Advanced Modulation Techniques for Telemetry

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

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

- **Information Fidelity**
  - Additive White Gaussian Noise (AWGN) channels
    - Bit Error Probability (BEP) or Bit Error Rate (BER)
  - Bursty (dropout) channels
    - Cumulative error count
    - Link Availability

- **Bandwidth Efficiency**
  - Power spectral density
  - Fractional Out-of-band Power
  - Channel spacing with adjacent channel interference (ACI)

- **Bandwidth-Power plane**
BER Performance Comparison
Cumulative Error Counts in Bursