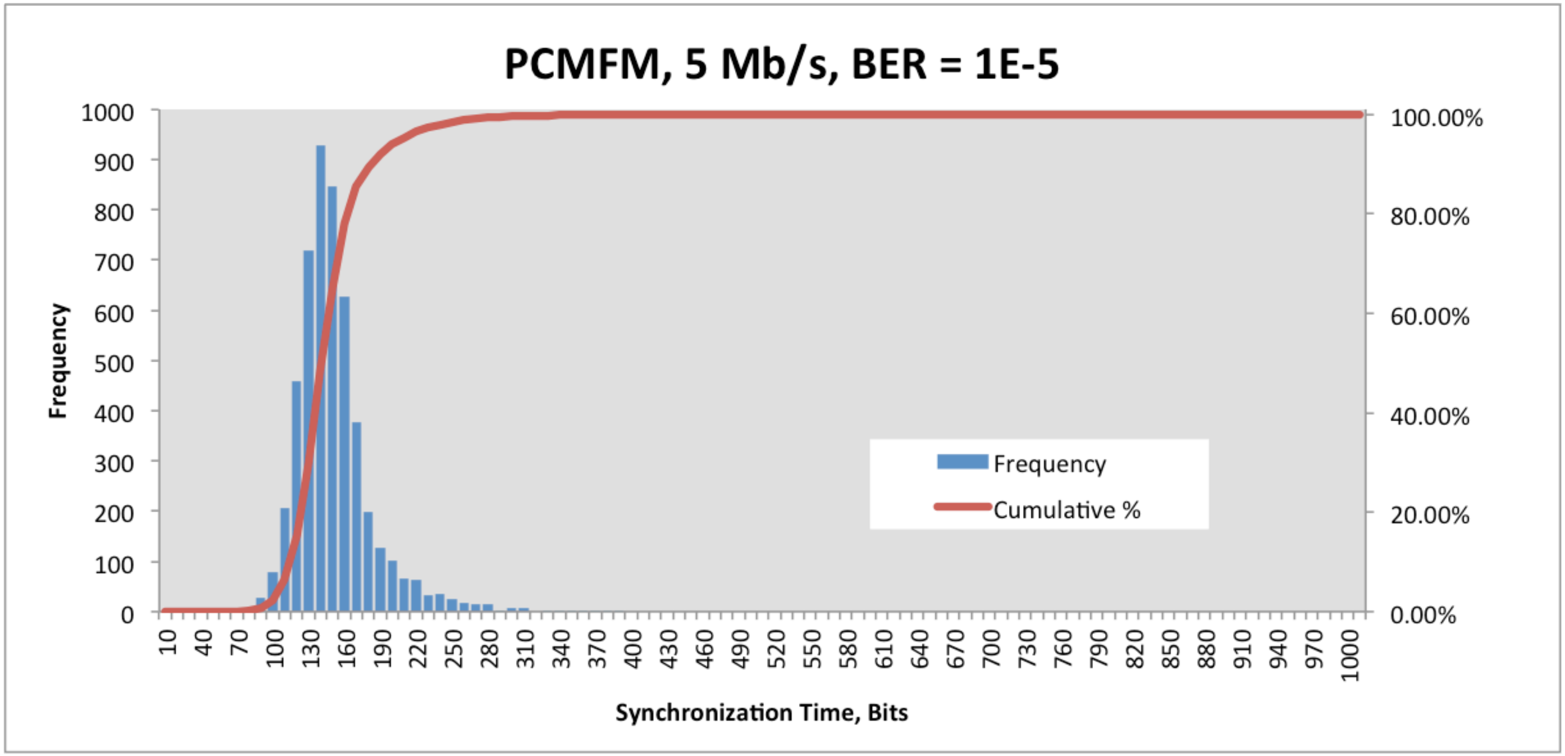
- IRIG 118-12, Procedure 7.4 (Flat Fade Recovery Test)
- Transmit randomized ones pattern
- Measure time at which output becomes “all (or mostly) ones”



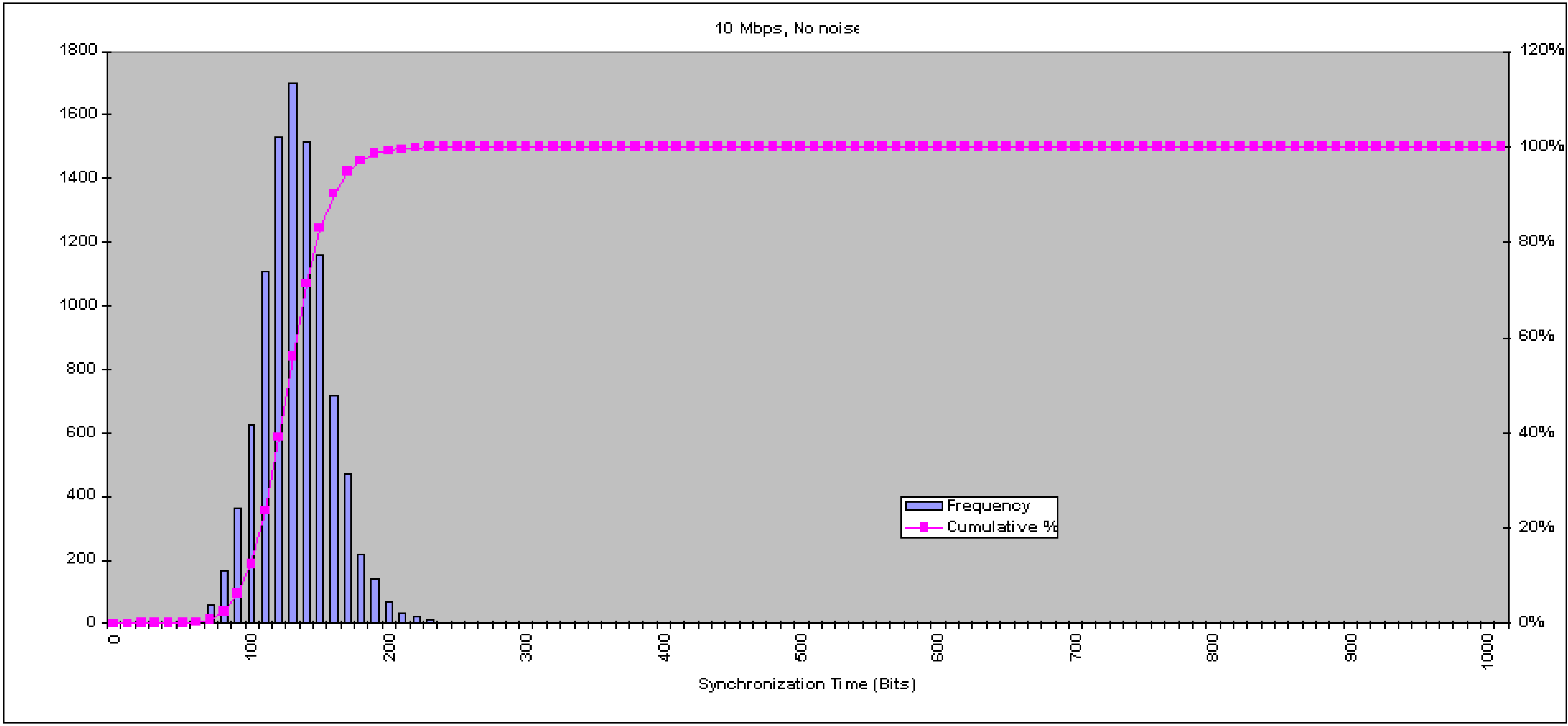
Synchronization Parameters

- 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



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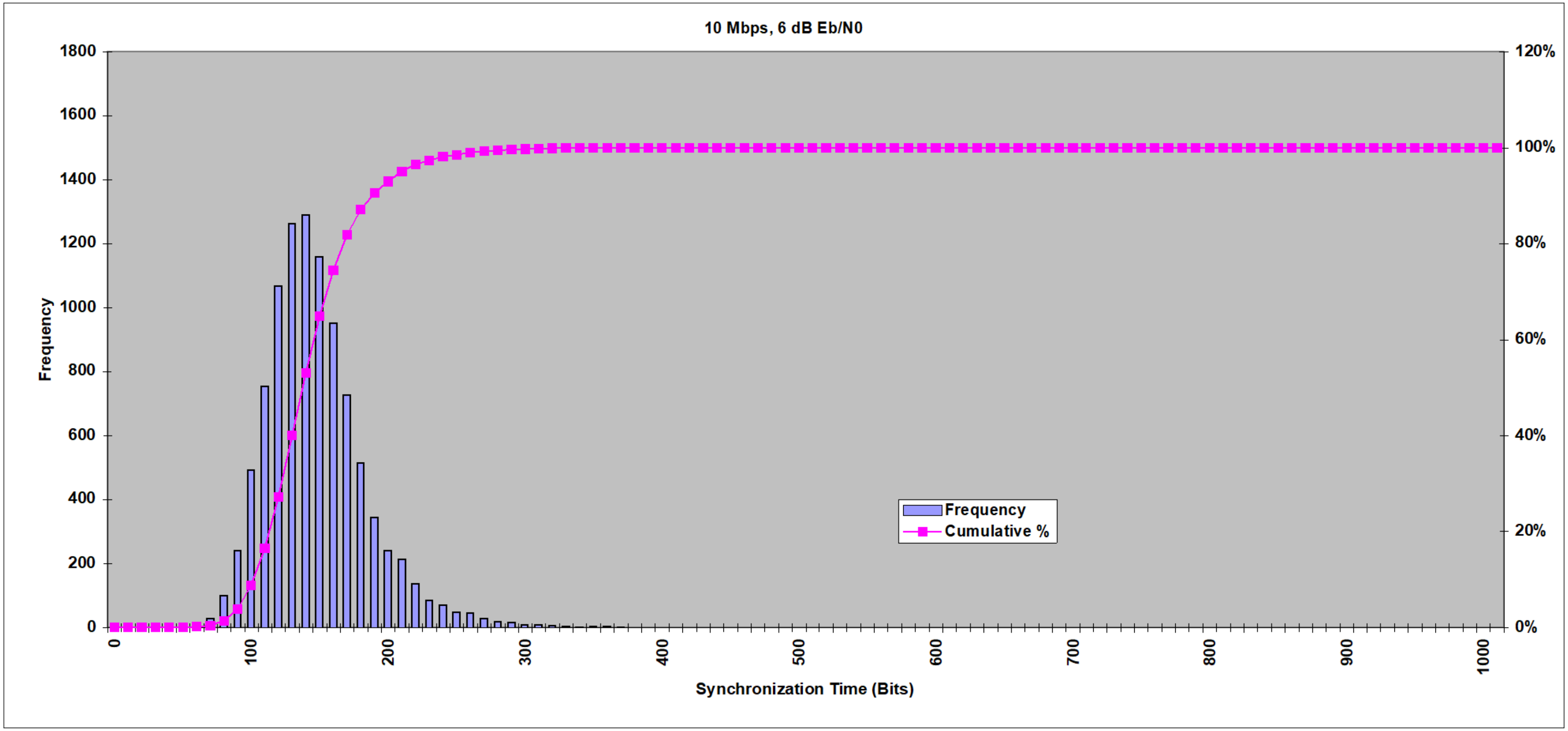
SOQPSK Synchronization, 6 dB



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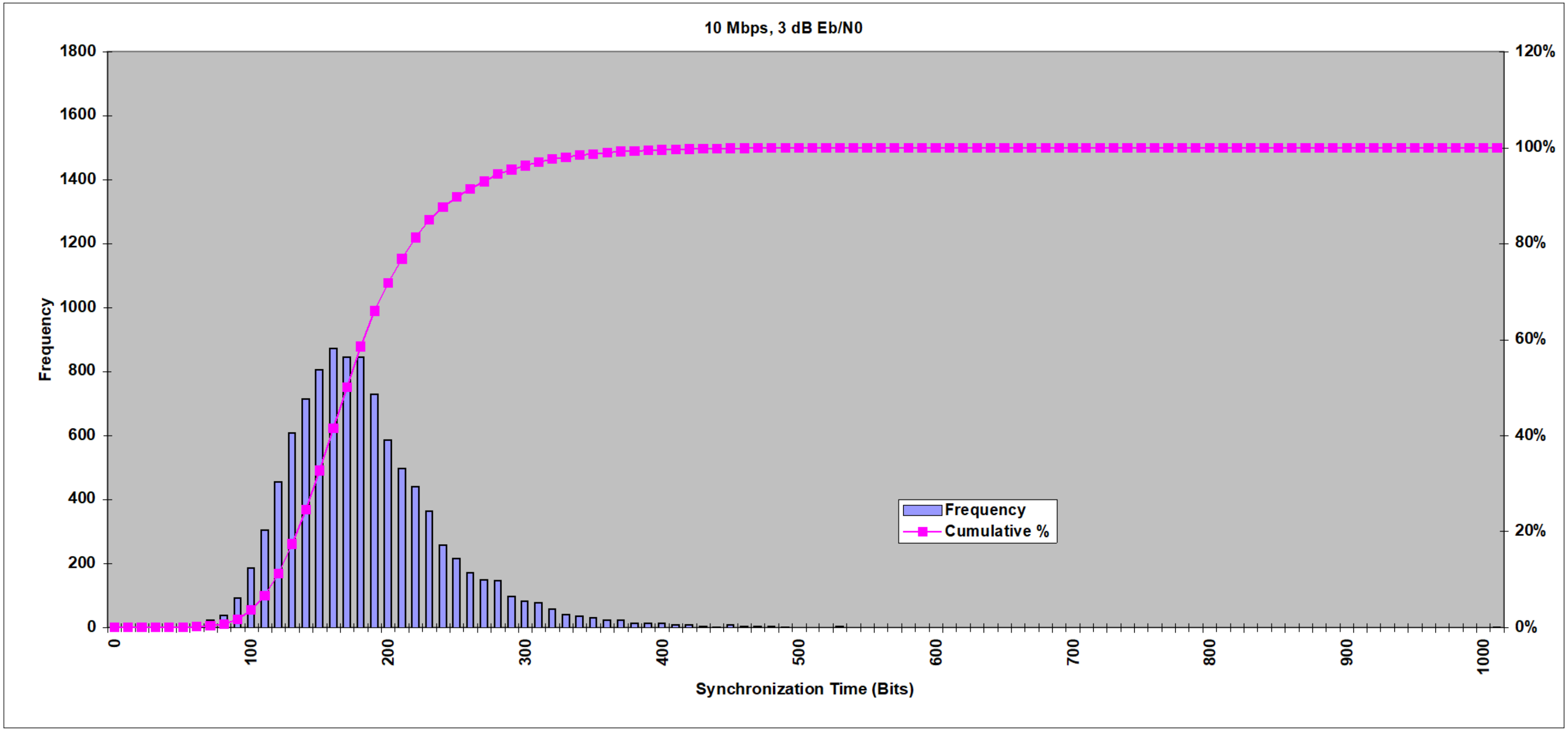
SOQPSK Synchronization, 3 dB



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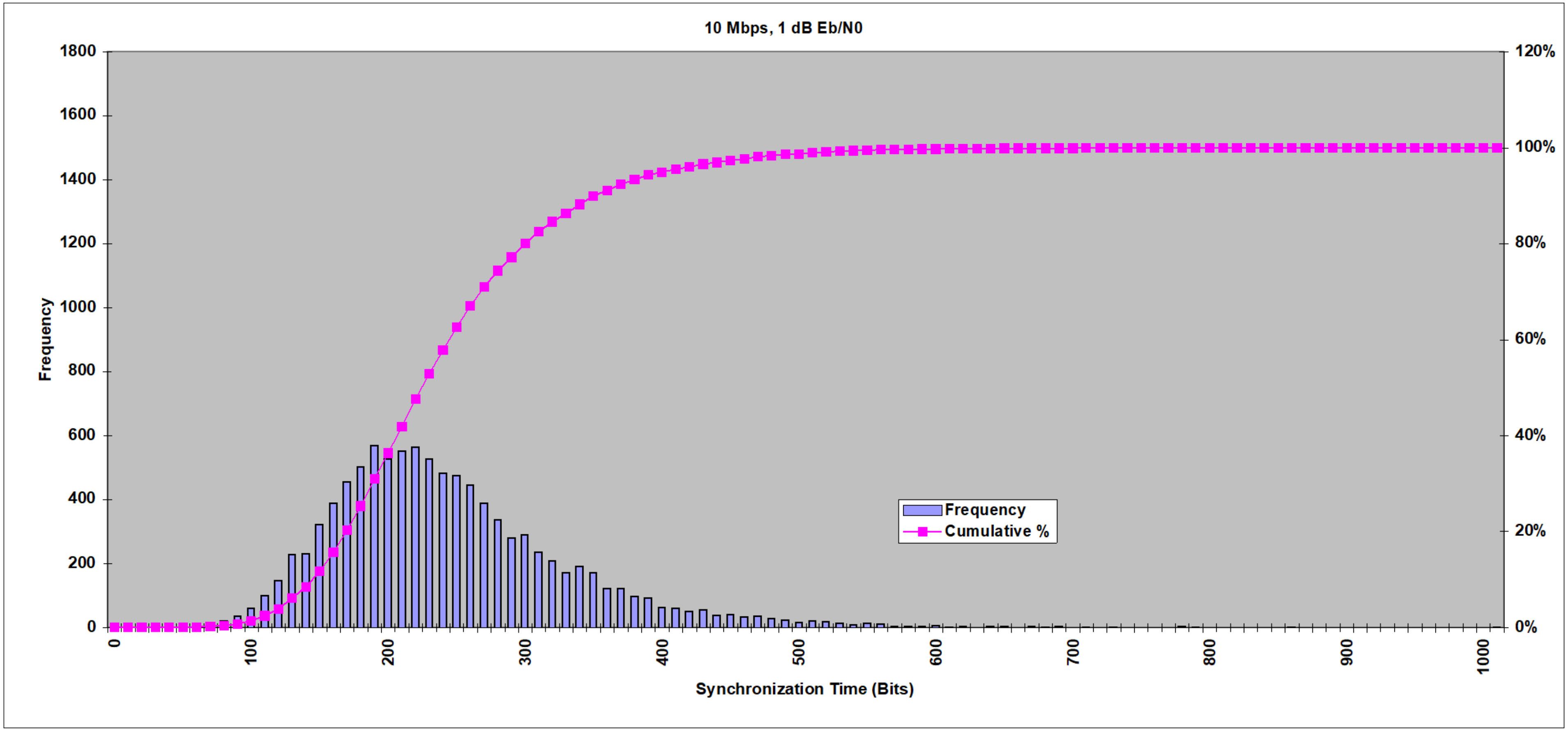
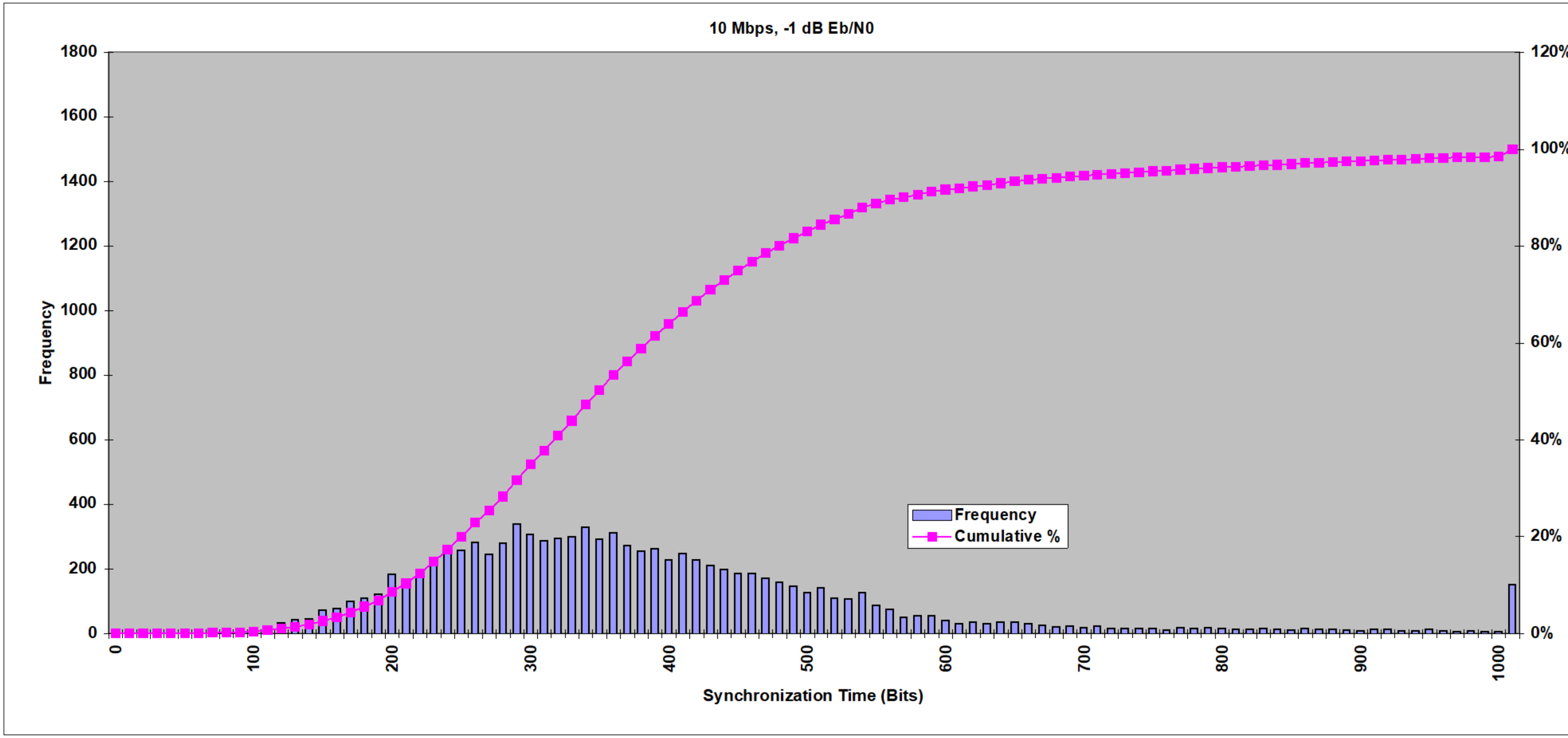
SOQPSK Synchronization, 1 dB



SOQPSK Synchronization, -1 dB



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Synchronization Summary

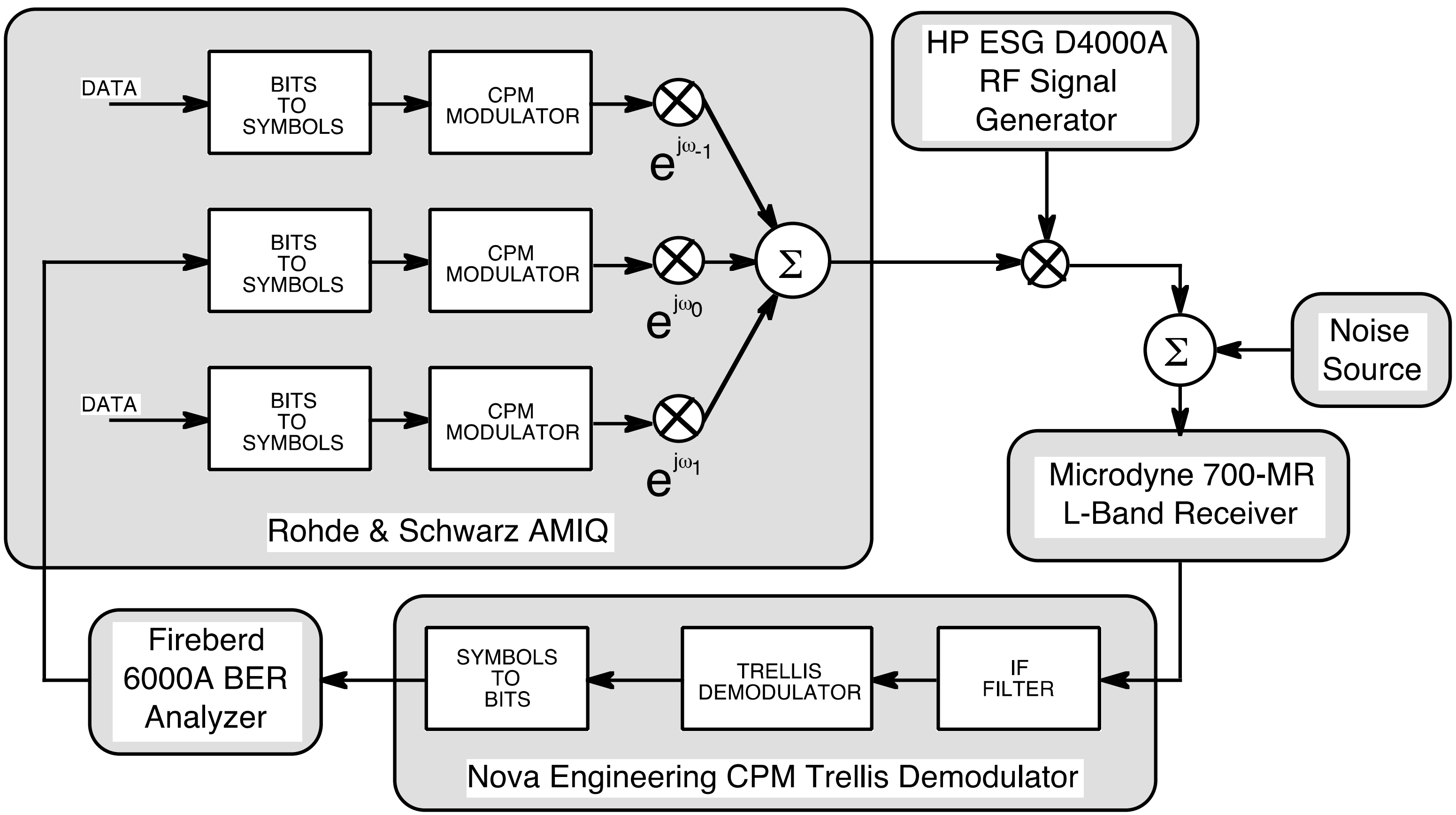
- The aeronautical telemetry channel is plagued with dropouts
- Rapid synchronization, and synchronization at low SNR, is the best means of minimizing the impact of these dropouts
- IRIG 118 defines test procedures for measuring sync time and sync thresholds
- Pay attention to synchronization performance!

Adjacent Channel Interference

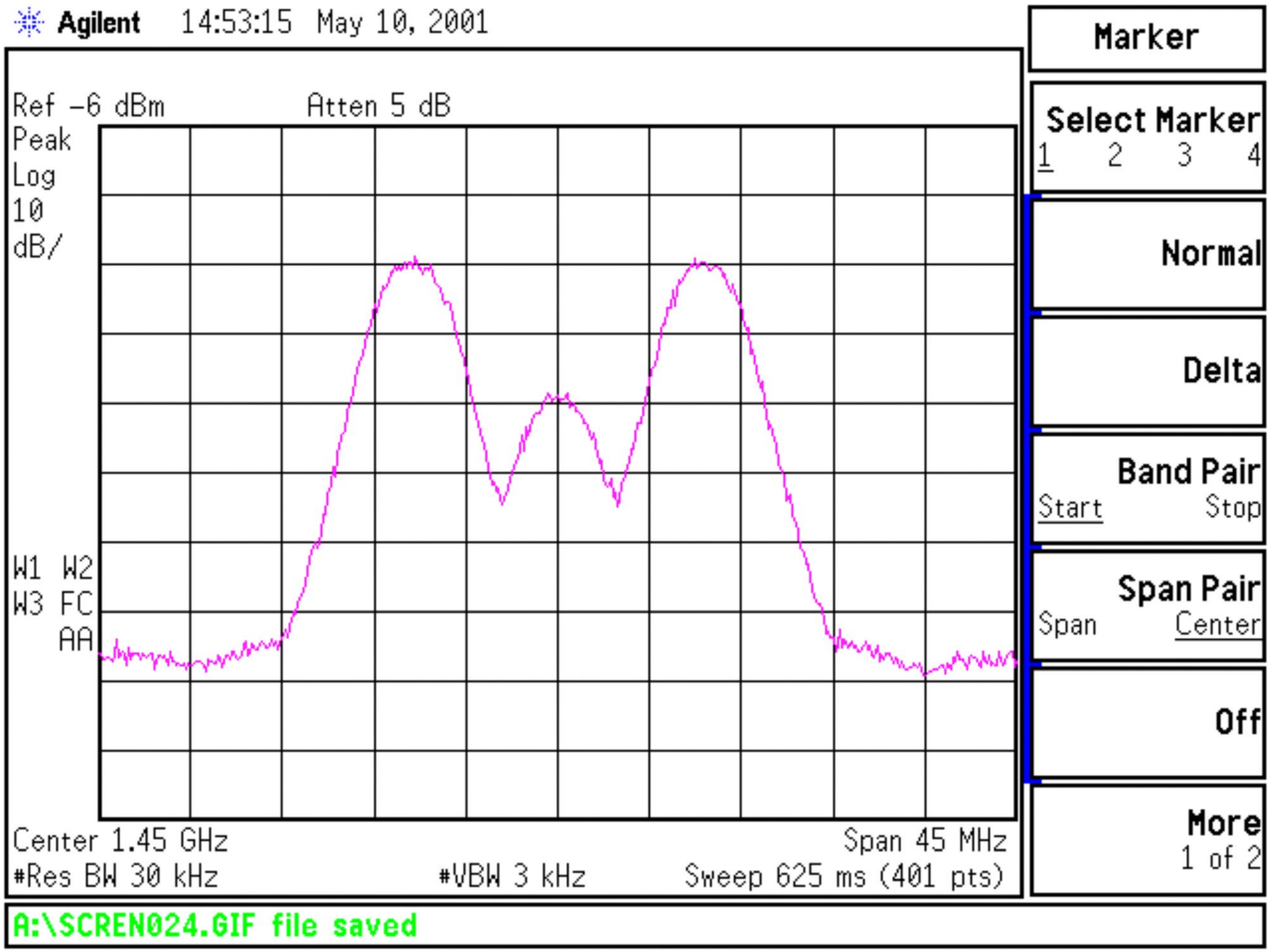
PSD is Half the Story

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

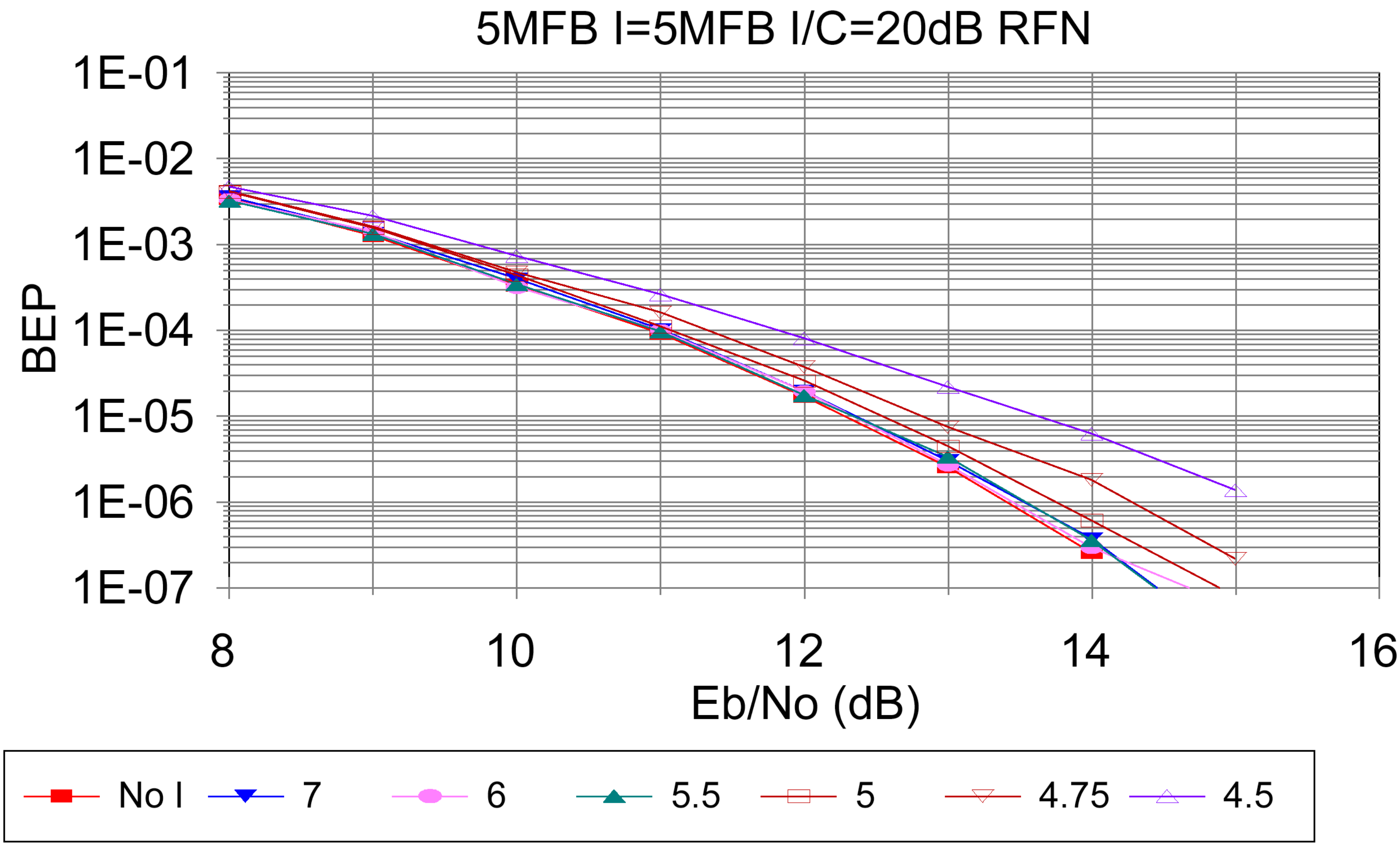
Multi-channel ACI Test Set



9 Mbps Multi-h CPM, Multichannel



BER as a Function of ΔF



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

Degradation as a Function of ΔF

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

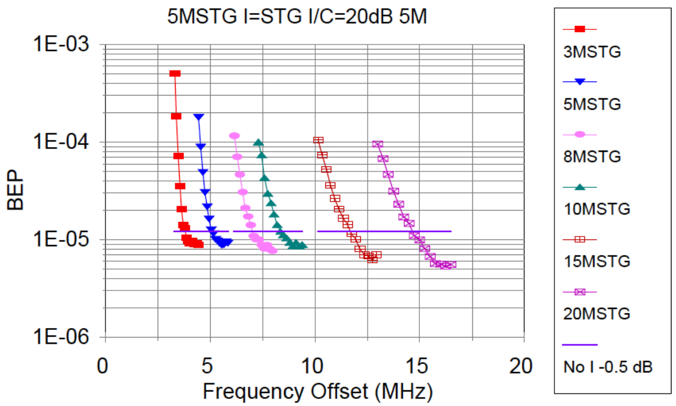


Figure 5. 5 Mbps SOQPSK-TG.

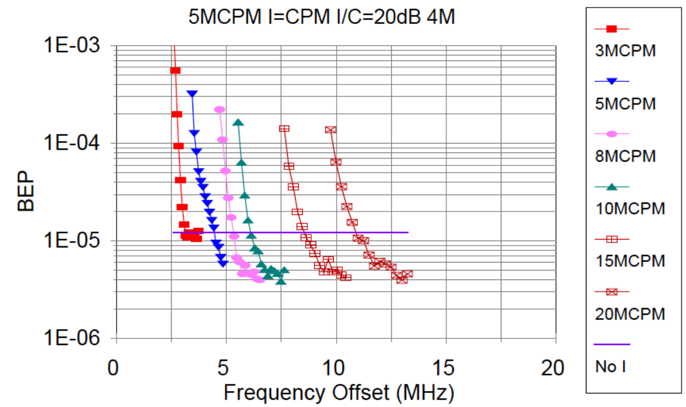


Figure 6. 5 Mbps multi-h CPM.

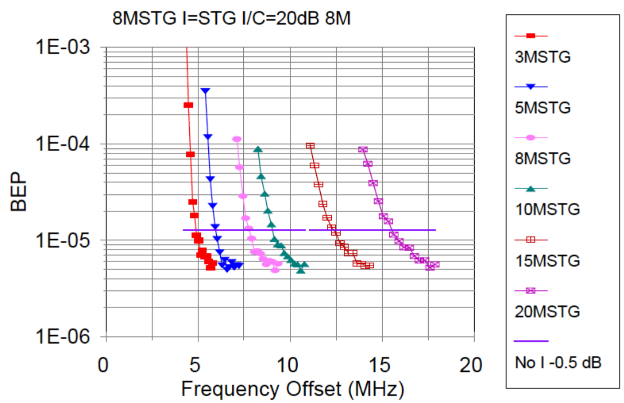


Figure 7. 8 Mbps SOQPSK-TG with 8 MHz IF BW.

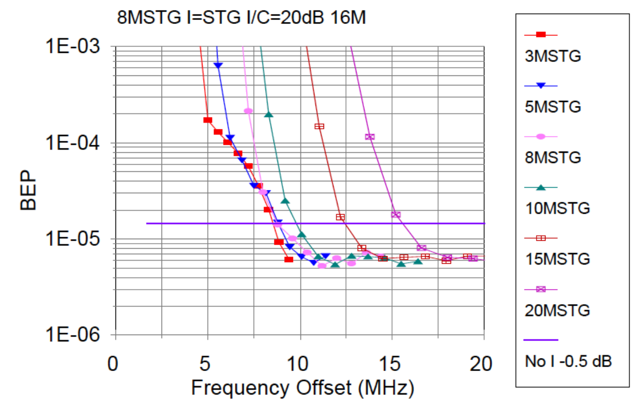
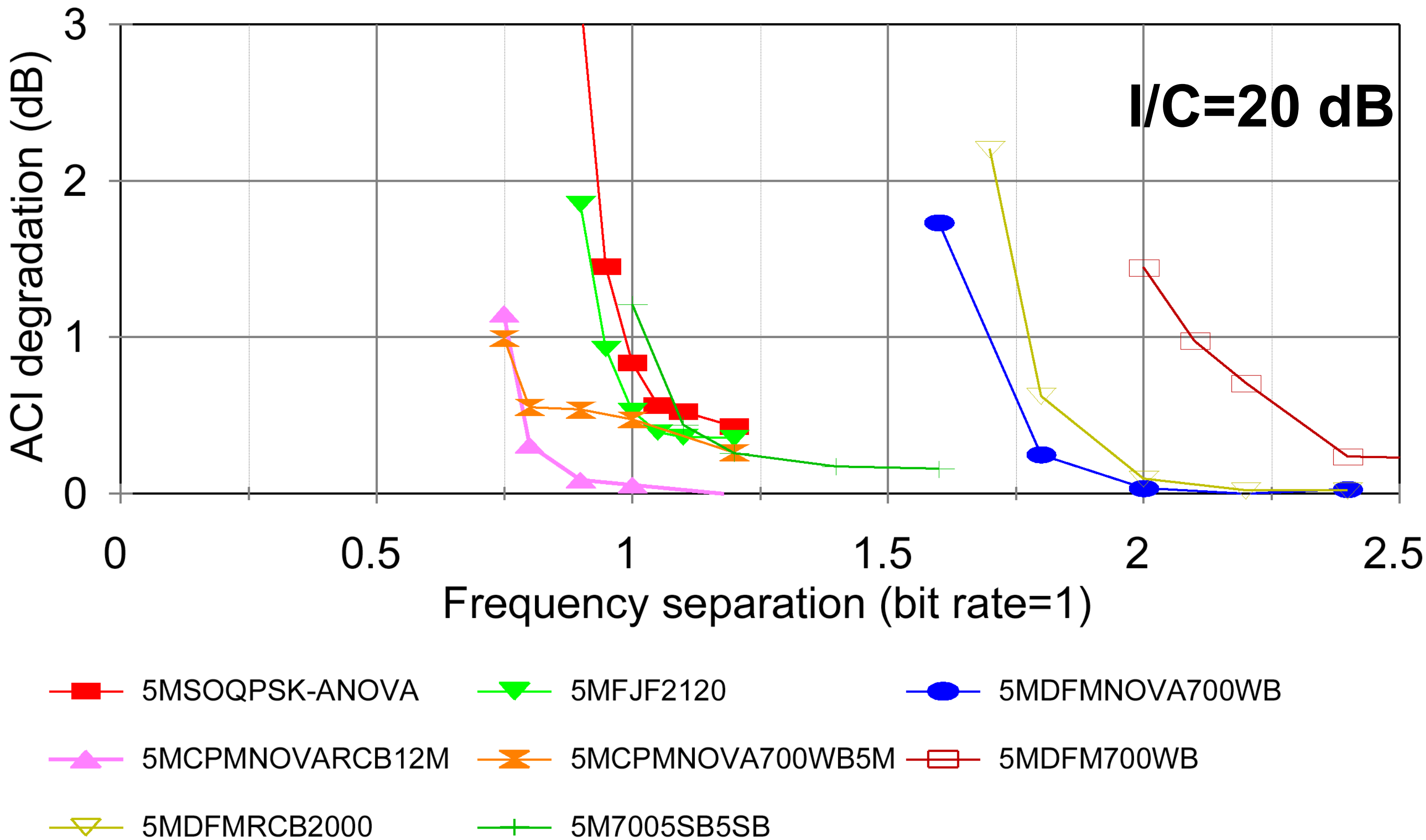


Figure 8. 8 Mbps SOQPSK-TG with 16 MHz IF BW.

ACI Summary



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

Frequency Separation Rule

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

where:

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

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

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

Multipath Propagation

Brace yourself!

Greek symbols ahead!

Multipath Propagation

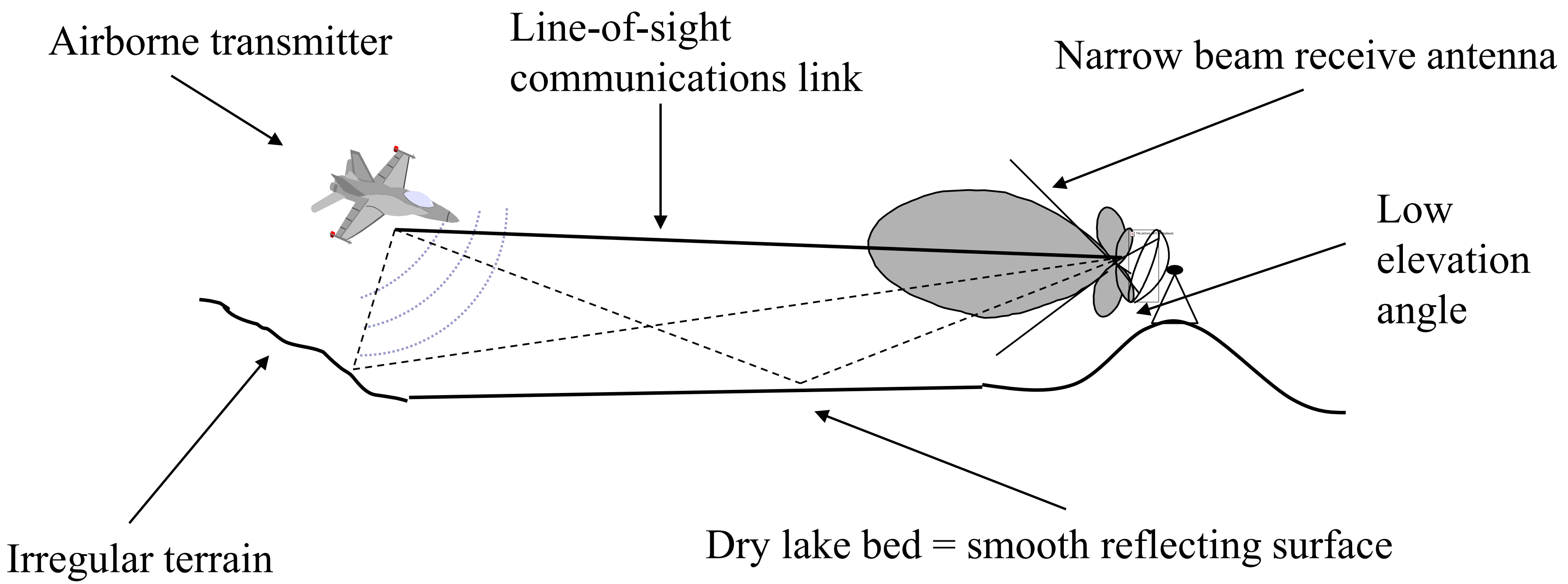


Figure from Dr.Michael Rice, BYU Telemetry Laboratory, Provo, Utah. Reprinted by permission of the author.

Assumptions

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

Complex-valued path loss

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

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

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 ~ $\omega_c \dot{\tau}_1 + \dot{\theta}_{\Gamma_1}$

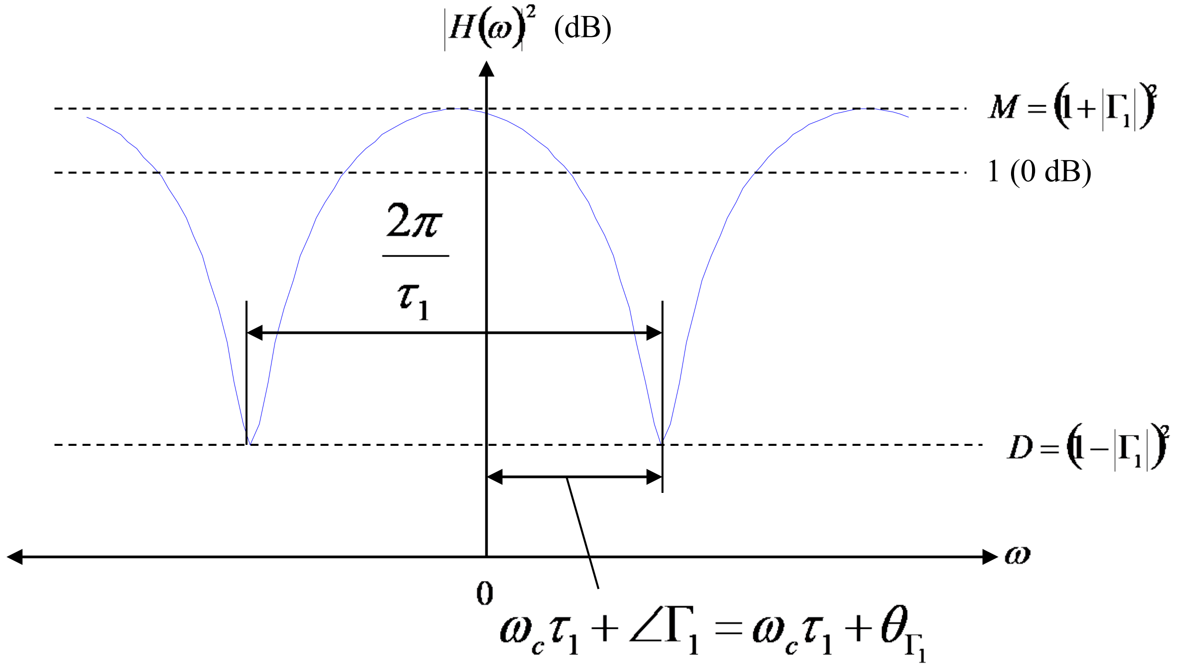
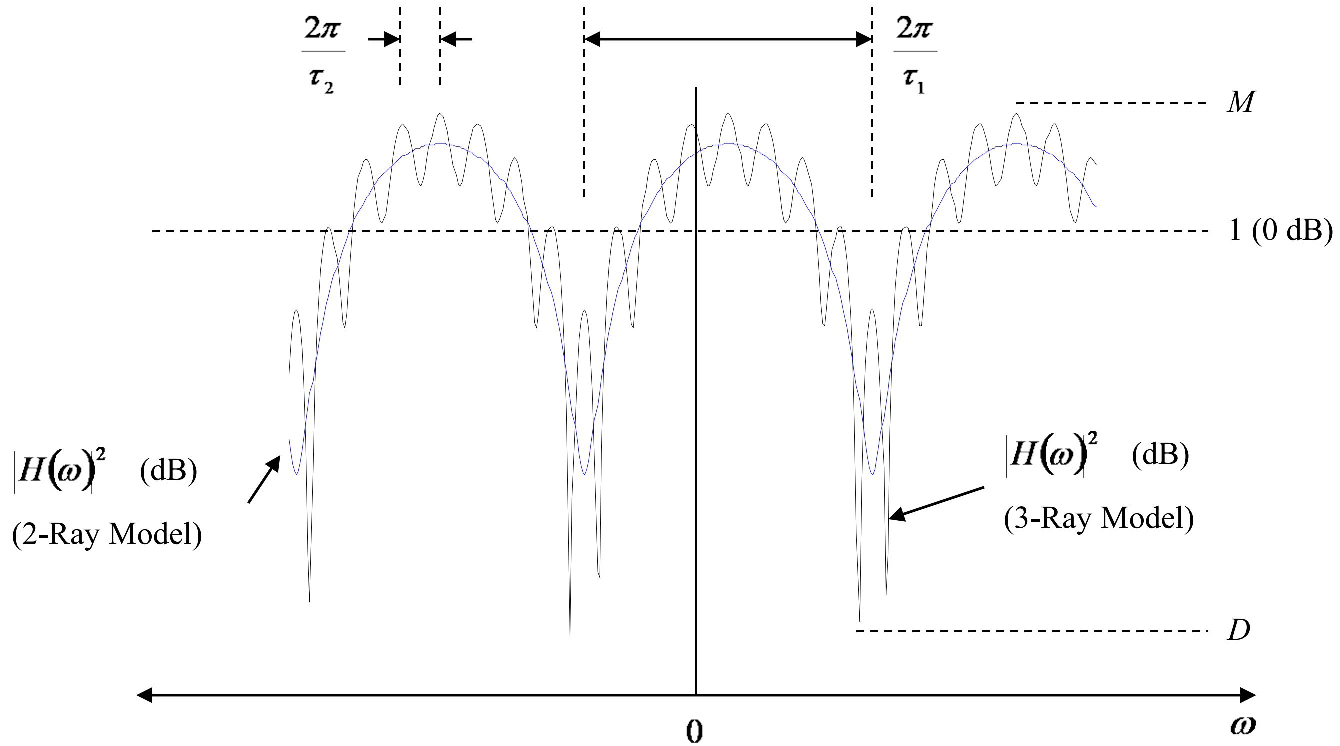


Figure from Dr.Michael Rice, BYU Telemetry Laboratory, Provo, Utah. Reprinted by permission of the author.

3-Ray Transfer Function

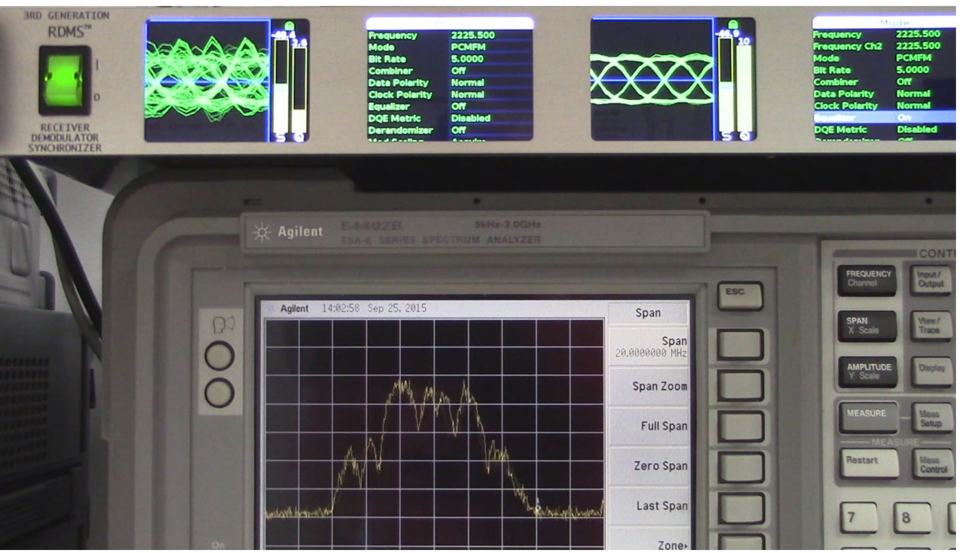


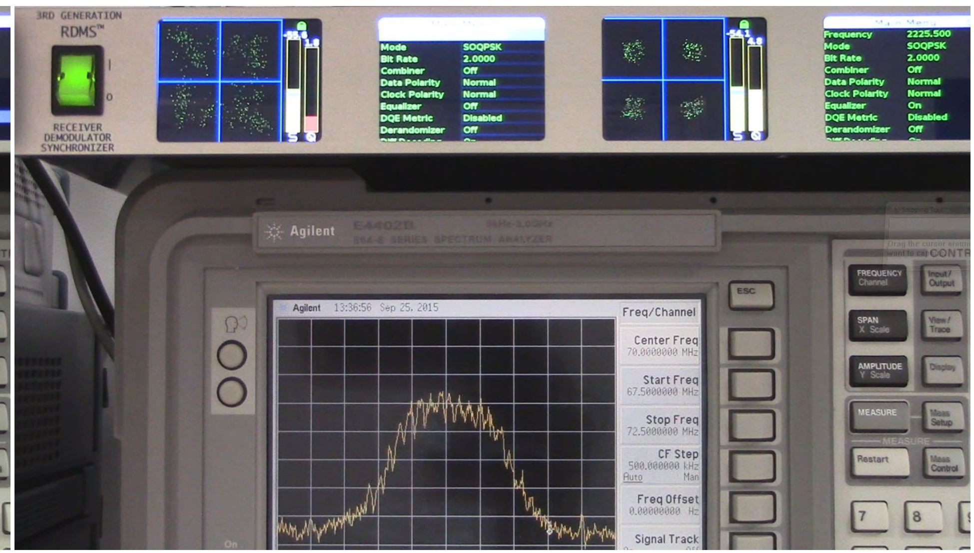
Assumes $\tau_1 < \tau_2$ and $|\Gamma_1| > |\Gamma_2|$

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

Multipath on the Tarmac

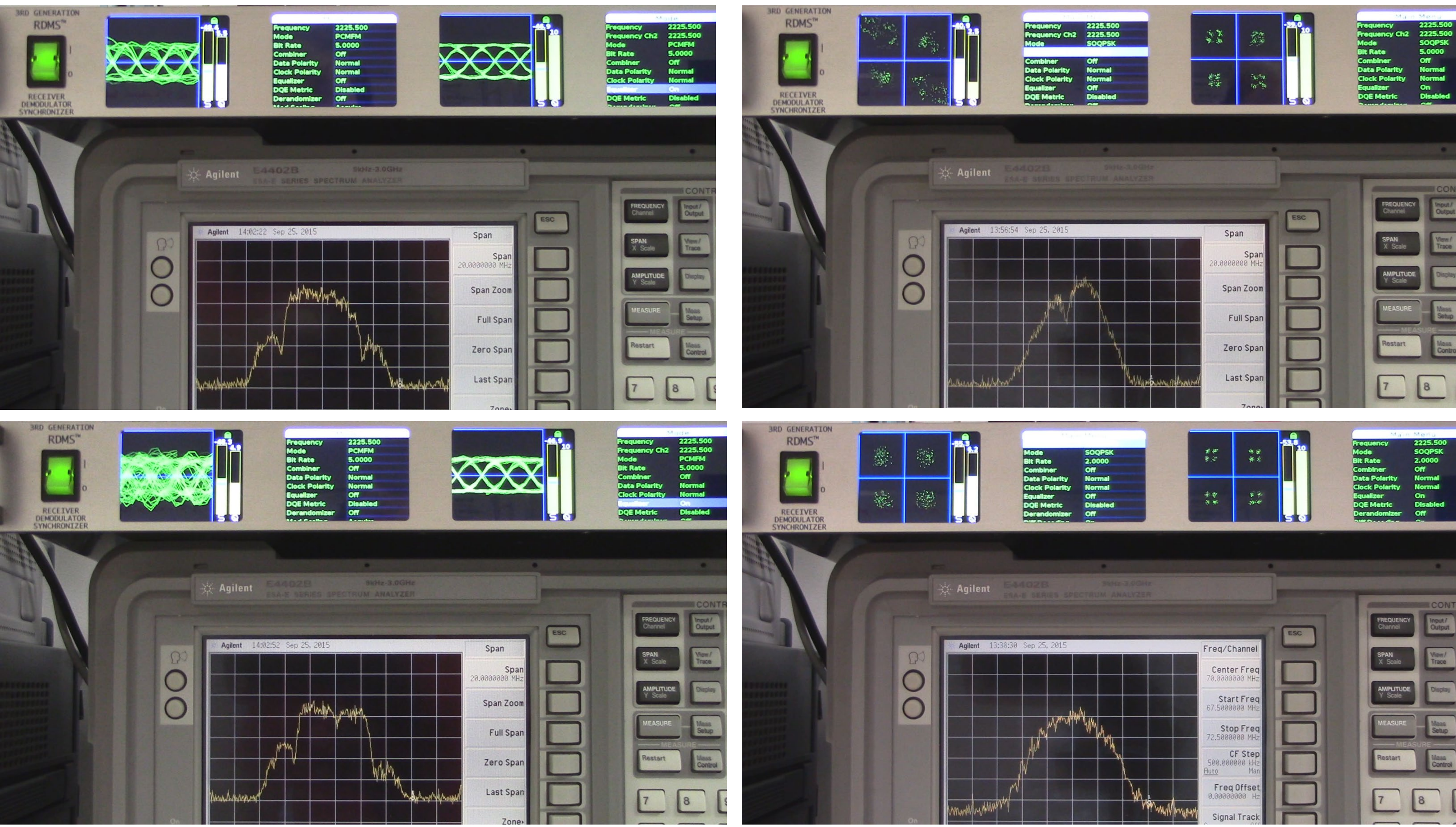
- Nearly static, frequency selective, long delays





Multipath in Flight

- Dynamic, frequency selective and flat fading, various delays



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

DSP Techniques for Telemetry

Receiver-Only DSP Techniques

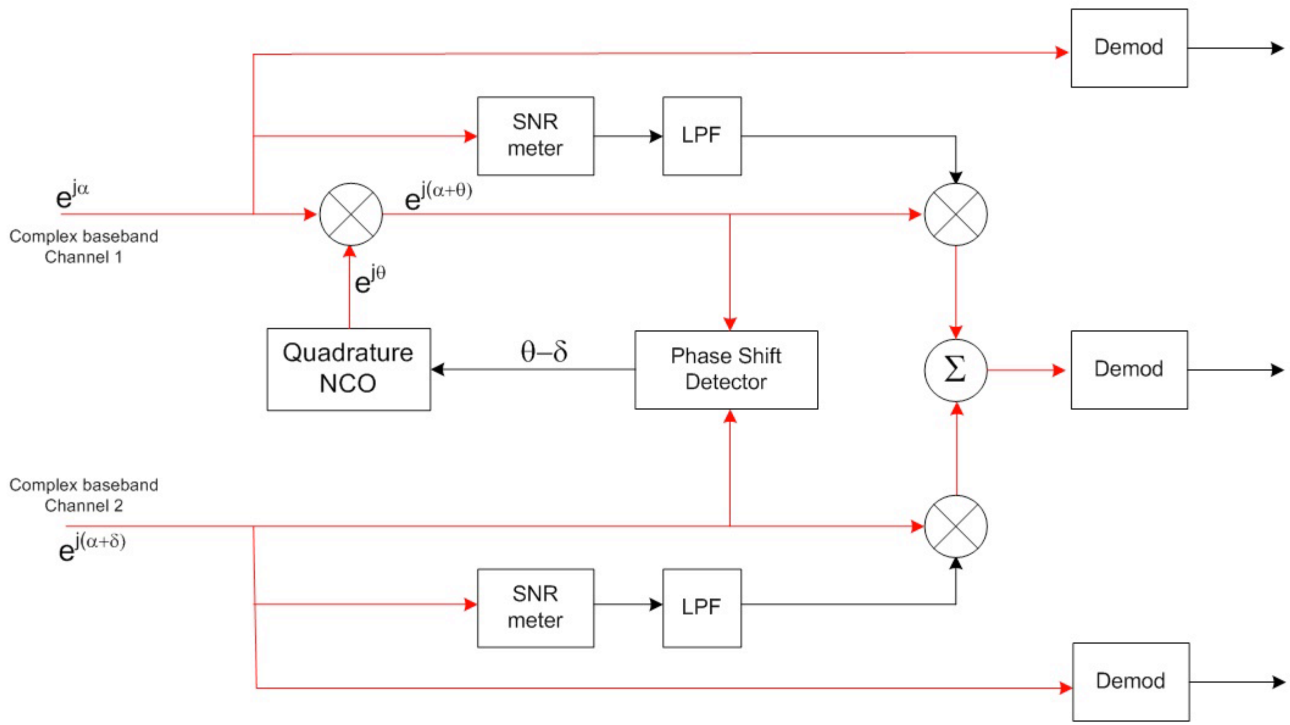
- Receive-side processing, no transmitter impact
- Maximal ratio combining – optimal against AWGN
  - Polarization diversity
  - Frequency diversity
- Data Quality Metric (DQM) / Data Quality Encapsulation (DQE)
  - IRIG 118-22, Chapter 11
- Adaptive equalization
  - Powerful tool against multipath
-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

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

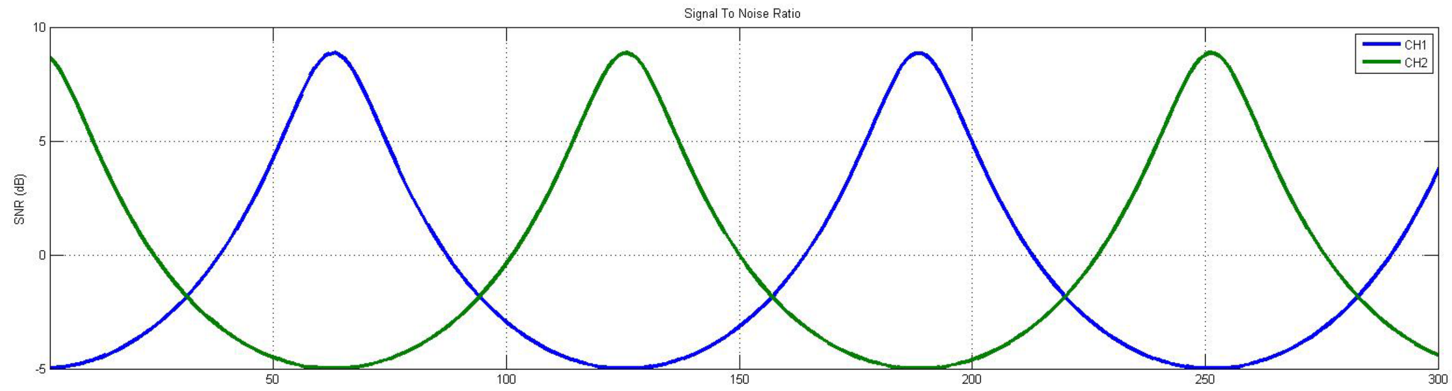


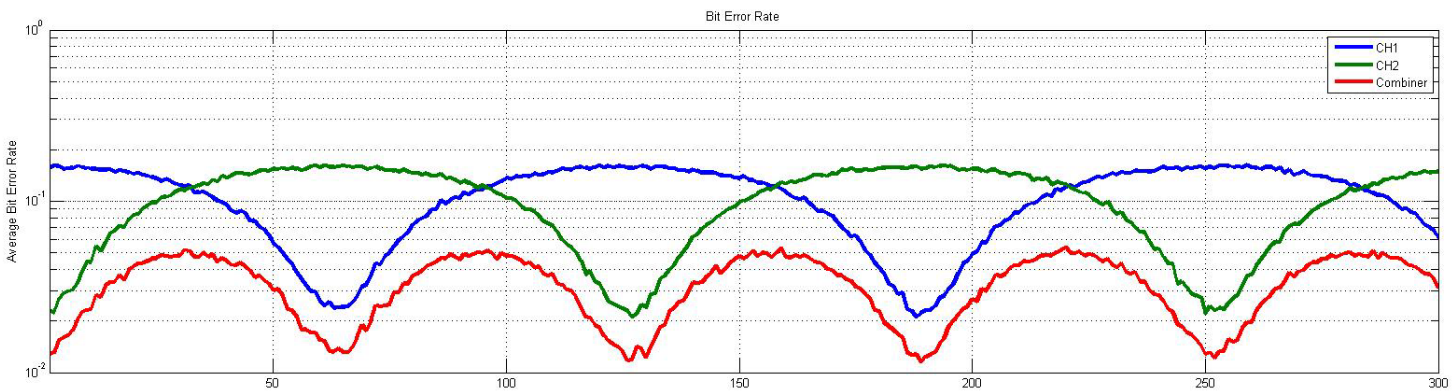
- Weight each signal in proportion to its SNR and add
- Yields optimum SNR on combined channel **in AWGN**
- $SNR_{combined} = SNR_a + SNR_b$

Maximal Ratio Combining

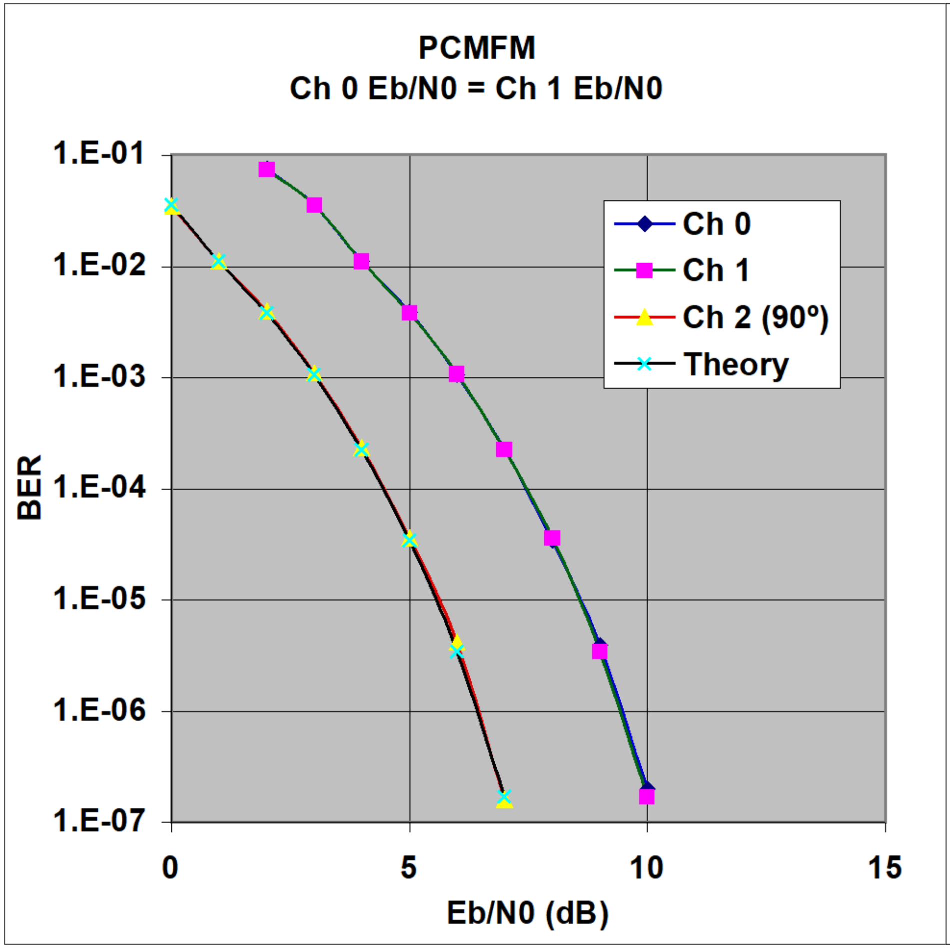
- Jump to file://localhost/Users/TerryHill/Documents/Quasonix/ITC 2015/Diversity Combiner.avi

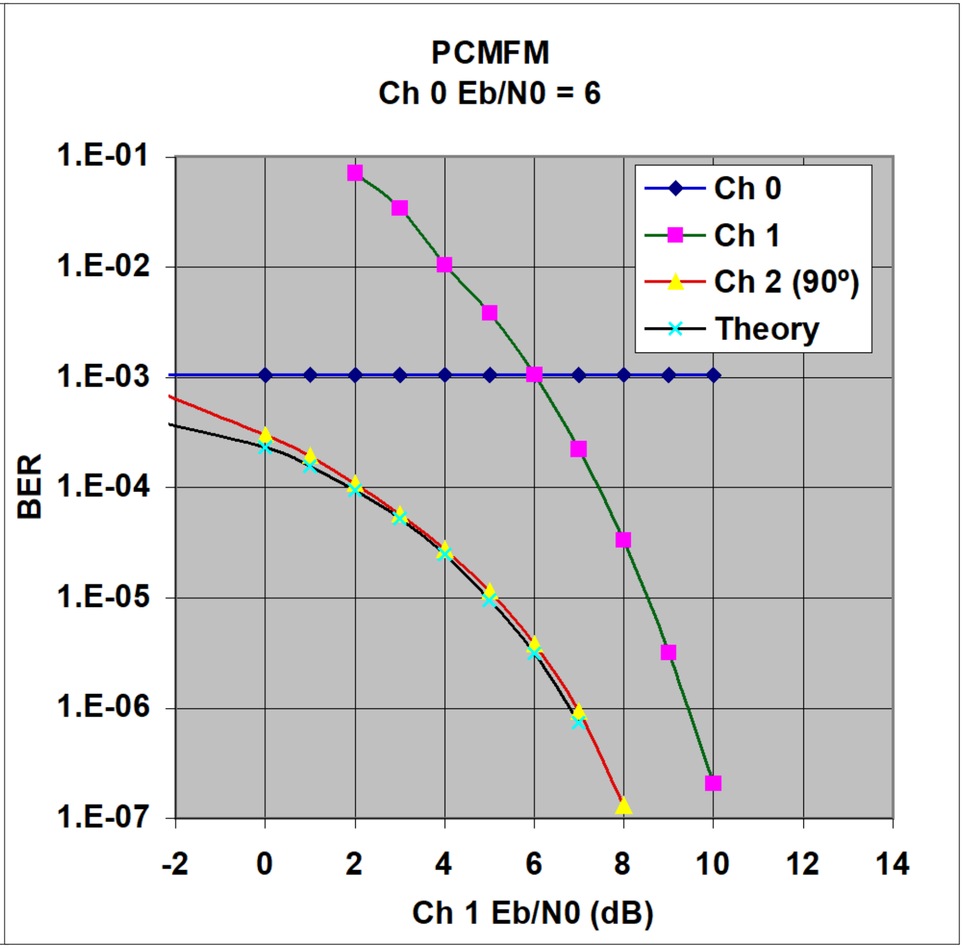
BER Results - Fading Signals



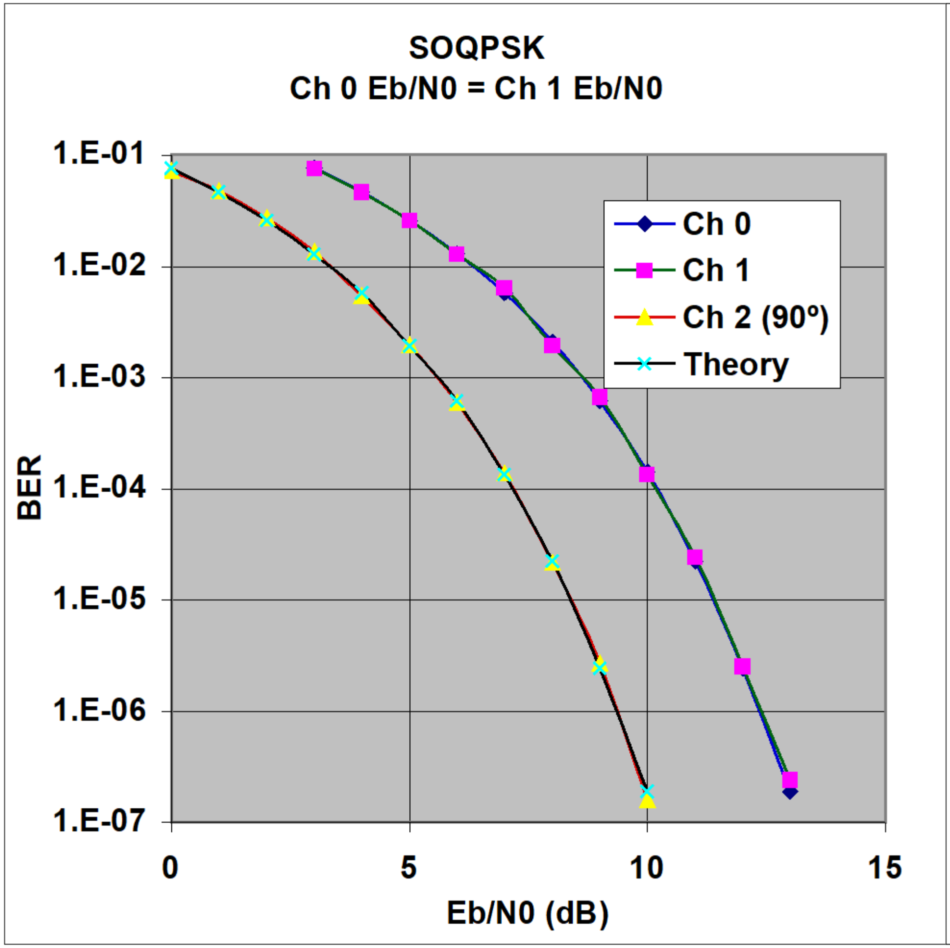


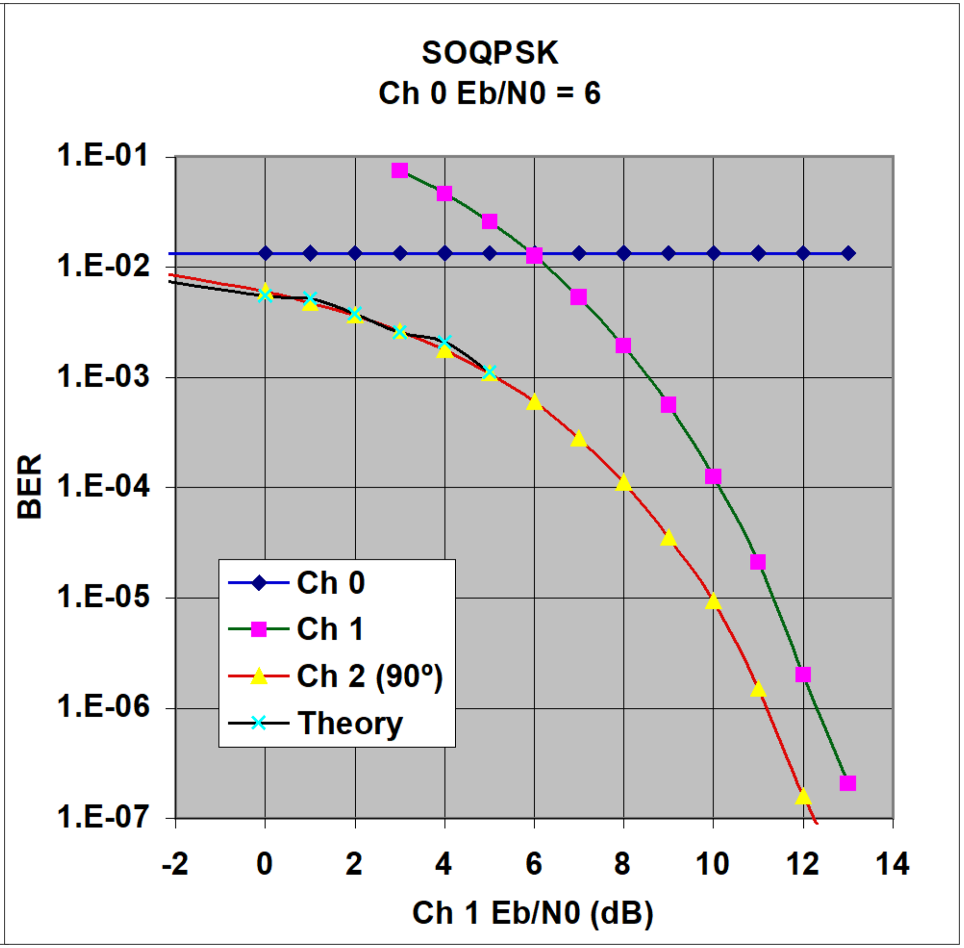
Measured Combiner BER - Tier 0



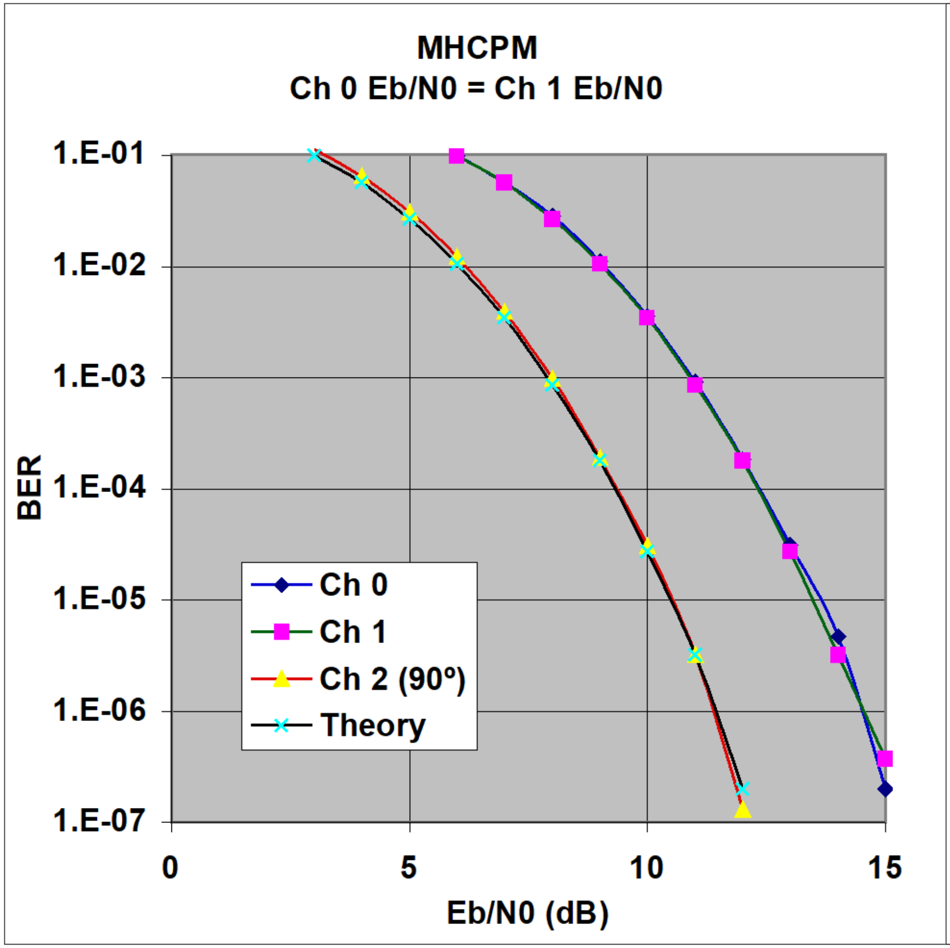


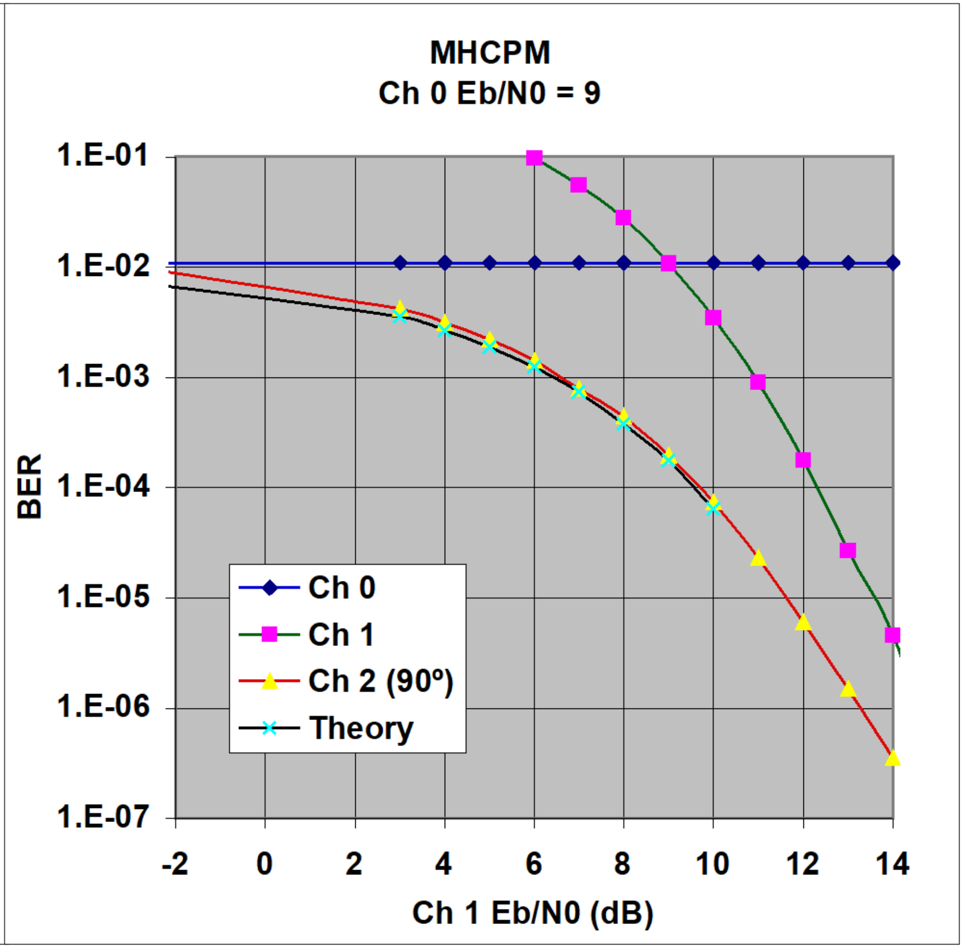
Measured Combiner BER - Tier I





Measured Combiner BER - Tier II





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Combiner Summary

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

~~Let's Eat Students!~~

Let's Eat, Students!

Commas Save Lives

See you back here at ________ PM

Data Quality Metric (DQM)

How to Assess Data Quality

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

Definition of DQM

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

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

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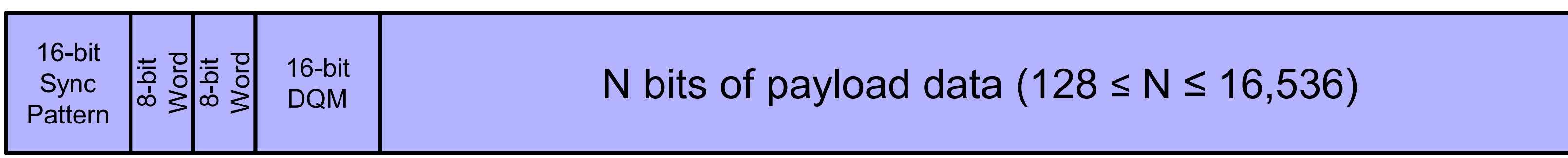
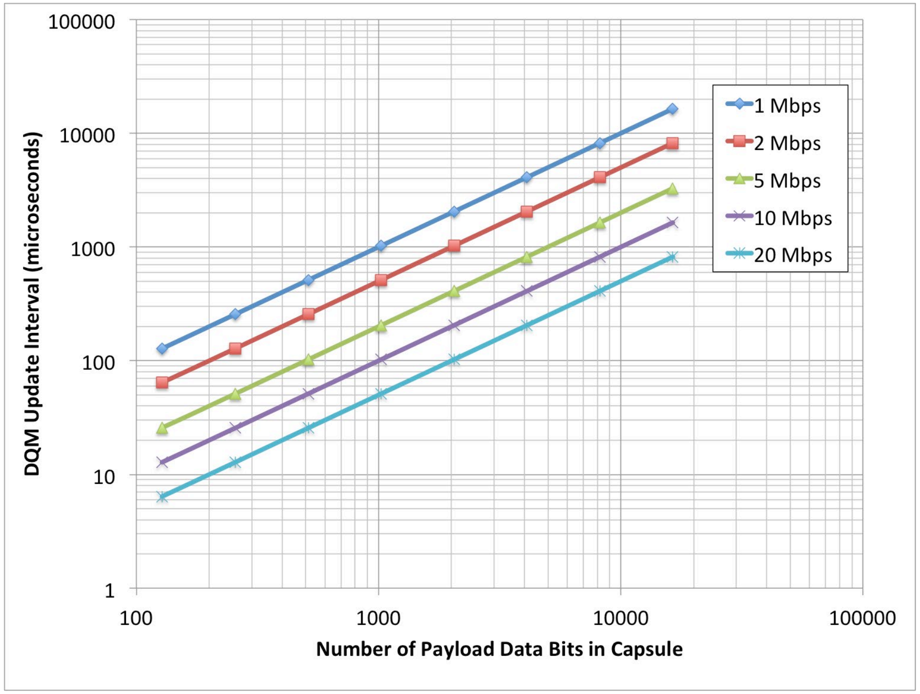
DQE Format

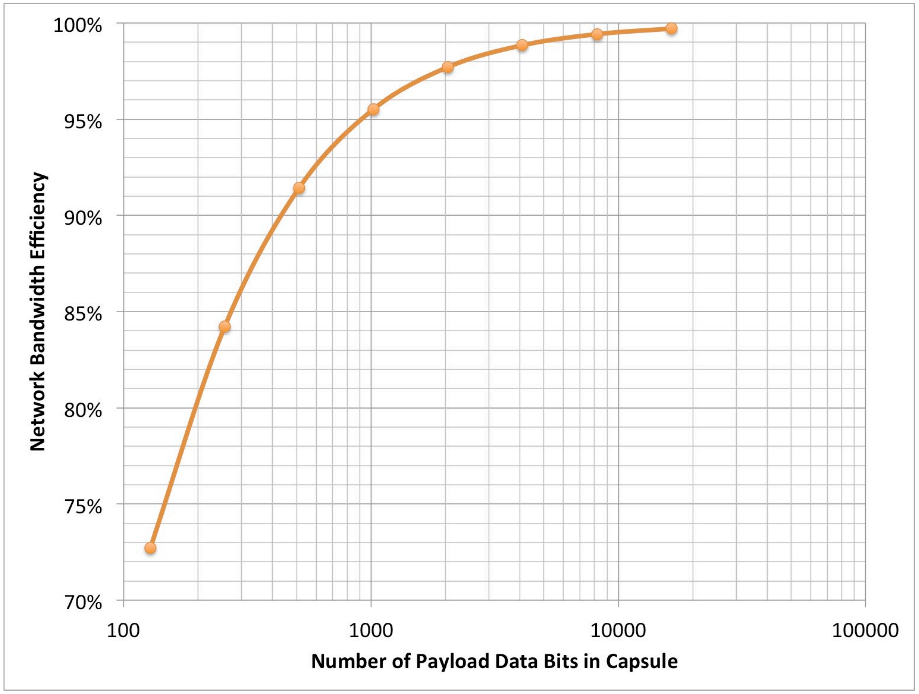
- Header
  - 16-bit sync pattern (0xFAC4)
    - MSB first: 1111101011000100
  - 8-bit reserved word, potentially for packet header version number (currently 0)
  - 8-bit reserved word, potentially for source ID tag (currently 0)
  - 16-bit DQM
- Payload data
  - User selectable length, (128 ≤ N ≤ 16,536)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



DQM Parameter Trades

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



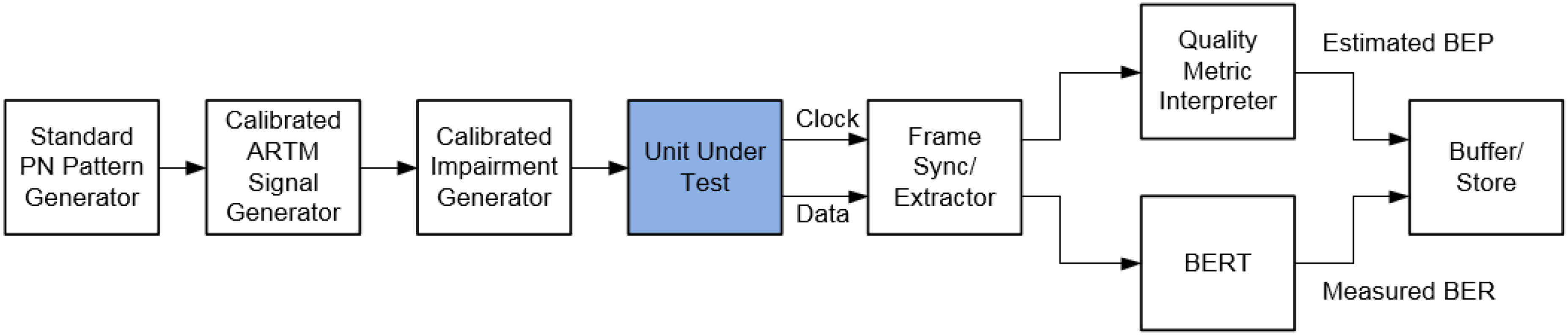


Calibration of DQM

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

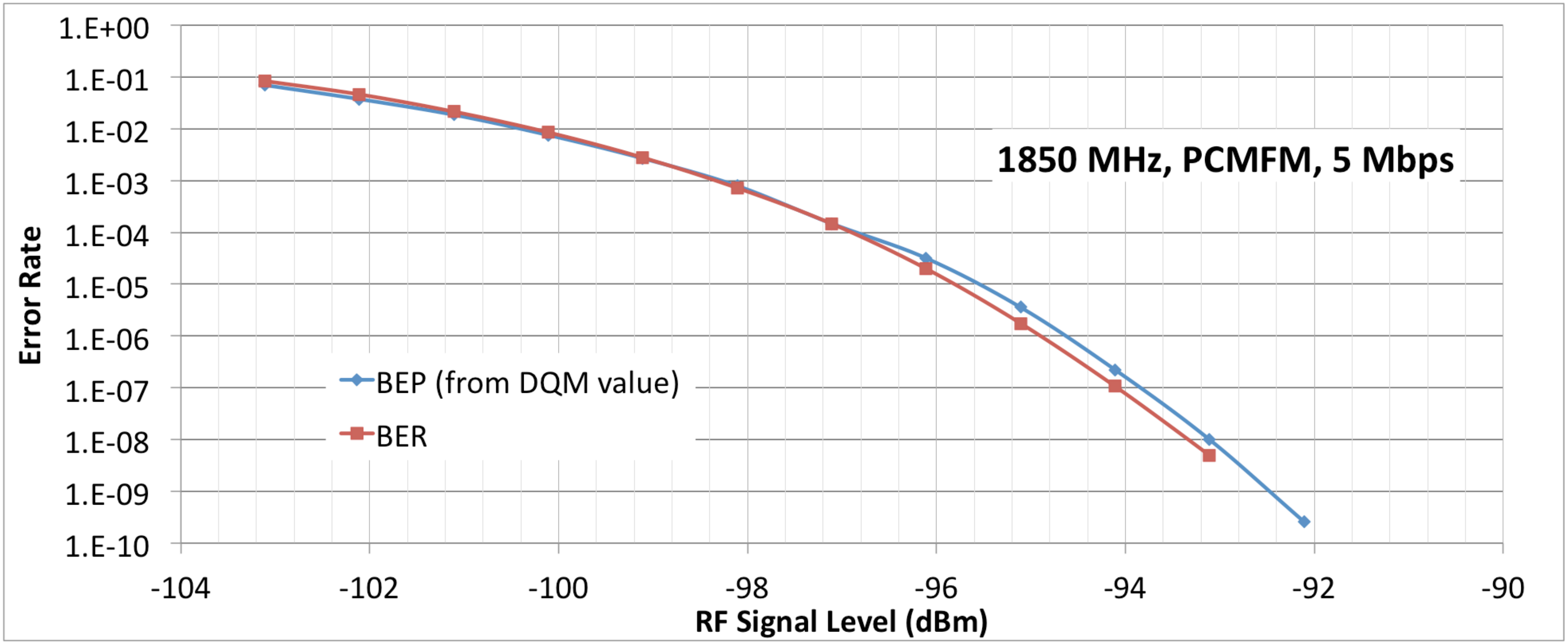
DQM Calibration Fixture

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



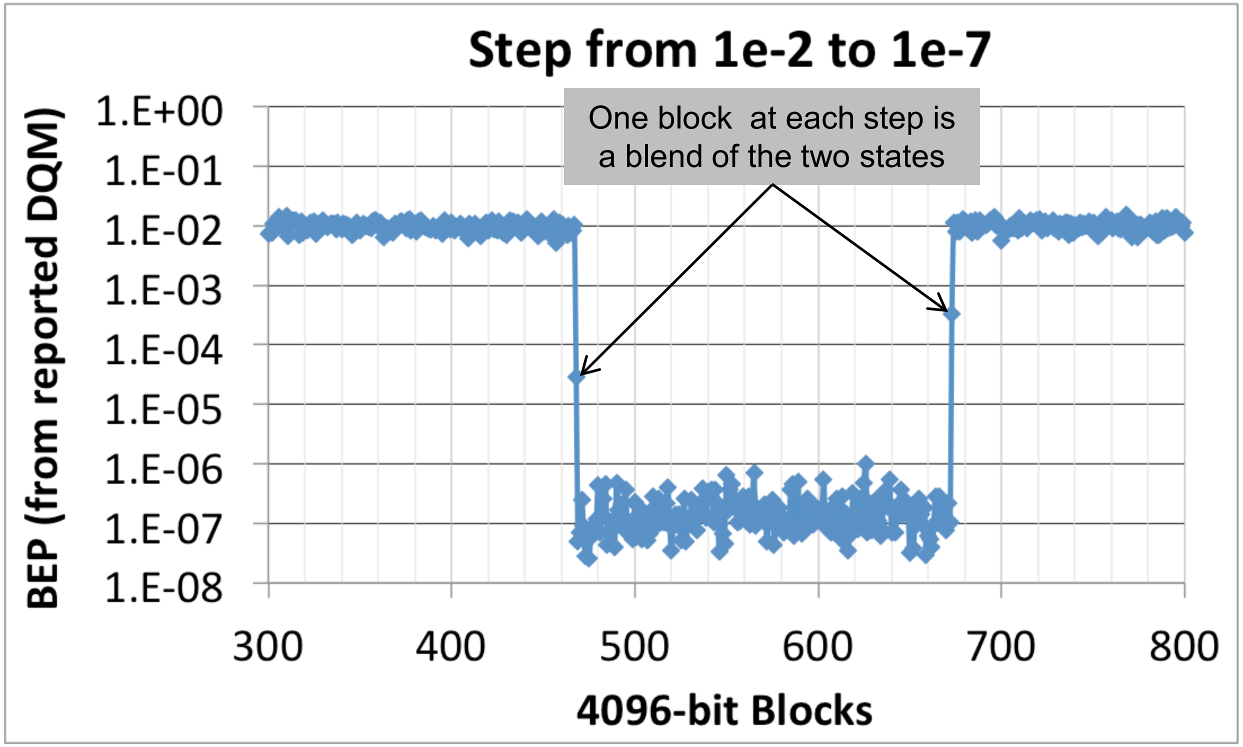
DQM Calibration in AWGN

- Required as a baseline for all other tests



DQM Step Response

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



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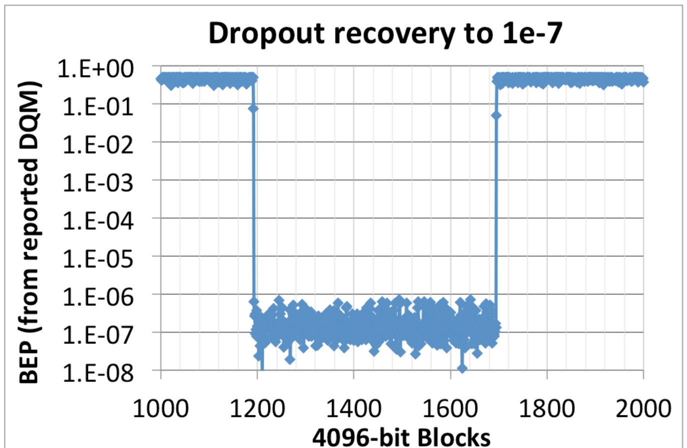
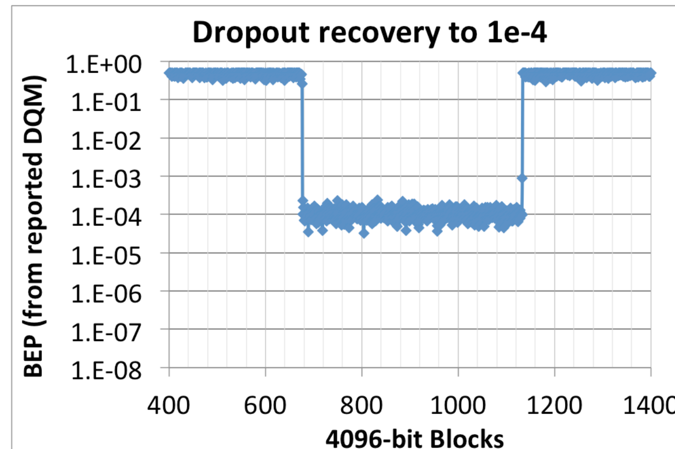
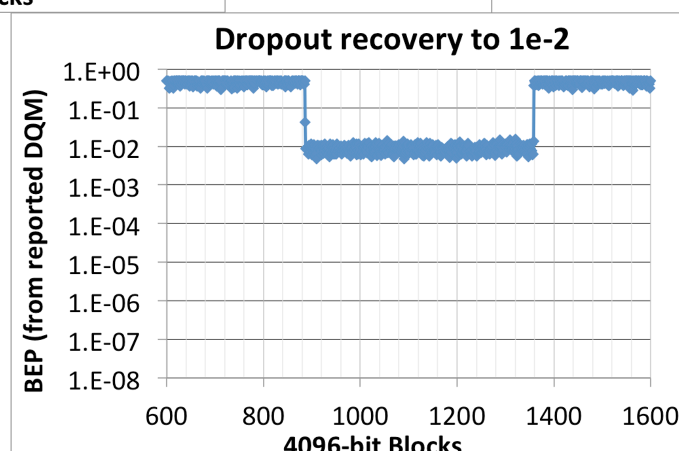
DQM Fade Recovery

- Includes UUT synchronization time







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IRIG 118-22 Chapter 11

- First, DQE frame format must be correct

16 Bits	12 Bits	4 Bits	16 Bits	1024 – 16384 Bits
SW	RSV	VER	DQM	PAYLOAD

a. SW = Sync Word. The sync word is a fixed value of 0xFAC4.

b. RSV = Reserved. Reserved for future use.

c. VER = IRIG 106 Version number.

d. DQM = Data Quality Metric.

e. PAYLOAD = Telemetry data payload to which the DQM value applies.

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

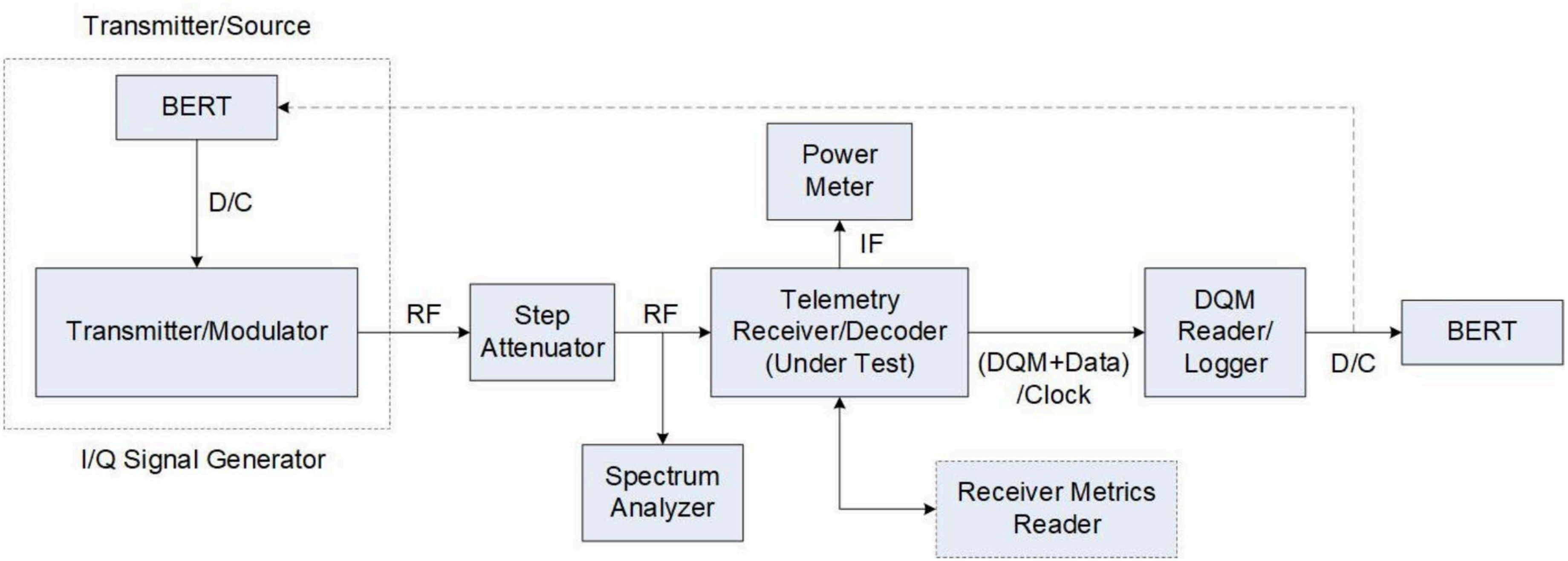
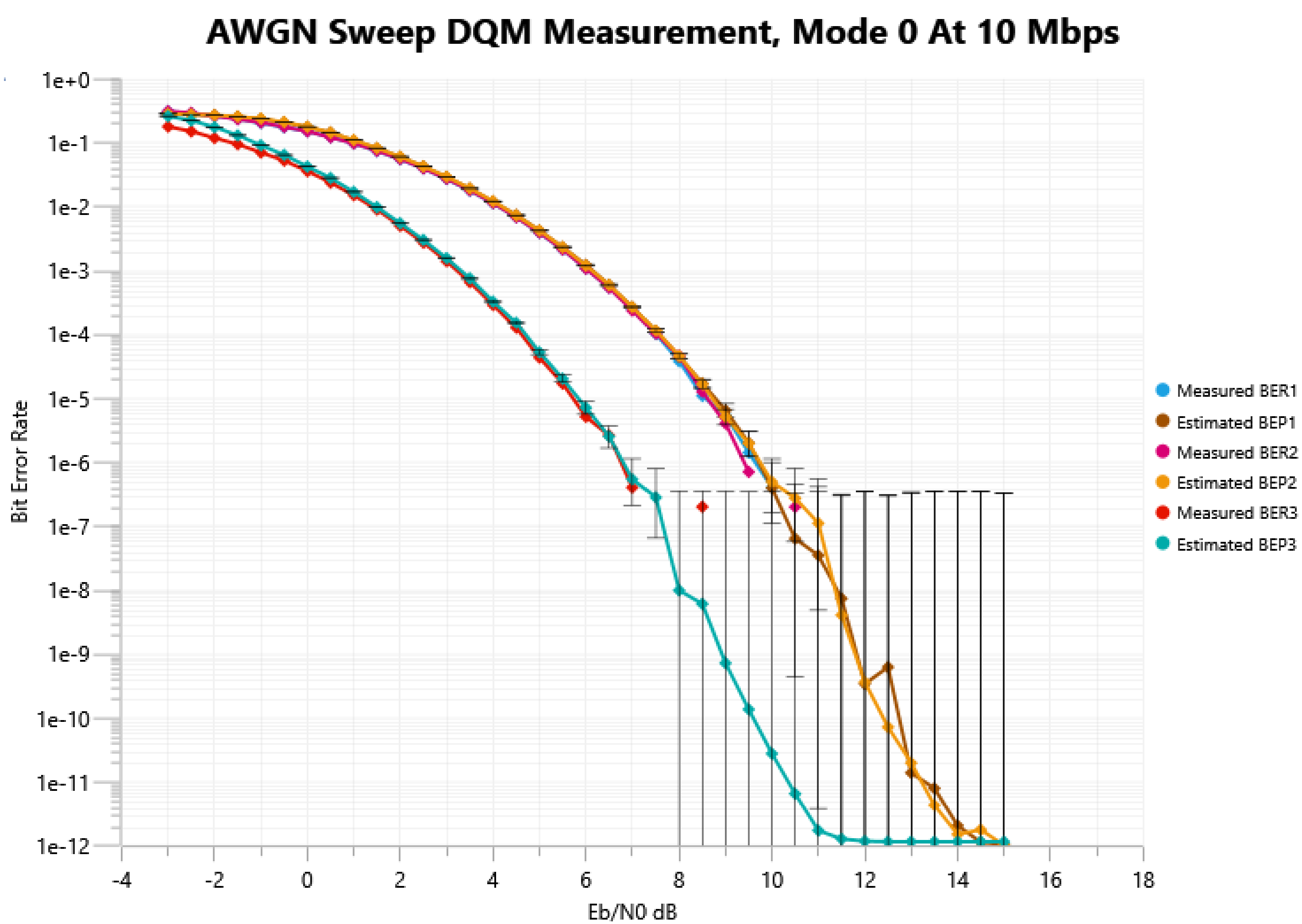


Figure 11-1. Setup for Step Attenuator/Power Meter for BER versus BEP Test

Basic AWGN Sweep



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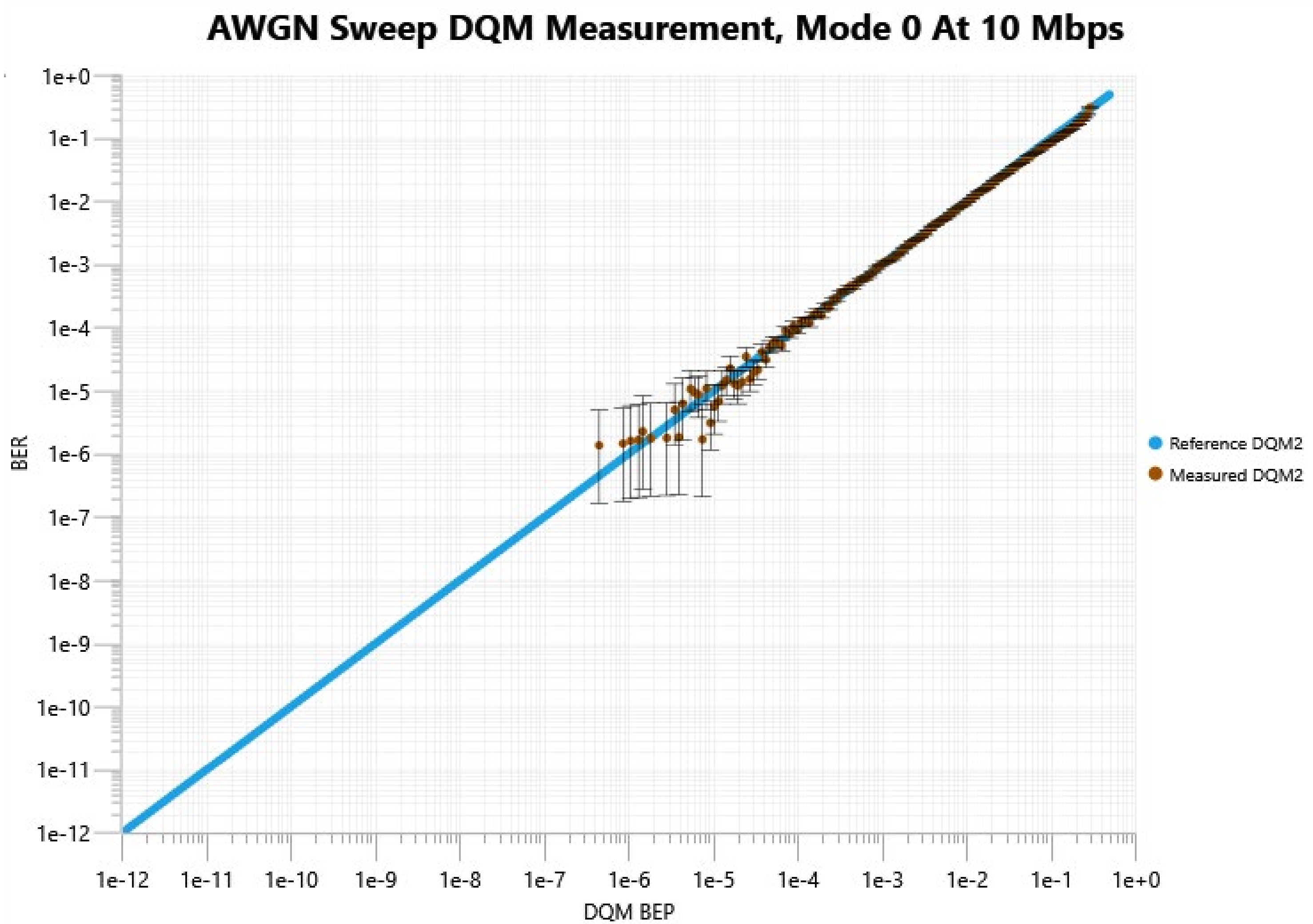
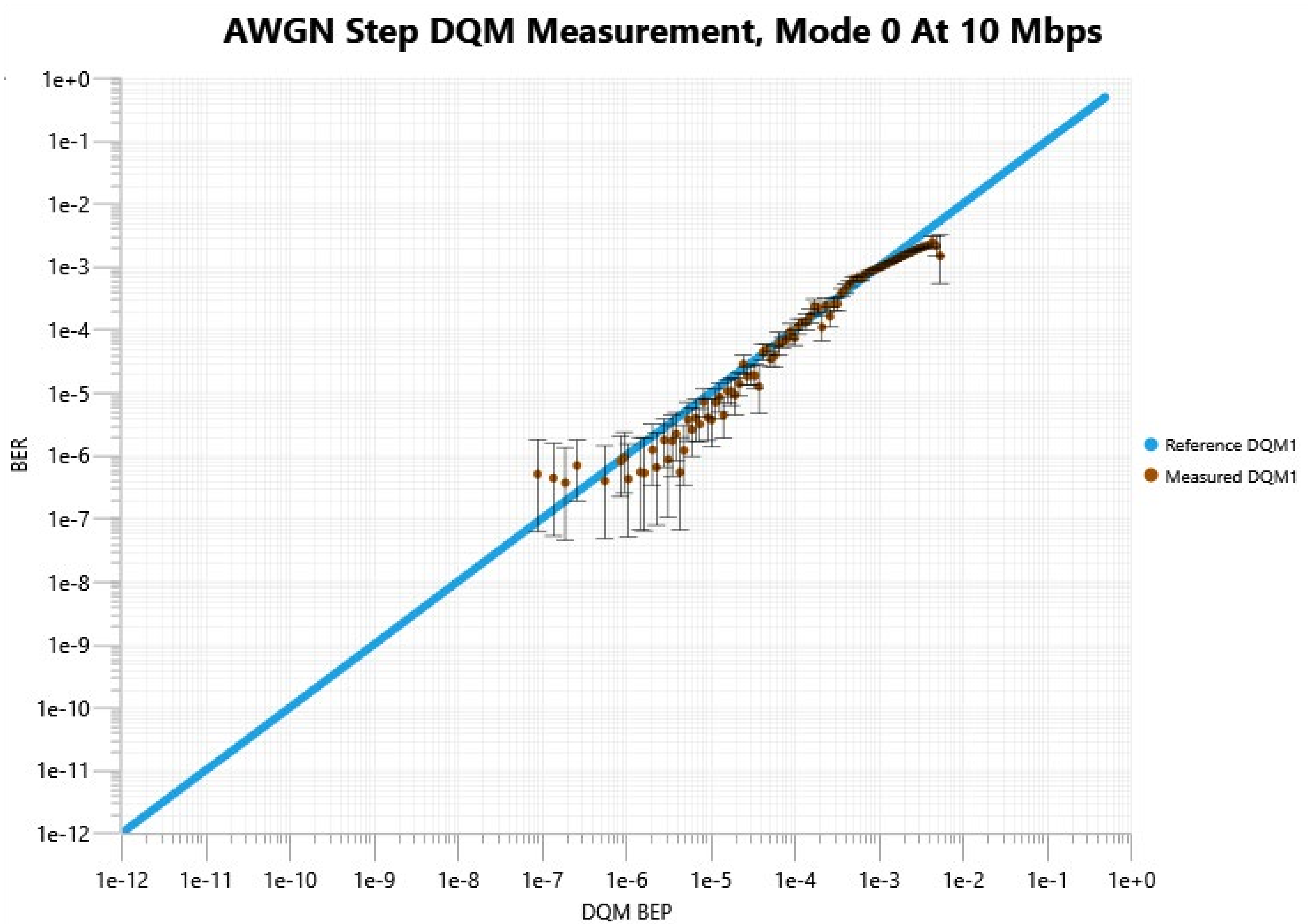
Basic AWGN BER v. BEP



Step AWGN BER v. BEP



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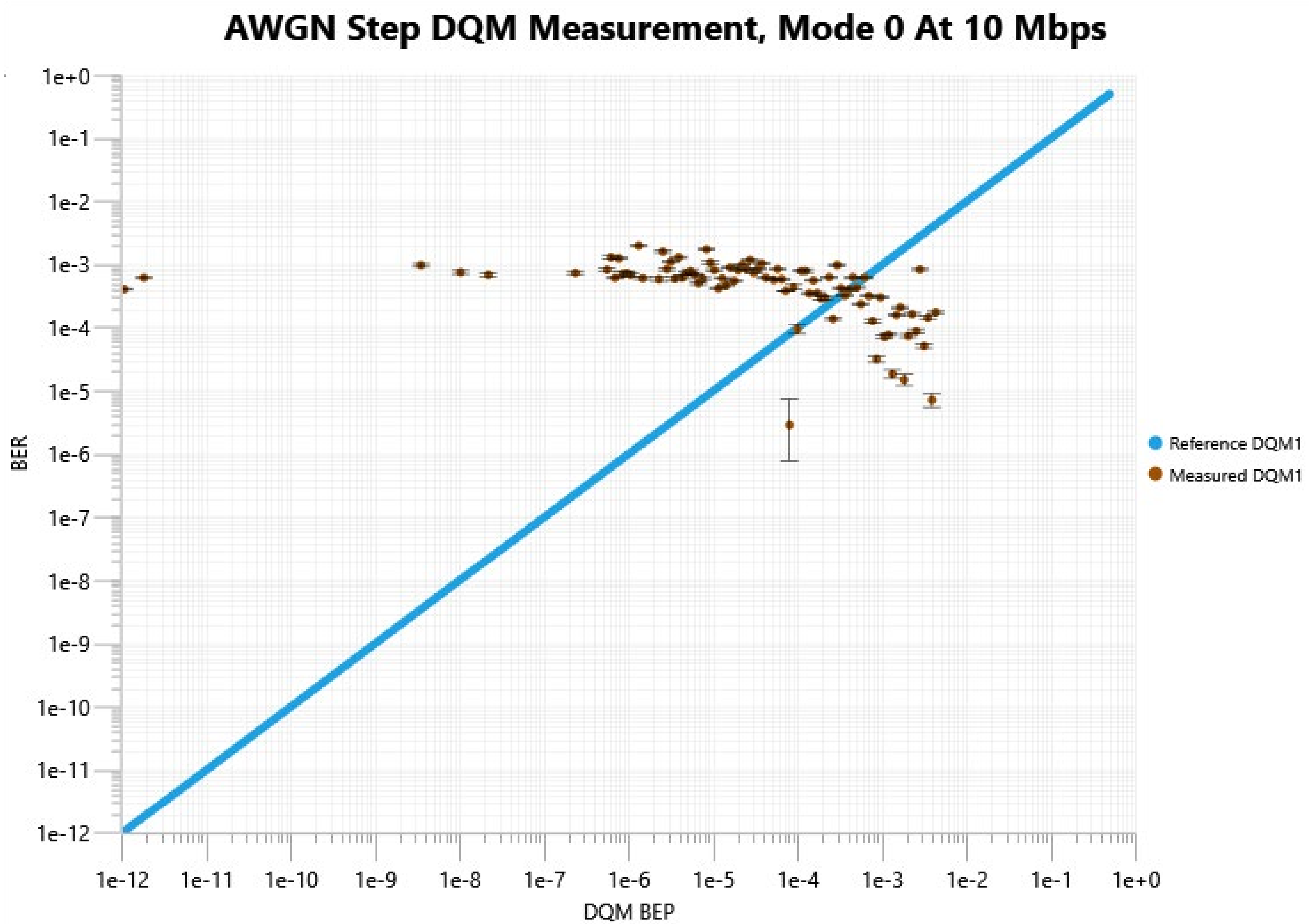
Not All DQMs are Created Equal



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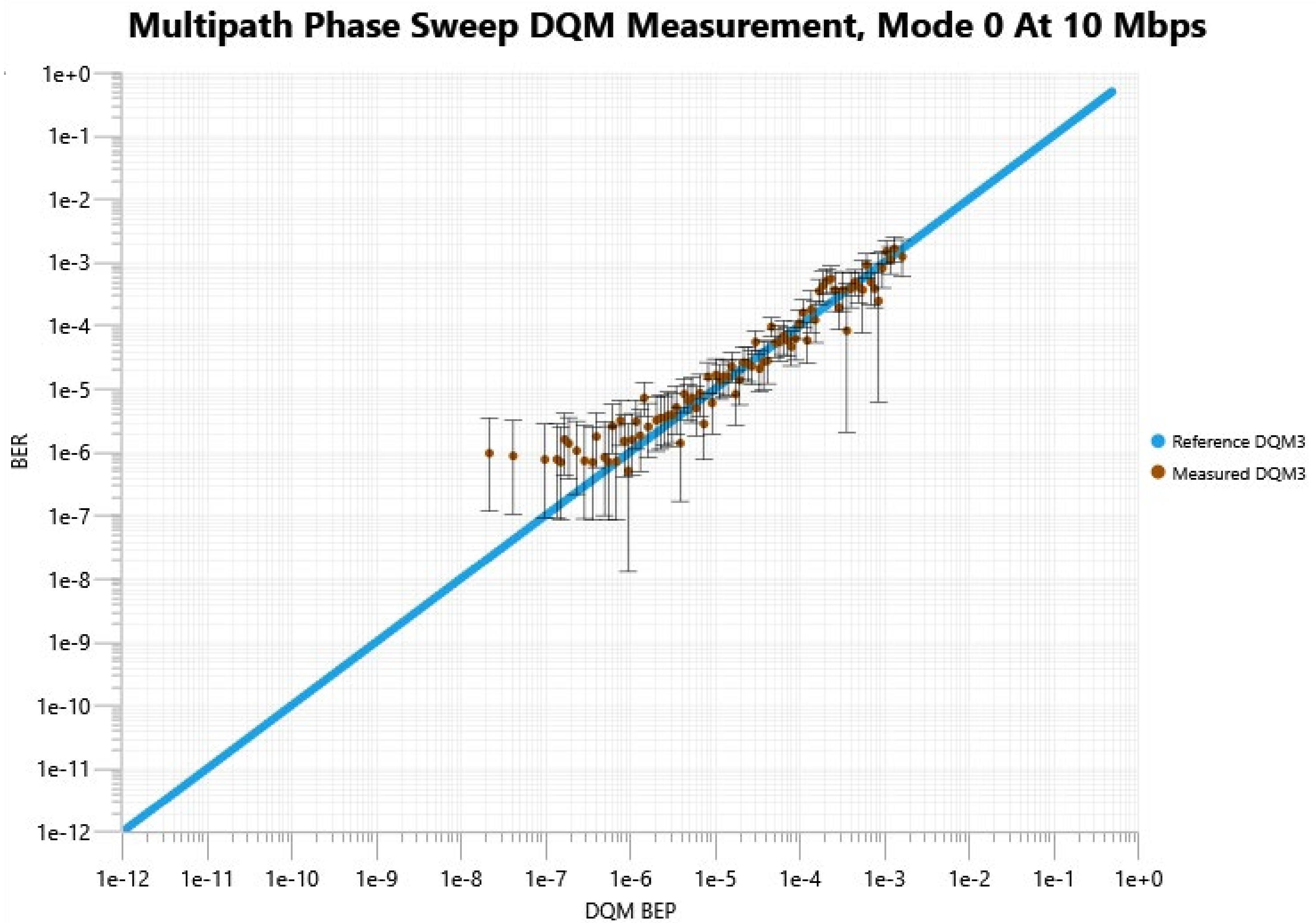
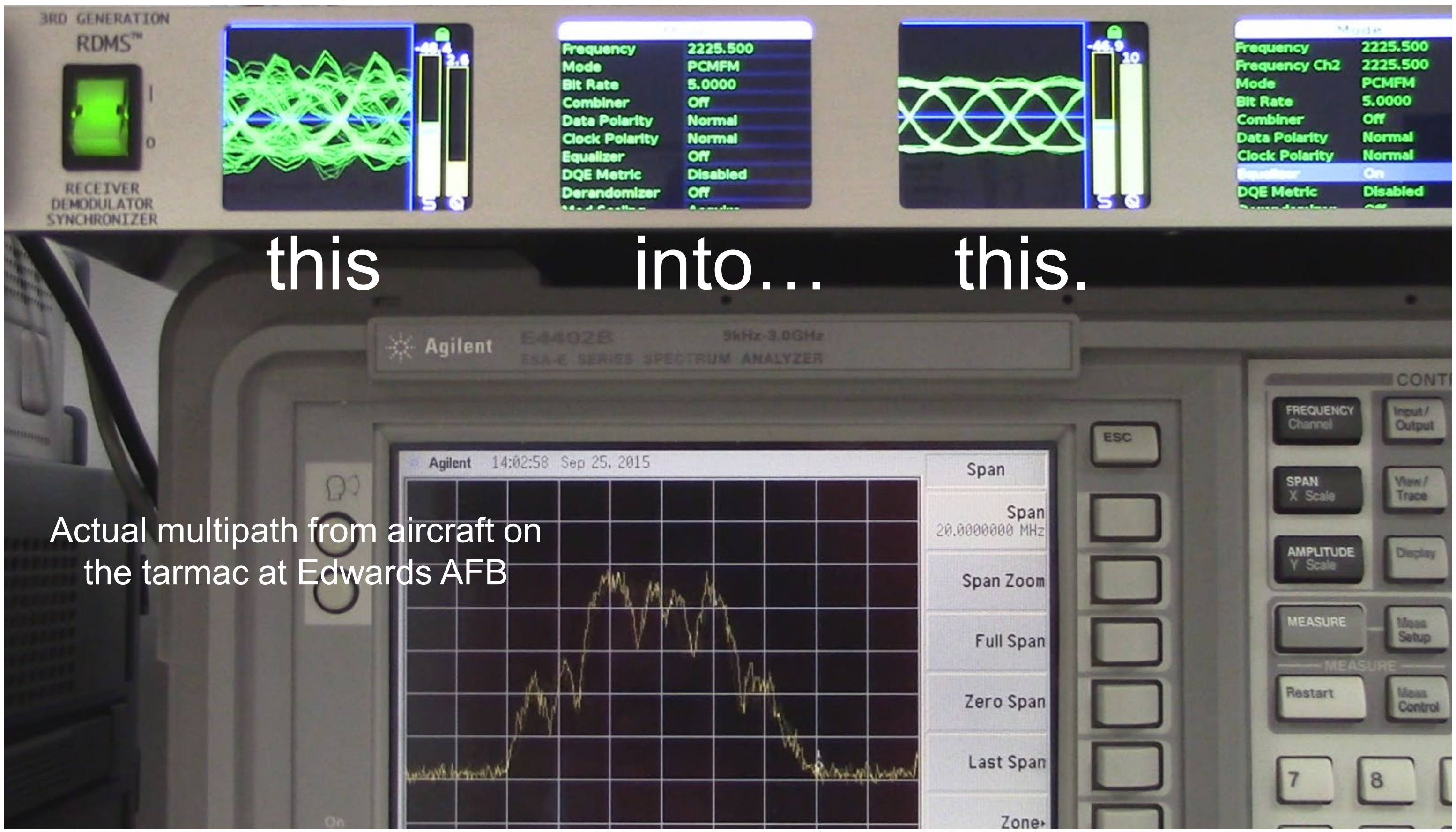
BER v. BEP in Multipath



Adaptive Equalization

Multipath is Ugly

- Equalization can turn
- this into… this.

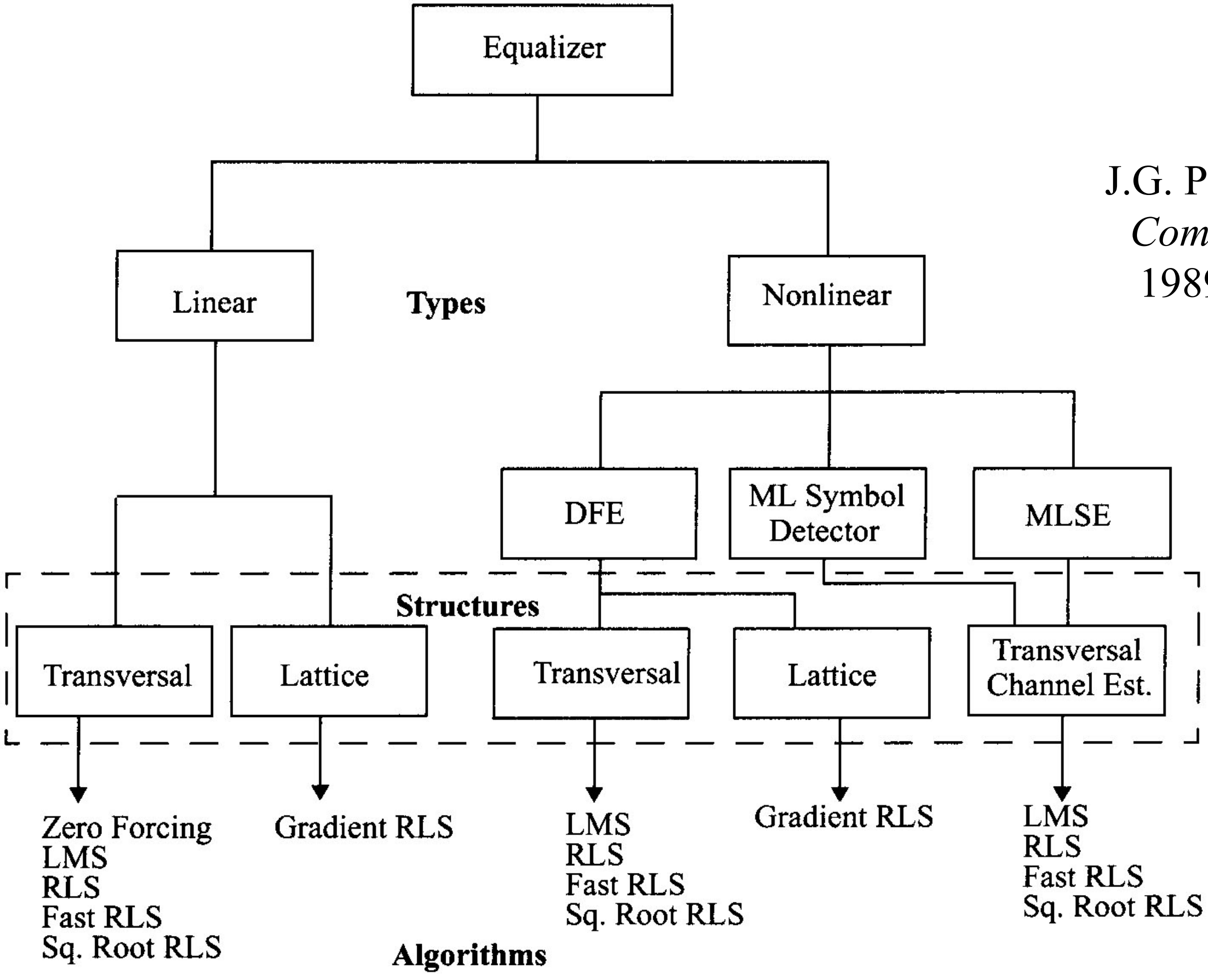


Actual multipath from aircraft on the tarmac at Edwards AFB

Adaptive Equalization

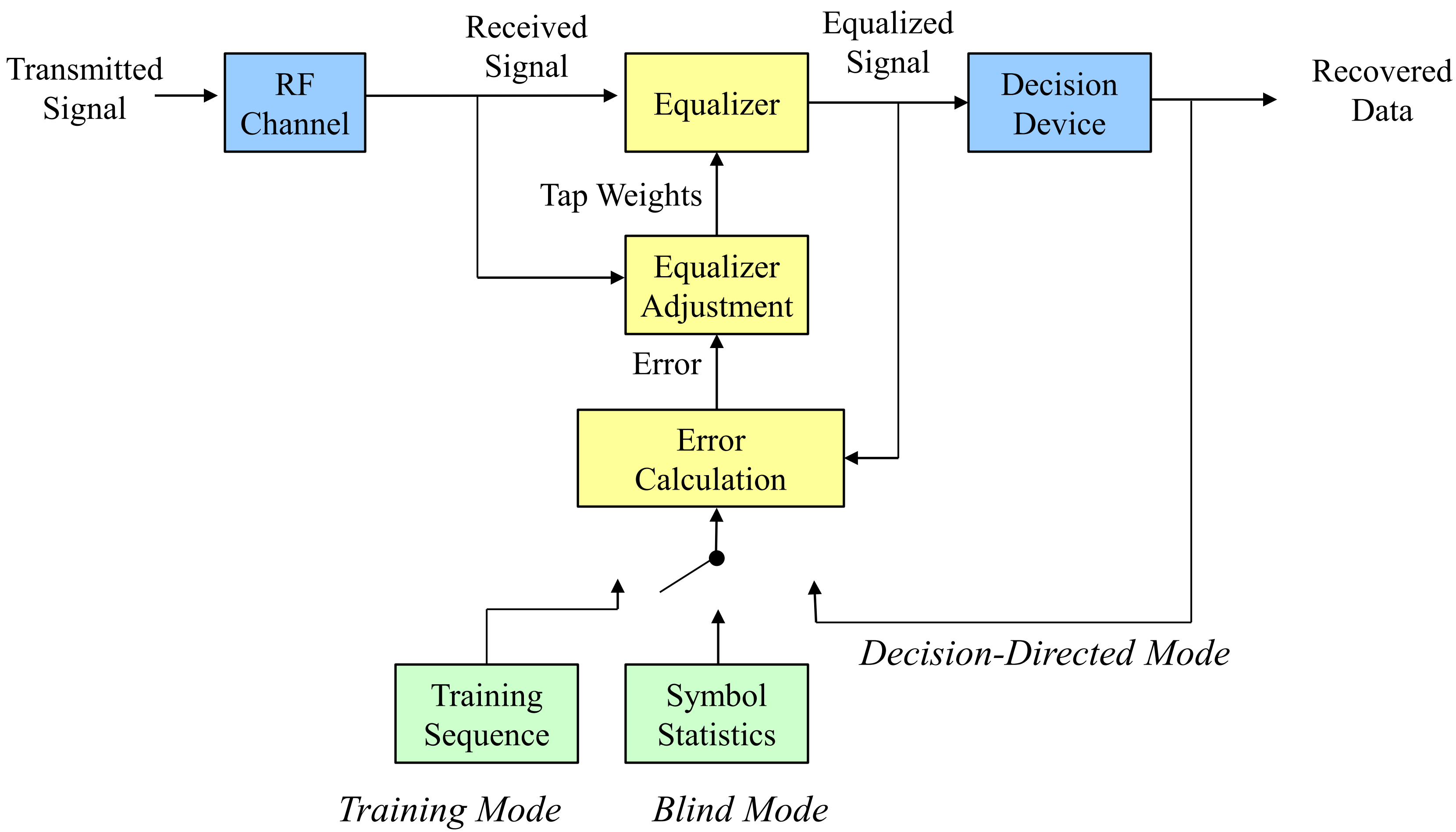
- Consider the multipath channel to be a filter
  - Varies over time
- Consider building a filter which "undoes" the filtering imposed by the channel
  - Let it keep track of the the channel and continuously adapt itself to the channel
- Presto! You have an adaptive equalizer
  - Can repair damage done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

Equalizer Techniques

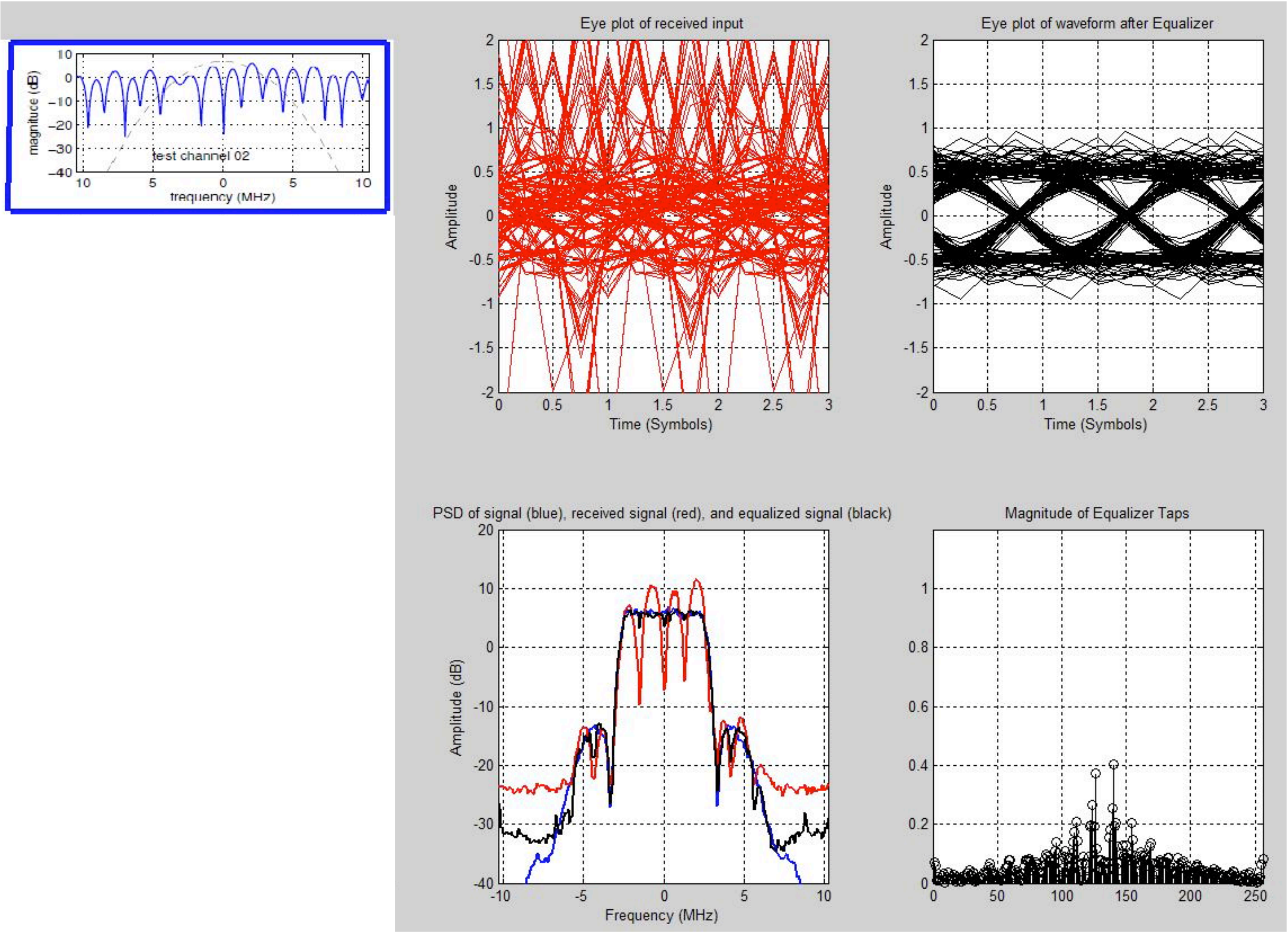


J.G. Proakis, *Digital Communications*. 1989 2nd Edition

Generic Adaptive Equalizer



Equalizer Adaptation



Adaptive Equalizer in Action

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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!

Performance Evaluation of Adaptive Equalizers

So Many Channels...

- Each path is characterized by
  - Delay
  - Amplitude
  - Phase shift (potentially time-varying)
- 2, 3, or more paths
- Modulation matters
- SNR matters
- Need a 10-dimensional universe to plot the results
- Way too many test points

Let’s Simplify

- Stick to 2-ray model
  - Easy to synthesize
  - Still allows a range of channels from easy to impossible
  - Maybe we add a third ray for a limited set of tests
- Stick to one SNR
  - High enough that the equalizer works on mitigating multipath, not rejecting noise
  - Not so high that there are never any bit errors
  - Should reflect actual use cases
  - Propose 20 dB
- Limited set of amplitudes and delays
- Many phase angles

Proposed Signal Conditions

- Pick a carrier frequency
  - How many?
  - Nulls “sweep faster” at higher frequencies (dynamic case only)
- 20 dB SNR (without multipath)
- Tier 0, I, and II
  - Tier 0: 1, 5, 10, 20 Mbps
  - Tier I and Tier II: 2, 10, 20, and 40 Mbps
- Areas for further research
  - STC – different multipath on each signal, hmmm….
  - LDPC – six codes?

Proposed *Static* Channels

- Channel response depends on
  - Carrier frequency, ω_c
  - Delay, τ_1
  - Reflection amplitude, $|\Gamma_1|$
  - Reflection phase, $\angle\Gamma_1$
- Delays (in bits) of 0.5, 1, 2, 5, 10, 20, and 50
  - Delays much shorter than 0.5 bit are essentially flat fades, where the signal power is simply gone. EQ cannot help.
- Amplitudes of 0.5 to 0.9 in steps of 0.1
  - For bonus points, include 0.95 and 0.98
- Phases of 0° to 360° in 10° steps

What is the Measured Value?

- Must be observable with EQ both on and off
- Bit error rate is universally understood
- DQM is readily computed from BER
  - With calibration, DQM is much more quickly measured
- Remind me again, what is DQM?

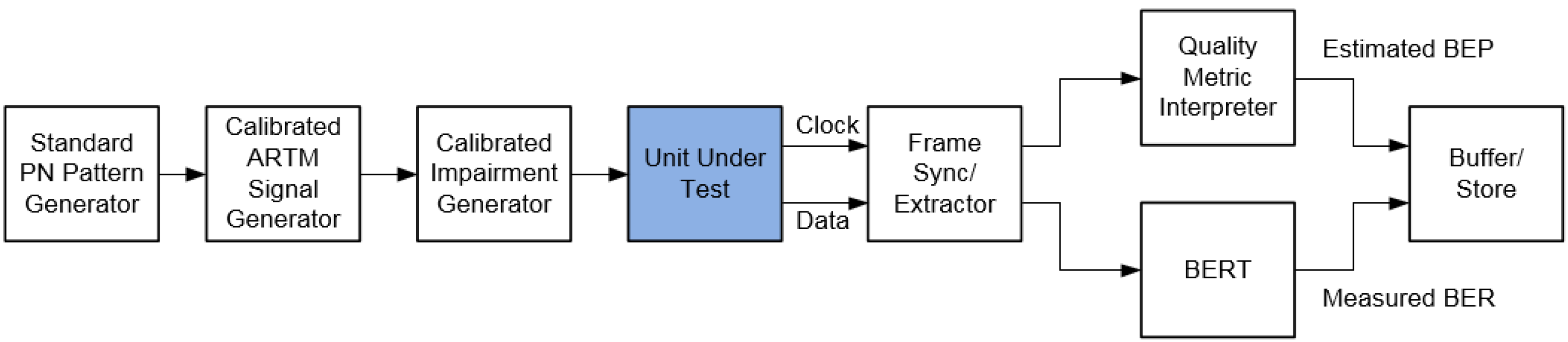
Definition of DQM (a.k.a. Q)

- To a statistician, DQM is the "Log Likelihood Ratio"
- Start with probability of error, P
  - Be practical: 0.5 < P < 1e-12
  - BEP, derived within demod
  - BER, measured with a BERT
- Likelihood Ratio (LR) = P / (1 – P)
- Q = min ($-\log_{10}$(LR), 12)
- Easily reversed:
  - $P = 10^{-Q} / (1 + 10^{-Q})$
- Short version
  - Q = 5 ➔ P = 1e-5

P	Q
0.5	0.000
1E-01	0.954
1E-02	1.996
1E-03	3.000
1E-04	4.000
1E-05	5.000
1E-06	6.000
1E-07	7.000
1E-08	8.000
1E-09	9.000
1E-10	10.000
1E-11	11.000
1E-12	12.000

DQM Calibration Fixture

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



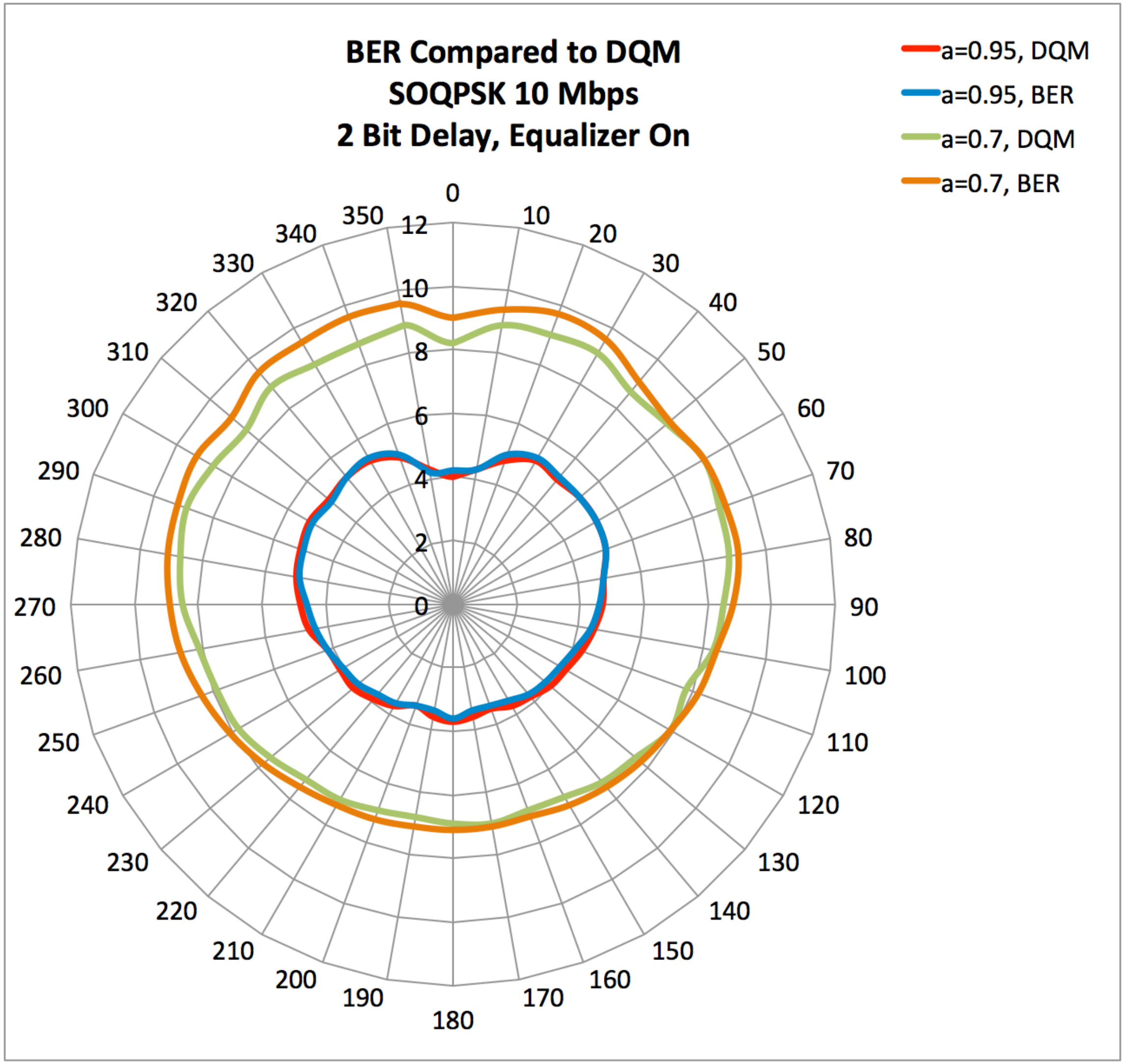
Test Procedure

- 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

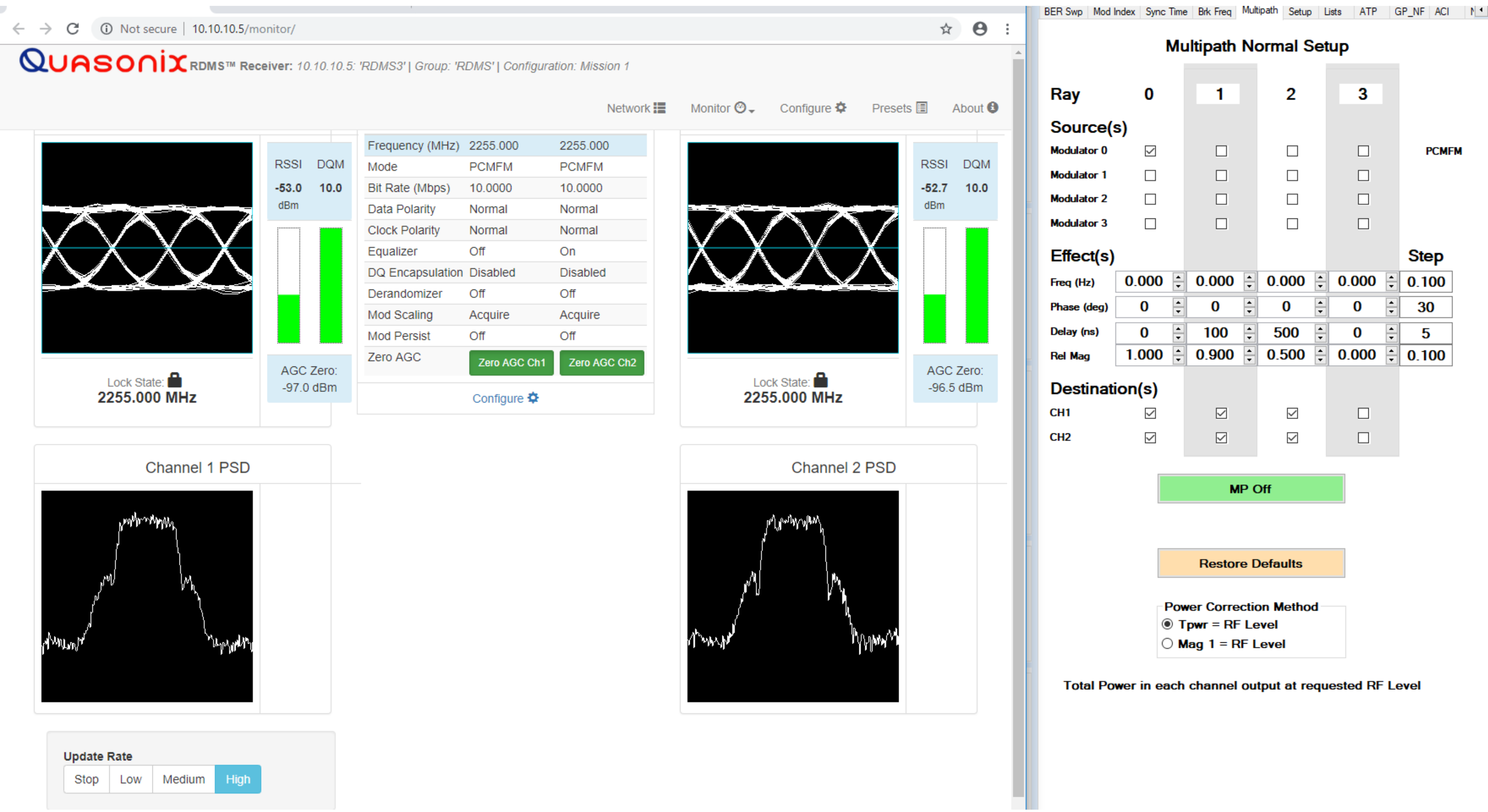
Grading the Tests

- 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" = $\text{Area}_{on} - \text{Area}_{off}$
  - Since the radius is (essentially) the logarithm of the BER, the difference is the number of orders of magnitude improvement in BER

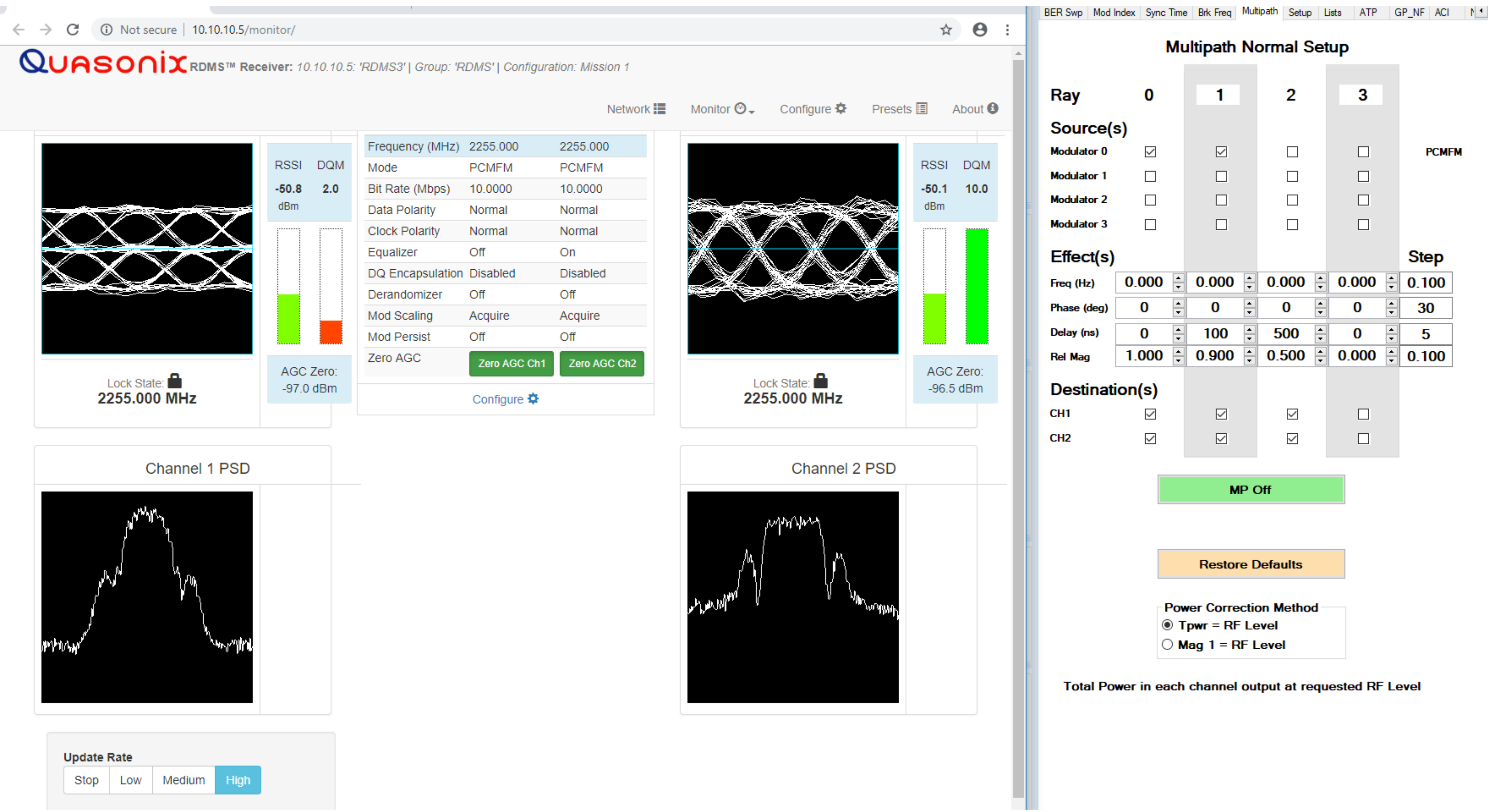
DQM Calibration



No Multipath, No Problem



0-100-0.9



Not secure | 10.10.10.5/monitor/
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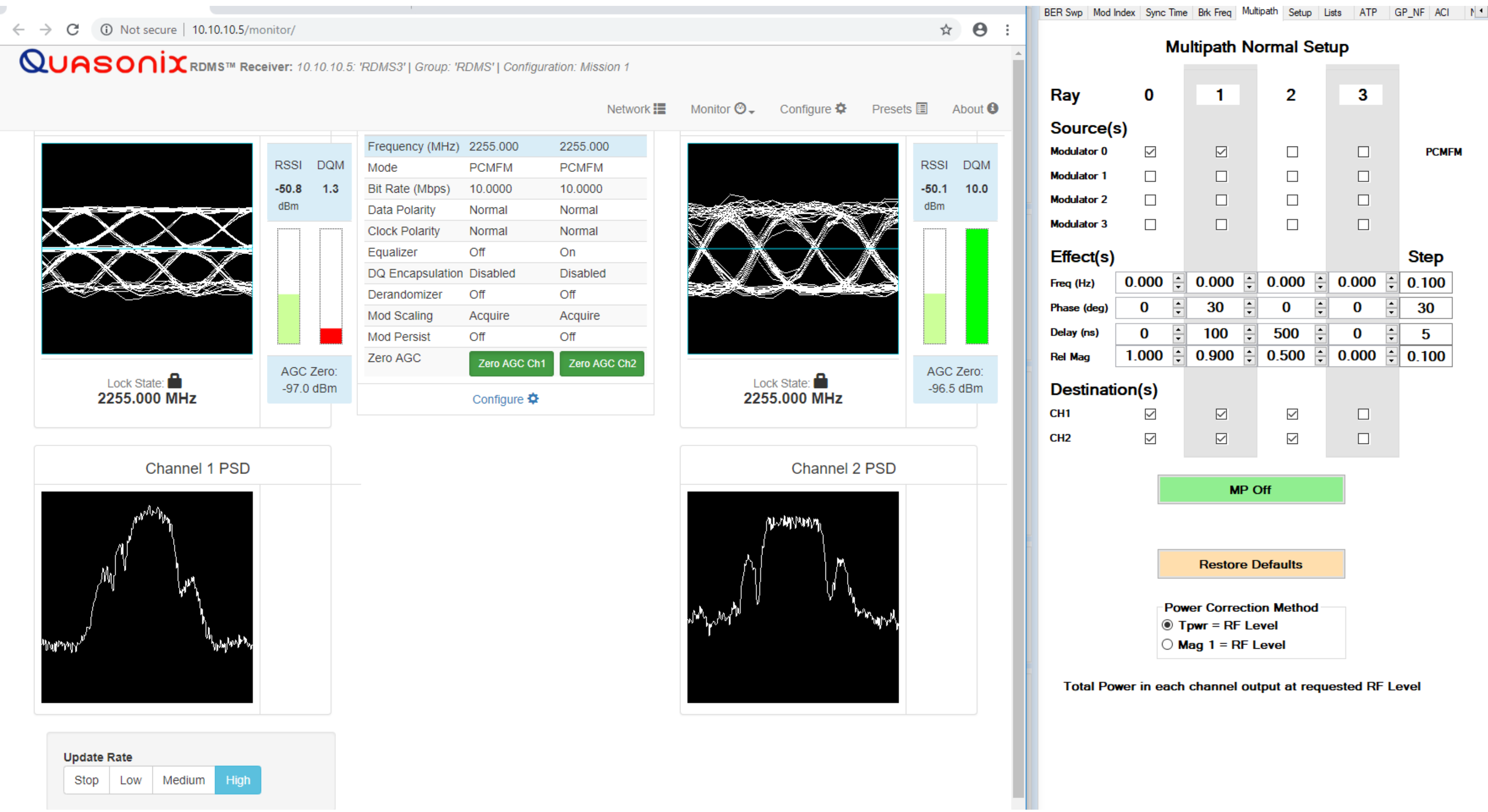
Network
Monitor
Configure
Presets
About
RSSI DQM
-50.8 2.0
dBm
Lock State:
2255.000 MHz
AGC Zero:
-97.0 dBm
Frequency (MHz) 2255.000 2255.000
Mode PCMFM PCMFM
Bit Rate (Mbps) 10.0000 10.0000
Data Polarity Normal Normal
Clock Polarity Normal Normal
Equalizer Off On
DQ Encapsulation Disabled Disabled
Derandomizer Off Off
Mod Scaling Acquire Acquire
Mod Persist Off Off
Zero AGC
Zero AGC Ch1
Zero AGC Ch2
Configure
RSSI DQM
-50.1 10.0
dBm
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

30-100-0.9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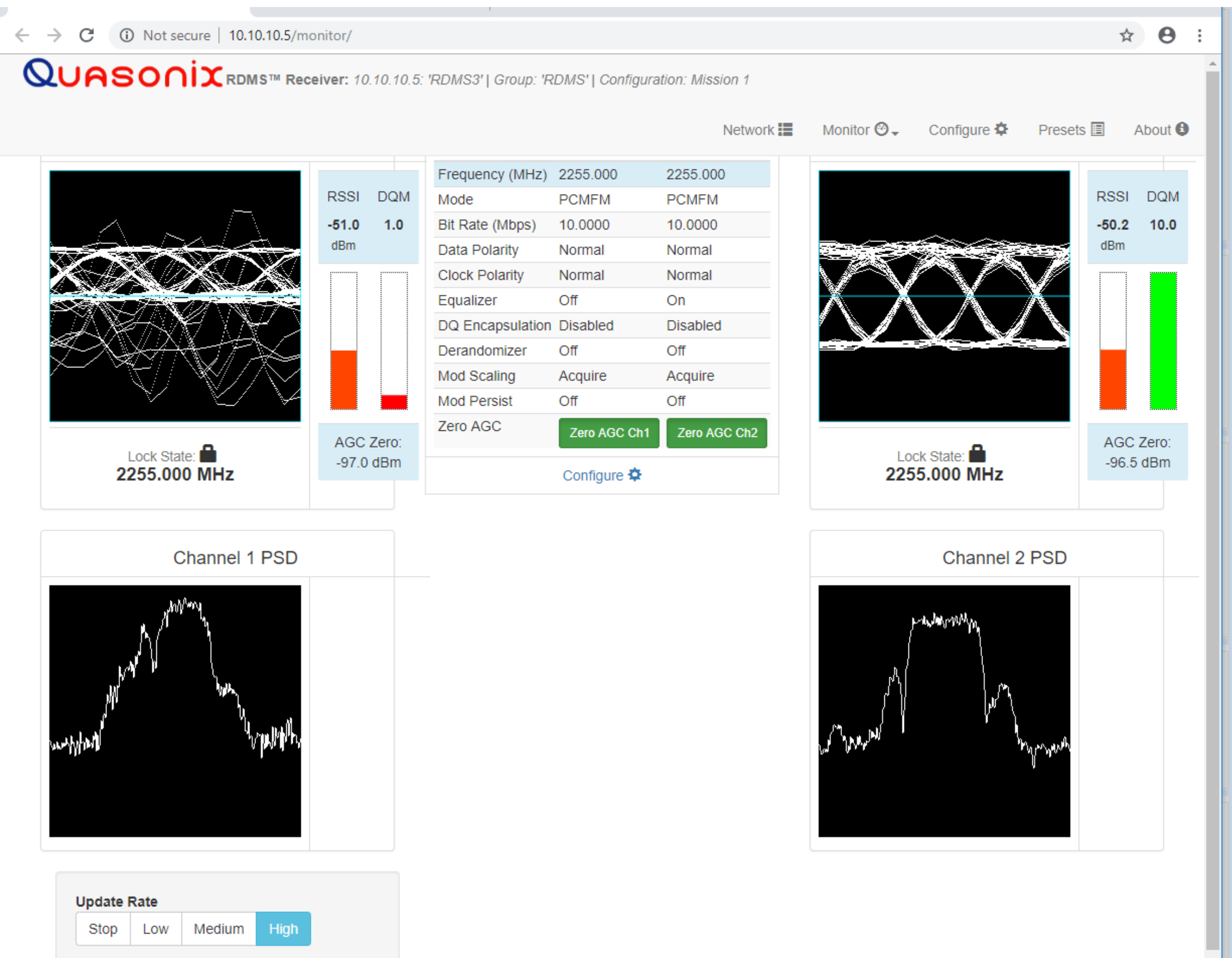
Network
Monitor
Configure
Presets
About
RSSI DQM
-50.8 1.3
dBm
Lock State:
2255.000 MHz
AGC Zero: -97.0 dBm
Frequency (MHz) 2255.000 2255.000
Mode PCMFM PCMFM
Bit Rate (Mbps) 10.0000 10.0000
Data Polarity Normal Normal
Clock Polarity Normal Normal
Equalizer Off On
DQ Encapsulation Disabled Disabled
Derandomizer Off Off
Mod Scaling Acquire Acquire
Mod Persist Off Off
Zero AGC
Zero AGC Ch1
Zero AGC Ch2
Configure
RSSI DQM
-50.1 10.0
dBm
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 30 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

60-100-0.9



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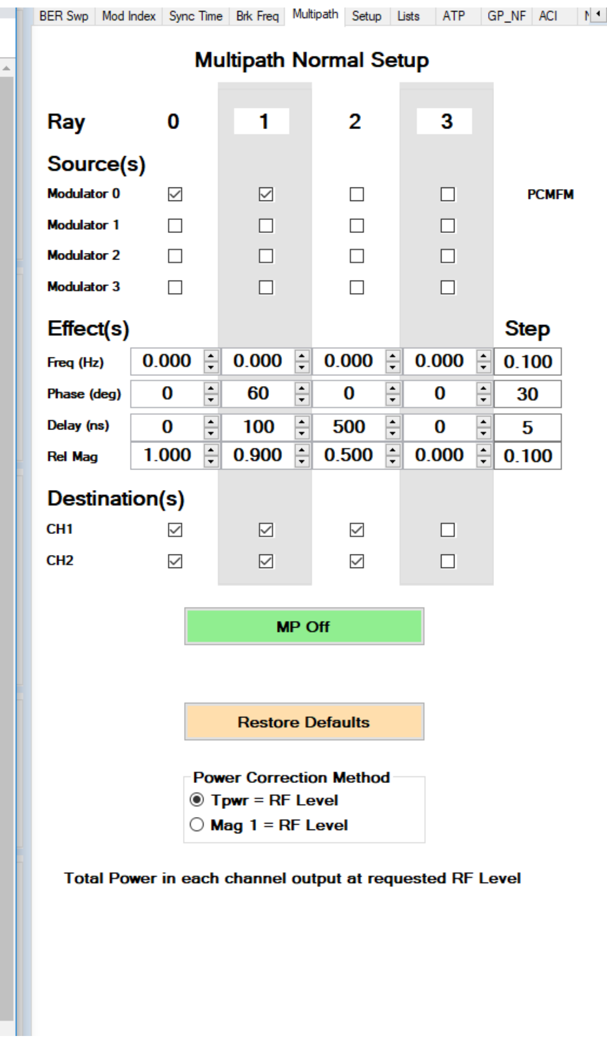
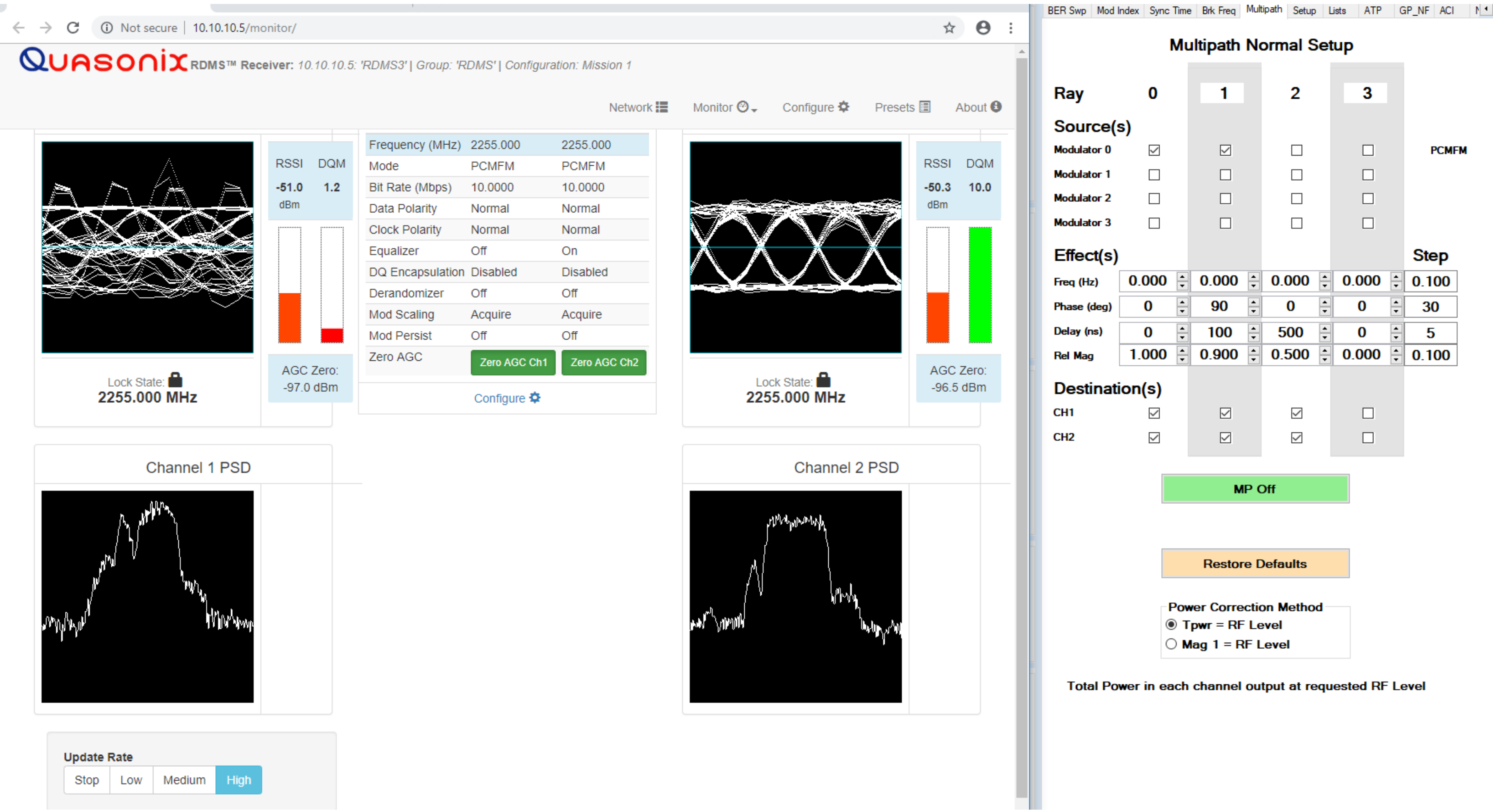
Network
Monitor
Configure
Presets
About
RSSI DQM
-51.0 1.0
dBm
Lock State:
2255.000 MHz
AGC Zero:
-97.0 dBm
Frequency (MHz) 2255.000 2255.000
Mode PCMFM PCMFM
Bit Rate (Mbps) 10.0000 10.0000
Data Polarity Normal Normal
Clock Polarity Normal Normal
Equalizer Off On
DQ Encapsulation Disabled Disabled
Derandomizer Off Off
Mod Scaling Acquire Acquire
Mod Persist Off Off
Zero AGC
Zero AGC Ch1
Zero AGC Ch2
Configure
RSSI DQM
-50.2 10.0
dBm
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 60 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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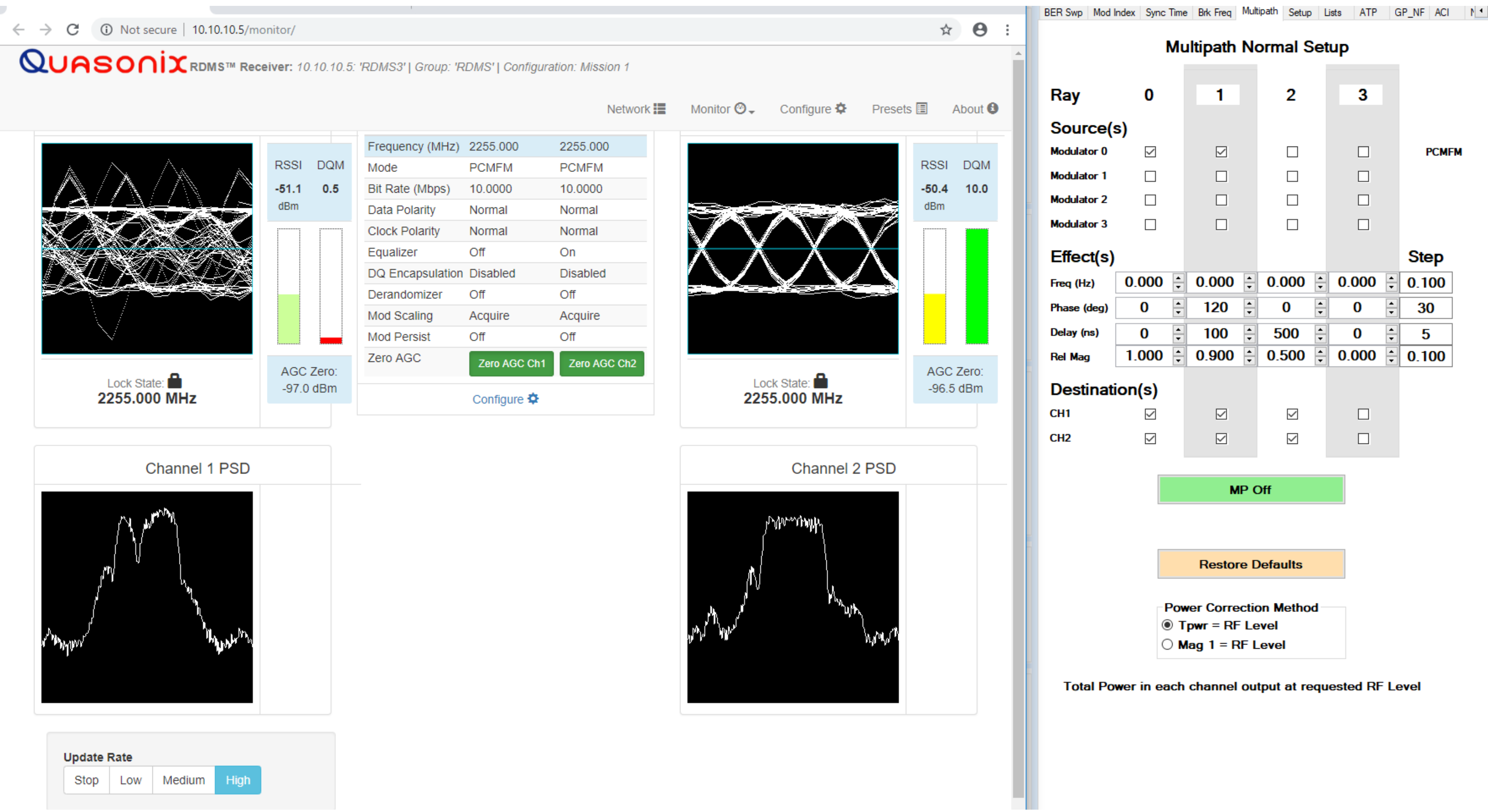
Network
Monitor
Configure
Presets
About
RSSI DQM
-51.0 1.2
dBm
Lock State:
2255.000 MHz
AGC Zero:
-97.0 dBm
Frequency (MHz) 2255.000 2255.000
Mode PCMFM PCMFM
Bit Rate (Mbps) 10.0000 10.0000
Data Polarity Normal Normal
Clock Polarity Normal Normal
Equalizer Off On
DQ Encapsulation Disabled Disabled
Derandomizer 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:
-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 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
Restore Defaults
Power Correction Method
Tpwr = RF Level
Mag 1 = RF Level
Total Power in each channel output at requested RF Level

120-100-0.9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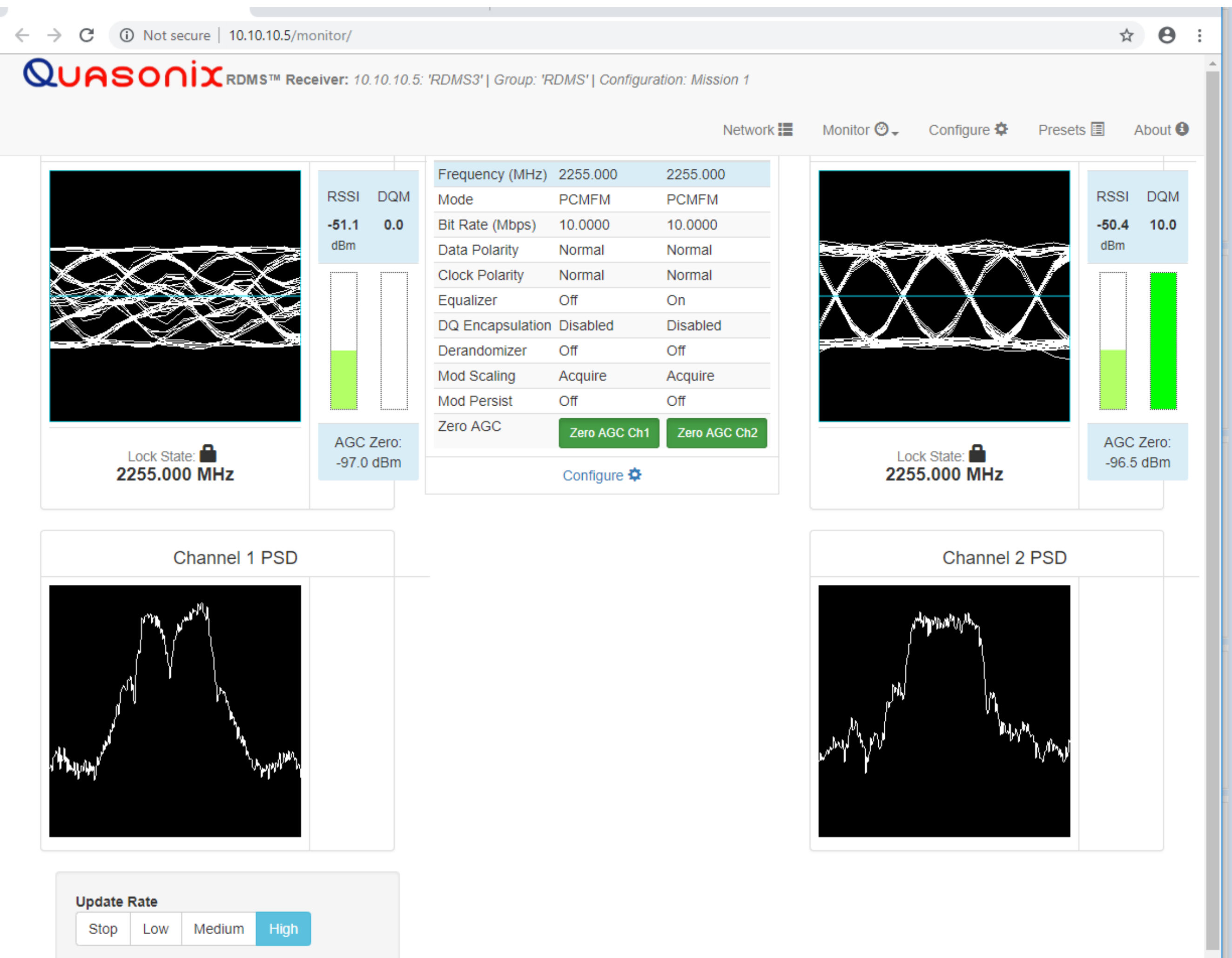
Network
Monitor
Configure
Presets
About
RSSI DQM
-51.1 0.5
dBm
Lock State:
2255.000 MHz
AGC Zero: -97.0 dBm
Frequency (MHz) 2255.000 2255.000
Mode PCMFM PCMFM
Bit Rate (Mbps) 10.0000 10.0000
Data Polarity Normal Normal
Clock Polarity Normal Normal
Equalizer Off On
DQ Encapsulation Disabled Disabled
Derandomizer Off Off
Mod Scaling Acquire Acquire
Mod Persist Off Off
Zero AGC
Zero AGC Ch1
Zero AGC Ch2
Configure
RSSI DQM
-50.4 10.0
dBm
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) 0 120 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

150-100-0.9



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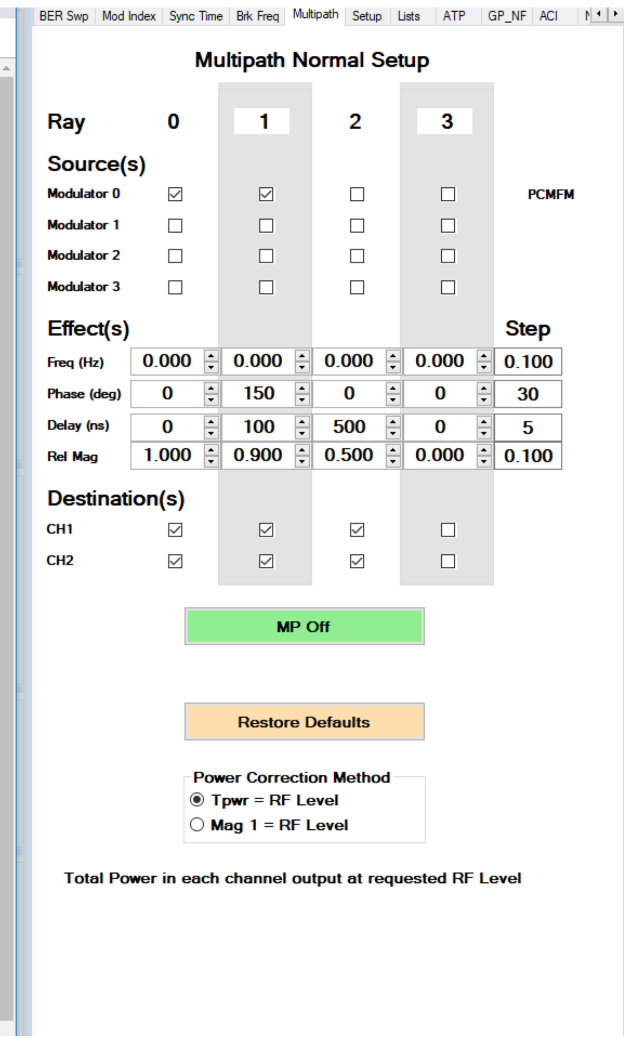
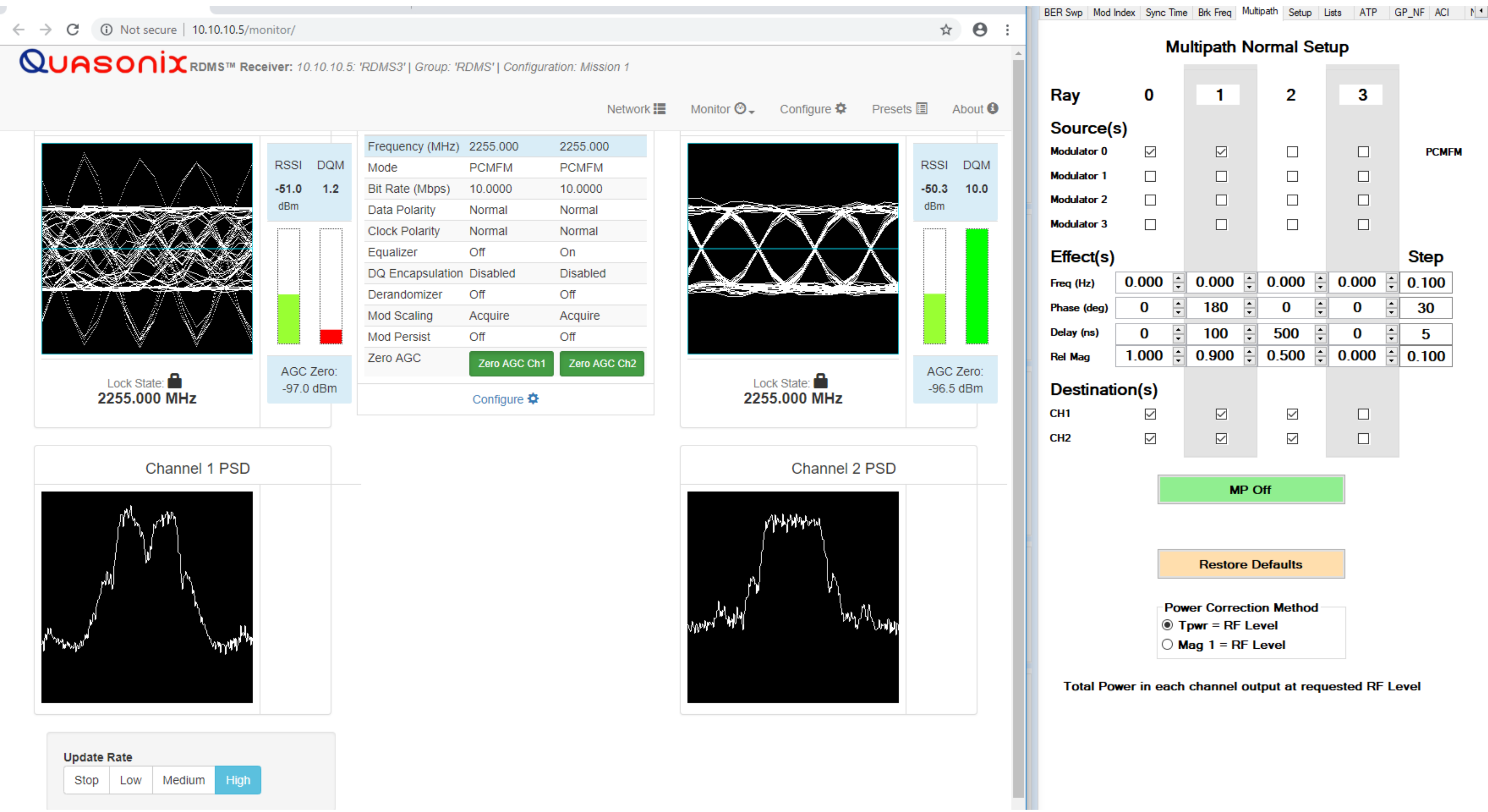
RDMS™ Receiver: 10.10.10.5: 'RDMS3' | Group: 'RDMS' | Configuration: Mission 1
Network
Monitor
Configure
Presets
About
RSSI DQM
-51.1 0.0
dBm
AGC Zero: -97.0 dBm
Lock State:
2255.000 MHz
Frequency (MHz) 2255.000 2255.000
Mode PCMFM PCMFM
Bit Rate (Mbps) 10.0000 10.0000
Data Polarity Normal Normal
Clock 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
-50.4 10.0
dBm
AGC Zero: -96.5 dBm
Lock State:
2255.000 MHz
Channel 1 PSD
Channel 2 PSD
Update Rate
Stop
Low
Medium
High

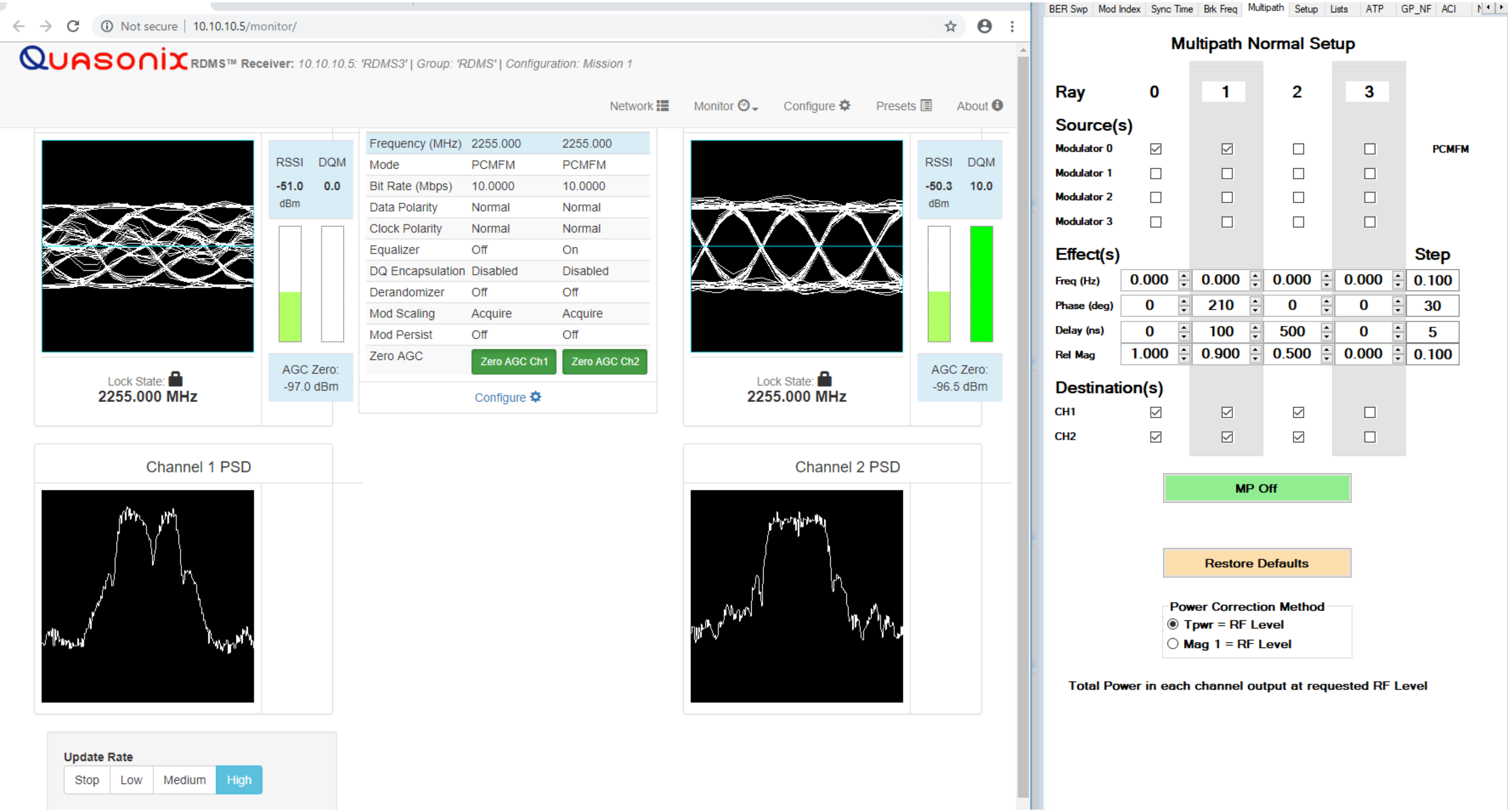


BER Swp
Mod Index
Sync Time
Brk Freq
Multipath
Setup
Lists
ATP
GP_NF
ACI
Multipath Normal Setup
Ray 0 1 2 3
Source(s)
Modulator 0
Modulator 1
Modulator 2
Modulator 3
PCMFM
Effect(s)
Step
Freq (Hz) 0.000 0.000 0.000 0.000 0.100
Phase (deg) 0 150 0 0 30
Delay (ns) 0 100 500 0 5
Rel Mag 1.000 0.900 0.500 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

180-100-0.9

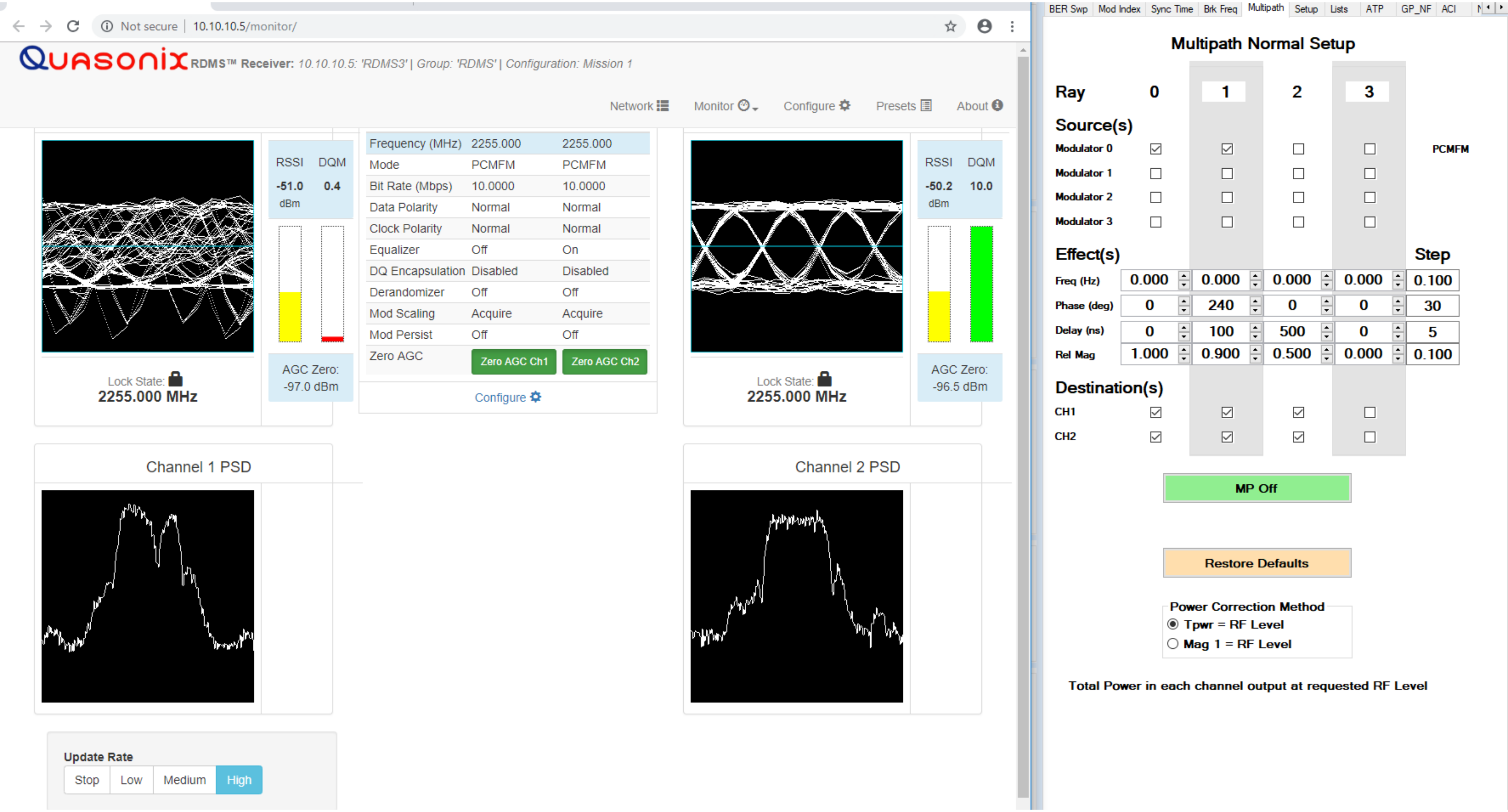

Not secure | 10.10.10.5/monitor/
QUASONIX RDMS™ Receiver: 10.10.10.5: 'RDMS3' | Group: 'RDMS' | Configuration: Mission 1
Network
Monitor
Configure
Presets
About
RSSI DQM
-51.0 1.2
dBm
Lock State:
2255.000 MHz
AGC Zero:
-97.0 dBm
Frequency (MHz) 2255.000 2255.000
Mode PCMFM PCMFM
Bit Rate (Mbps) 10.0000 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:
-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) 0 180 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

210-100-0.9



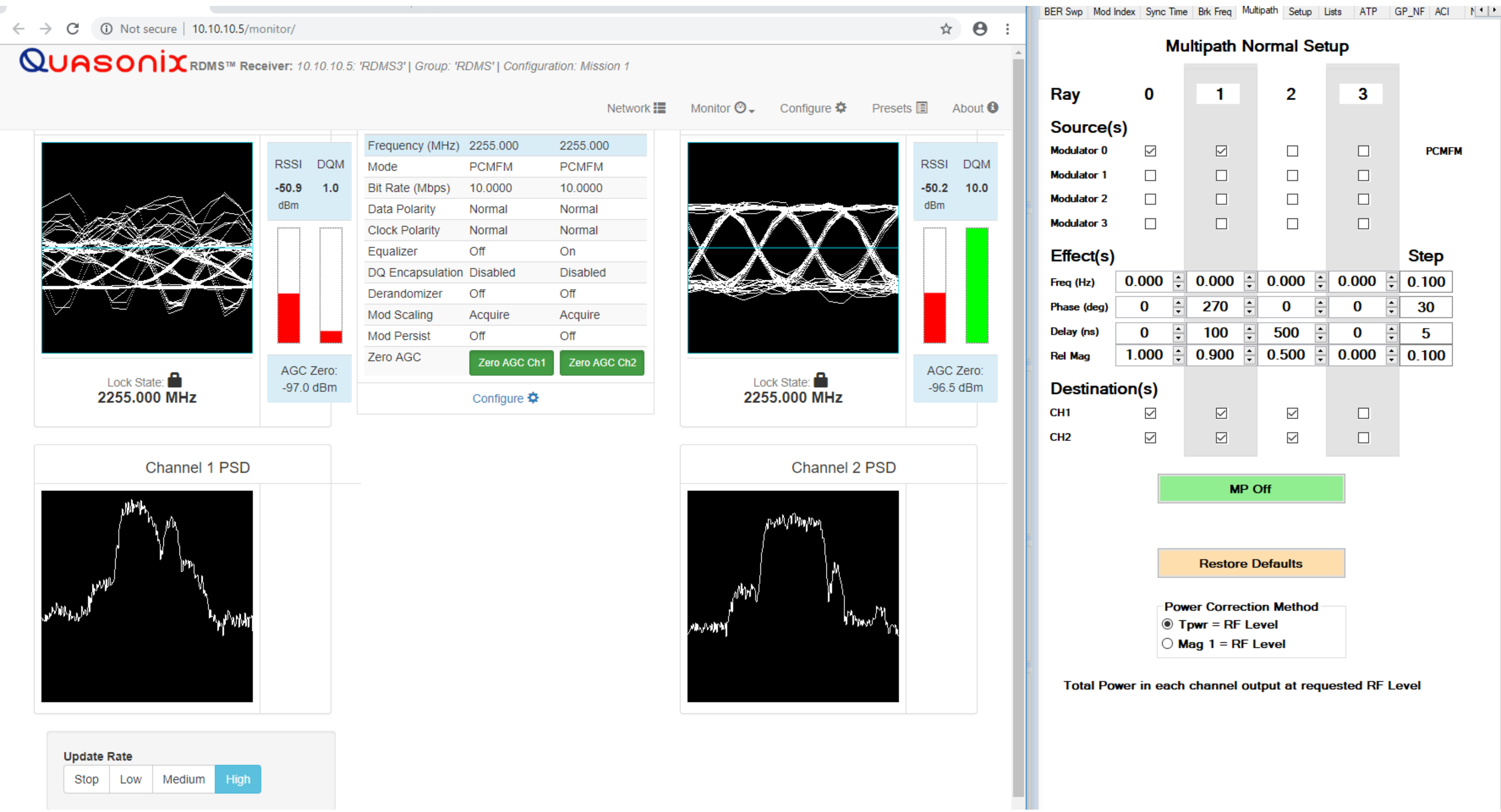
Not secure | 10.10.10.5/monitor/
QUASONIX RDMS™ Receiver: 10.10.10.5: 'RDMS3' | Group: 'RDMS' | Configuration: Mission 1
Network
Monitor
Configure
Presets
About
RSSI DQM
-51.0 0.0
dBm
Lock State:
2255.000 MHz
AGC Zero: -97.0 dBm
Frequency (MHz) 2255.000 2255.000
Mode PCMFM PCMFM
Bit Rate (Mbps) 10.0000 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: -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) 0 210 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

240-100-0.9



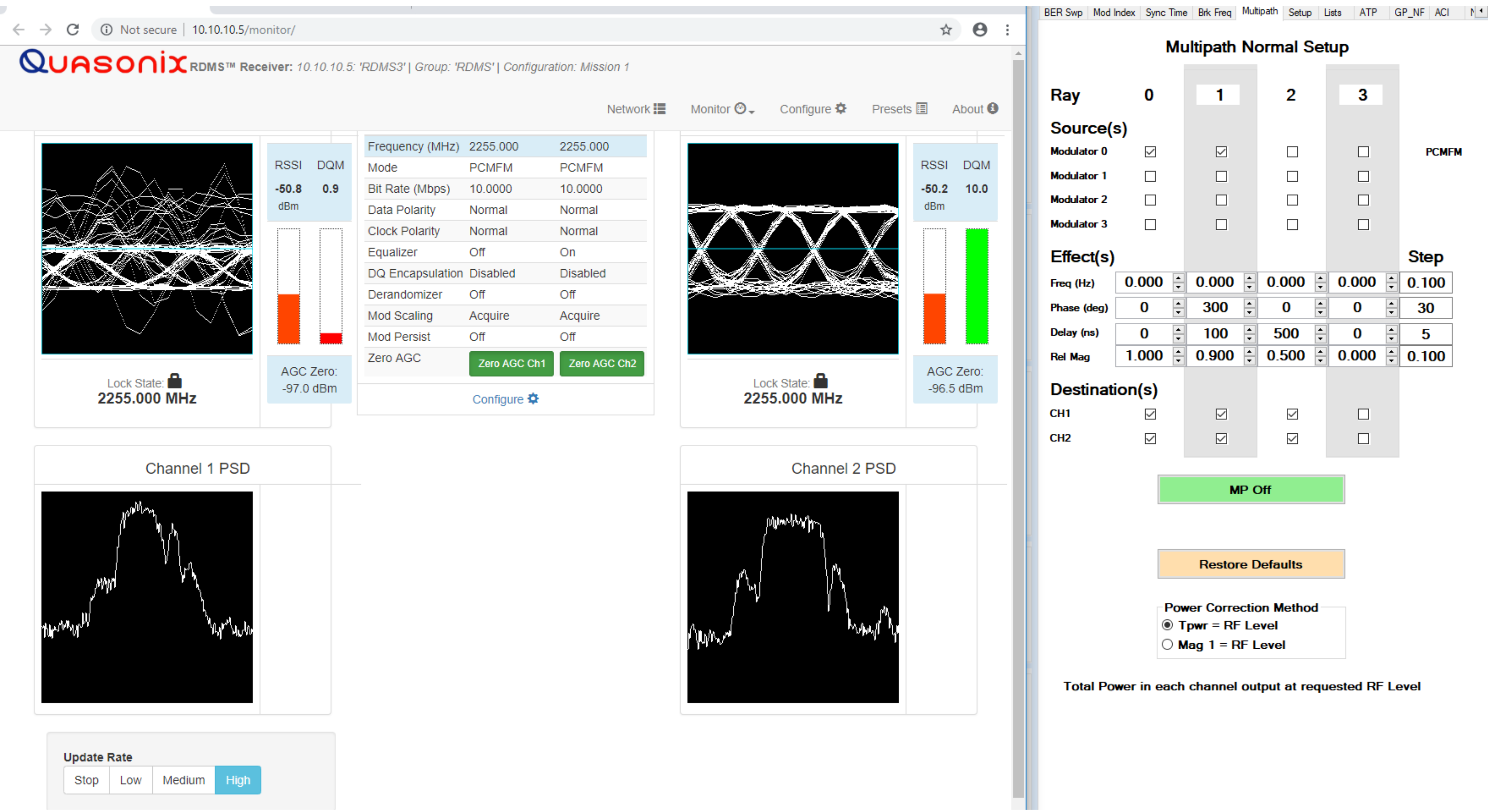
Not secure | 10.10.10.5/monitor/
RDMS™ Receiver: 10.10.10.5: 'RDMS3' | Group: 'RDMS' | Configuration: Mission 1
Network
Monitor
Configure
Presets
About
RSSI DQM
-51.0 0.4
dBm
Lock State:
2255.000 MHz
AGC Zero:
-97.0 dBm
Frequency (MHz) 2255.000 2255.000
Mode PCMFM PCMFM
Bit Rate (Mbps) 10.0000 10.0000
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
-50.2 10.0
dBm
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) 0 240 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

270-100-0.9



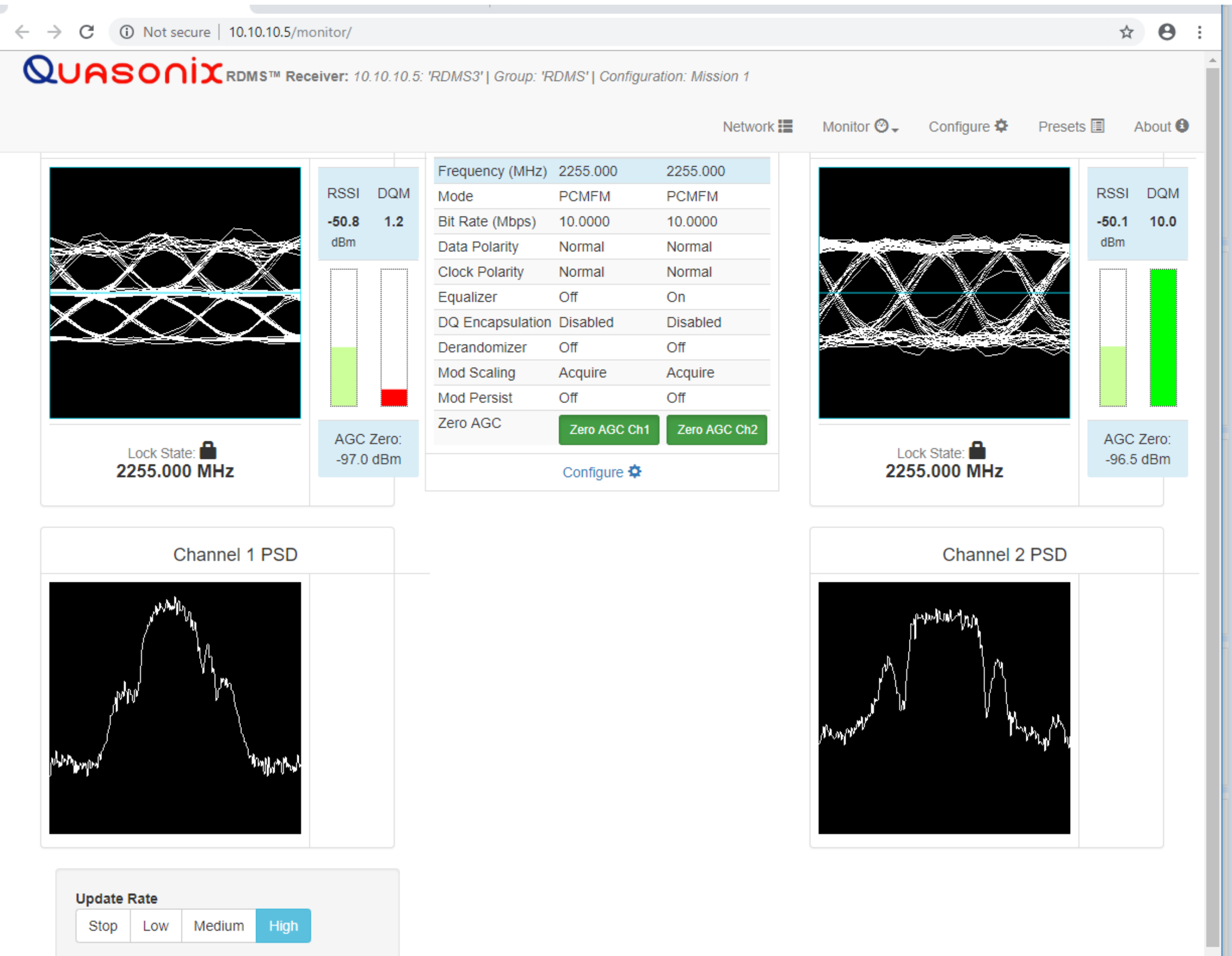
Terry Hill - thill@quasonix.com

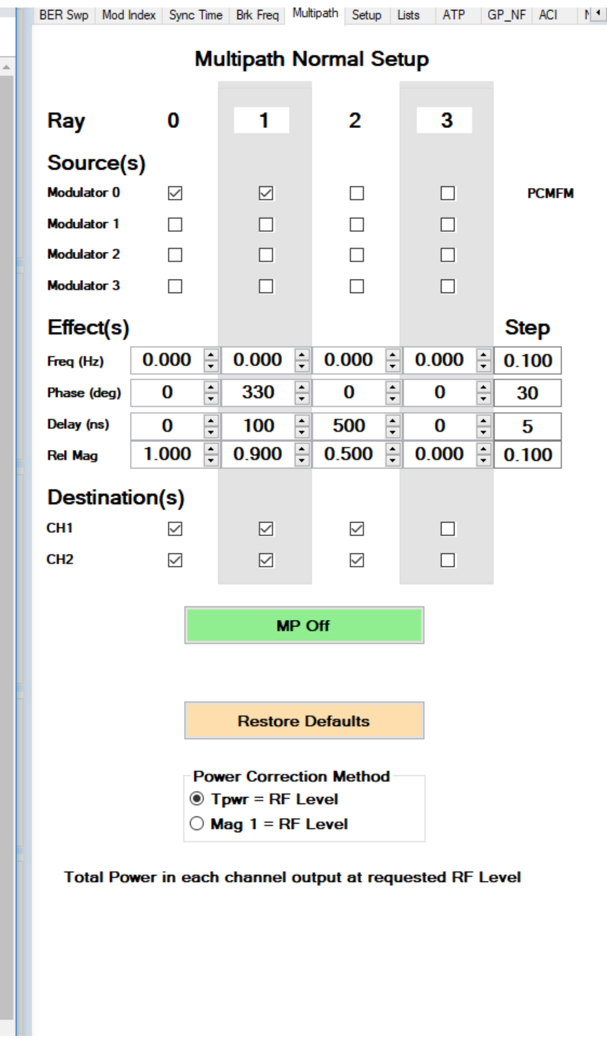
300-100-0.9



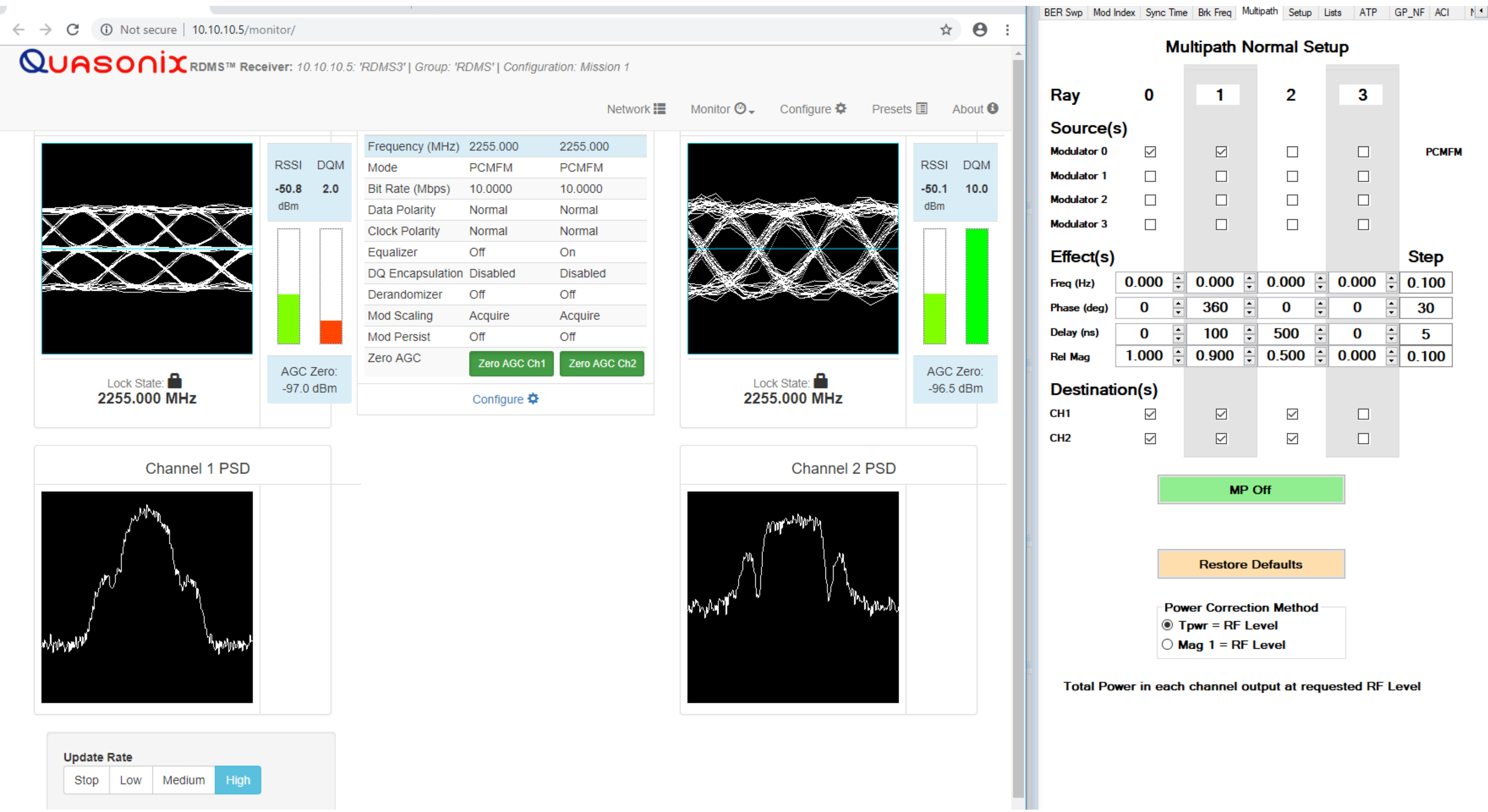
Not secure | 10.10.10.5/monitor/
QUASONIX RDMS™ Receiver: 10.10.10.5: 'RDMS3' | Group: 'RDMS' | Configuration: Mission 1
Network
Monitor
Configure
Presets
About
RSSI DQM
-50.8 0.9
dBm
Lock State:
2255.000 MHz
AGC Zero:
-97.0 dBm
Frequency (MHz) 2255.000 2255.000
Mode PCMFM PCMFM
Bit Rate (Mbps) 10.0000 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
-50.2 10.0
dBm
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) 0 300 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

330-100-0.9

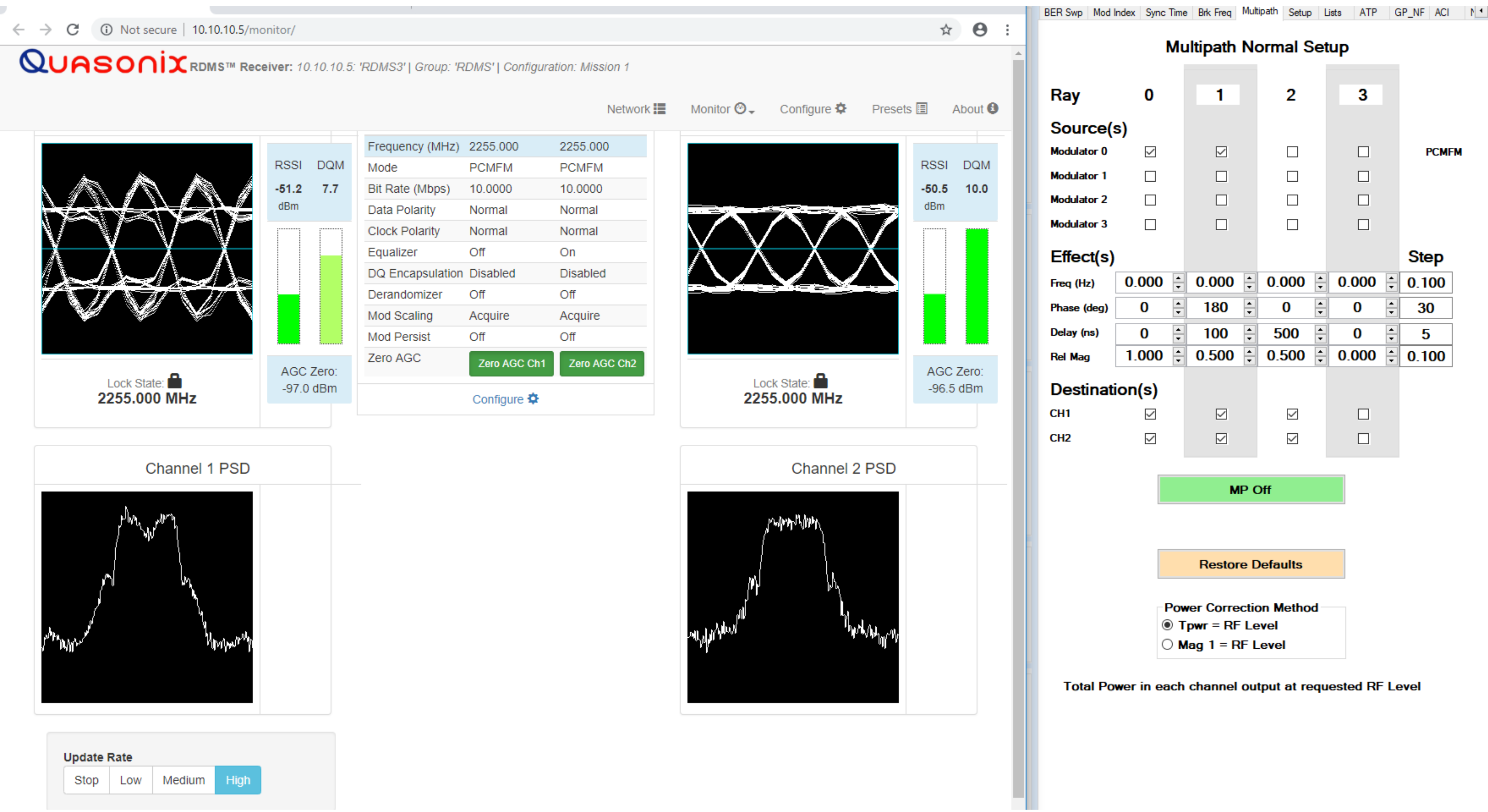

Not secure | 10.10.10.5/monitor/
QUASONIX RDMS™ Receiver: 10.10.10.5: 'RDMS3' | Group: 'RDMS' | Configuration: Mission 1
Network
Monitor
Configure
Presets
About
RSSI DQM
-50.8 1.2
dBm
Lock State:
2255.000 MHz
AGC Zero:
-97.0 dBm
Frequency (MHz) 2255.000 2255.000
Mode PCMFM PCMFM
Bit Rate (Mbps) 10.0000 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
-50.1 10.0
dBm
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) 0 330 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

360-100-0.9

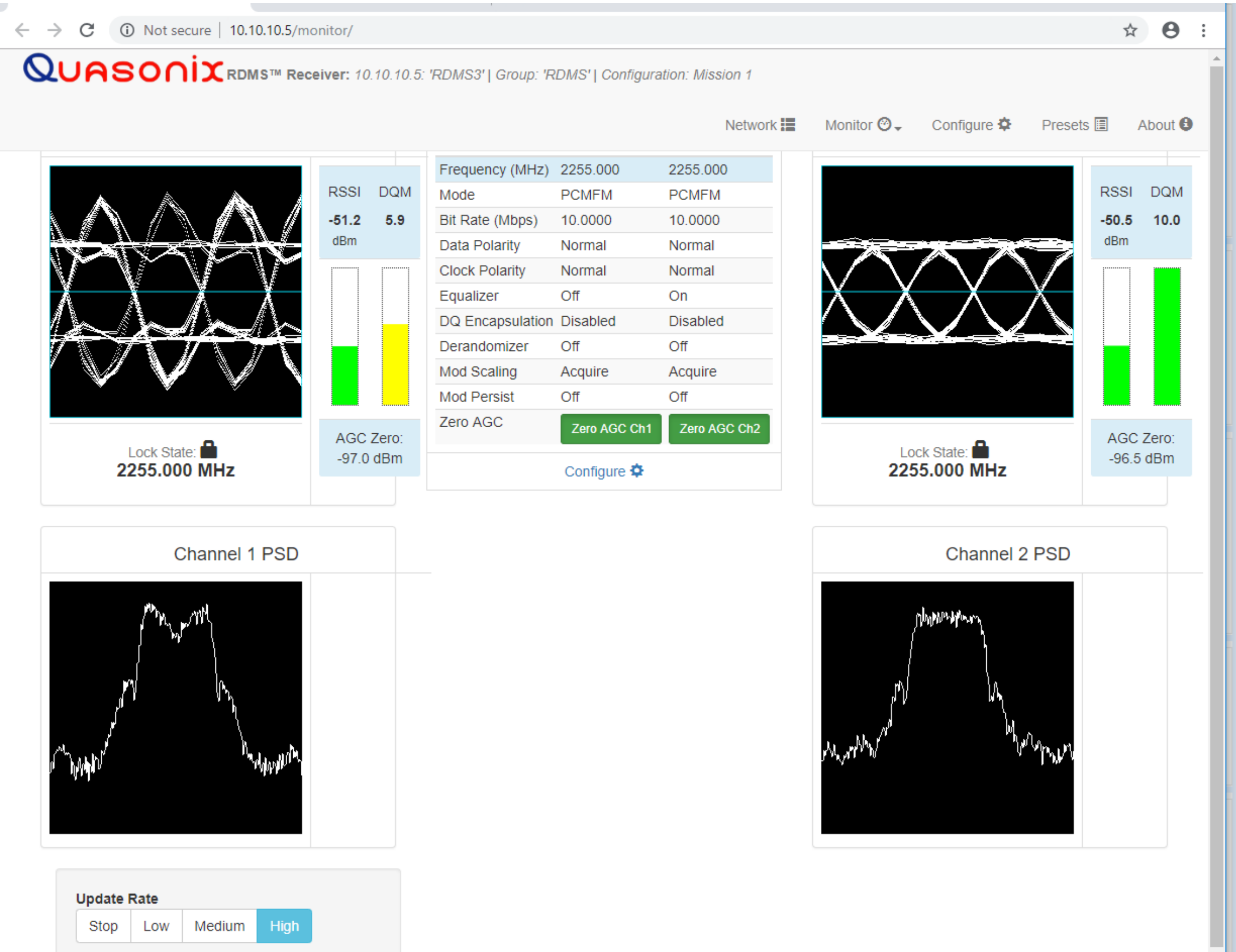

Not secure | 10.10.10.5/monitor/
Quasonix RDMS™ Receiver: 10.10.10.5: 'RDMS3' | Group: 'RDMS' | Configuration: Mission 1
Network
Monitor
Configure
Presets
About
RSSI DQM
-50.8 2.0
dBm
Lock State:
2255.000 MHz
AGC Zero:
-97.0 dBm
Frequency (MHz) 2255.000 2255.000
Mode PCMFM PCMFM
Bit Rate (Mbps) 10.0000 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
-50.1 10.0
dBm
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) 0 360 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

180-100-0.5

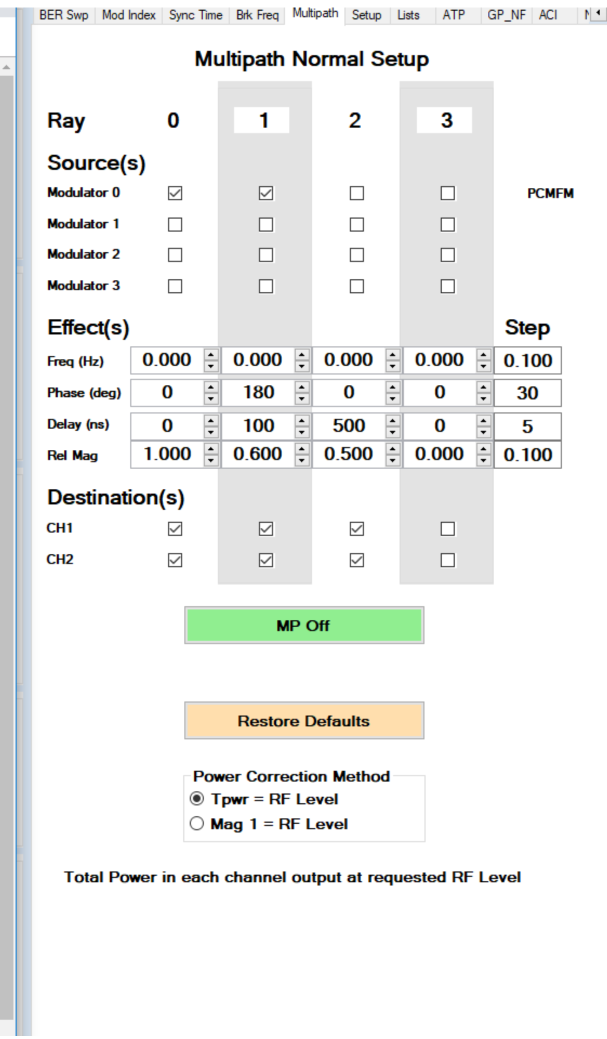


Not secure | 10.10.10.5/monitor/
QUASONIX RDMS™ Receiver: 10.10.10.5: 'RDMS3' | Group: 'RDMS' | Configuration: Mission 1
Network
Monitor
Configure
Presets
About
RSSI DQM
-51.2 7.7
dBm
Lock State:
2255.000 MHz
AGC Zero: -97.0 dBm
Frequency (MHz) 2255.000 2255.000
Mode PCMFM PCMFM
Bit Rate (Mbps) 10.0000 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
-50.5 10.0
dBm
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) 0 180 0 0 30
Delay (ns) 0 100 500 0 5
Rel Mag 1.000 0.500 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

180-100-0.6

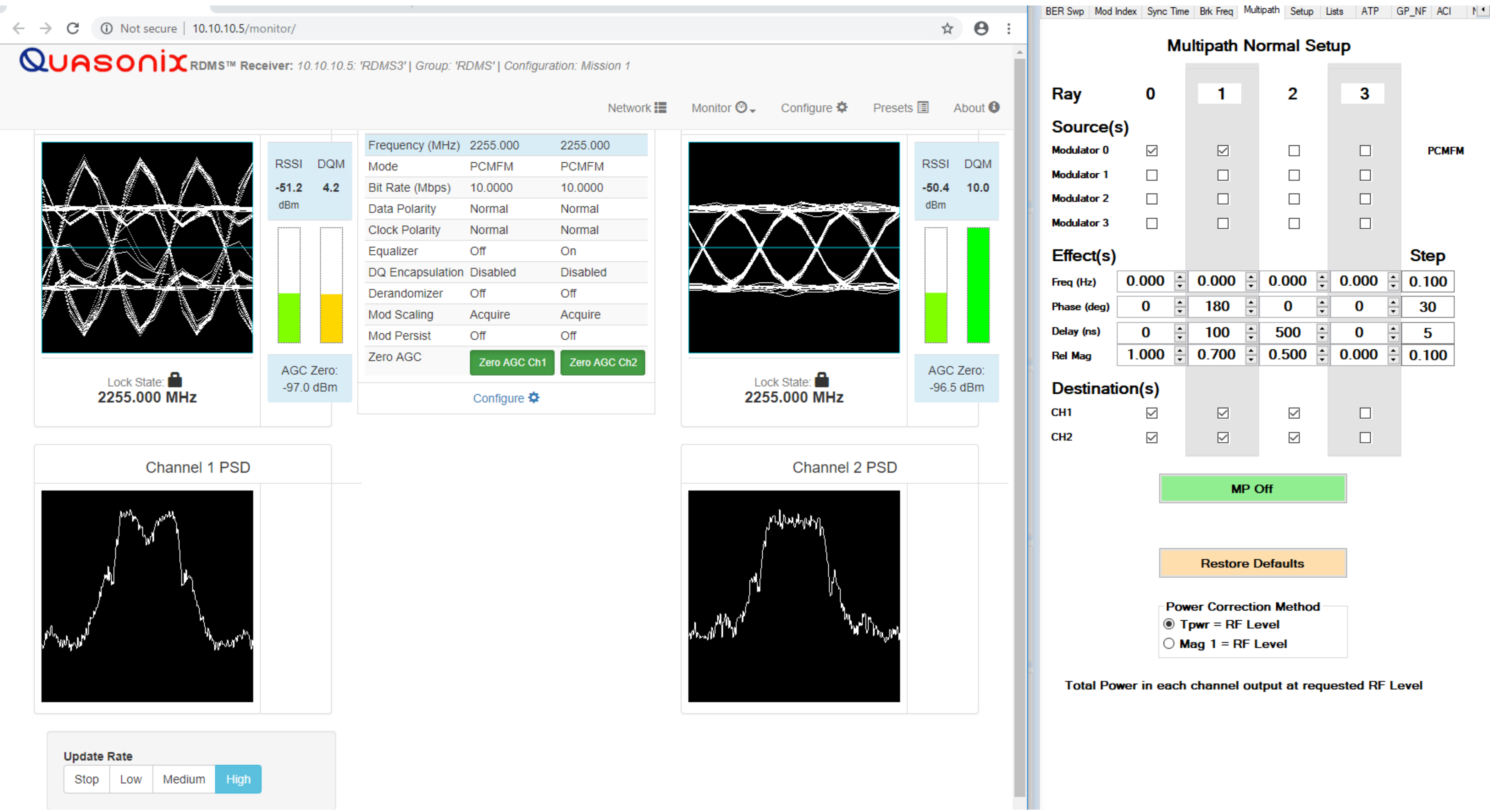


Not secure | 10.10.10.5/monitor/
RDMS™ Receiver: 10.10.10.5: 'RDMS3' | Group: 'RDMS' | Configuration: Mission 1
Network
Monitor
Configure
Presets
About
RSSI DQM
-51.2 5.9
dBm
Lock State:
2255.000 MHz
AGC Zero: -97.0 dBm
Frequency (MHz) 2255.000 2255.000
Mode PCMFM PCMFM
Bit Rate (Mbps) 10.0000 10.0000
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
-50.5 10.0
dBm
Lock State:
2255.000 MHz
AGC Zero: -96.5 dBm
Channel 1 PSD
Channel 2 PSD
Update Rate
Stop
Low
Medium
High



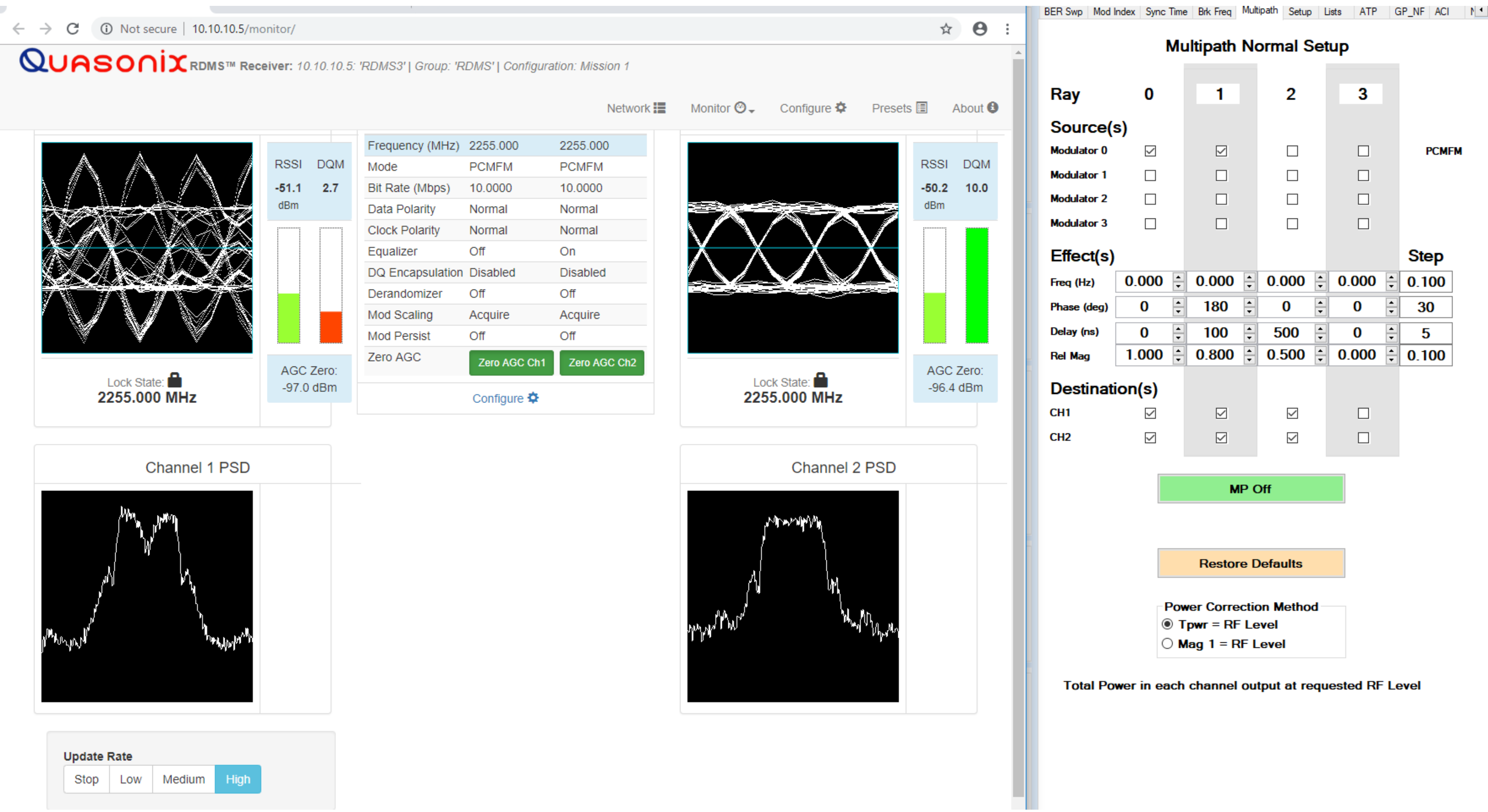
BER Swp
Mod Index
Sync Time
Brk Freq
Multipath
Setup
Lists
ATP
GP_NF
ACI
Multipath Normal Setup
Ray 0 1 2 3
Source(s)
Modulator 0
Modulator 1
Modulator 2
Modulator 3
PCMFM
Effect(s)
Step
Freq (Hz) 0.000 0.000 0.000 0.000 0.100
Phase (deg) 0 180 0 0 30
Delay (ns) 0 100 500 0 5
Rel Mag 1.000 0.600 0.500 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

180-100-0.7



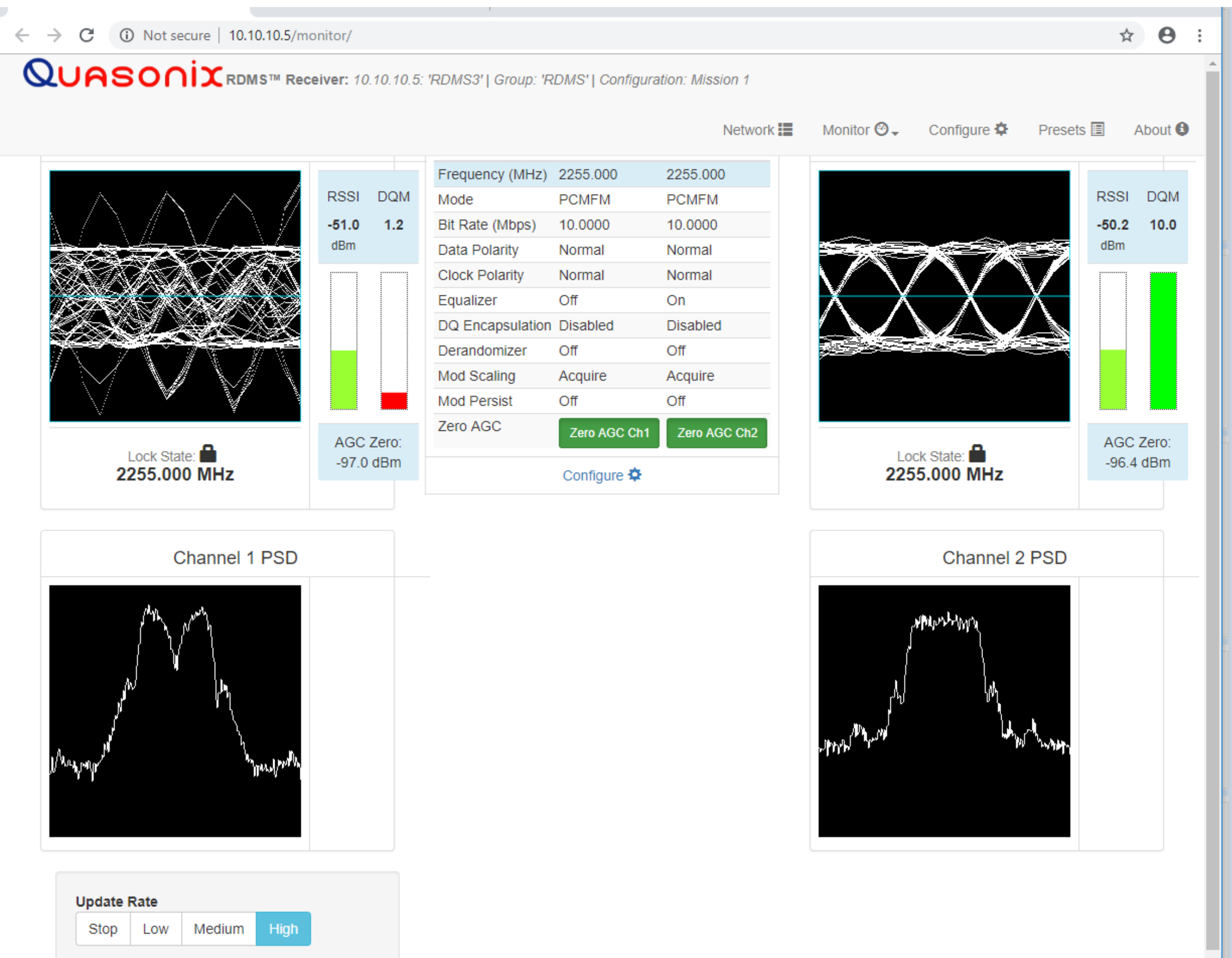
Not secure | 10.10.10.5/monitor/
RDMS™ Receiver: 10.10.10.5: 'RDMS3' | Group: 'RDMS' | Configuration: Mission 1
Network
Monitor
Configure
Presets
About
RSSI DQM
-51.2 4.2
dBm
Lock State:
2255.000 MHz
AGC Zero:
-97.0 dBm
Frequency (MHz) 2255.000 2255.000
Mode PCMFM PCMFM
Bit Rate (Mbps) 10.0000 10.0000
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
-50.4 10.0
dBm
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) 0 180 0 0 30
Delay (ns) 0 100 500 0 5
Rel Mag 1.000 0.700 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

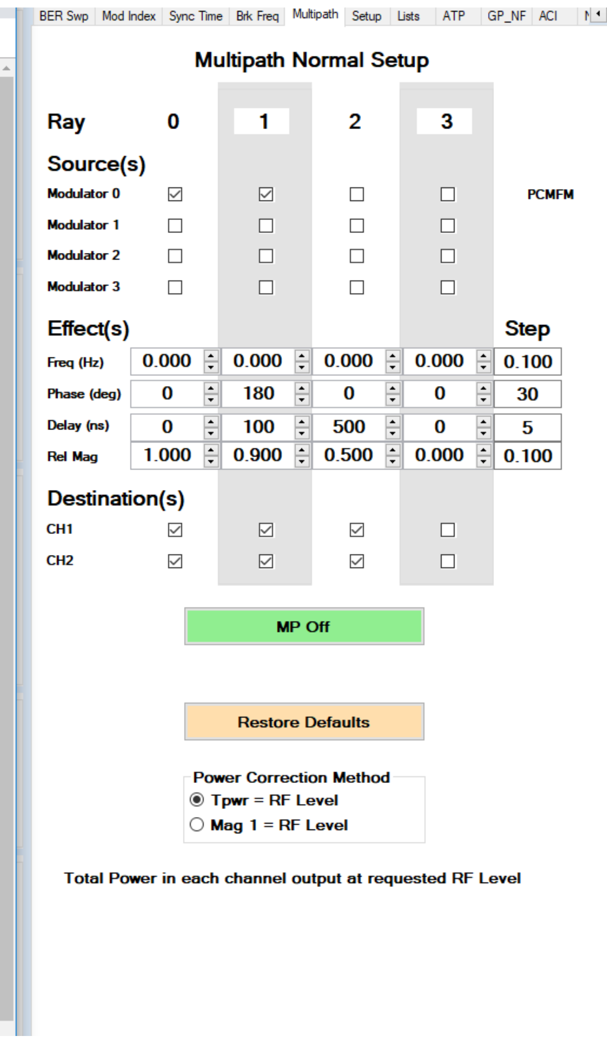
180-100-0.8



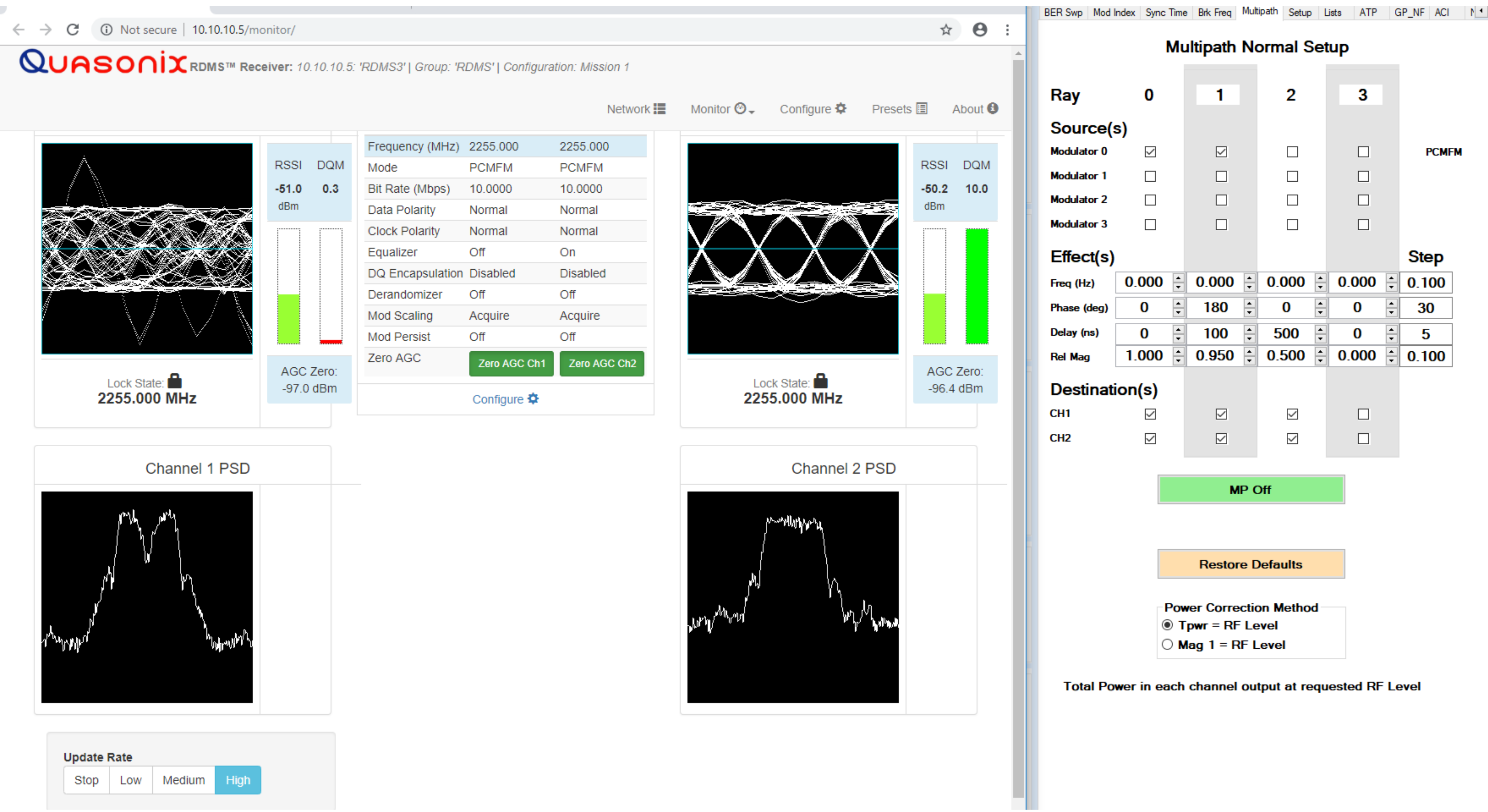
Not secure | 10.10.10.5/monitor/
QUASONIX RDMS™ Receiver: 10.10.10.5: 'RDMS3' | Group: 'RDMS' | Configuration: Mission 1
Network
Monitor
Configure
Presets
About
RSSI DQM
-51.1 2.7
dBm
Lock State:
2255.000 MHz
AGC Zero: -97.0 dBm
Frequency (MHz) 2255.000 2255.000
Mode PCMFM PCMFM
Bit Rate (Mbps) 10.0000 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
-50.2 10.0
dBm
Lock State:
2255.000 MHz
AGC Zero: -96.4 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) 0 180 0 0 30
Delay (ns) 0 100 500 0 5
Rel Mag 1.000 0.800 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

180-100-0.9


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
-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
-50.2 10.0
dBm
Lock State:
2255.000 MHz
AGC Zero:
-96.4 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) 0 180 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

180-100-0.95



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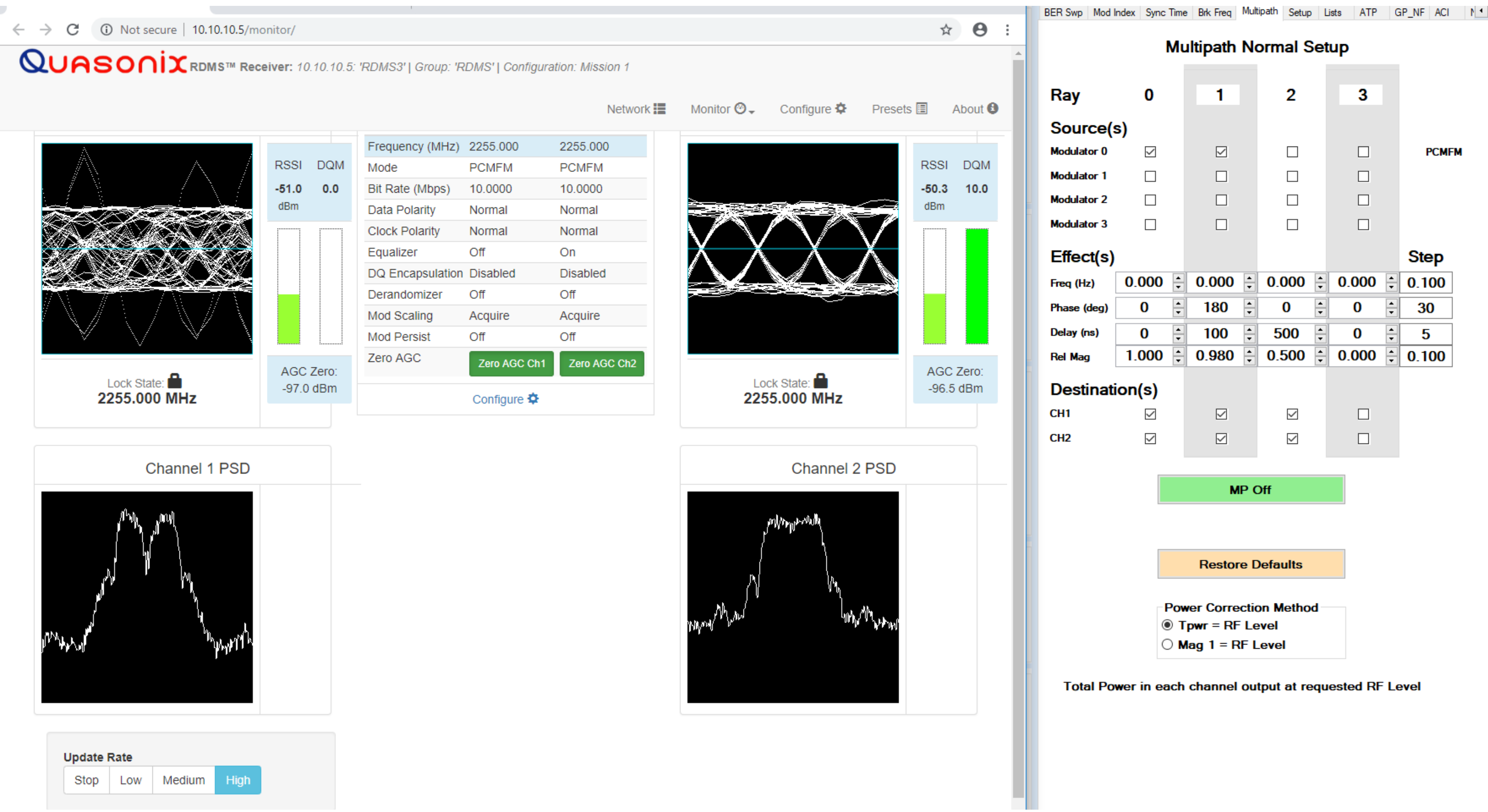
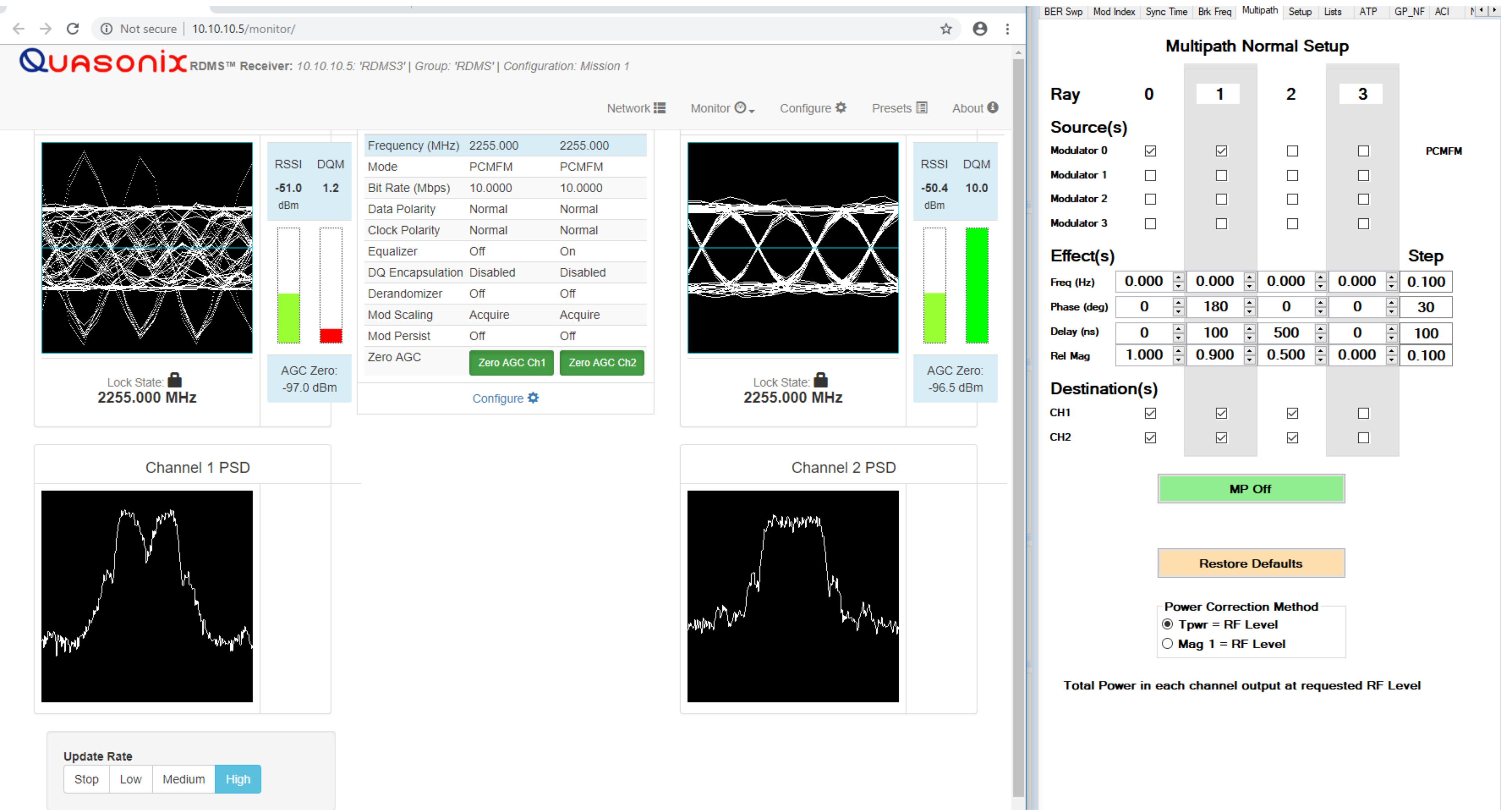
Terry Hill - thill@quasonix.com

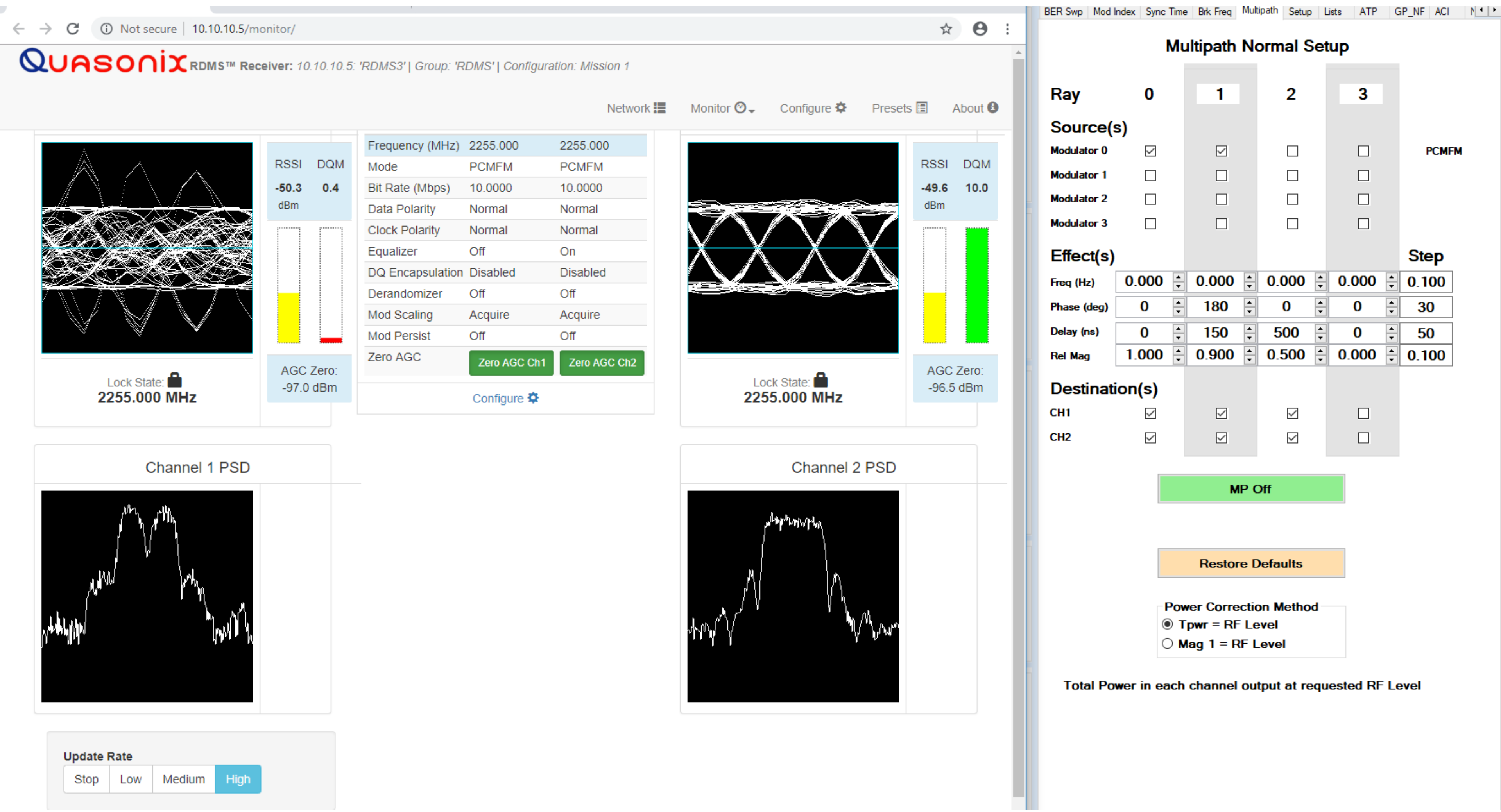
180-100-0.98


Not secure | 10.10.10.5/monitor/
RDMS™ Receiver: 10.10.10.5: 'RDMS3' | Group: 'RDMS' | Configuration: Mission 1
Network
Monitor
Configure
Presets
About
RSSI DQM
-51.0 0.0
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:
-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) 0 180 0 0 30
Delay (ns) 0 100 500 0 5
Rel Mag 1.000 0.980 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

180-100-0.9

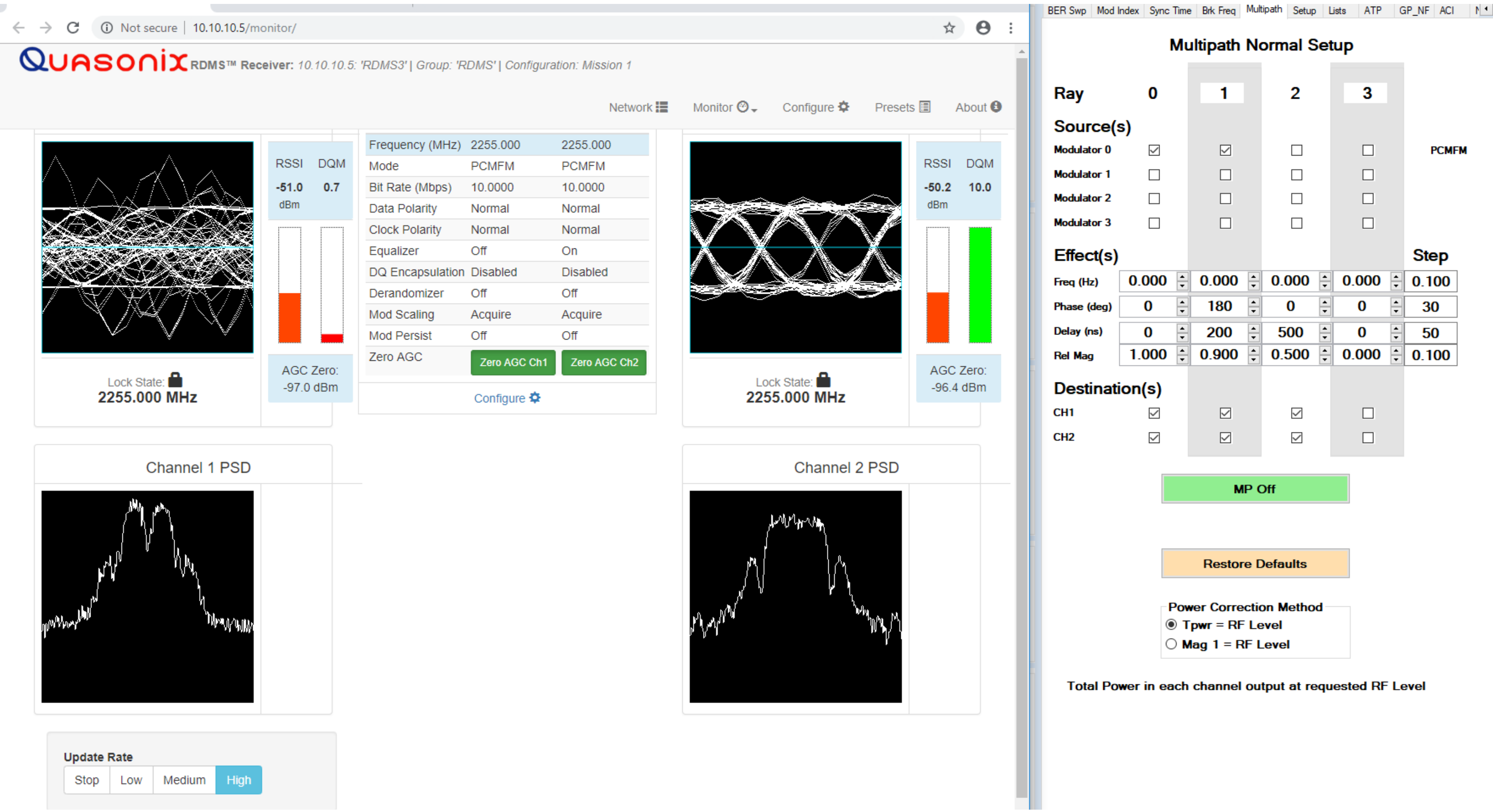

Not secure | 10.10.10.5/monitor/
QUASONIX RDMS™ Receiver: 10.10.10.5: 'RDMS3' | Group: 'RDMS' | Configuration: Mission 1
Network Monitor Configure Presets About
RSSI DQM
-51.0 1.2
dBm
Lock State:
2255.000 MHz
AGC Zero:
-97.0 dBm
Frequency (MHz) 2255.000 2255.000
Mode PCMFM PCMFM
Bit Rate (Mbps) 10.0000 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
-50.4 10.0
dBm
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) 0 180 0 0 30
Delay (ns) 0 100 500 0 100
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

180-150-0.9

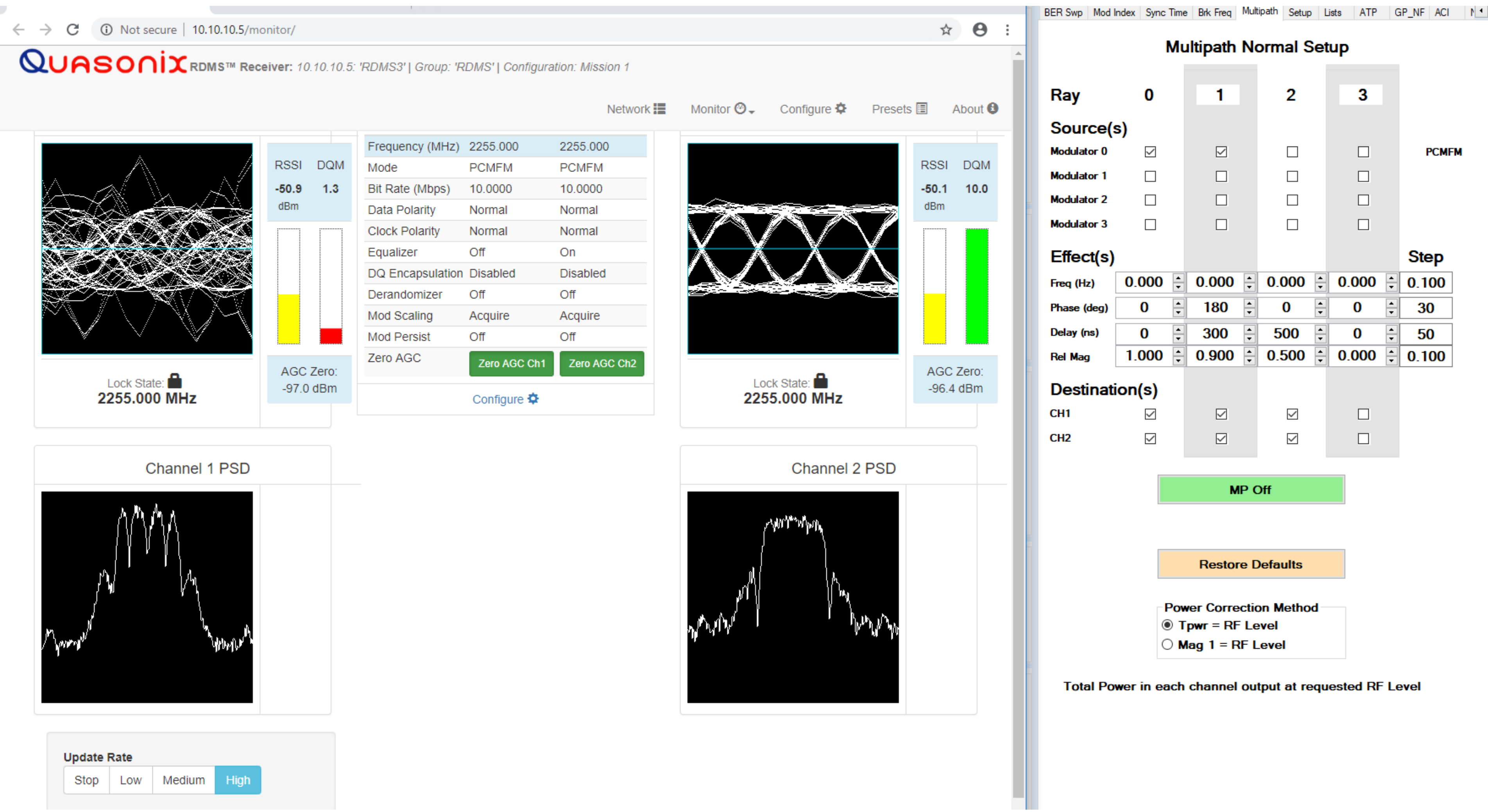


Not secure | 10.10.10.5/monitor/
RDMS™ Receiver: 10.10.10.5: 'RDMS3' | Group: 'RDMS' | Configuration: Mission 1
Network
Monitor
Configure
Presets
About
RSSI DQM
-50.3 0.4
dBm
Lock State:
2255.000 MHz
AGC Zero: -97.0 dBm
Frequency (MHz) 2255.000 2255.000
Mode PCMFM PCMFM
Bit Rate (Mbps) 10.0000 10.0000
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
-49.6 10.0
dBm
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) 0 180 0 0 30
Delay (ns) 0 150 500 0 50
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

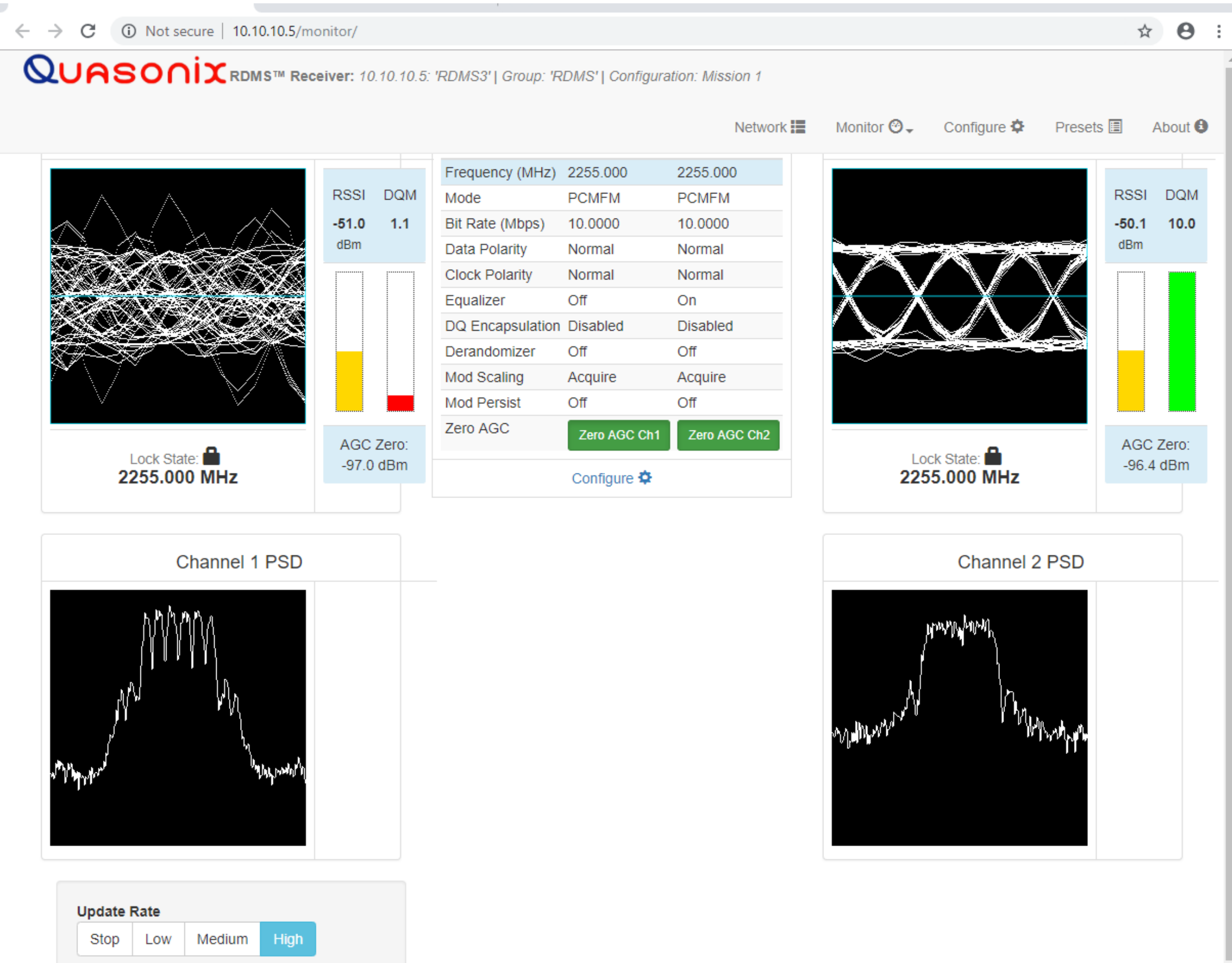
180-200-0.9


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
-51.0 0.7
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
-50.2 10.0
dBm
Lock State:
2255.000 MHz
AGC Zero:
-96.4 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) 0 180 0 0 30
Delay (ns) 0 200 500 0 50
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

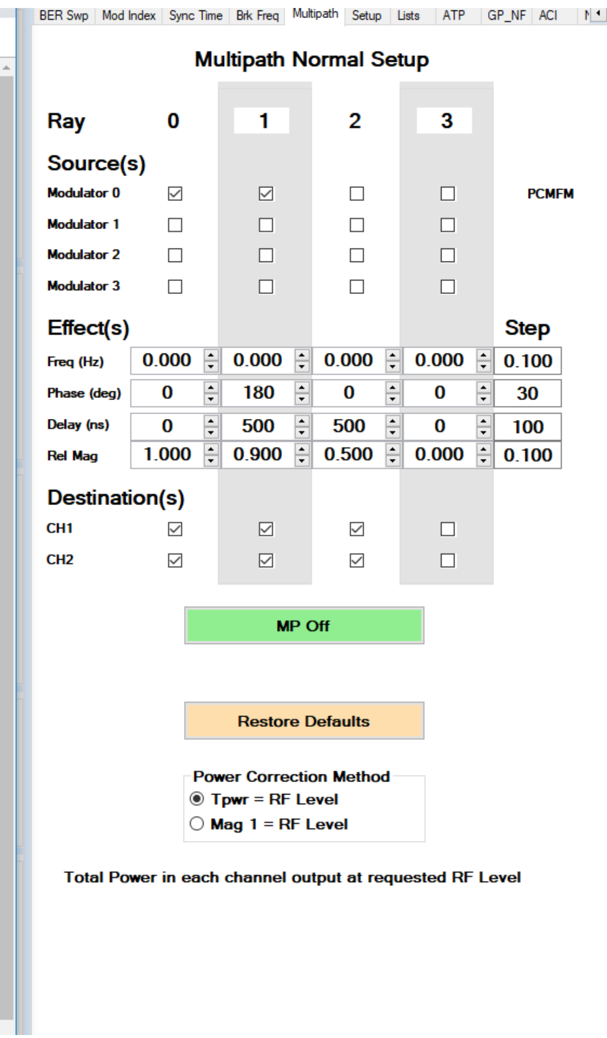
180-250-0.9


Not secure | 10.10.10.5/monitor/
RDMS™ Receiver: 10.10.10.5: 'RDMS3' | Group: 'RDMS' | Configuration: Mission 1
Network
Monitor
Configure
Presets
About
RSSI DQM
-50.9 1.3
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
-50.1 10.0
dBm
Lock State:
2255.000 MHz
AGC Zero: -96.4 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) 0 180 0 0 30
Delay (ns) 0 300 500 0 50
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

180-300-0.9

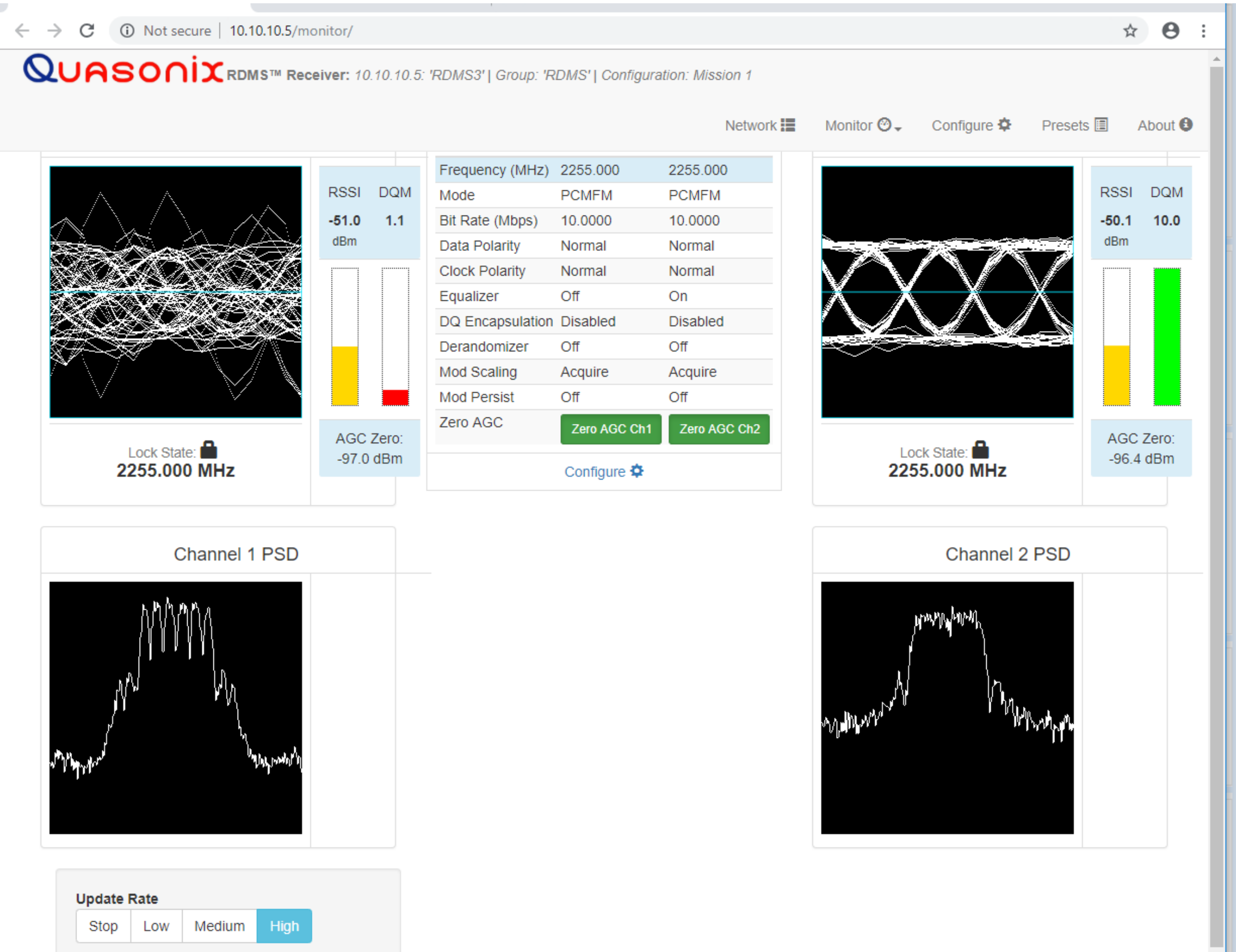


Not secure | 10.10.10.5/monitor/
QUASONIX RDMS™ Receiver: 10.10.10.5: 'RDMS3' | Group: 'RDMS' | Configuration: Mission 1
Network
Monitor
Configure
Presets
About
RSSI DQM
-51.0 1.1
dBm
Lock State:
2255.000 MHz
AGC Zero:
-97.0 dBm
Frequency (MHz) 2255.000 2255.000
Mode PCMFM PCMFM
Bit Rate (Mbps) 10.0000 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
-50.1 10.0
dBm
Lock State:
2255.000 MHz
AGC Zero:
-96.4 dBm
Channel 1 PSD
Channel 2 PSD
Update Rate
Stop
Low
Medium
High

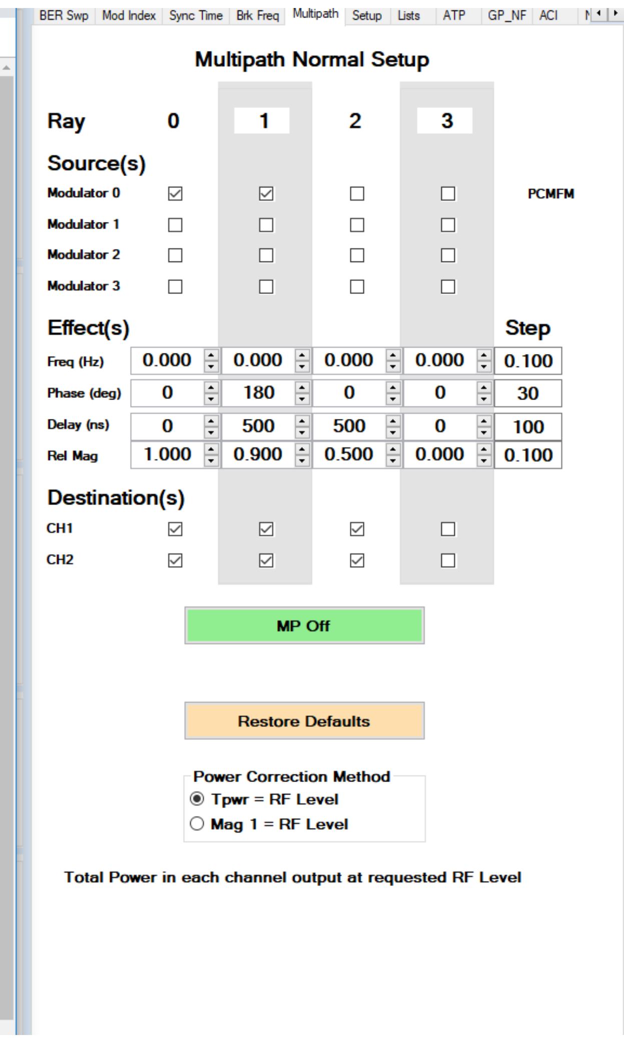


BER Swp
Mod Index
Sync Time
Brk Freq
Multipath
Setup
Lists
ATP
GP_NF
ACI
Multipath Normal Setup
Ray 0 1 2 3
Source(s)
Modulator 0
Modulator 1
Modulator 2
Modulator 3
PCMFM
Effect(s)
Step
Freq (Hz) 0.000 0.000 0.000 0.000 0.100
Phase (deg) 0 180 0 0 30
Delay (ns) 0 500 500 0 100
Rel Mag 1.000 0.900 0.500 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

180-500-0.9

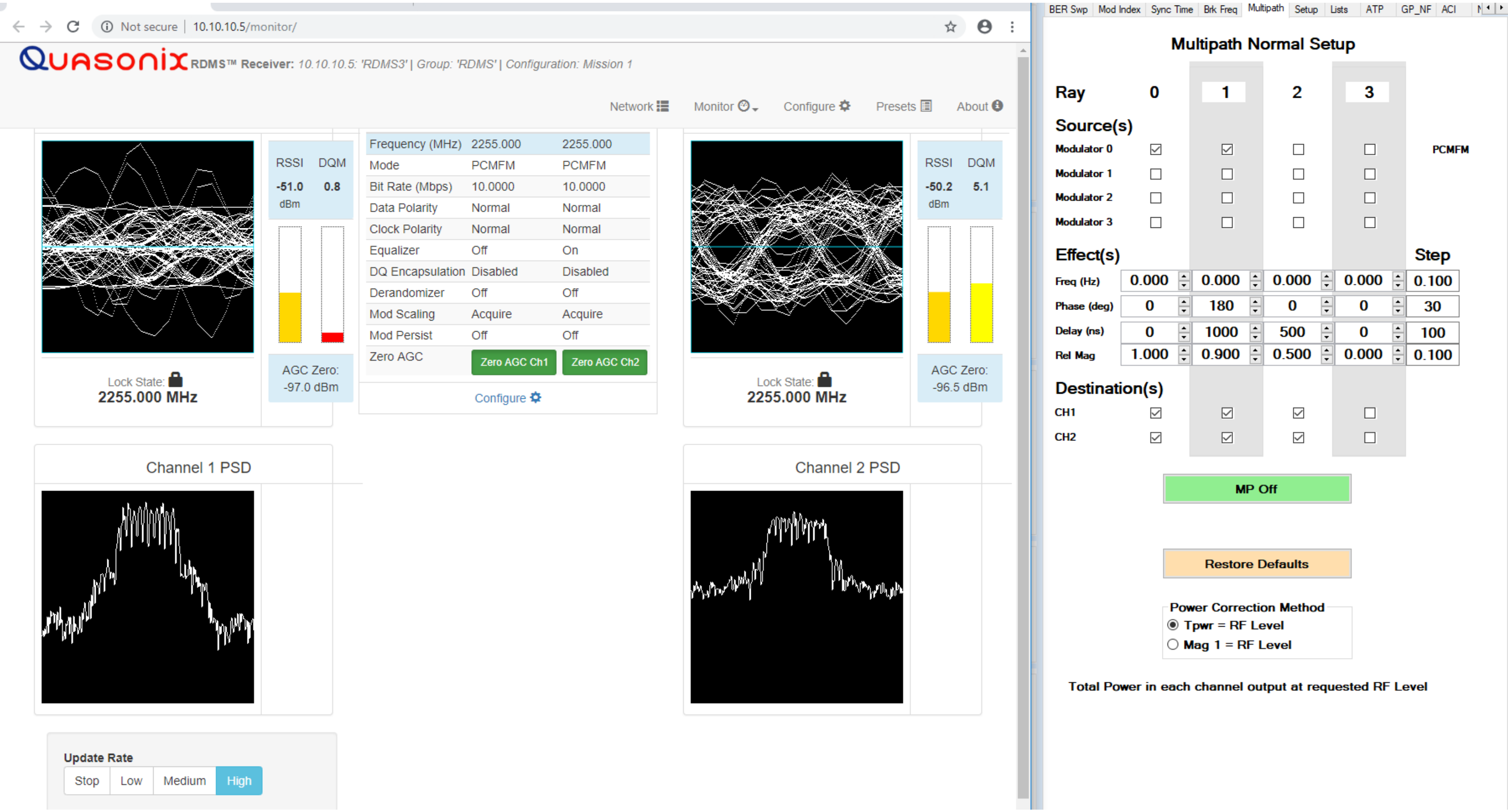


Not secure | 10.10.10.5/monitor/
QUASONIX RDMS™ Receiver: 10.10.10.5: 'RDMS3' | Group: 'RDMS' | Configuration: Mission 1
Network
Monitor
Configure
Presets
About
RSSI DQM
-51.0 1.1
dBm
Lock State:
2255.000 MHz
AGC Zero: -97.0 dBm
Frequency (MHz) 2255.000 2255.000
Mode PCMFM PCMFM
Bit Rate (Mbps) 10.0000 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
-50.1 10.0
dBm
Lock State:
2255.000 MHz
AGC Zero: -96.4 dBm
Channel 1 PSD
Channel 2 PSD
Update Rate
Stop
Low
Medium
High



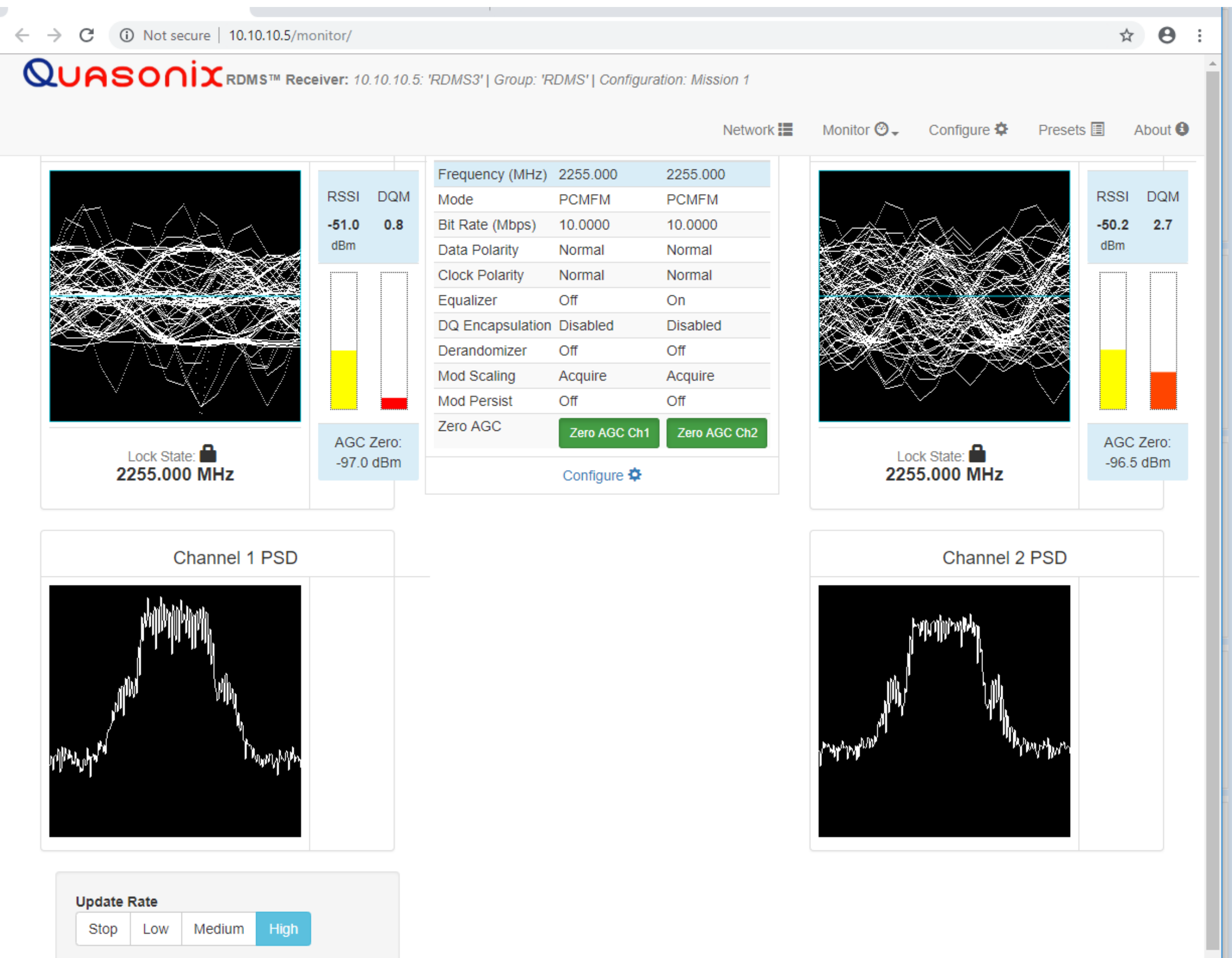
BER Swp
Mod Index
Sync Time
Brk Freq
Multipath
Setup
Lists
ATP
GP_NF
ACI
Multipath Normal Setup
Ray 0 1 2 3
Source(s)
Modulator 0
Modulator 1
Modulator 2
Modulator 3
PCMFM
Effect(s)
Step
Freq (Hz) 0.000 0.000 0.000 0.000 0.100
Phase (deg) 0 180 0 0 30
Delay (ns) 0 500 500 0 100
Rel Mag 1.000 0.900 0.500 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

180-1000-0.9

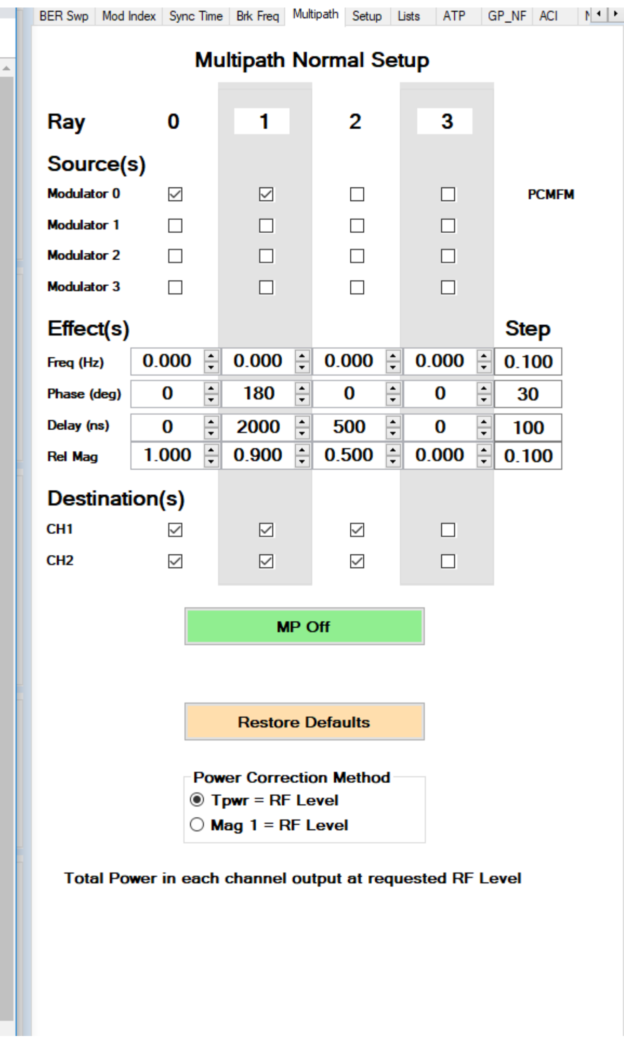


Not secure | 10.10.10.5/monitor/
RDMS™ Receiver: 10.10.10.5: 'RDMS3' | Group: 'RDMS' | Configuration: Mission 1
Network Monitor Configure Presets About
RSSI DQM
-51.0 0.8
dBm
Lock State:
2255.000 MHz
AGC Zero: -97.0 dBm
Frequency (MHz) 2255.000 2255.000
Mode PCMFM PCMFM
Bit Rate (Mbps) 10.0000 10.0000
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
-50.2 5.1
dBm
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 PCMFM
Modulator 1
Modulator 2
Modulator 3
Effect(s) Step
Freq (Hz) 0.000 0.000 0.000 0.000 0.100
Phase (deg) 0 180 0 0 30
Delay (ns) 0 1000 500 0 100
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

180-2000-0.9



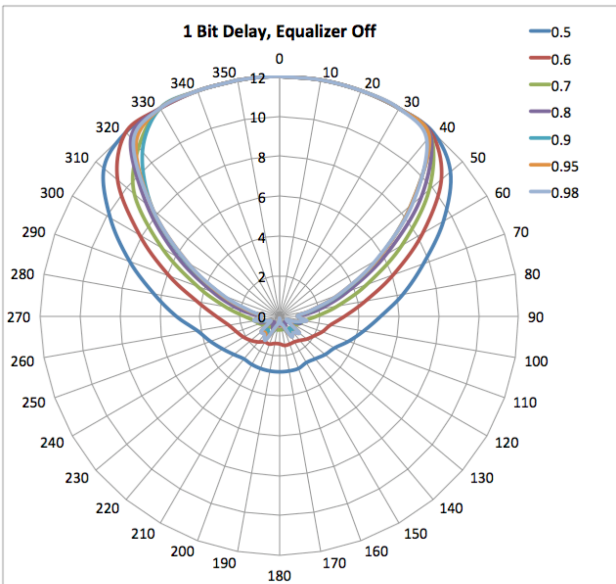
Not secure | 10.10.10.5/monitor/
RDMS™ Receiver: 10.10.10.5: 'RDMS3' | Group: 'RDMS' | Configuration: Mission 1
Network
Monitor
Configure
Presets
About
RSSI DQM
-51.0 0.8
dBm
Lock State:
2255.000 MHz
AGC Zero:
-97.0 dBm
Frequency (MHz) 2255.000 2255.000
Mode PCMFM PCMFM
Bit Rate (Mbps) 10.0000 10.0000
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
-50.2 2.7
dBm
Lock State:
2255.000 MHz
AGC Zero:
-96.5 dBm
Channel 1 PSD
Channel 2 PSD
Update Rate
Stop
Low
Medium
High

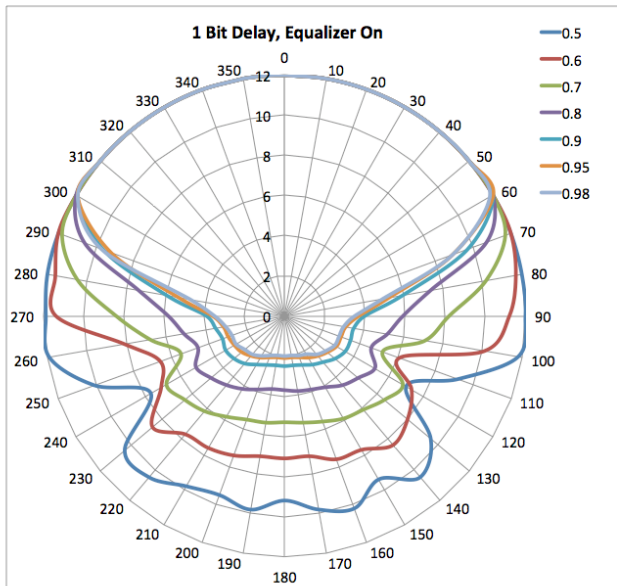


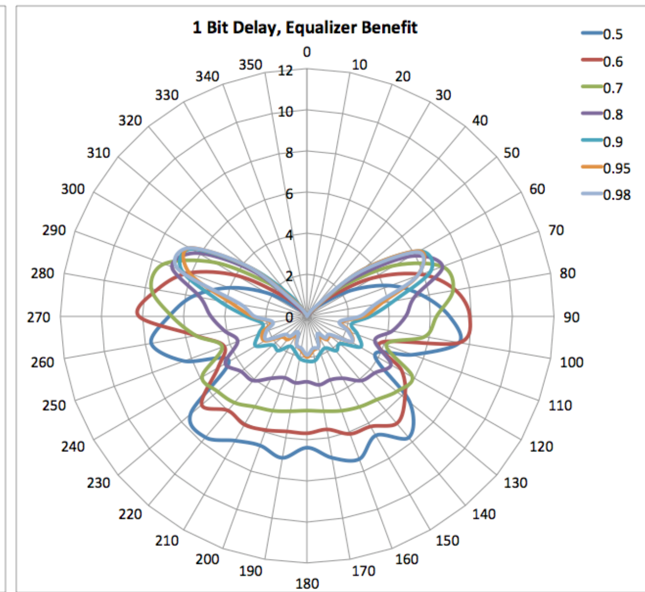
BER Swp
Mod Index
Sync Time
Brk Freq
Multipath
Setup
Lists
ATP
GP_NF
ACI
Multipath Normal Setup
Ray 0 1 2 3
Source(s)
Modulator 0
Modulator 1
Modulator 2
Modulator 3
PCMFM
Effect(s)
Step
Freq (Hz) 0.000 0.000 0.000 0.000 0.100
Phase (deg) 0 180 0 0 30
Delay (ns) 0 2000 500 0 100
Rel Mag 1.000 0.900 0.500 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

Test Results Examples

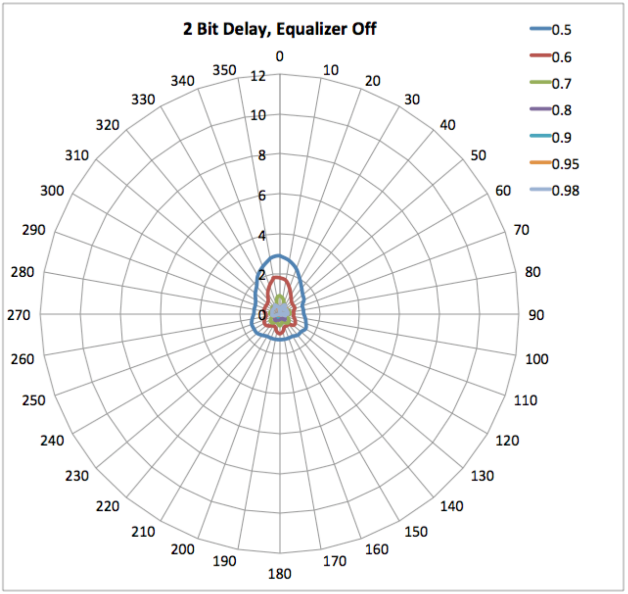
10 Mbps SOQPSK, 1 bit Delay

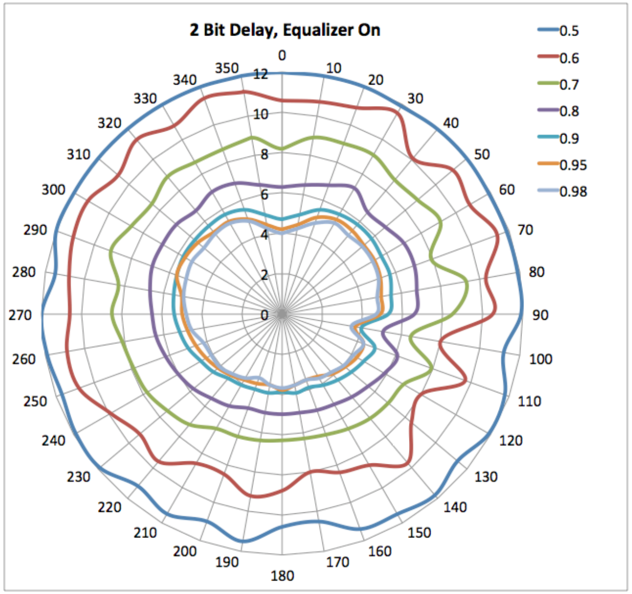


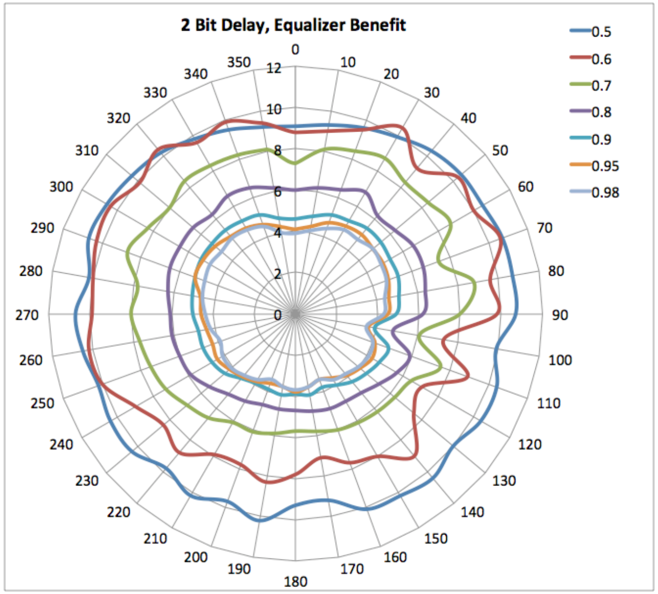




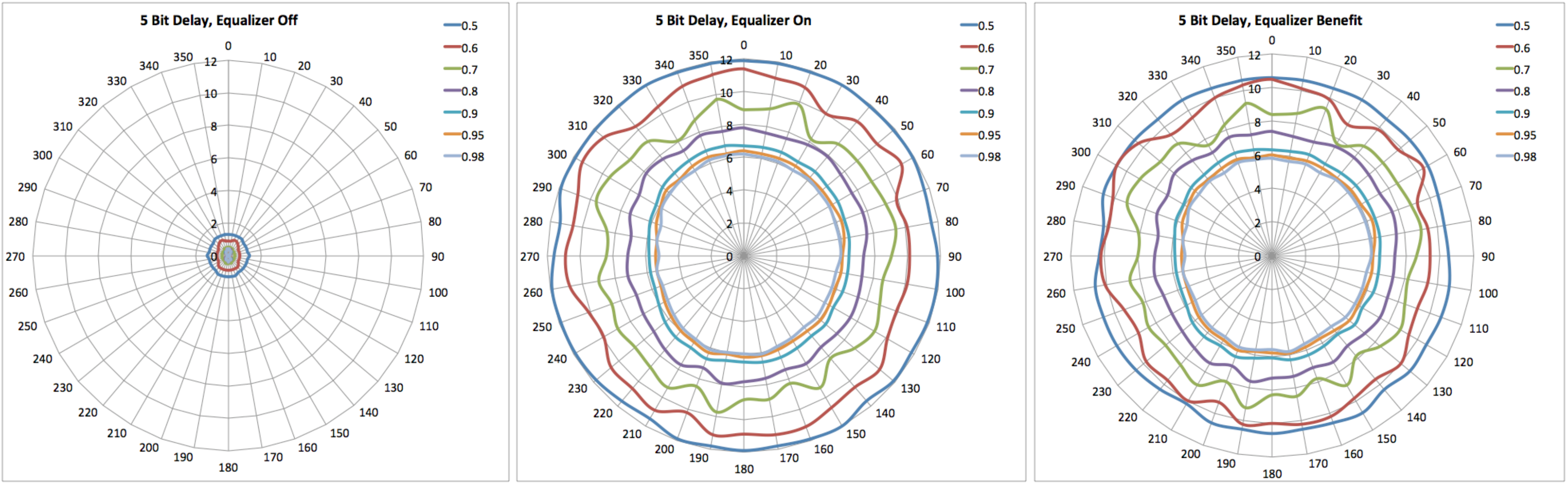
10 Mbps SOQPSK, 2 Bits Delay







10 Mbps SOQPSK, 5 Bits Delay



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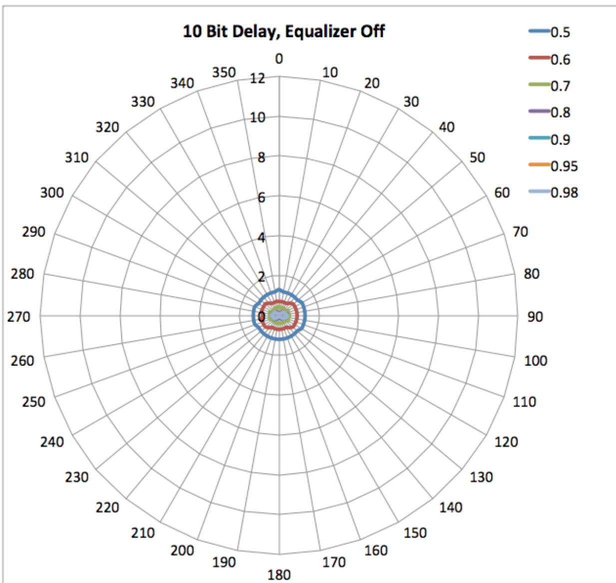
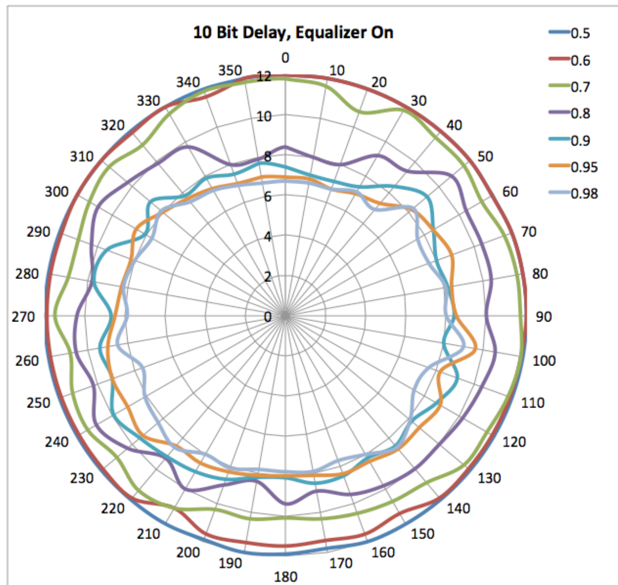
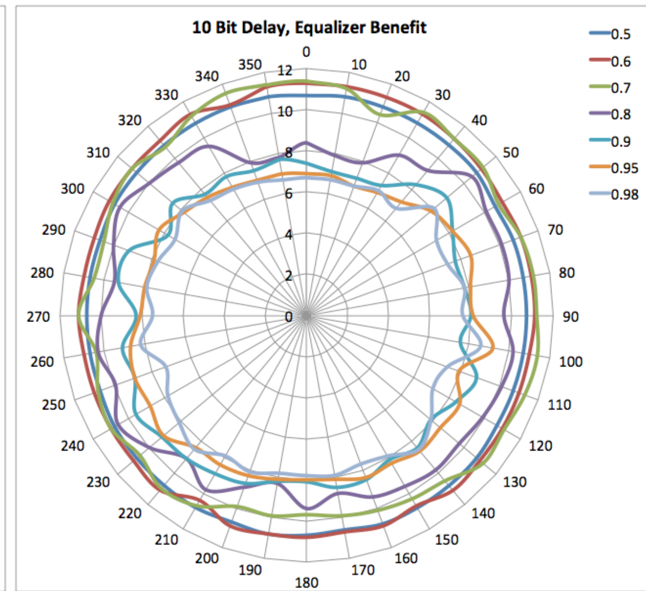
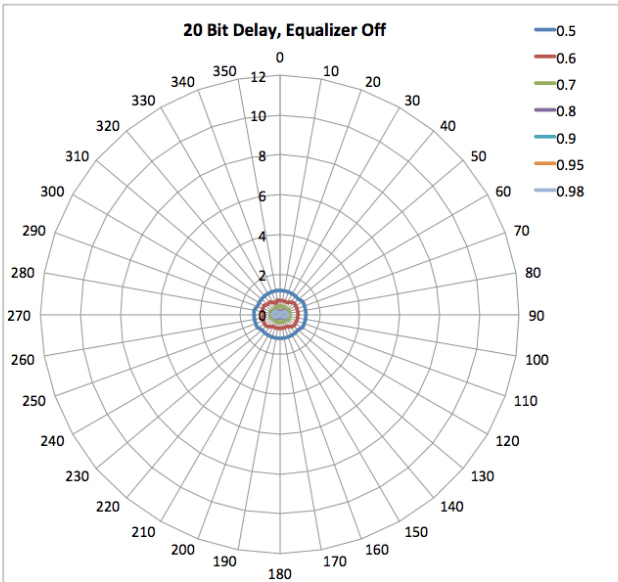
10 Mbps SOQPSK, 10 Bits Delay

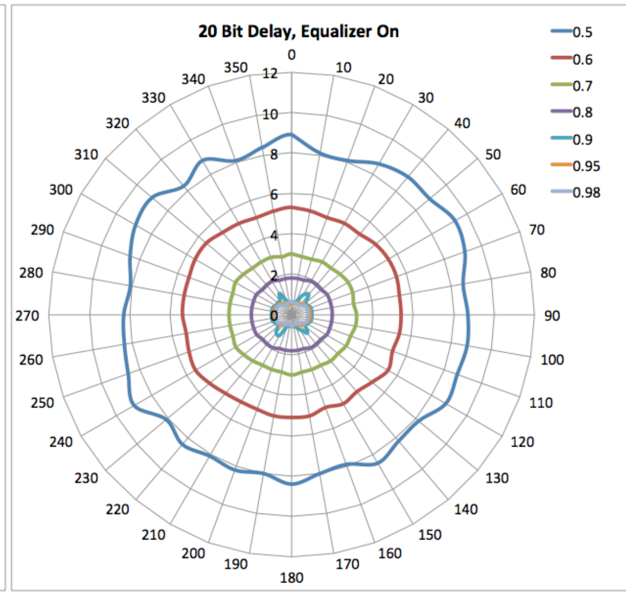


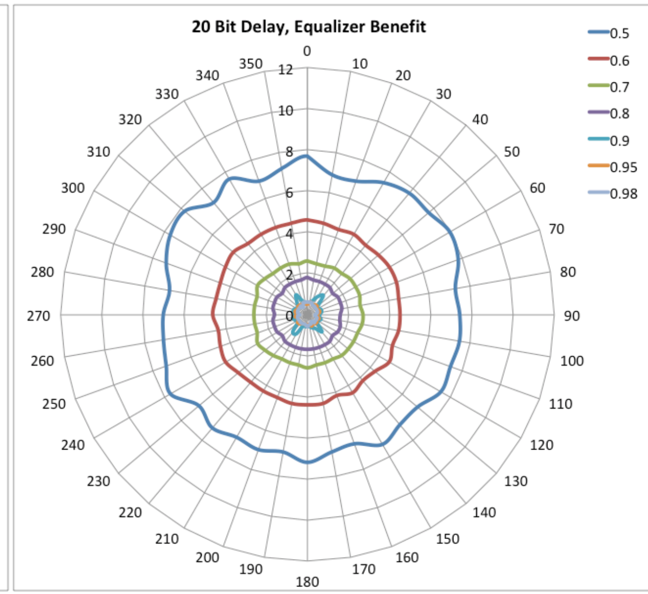




10 Mbps SOQPSK, 20 Bits Delay







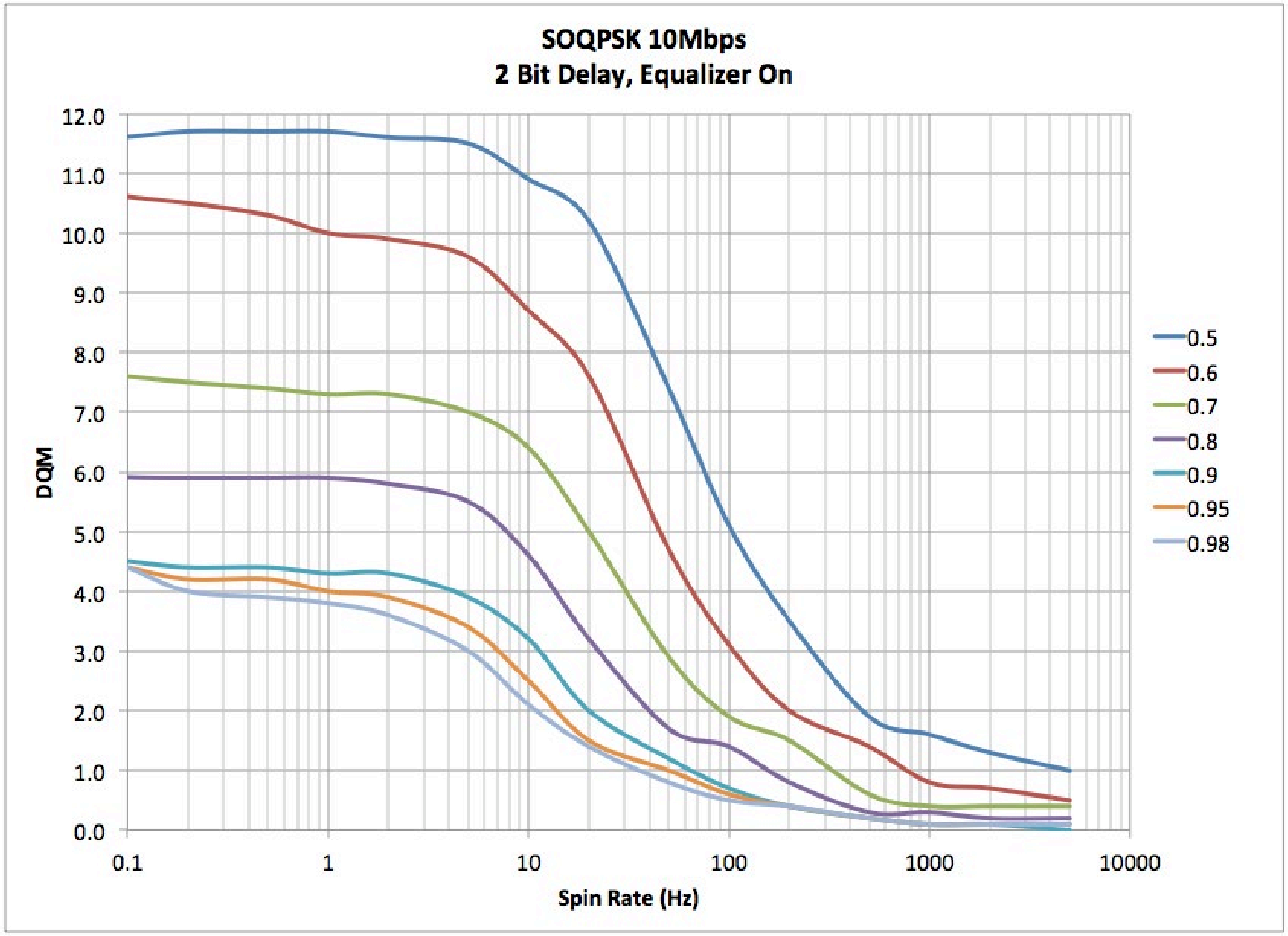
What About Dynamics?

- 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

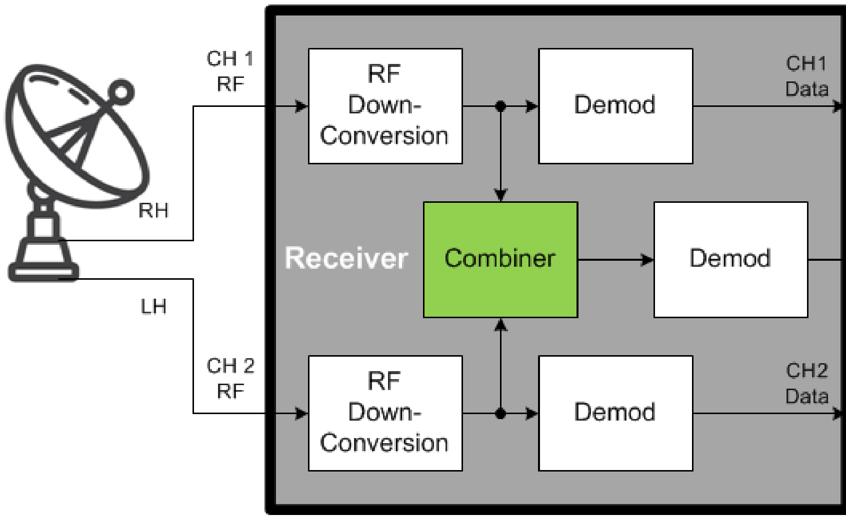
Equalizer Break Frequency

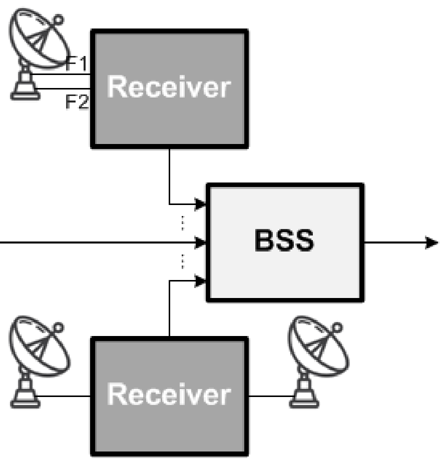


Best Channel Selector (BCS)

Handling the “Un-Combinable” Signals

Receive Diversity – Combiner

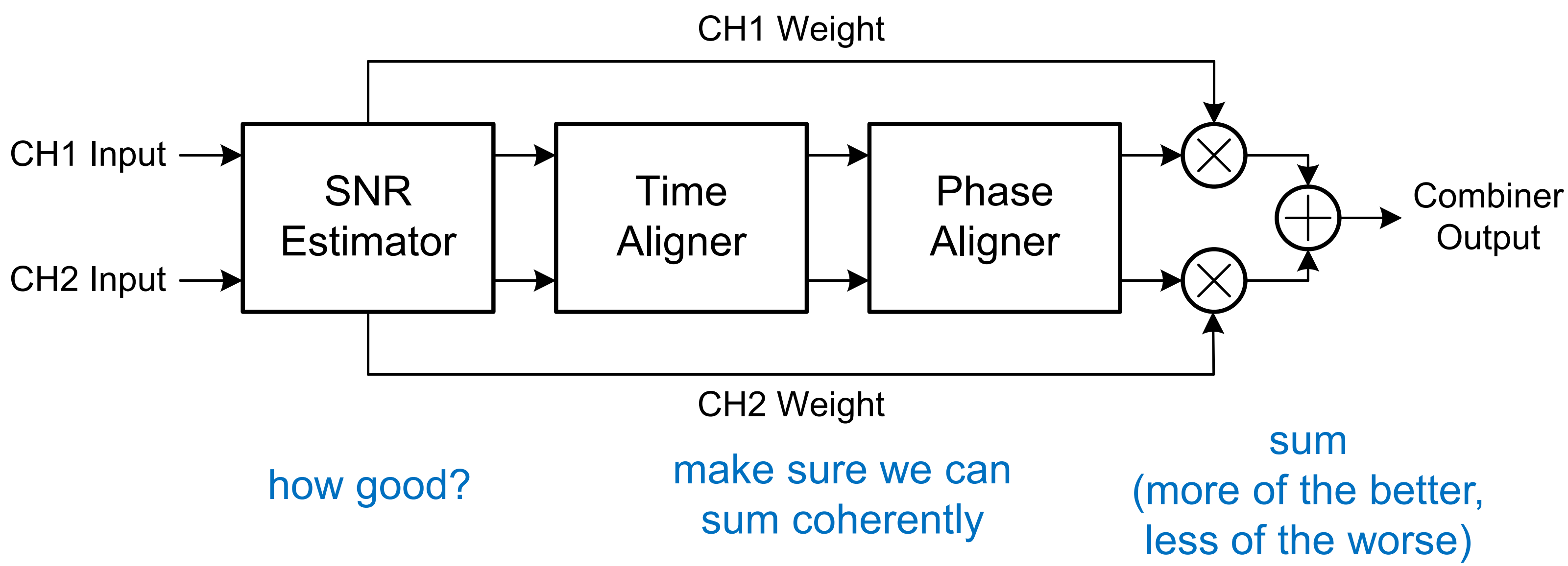




- Polarization, frequency, or short-range spatial diversity
- Maximal Ratio Combiner sums input channels proportional to their SNR
  - Optimal in additive white Gaussian noise (AWGN) – up to 3 dB gain
  - Use as only receiver output?

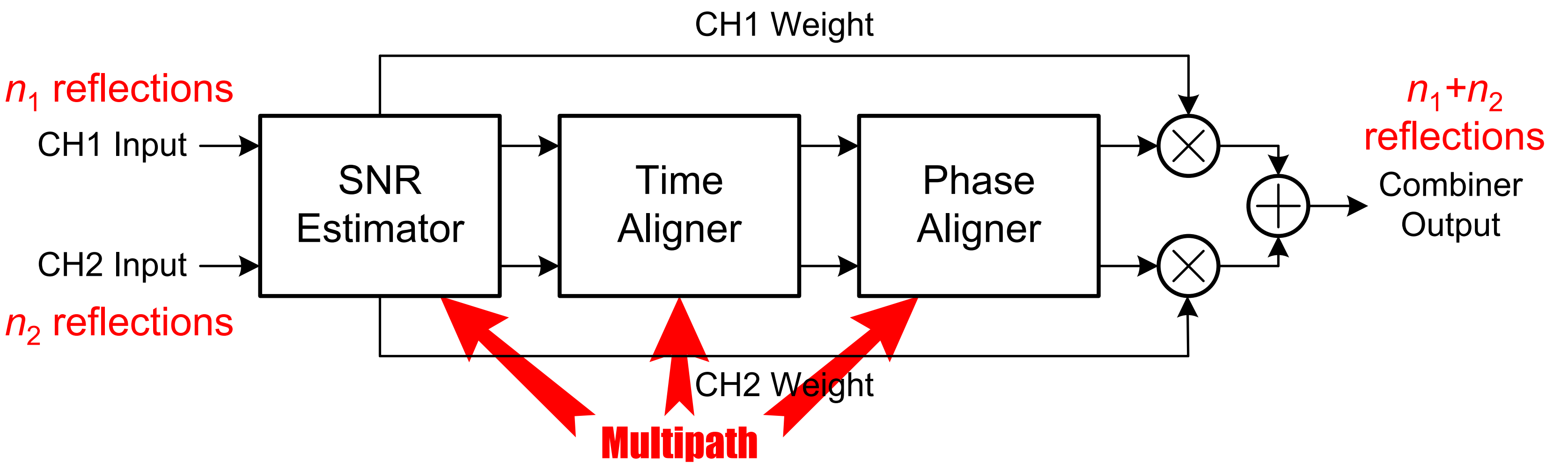
Combiner Structure

- Maximal ratio combining



Combiner Performance

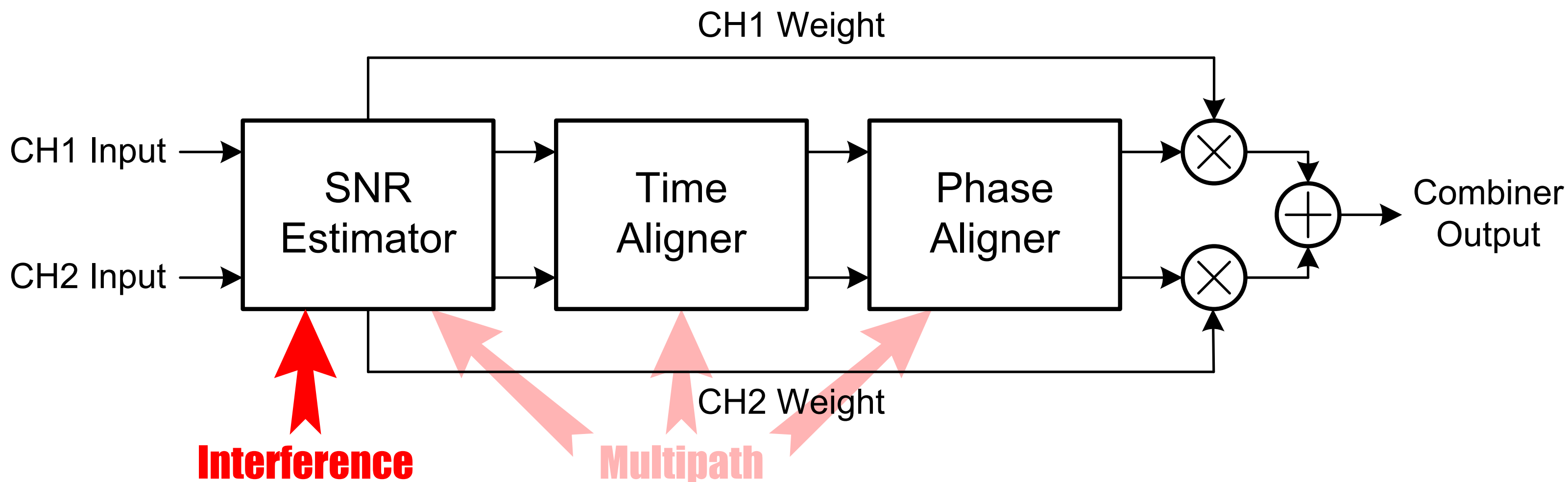
- Maximal ratio combining issues



  - 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

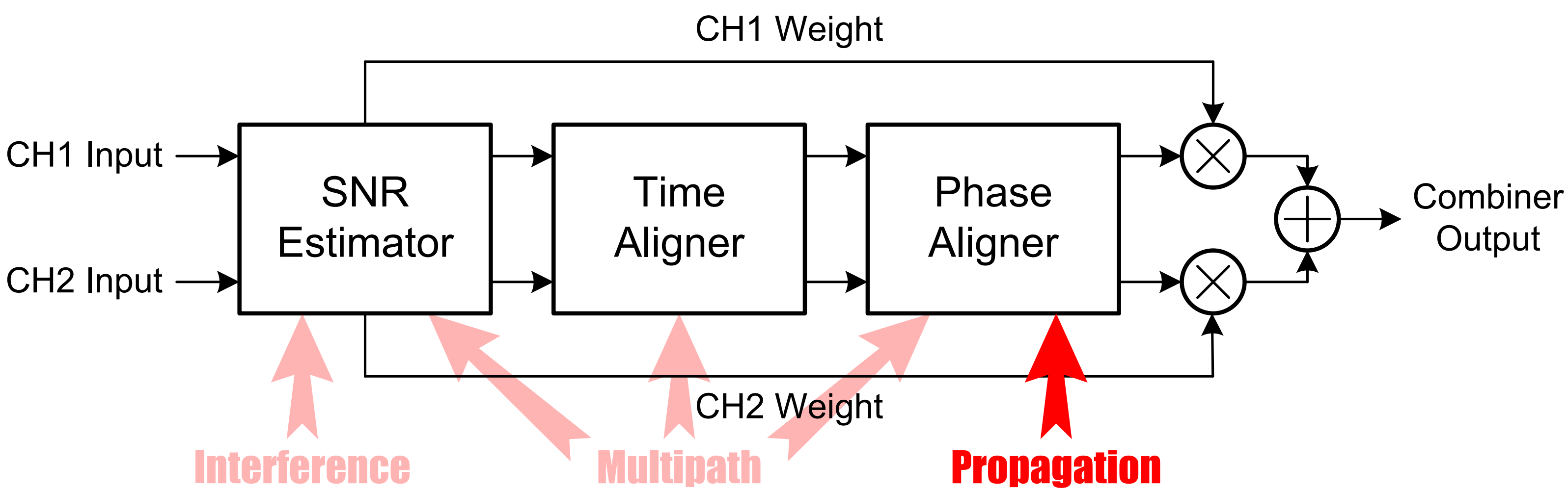
- Maximal ratio combining issues



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

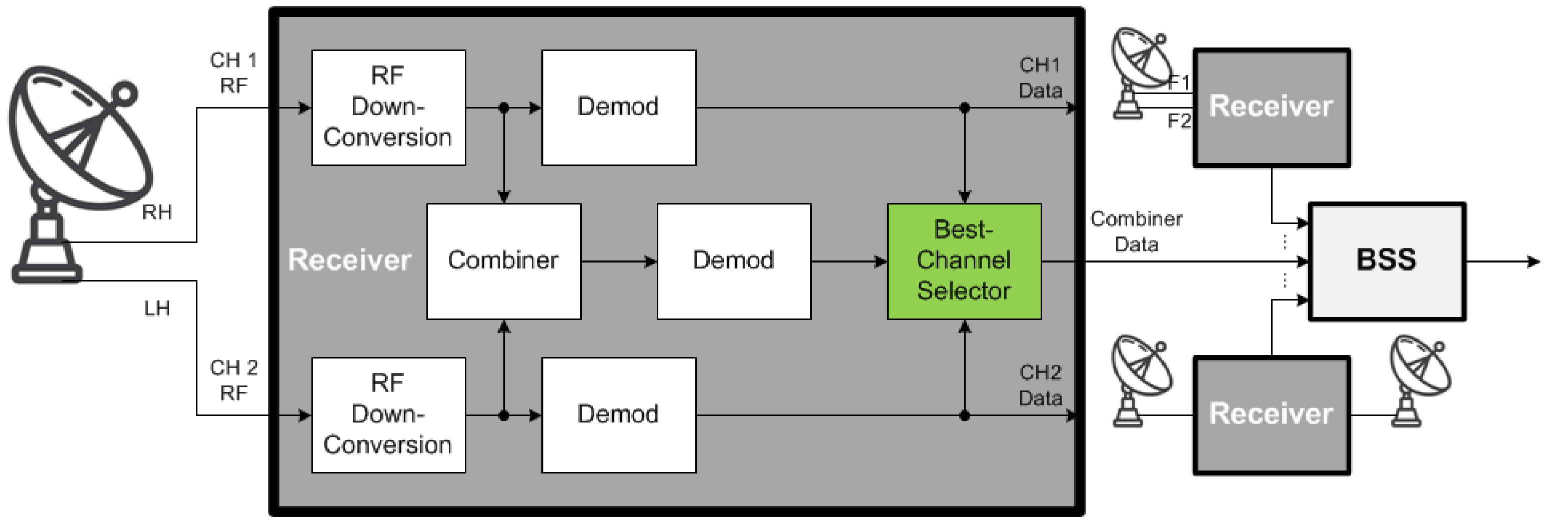
Combiner Performance

- Maximal ratio combining issues



  - Propagation effects may result in non-combinable signals

Receive Diversity – BCS

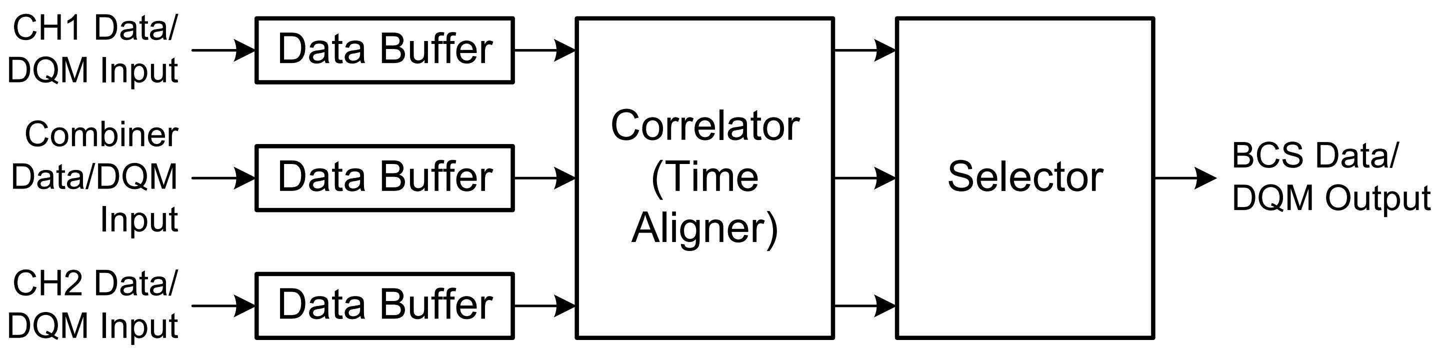


- Like a mini-BSS *inside the receiver*
- Selects and outputs best data from just three sources (Channel 1, Channel 2, and Combiner)
- Optimized for this narrowly scoped role

BCS Structure

- 3-channel correlating selection

"hit-less" – no dropped or duplicated bits



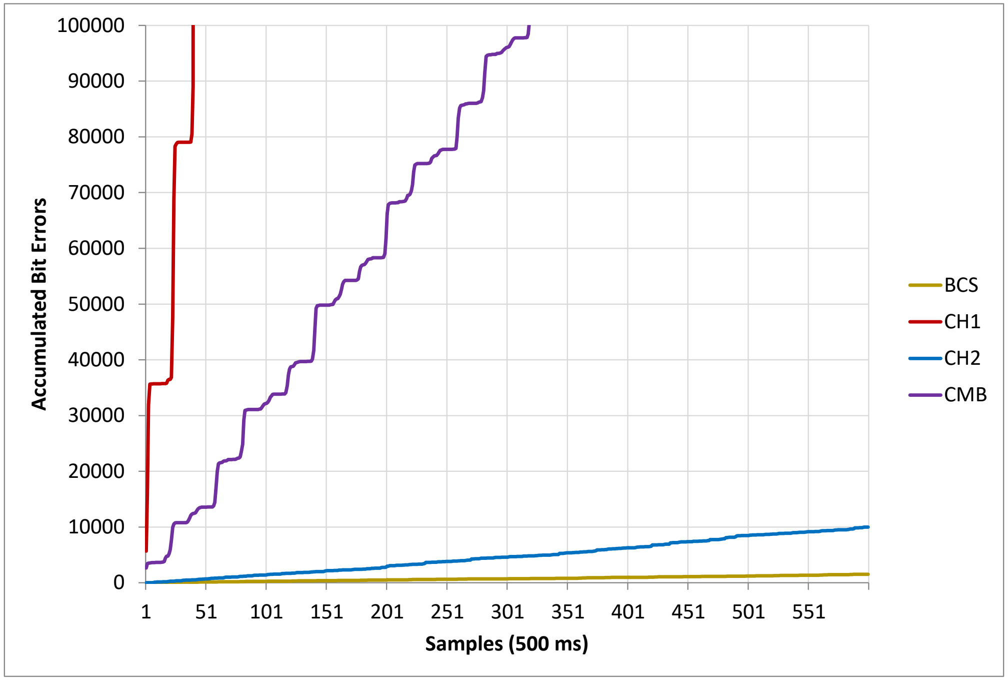
line up bits from all channels

select best bit based on best DQM

Terry Hill - thill@quasonix.com

BCS Test – Multipath

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



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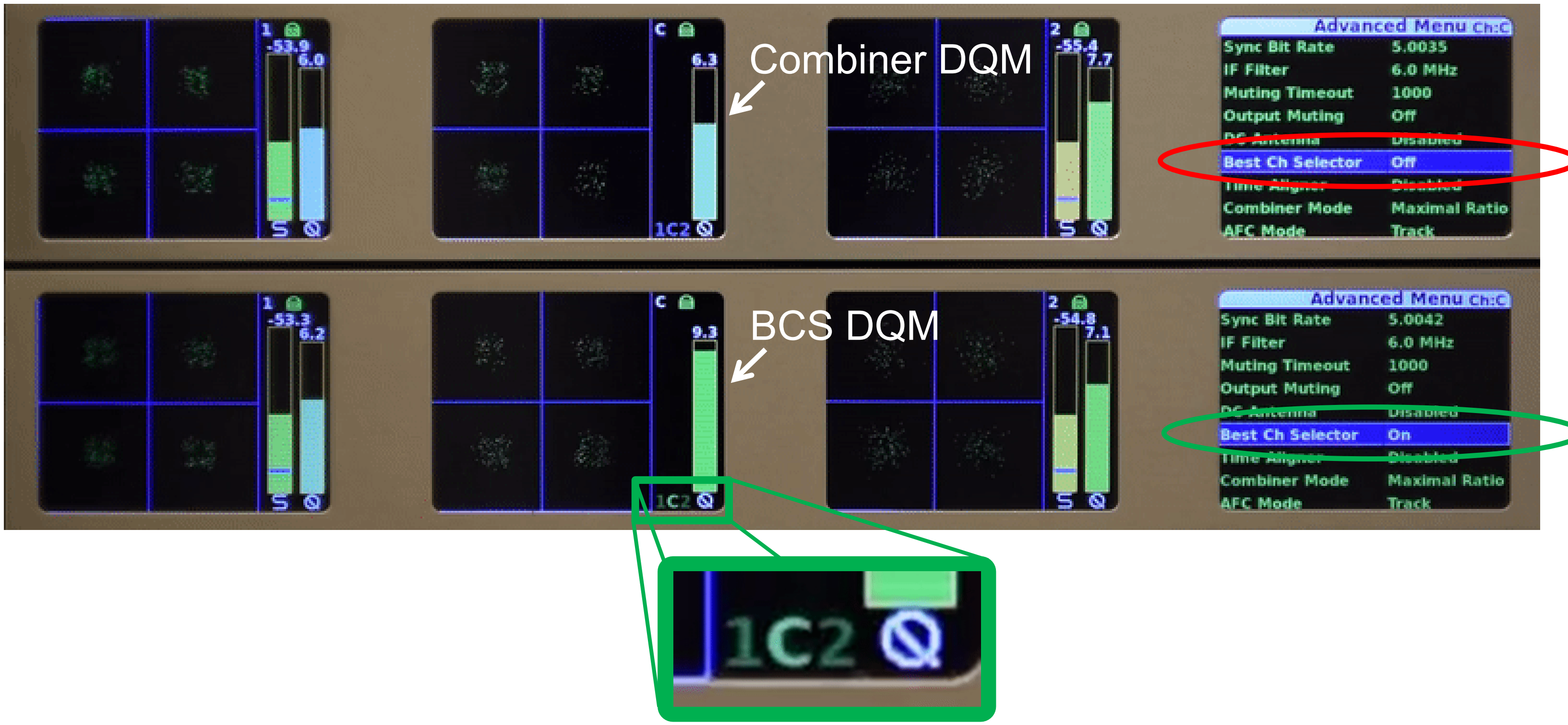
BCS Test – Multipath

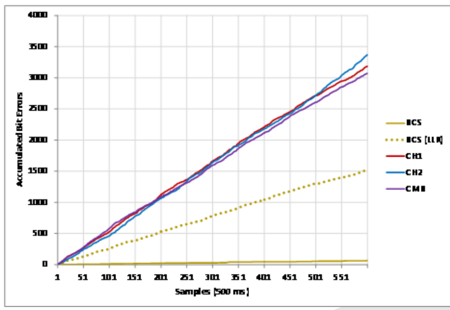


- DQM reduction of 1 = BER increase of 10x (!)
- BCS selection > 1000x faster than display

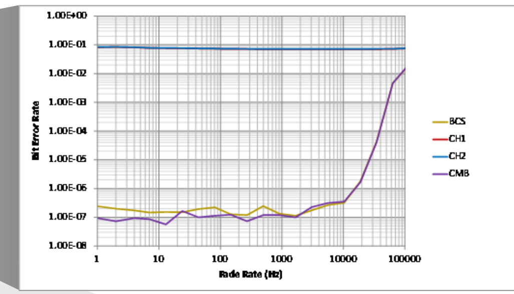
BCS Test – Summary

- Uniformly equals or exceeds best channel's performance

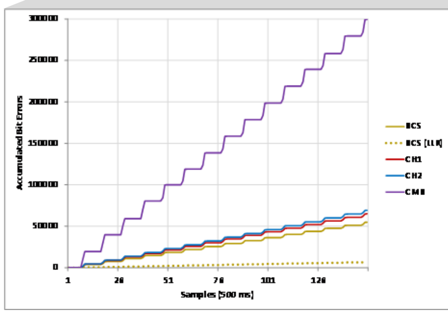
BCS



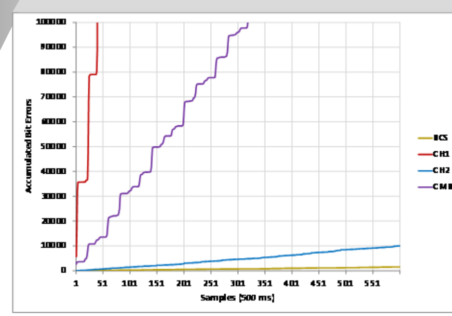
AWGN



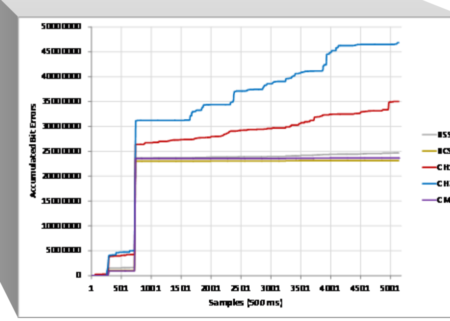
Break Frequency



STC polarization



Multipath



Flight Recording

Quasonix

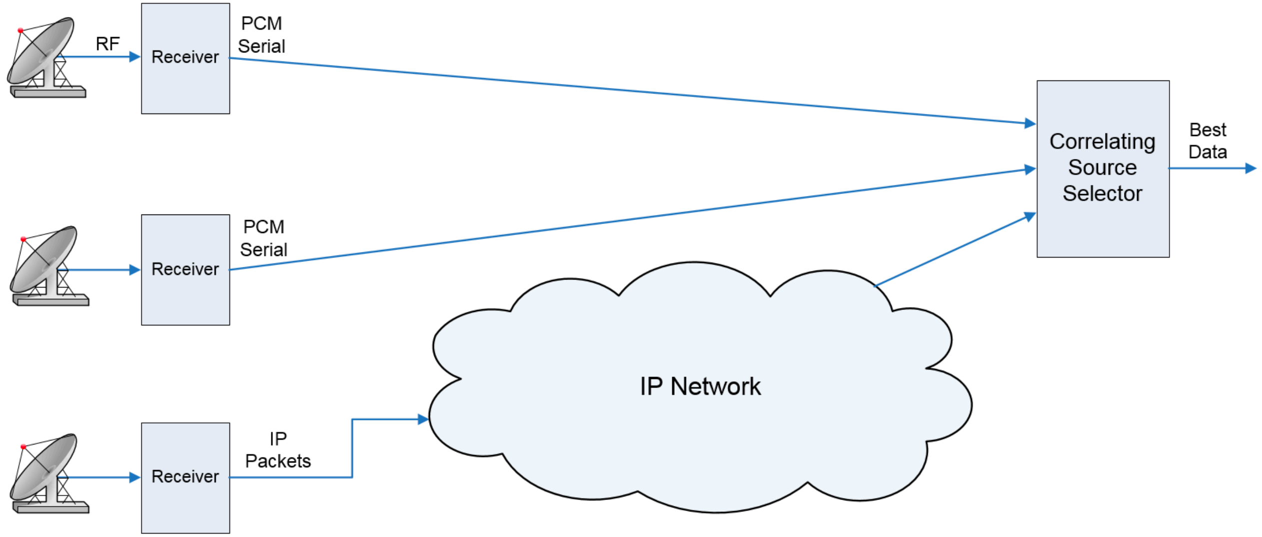
Conclusions

- 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

Best Source Selection

Combining Multiple Sources

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



Selection Algorithms

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

Why Measure Data Quality?

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

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

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

Terminology

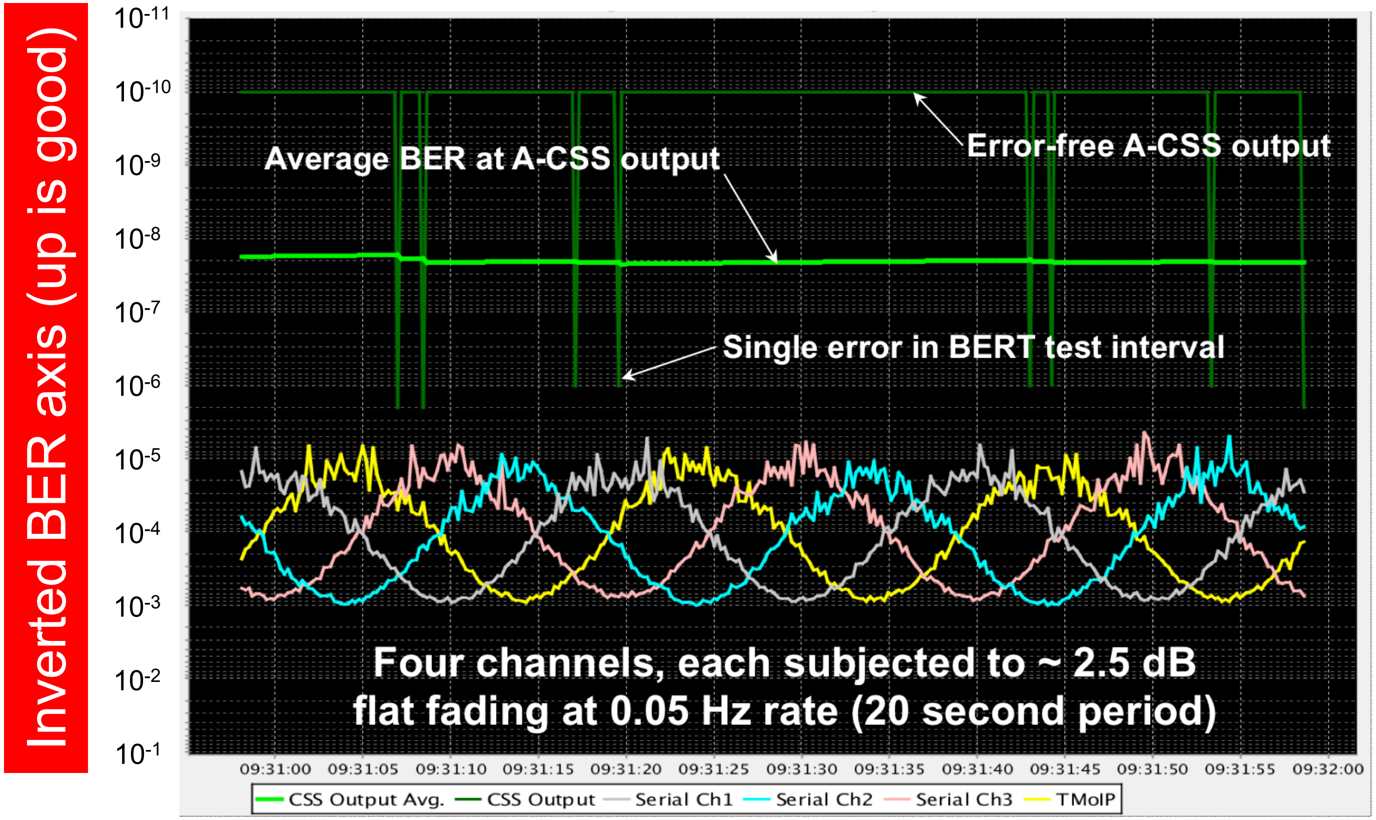
- BER (Bit Error Rate)
  - *Measured* as (number of errors / number of bits)
  - Assumes you know the data in advance
  - Measuring very low BER requires a long time
  - Converges to BEP if test runs long enough, *and channel is static*
- BEP (Bit Error Probability)
  - *Calculated* likelihood that a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

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

Does it work?

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



BSS Summary

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

Rx/TX DSP Techniques

Rx/Tx DSP Techniques

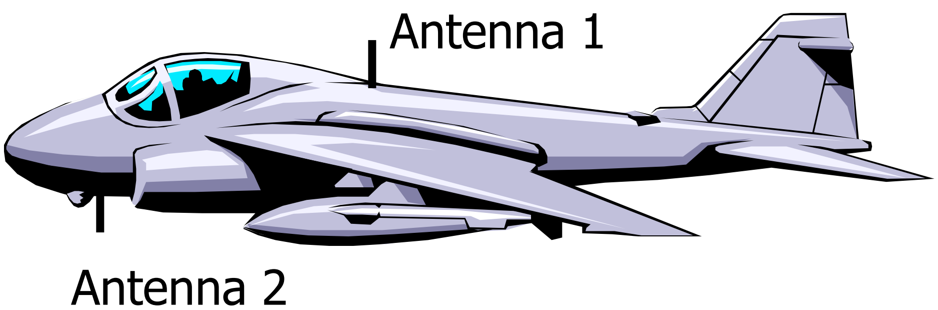
- If you can choose your transmitter…
- Space-time coding (STC)
  - Mitigates “built-in” multipath from dual TX antennas
  - Requires dual transmitters
- Forward error correction
  - Spending bandwidth to buy link margin
  - Requires encoder implemented in transmitter

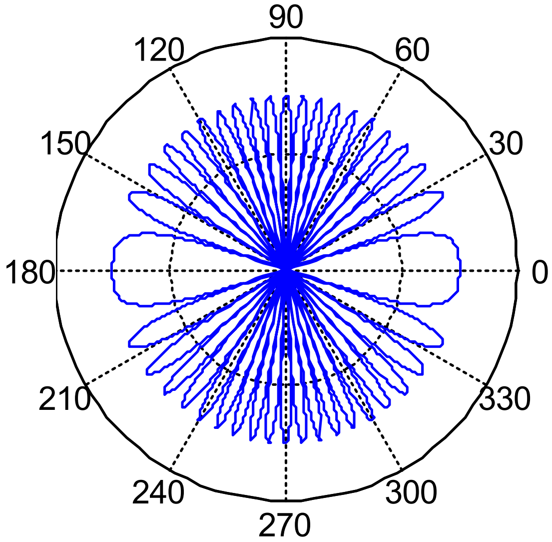
Space-Time Coding

Eradicates Porcupines!

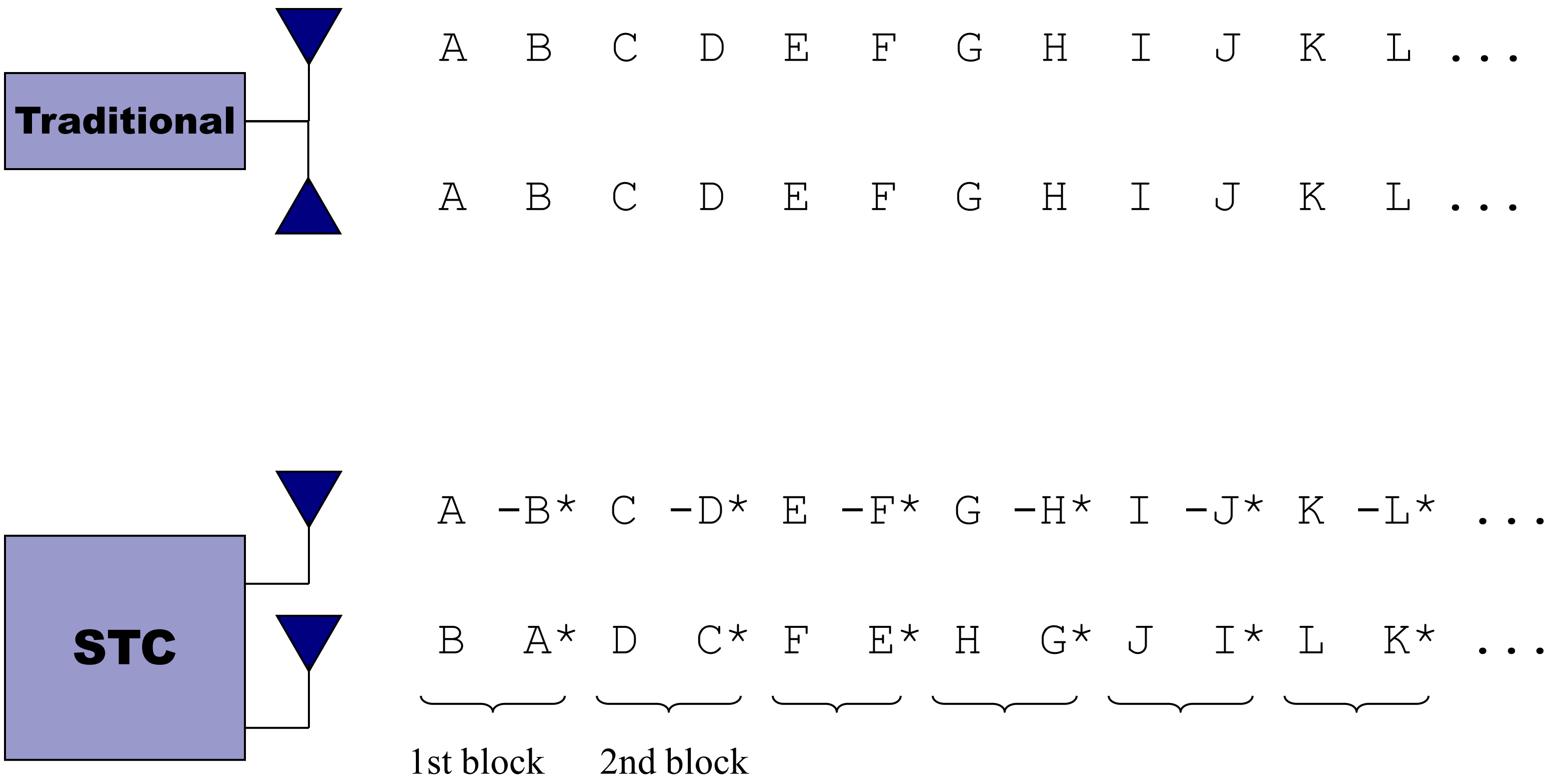
Difficulties with TX Diversity

Spatially Separated Antennas Create Interference Pattern





Alamouti Space-Time Coding (STC)



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Symbol Error Rate - QPSK

Traditional signaling

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

Addition of transfer functions leads to reduction in effective SNR

For Alamouti signaling

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

Only magnitudes of transfer functions used in sum

Antenna Pattern Interpretation

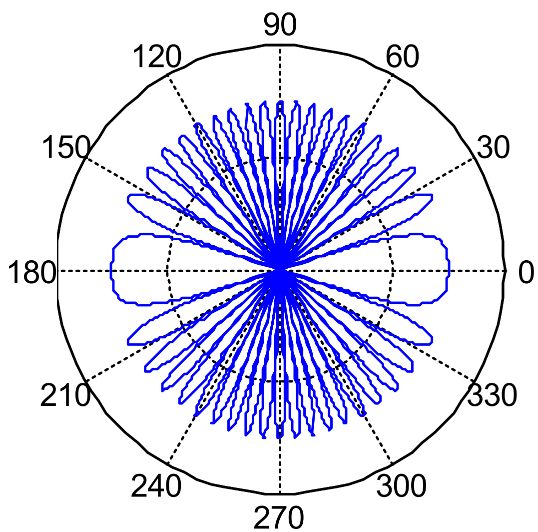
Consider BPSK Signaling and Assume $s_1 = s_2 = 1$

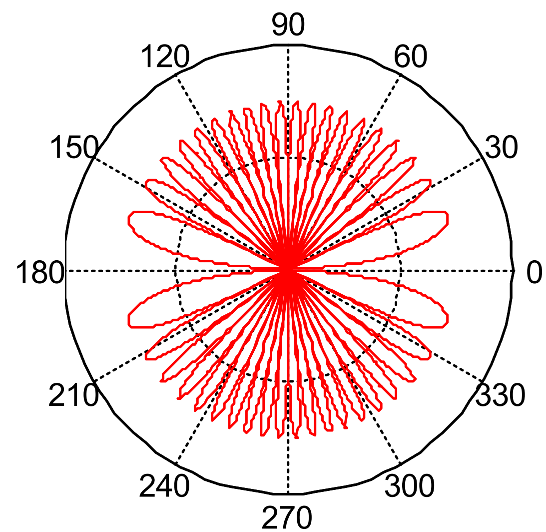
Time Slot 1:

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

Time Slot 2:

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





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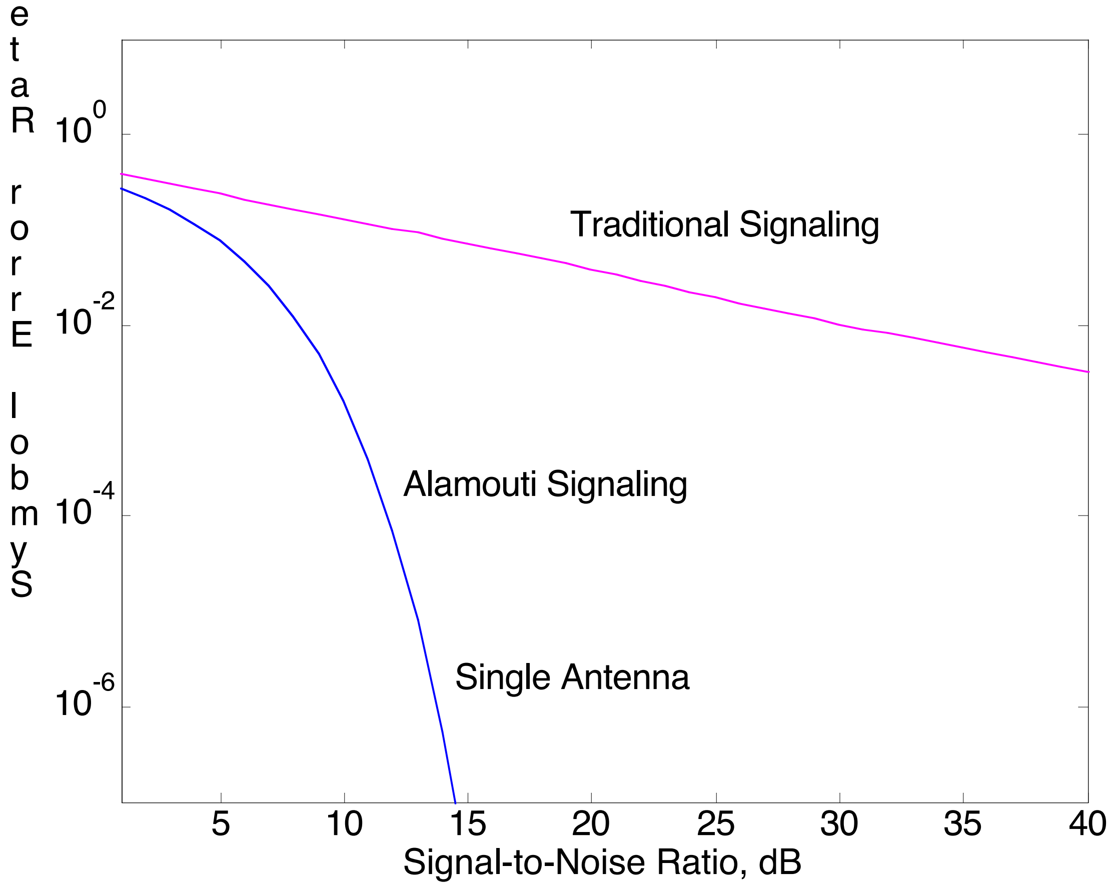
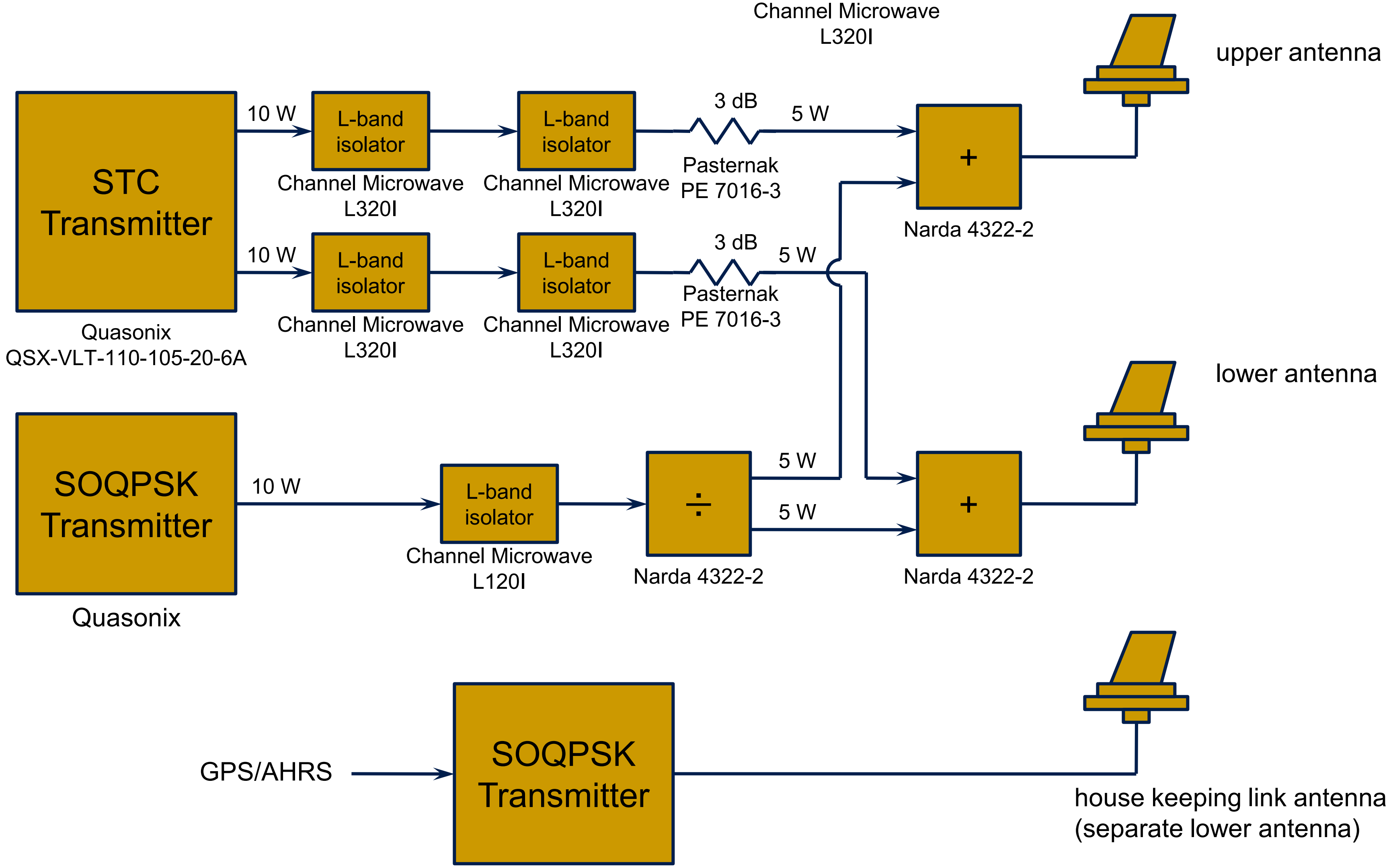
SER Simulations



Circular Polarization Diversity Reception

Results Identical to Single Receive Antenna System

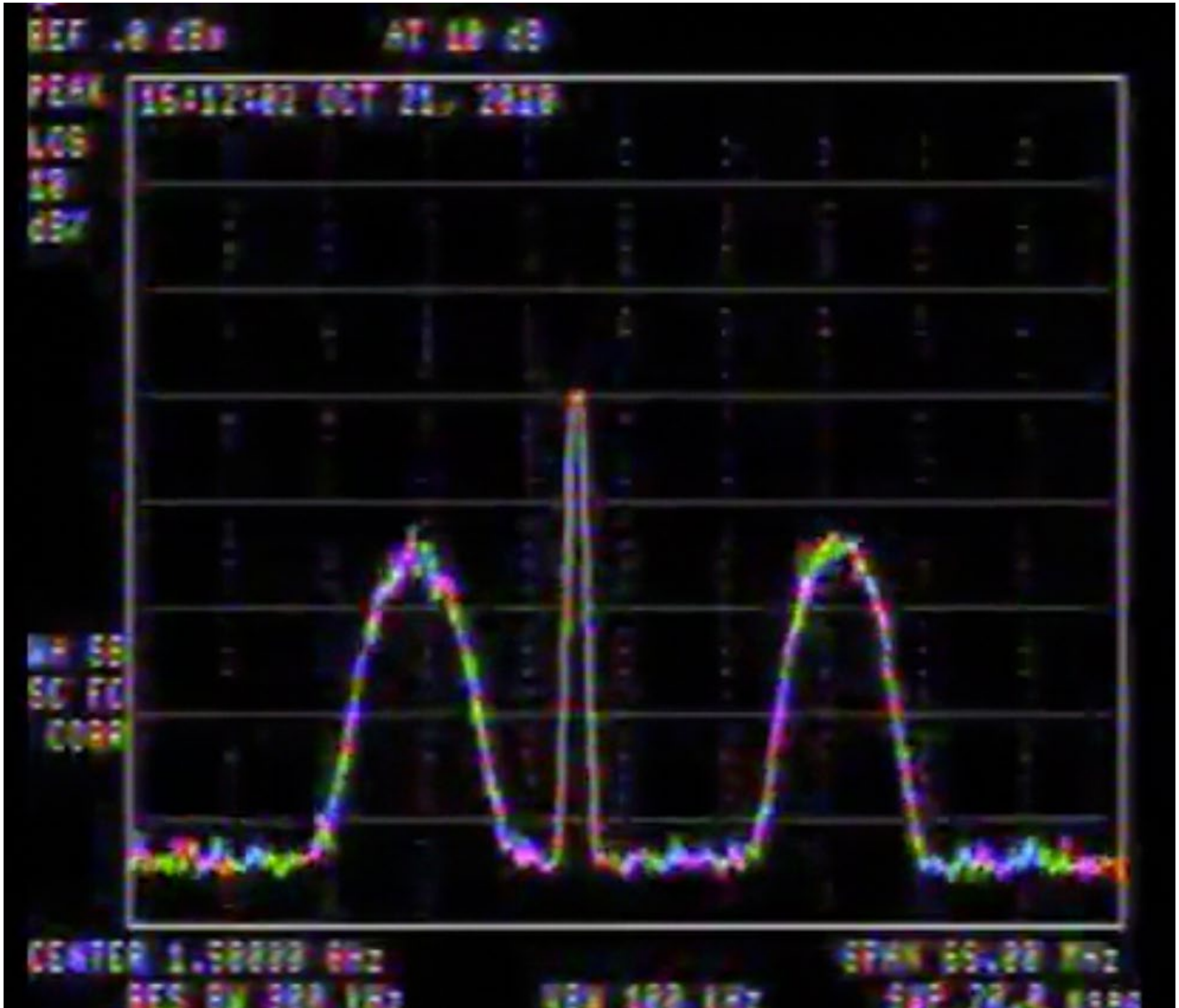
Flight Tests: Airborne Configuration



C-12 Beechcraft: Airborne Platform

BYU

STC Video Clip

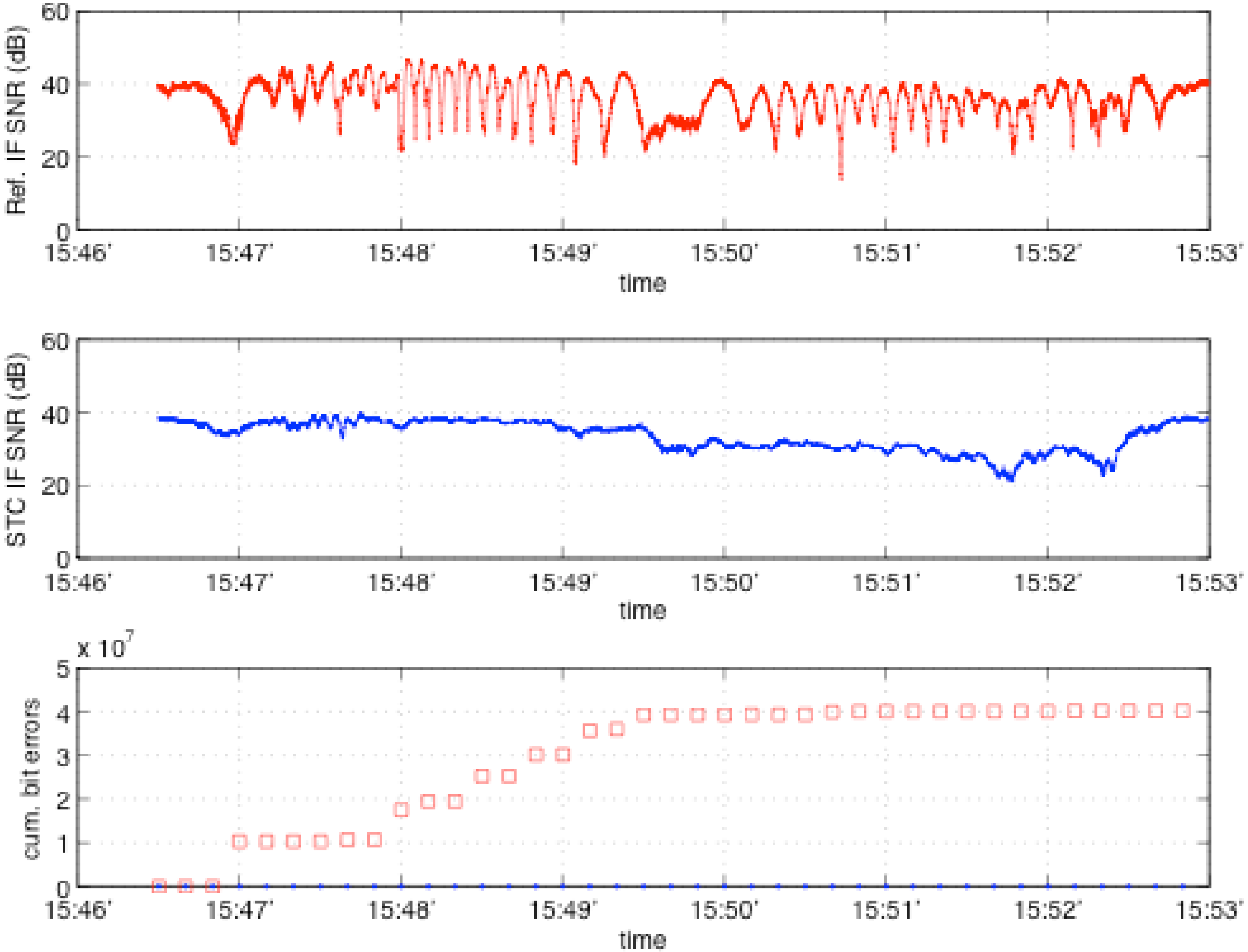


STC Summary

- 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

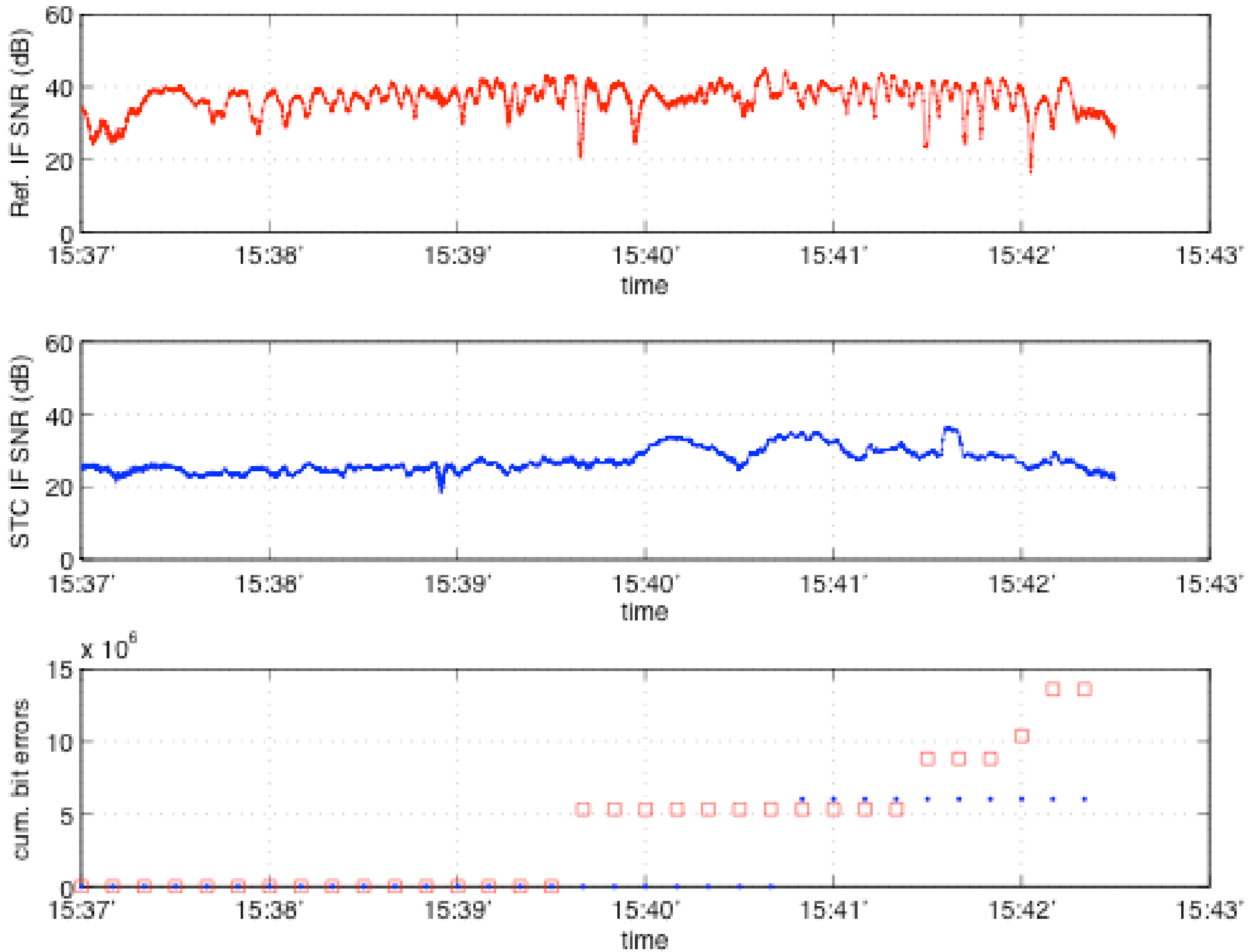
M1: Test Results

BYU



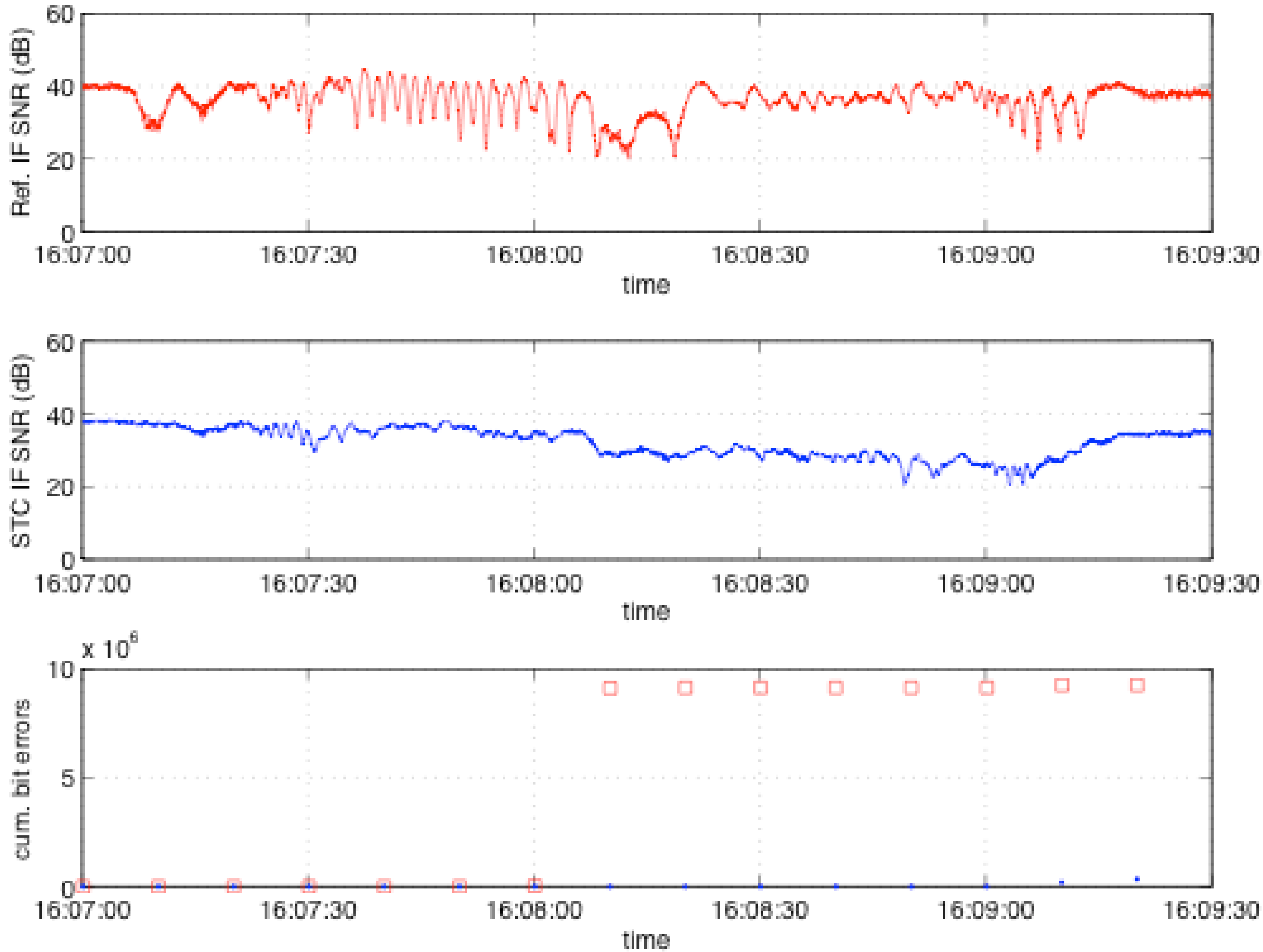
M2: Test Results

BYU



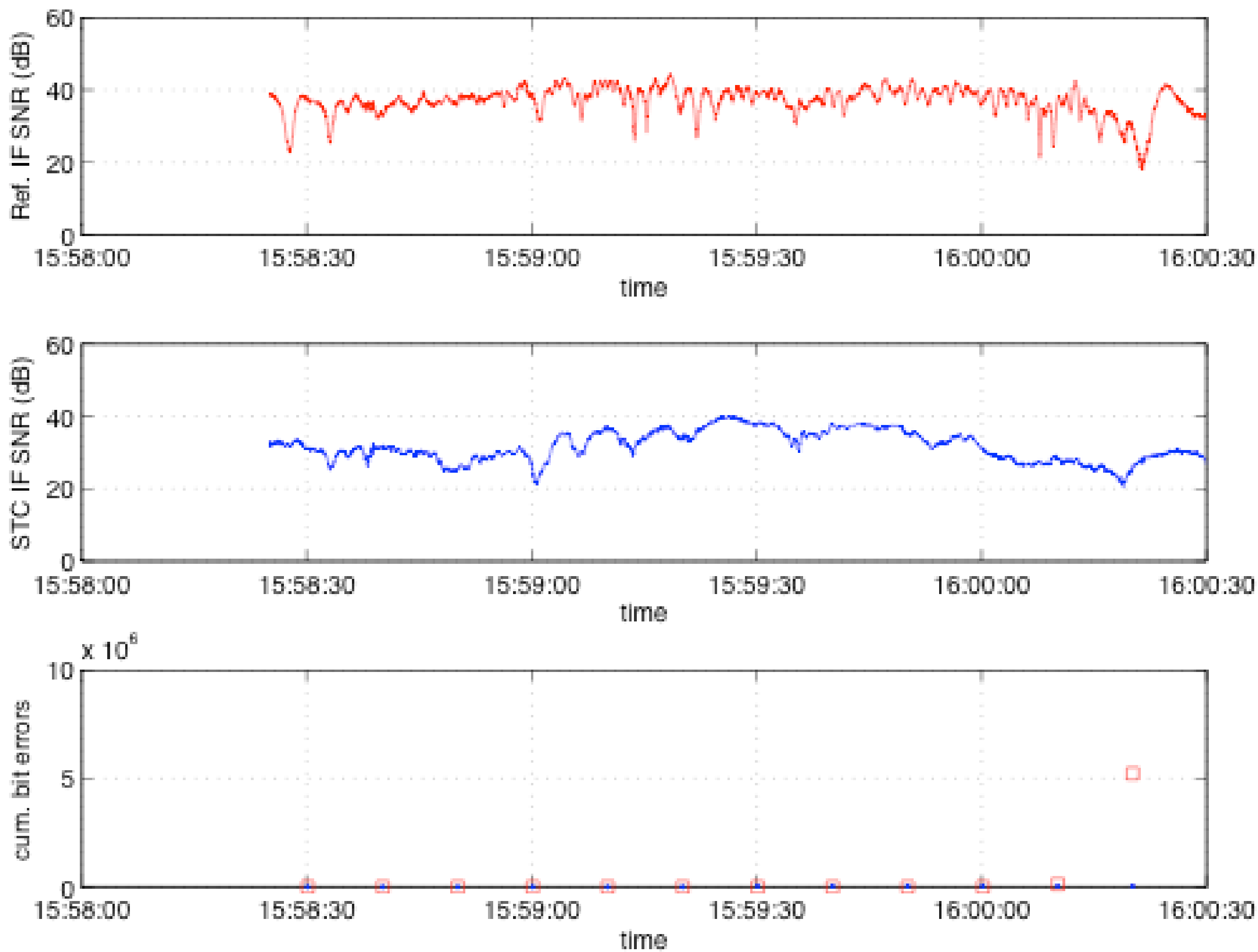
M3: Test Results

BYU



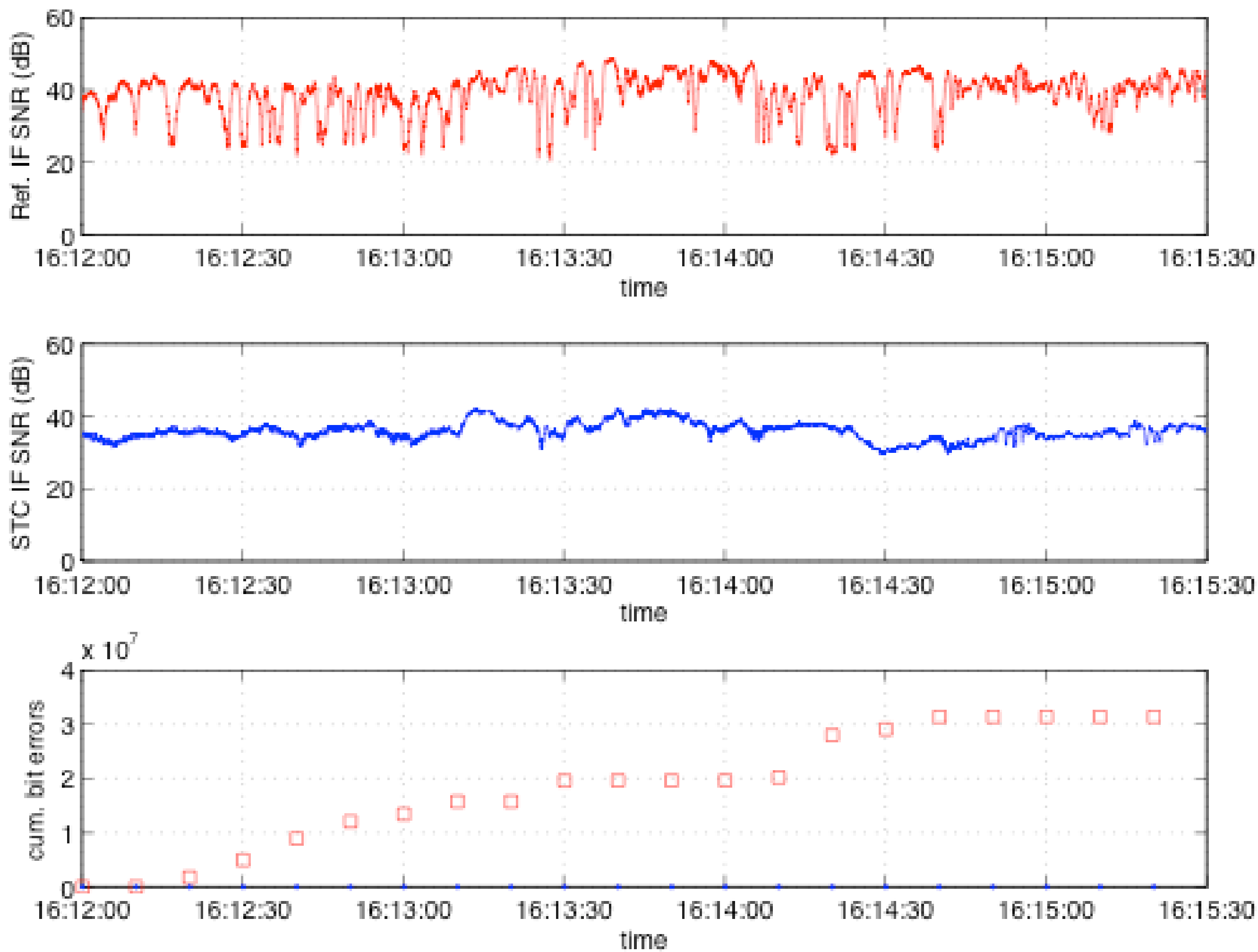
M4: Test Results

BYU



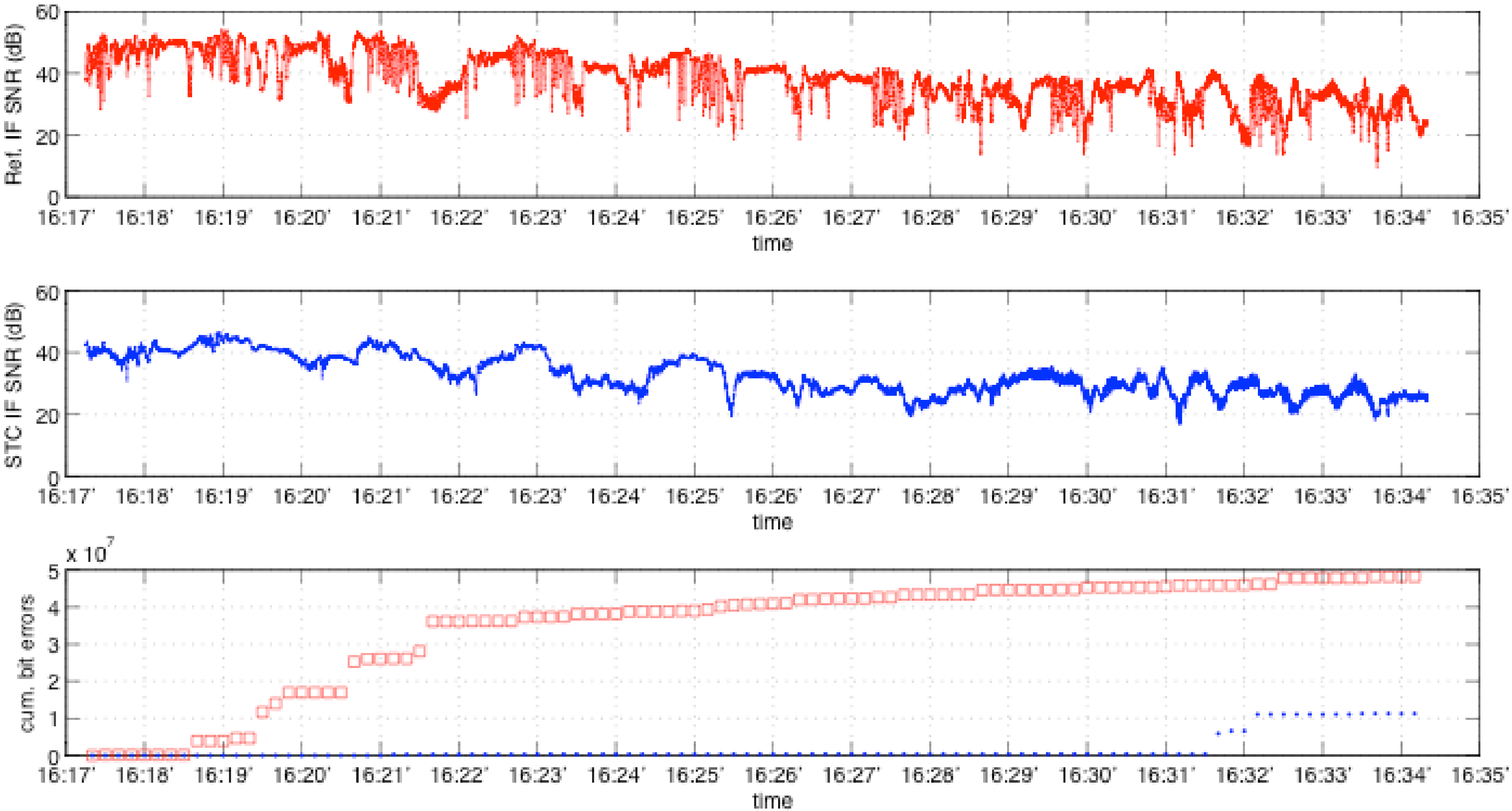
M3 to C2 Transition Test Results

BYU

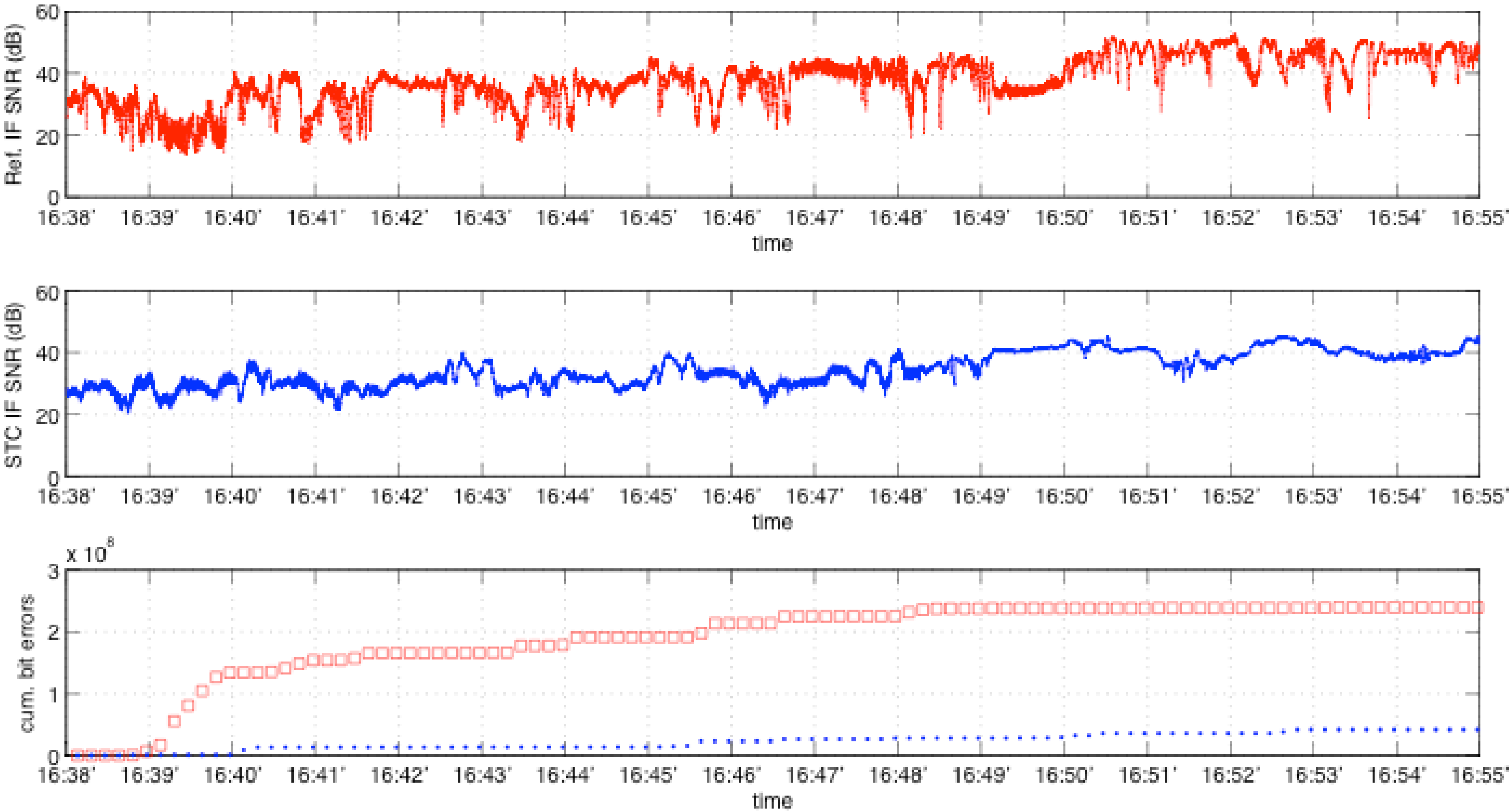


C2: Test Results

BYU



D2: Test Results



STC Summary

Dual-Antenna Diversity Scheme

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

Forward Error Correction

Forward Error Correction

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

LDPC Codes - History

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

LDPC AR4JA Codes

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

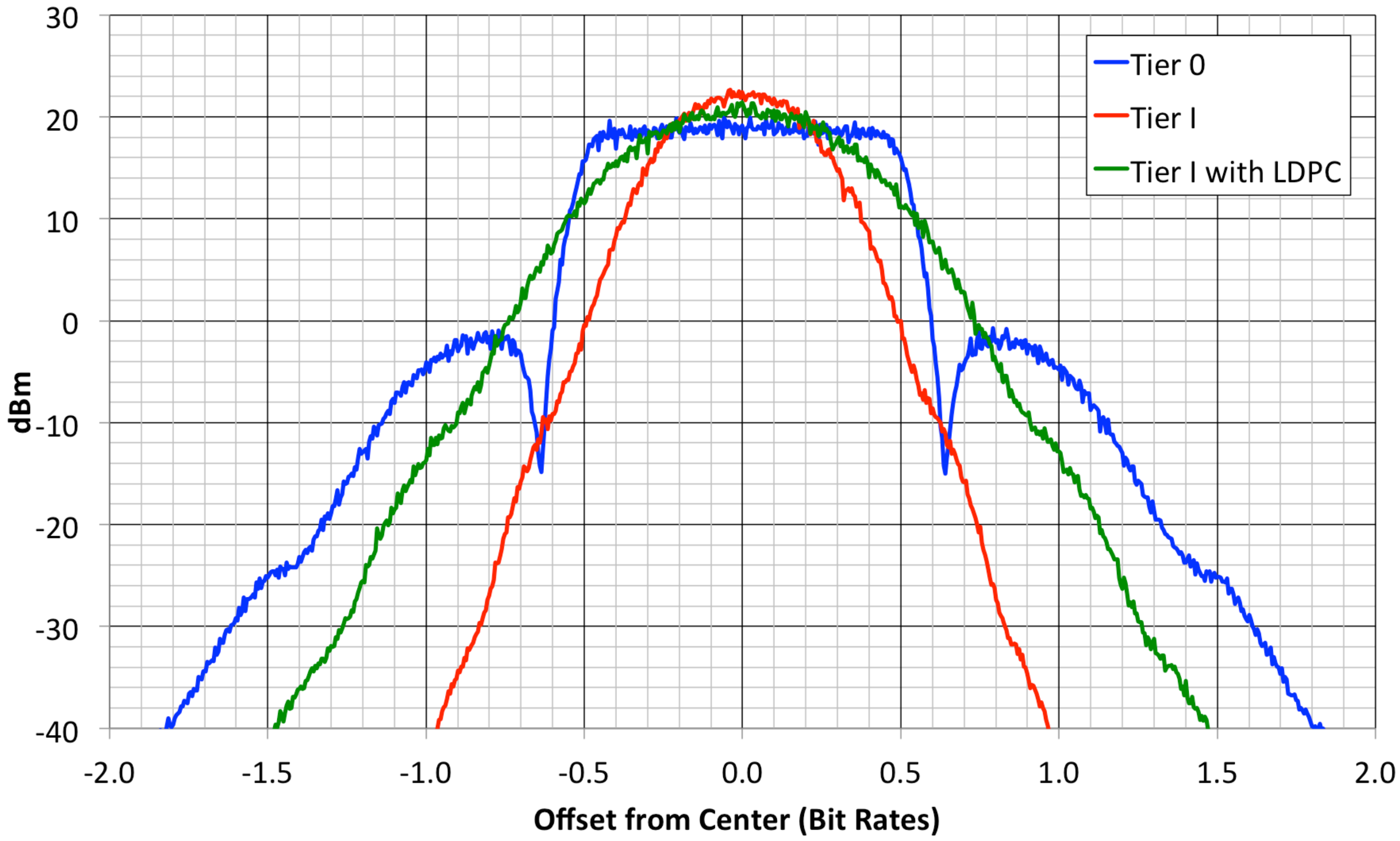
Information block length k	Code block length n		
	rate 1/2	rate 2/3	rate 4/5
1024	2048	1536	1280
4096	8192	6144	5120
16384	32768	24576	20480

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

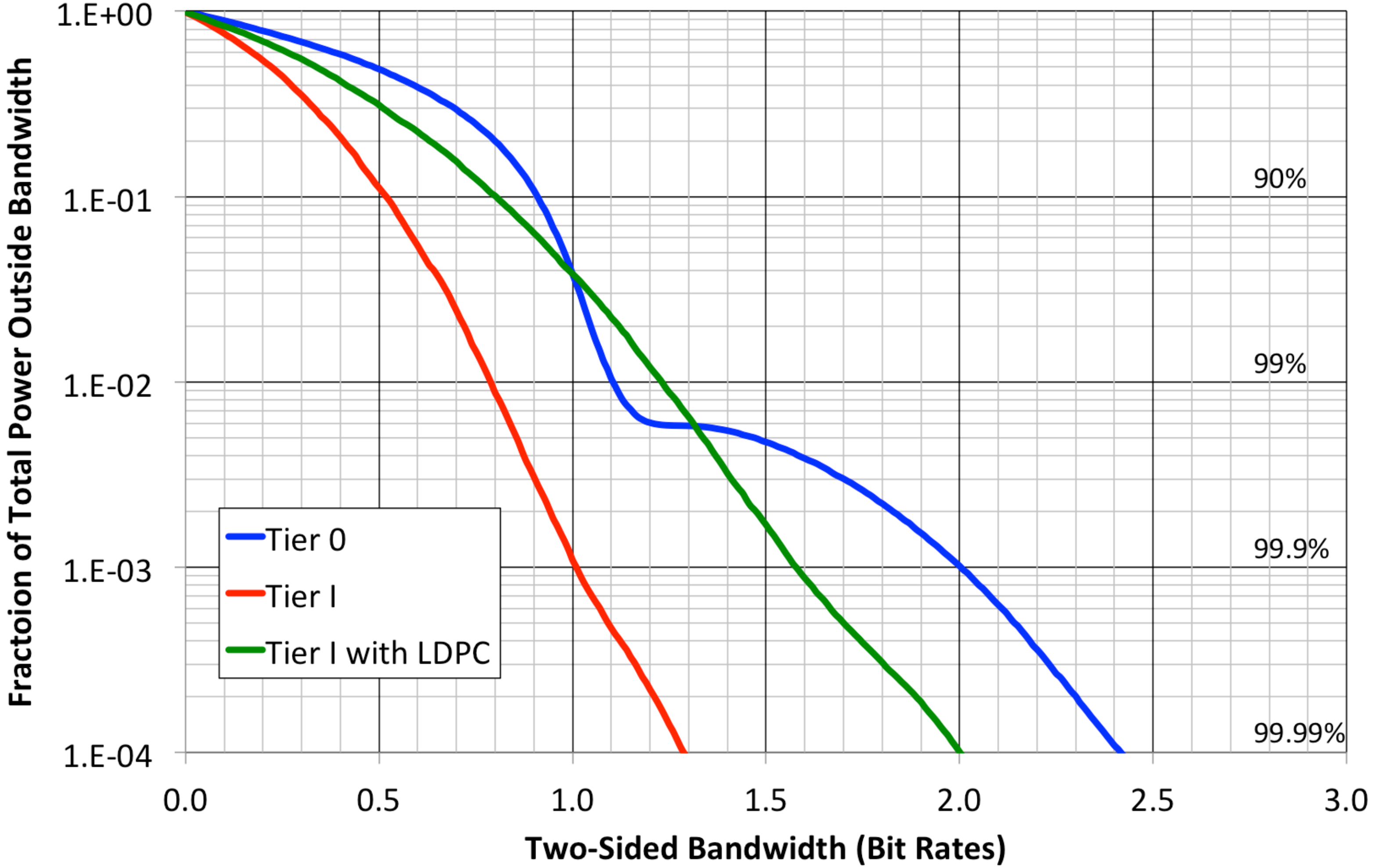
Packet Assembly

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

Spectral Characterization



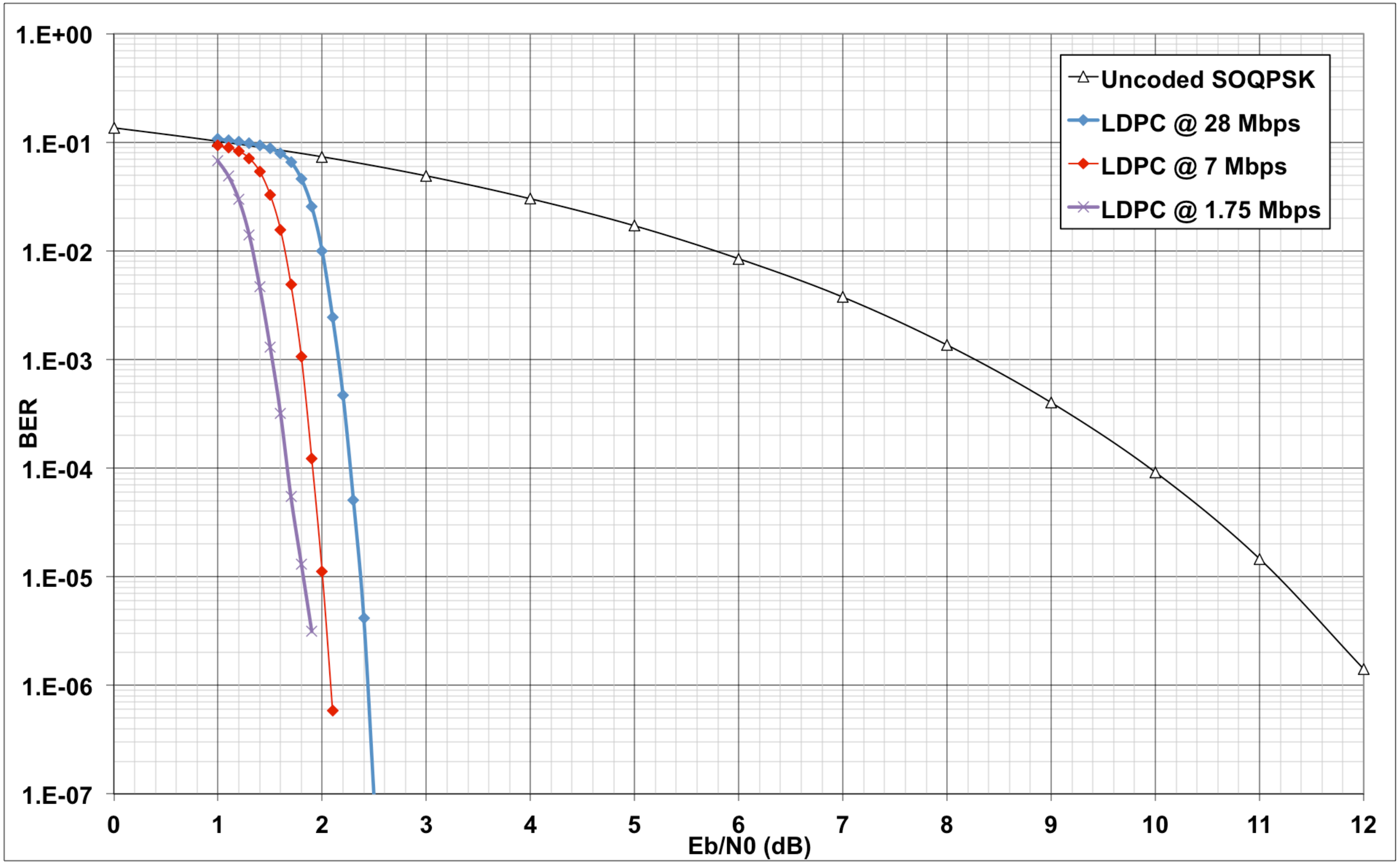
Fractional Out-of-Band Power



Decoder

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

Measured BER Results



LDPC from Appendix 2-D

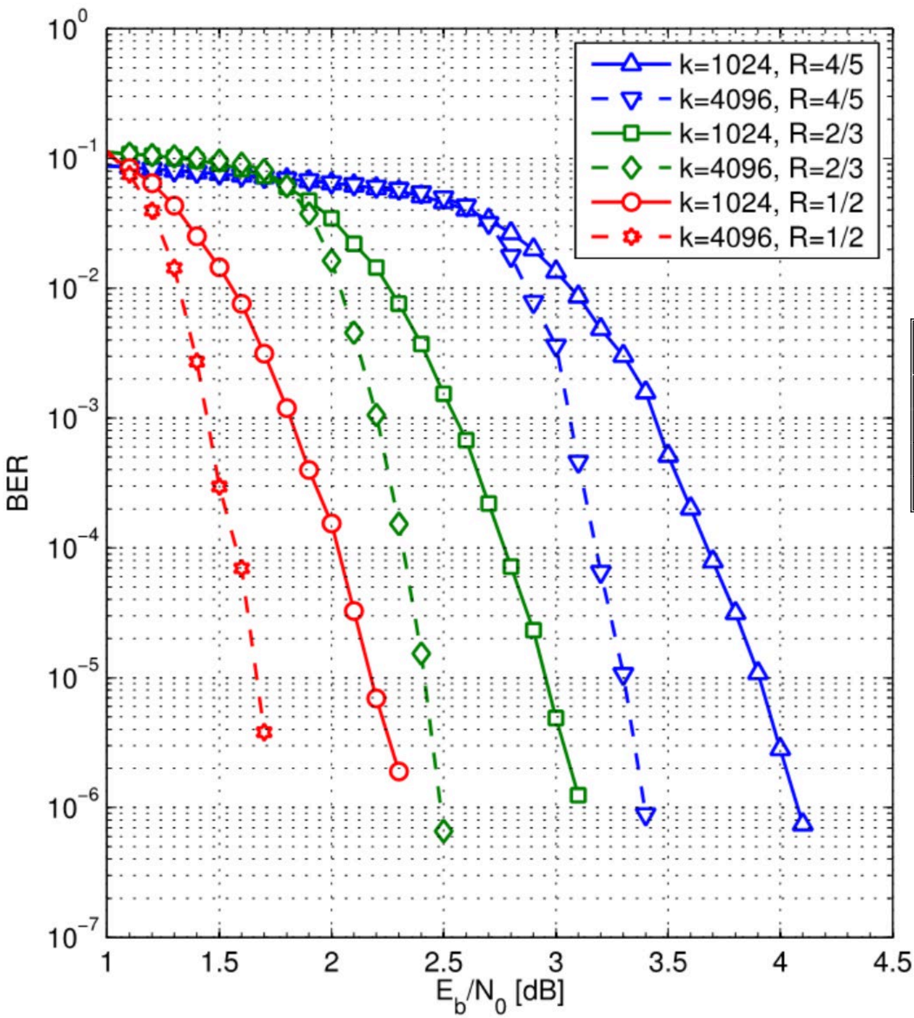
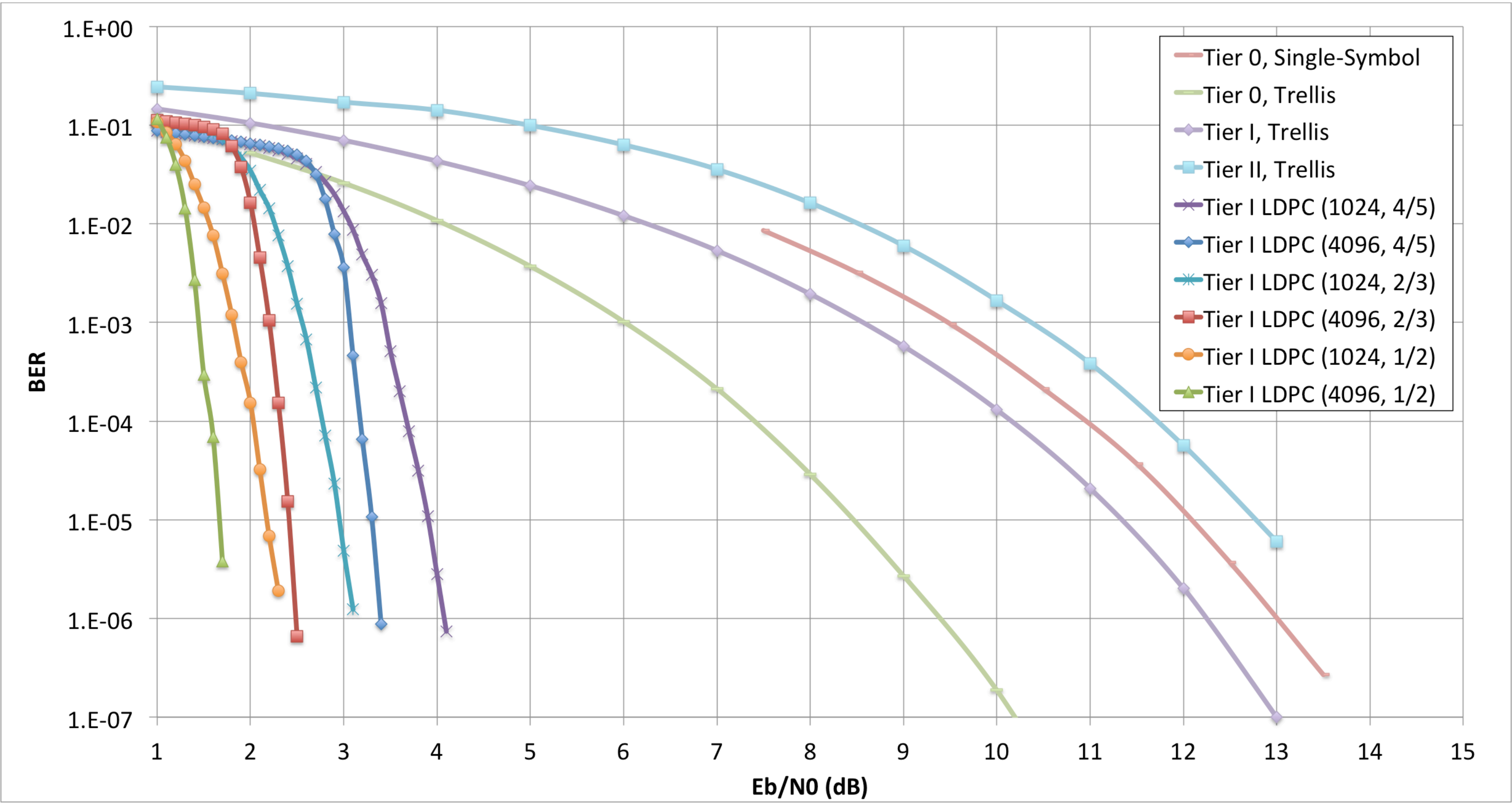


Table D-11. Bandwidth Expansion Factor

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

BER – All Modes



Conclusions

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

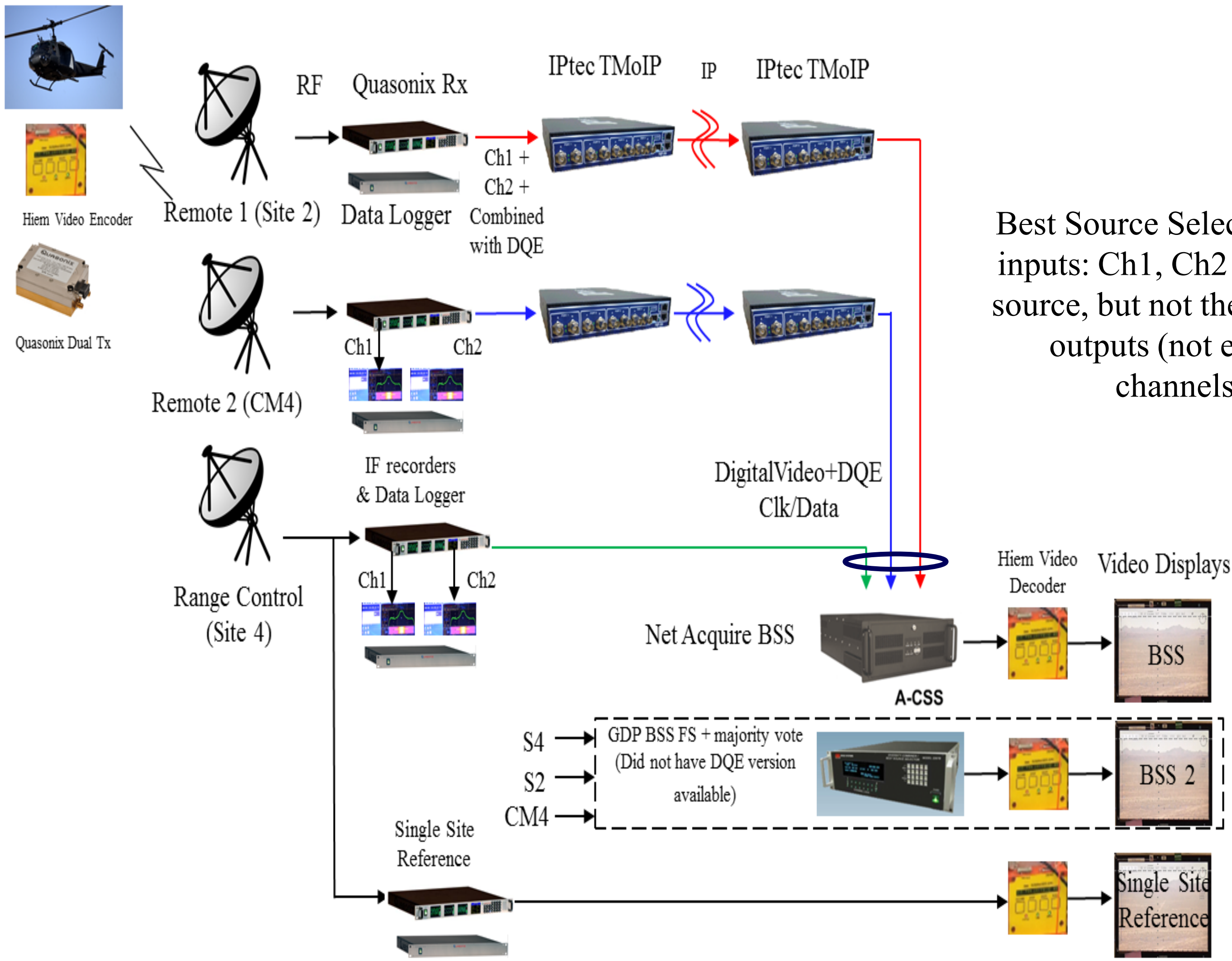
How Well Does It All Work Together?

Yuma Proving Grounds, AZ
Feb 8-11, 2016

Recipe for Delivering Every Bit

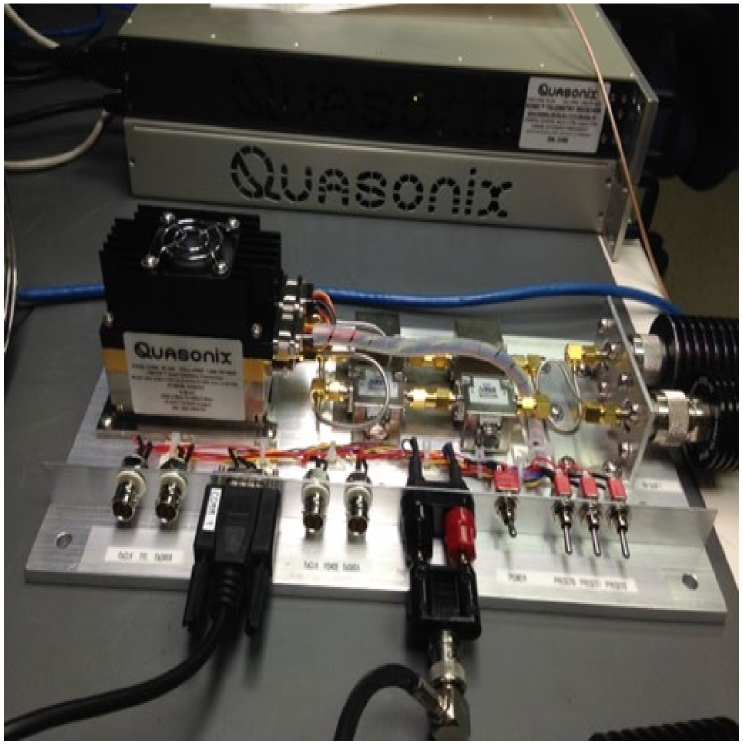
- Space Time Coding (STC)
  - Eliminates aircraft pattern nulls
- Low Density Parity Check (LDPC) coding
  - Improves margin, stops “dribbling errors”
- Adaptive Equalization (for non-STC signals)
  - Mitigates multipath
- Spatial diversity with correlating source selection
  - Eliminate coverage-based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

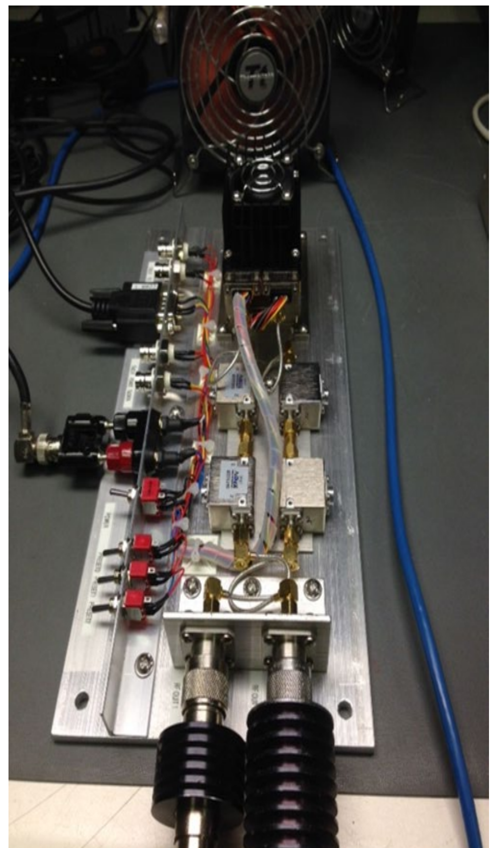
Multiple Receiving Sites



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

Dual Transmitter – S band – 10 W each output





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

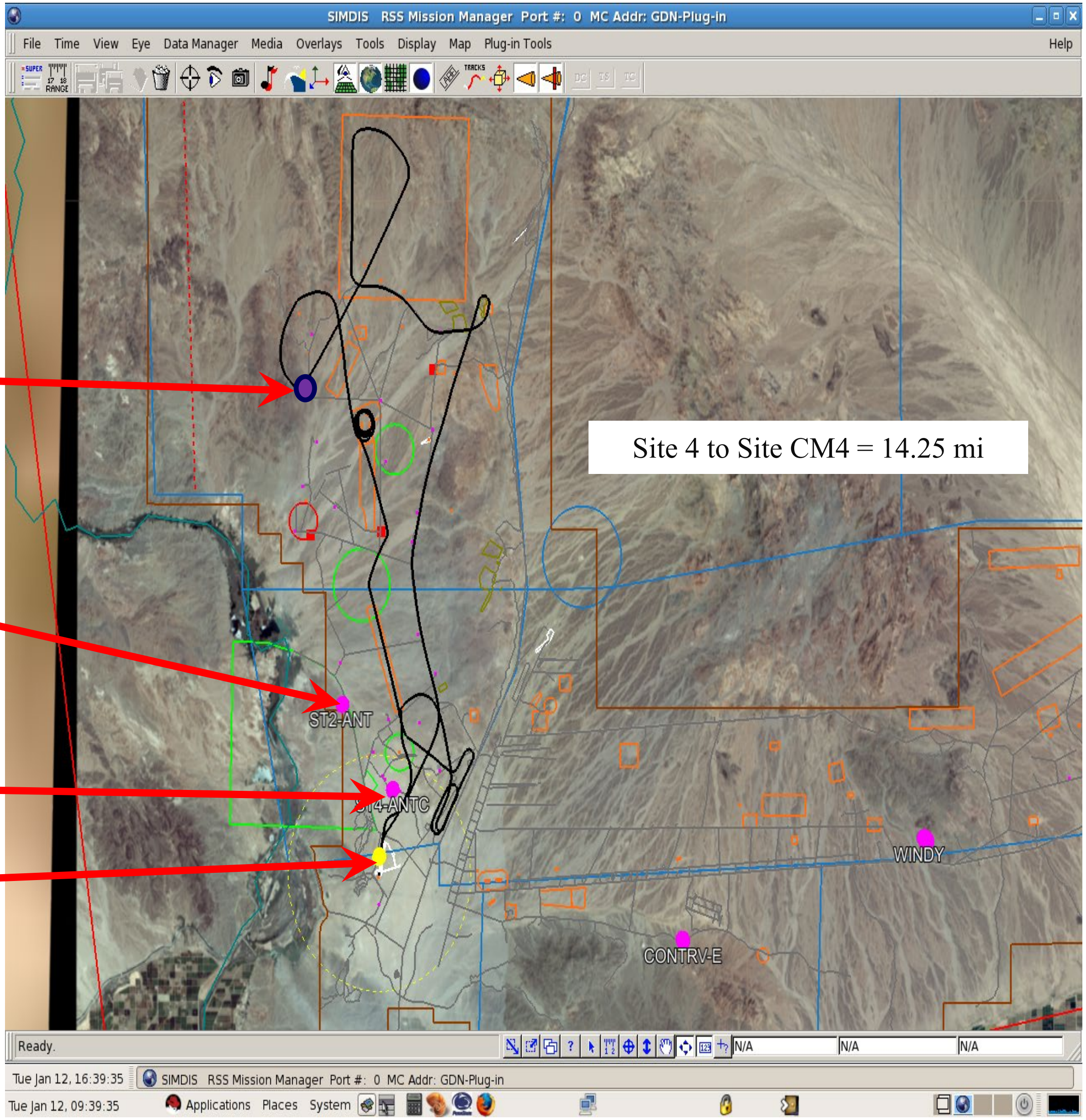
YPG Test Sites

Site CM4

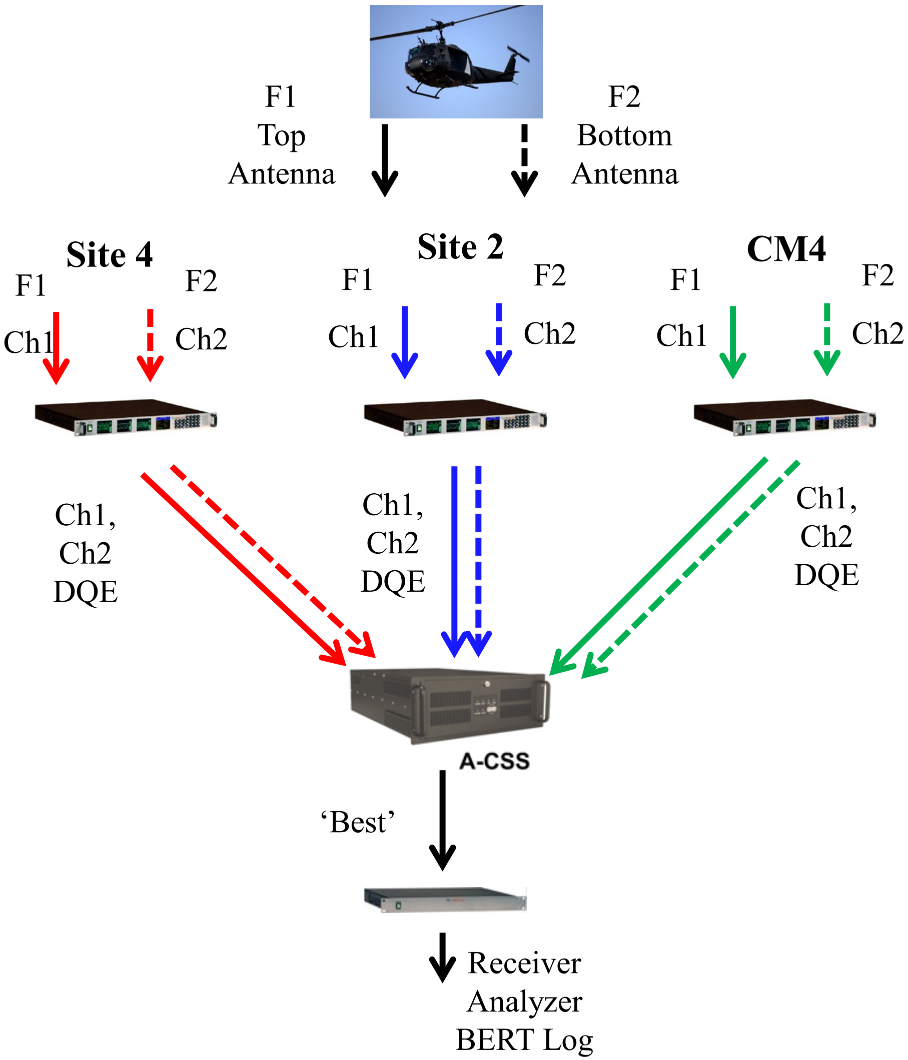
Site 2

Site 4

Laguna Airfield



Analysis using Data Logs



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

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

Receiver Analyzer Log
(BER of A-CSS output)

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

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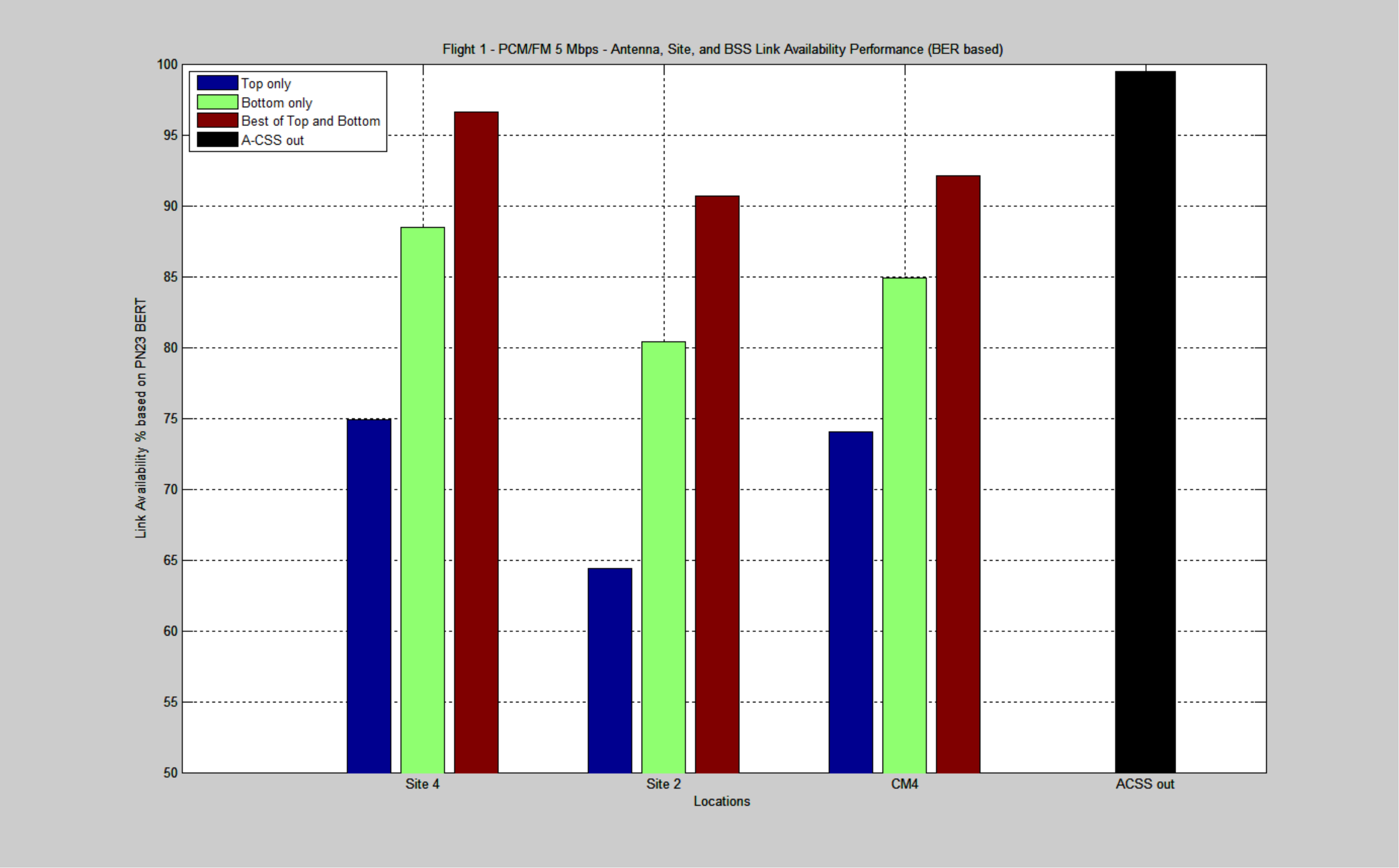
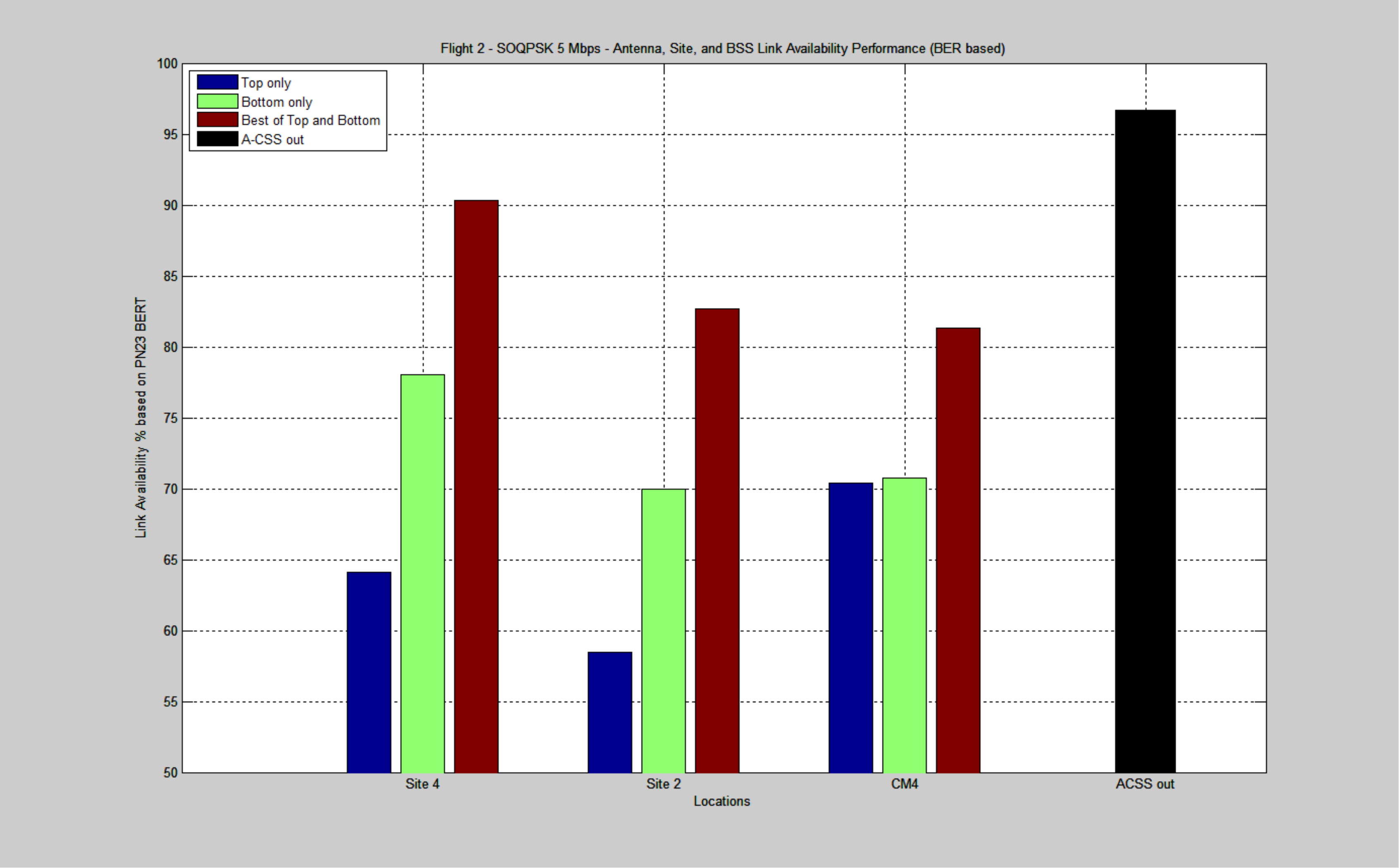
Flight 1 – PCM/FM 5 Mbps
Link Availability Summary (PN23 BER)



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



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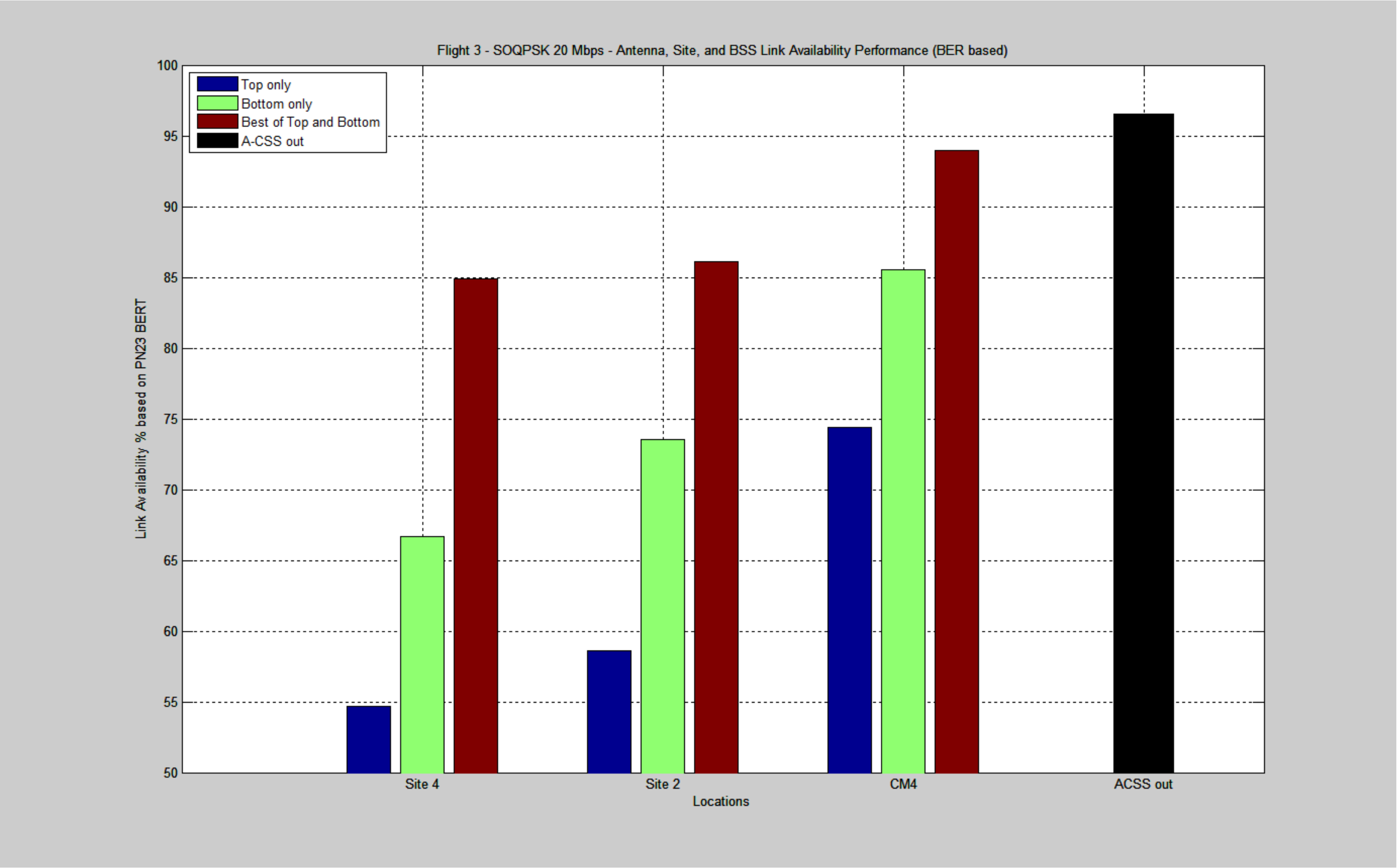
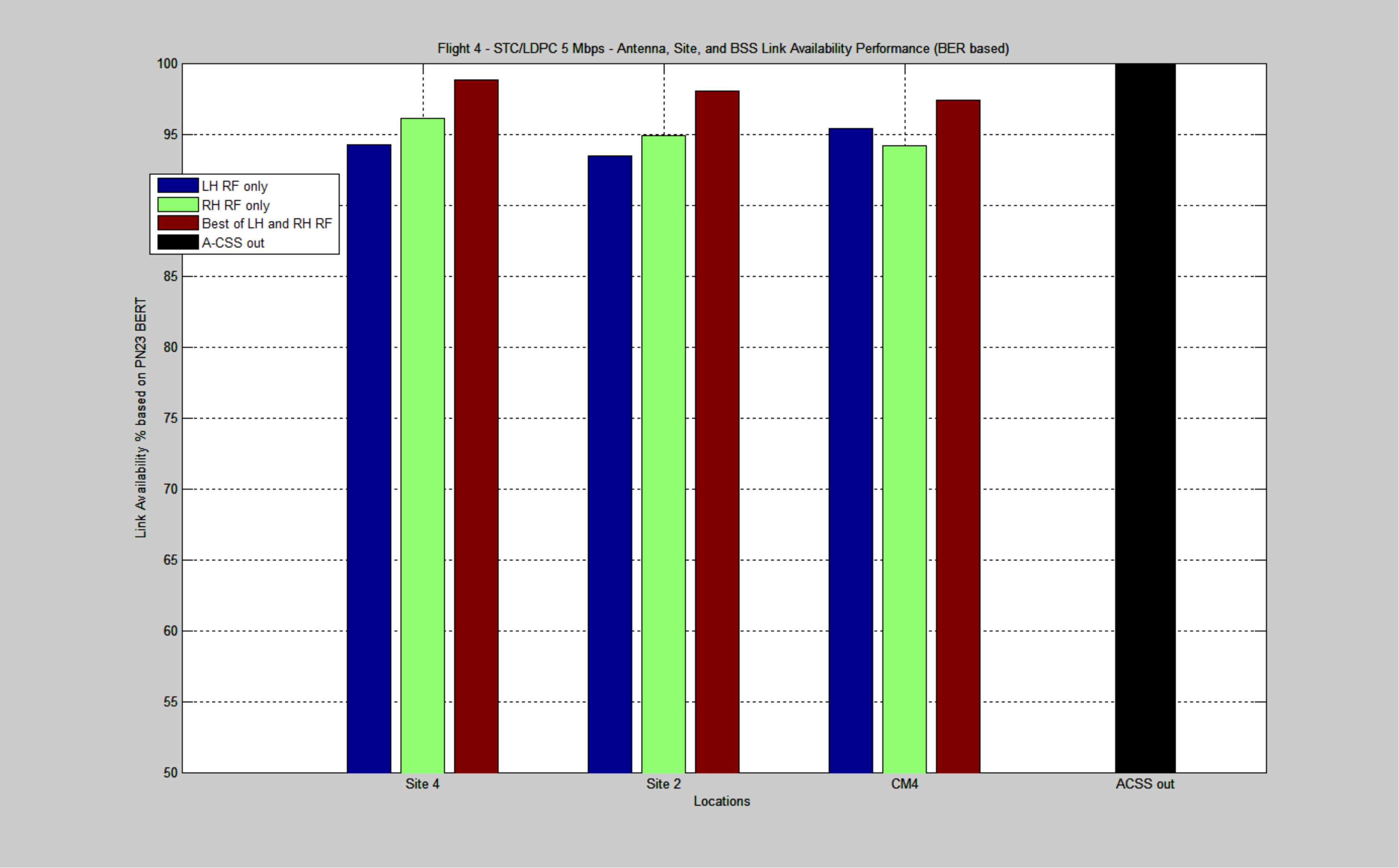
Flight 3 – SOQPSK 20 Mbps Link Availability Summary (PN23 BER)

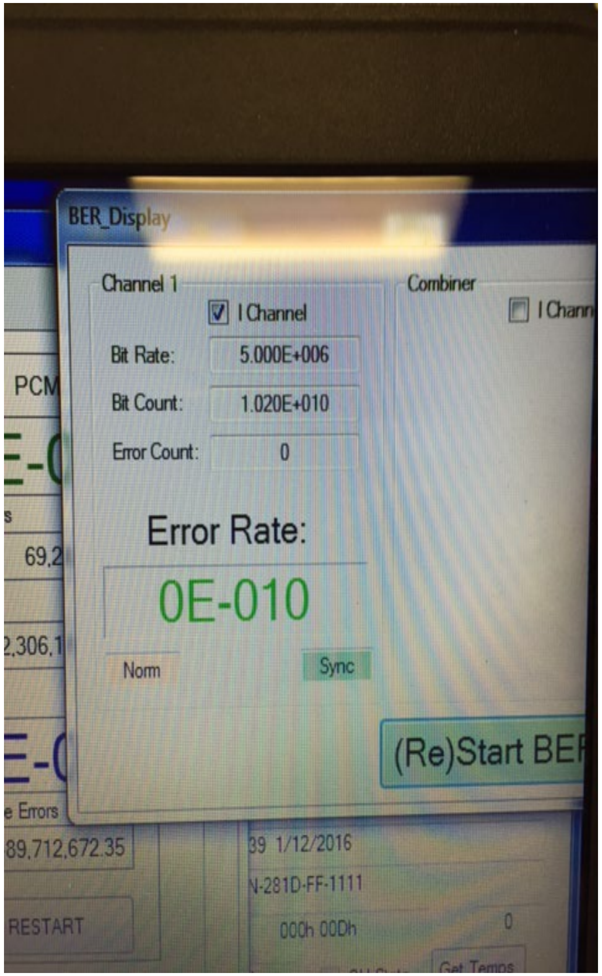


Flight 4 – STC/LDPC 5 Mbps Link Availability Summary (PN23 BER)



The elusive zero-error link…..

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



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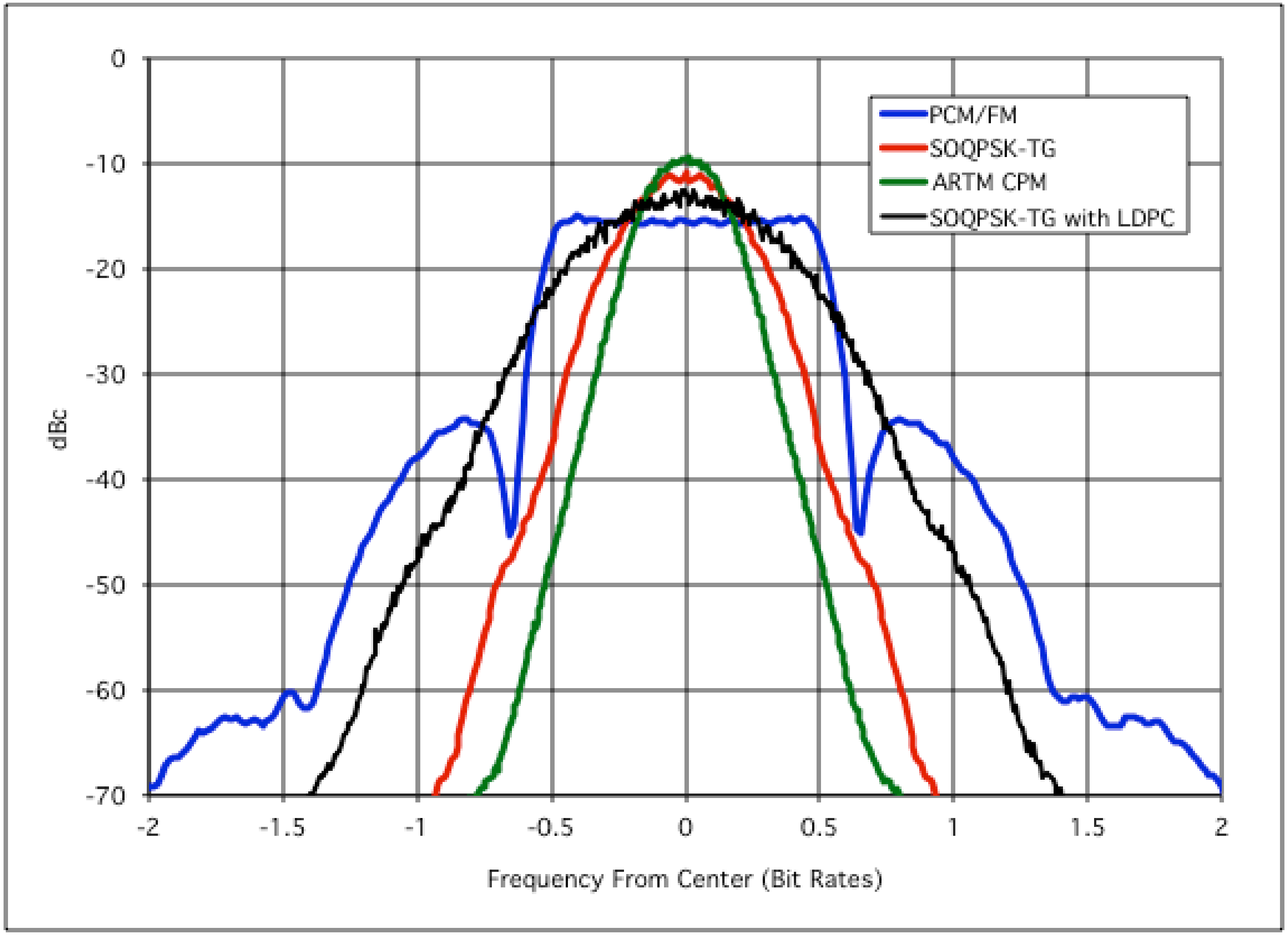
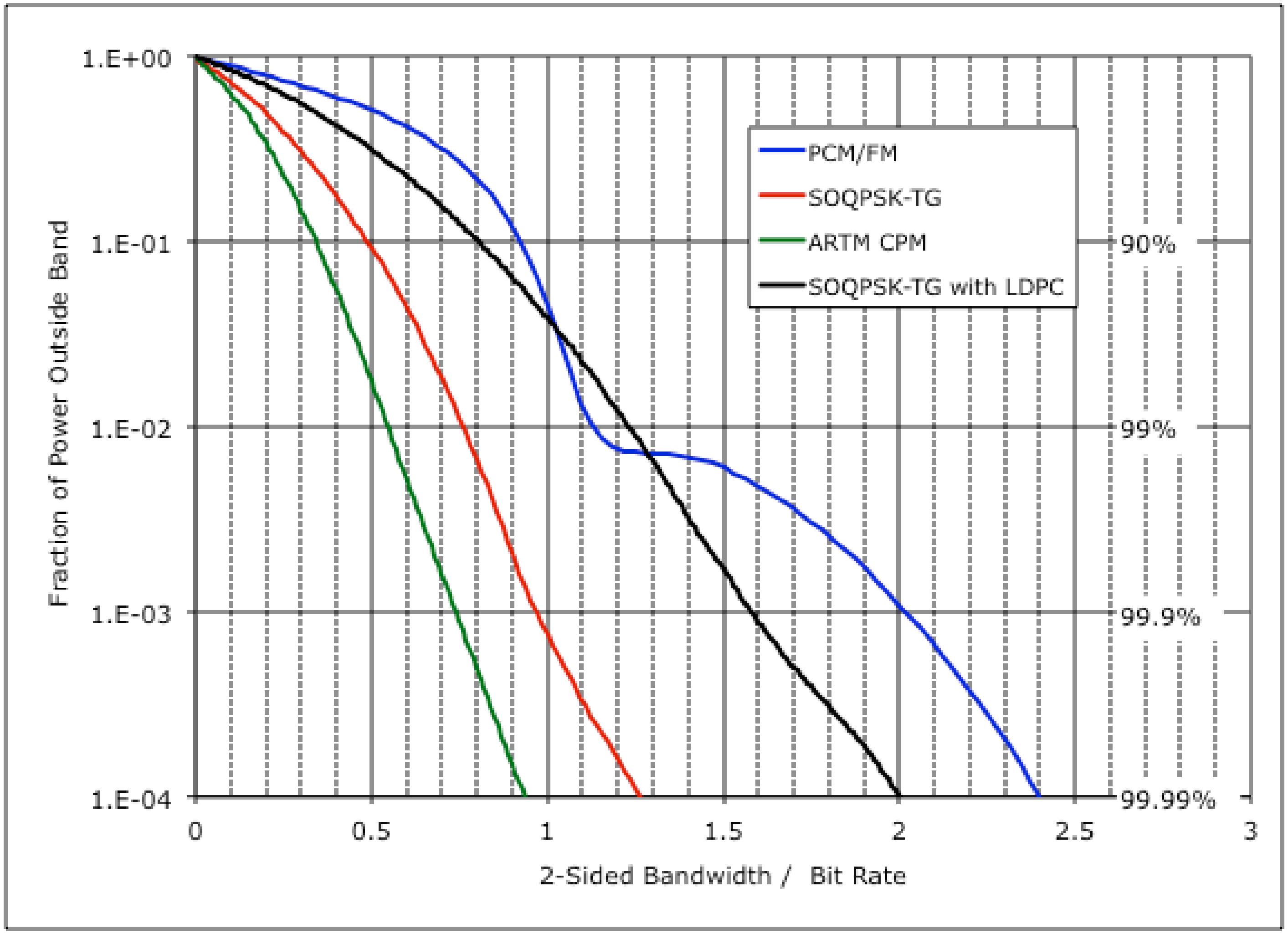
Performance Comparison and Summary

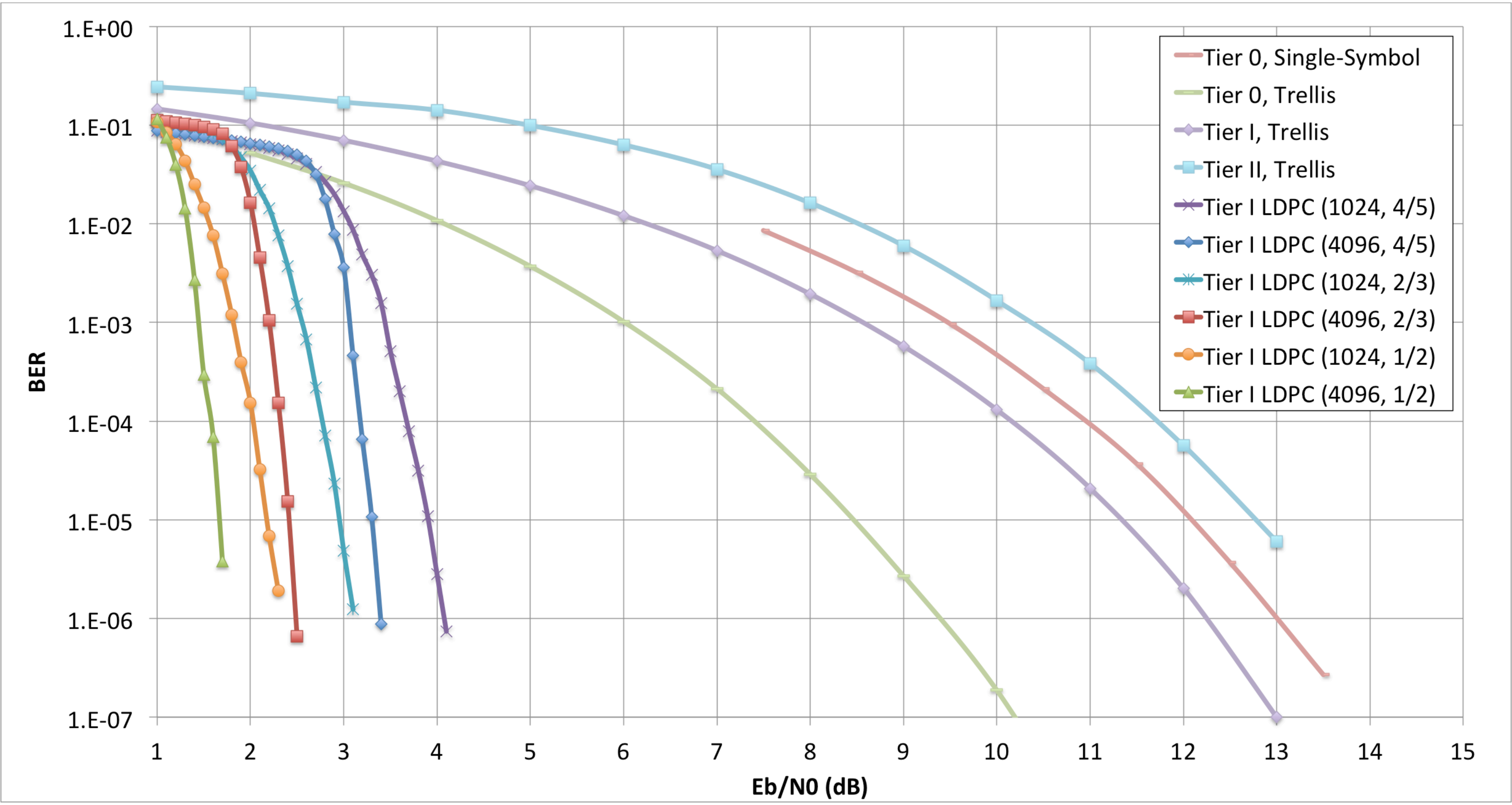
Power Spectral Densities



Out-of-Band Power



BER Performance Comparison



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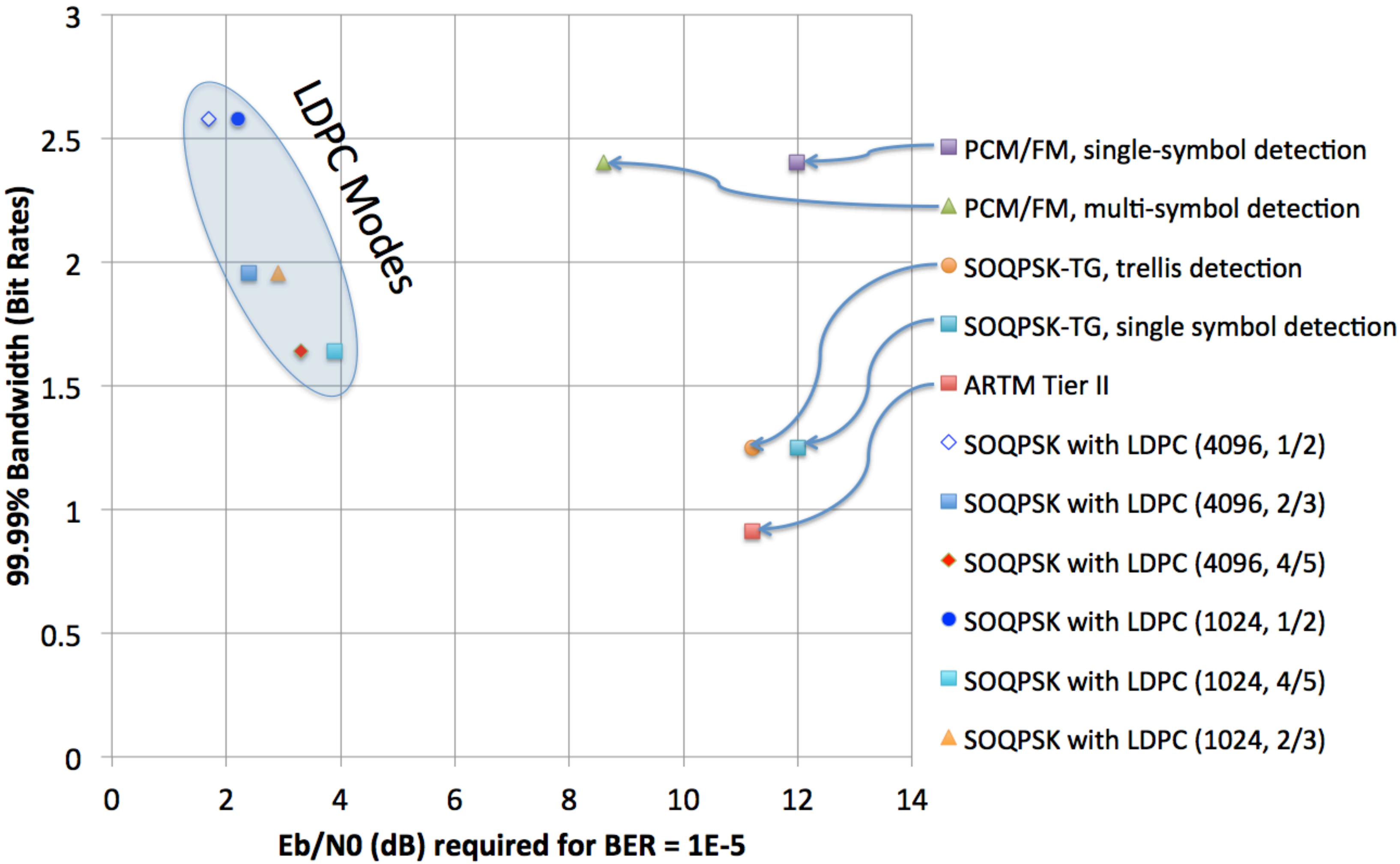
Bandwidth-Power Plane



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- Kip Temple, ARTM, Edwards AFB
- Gene Law, NAWCWD, Pt. Mugu
- Vickie Reynolds, White Sands Missile Range

Questions/Comments

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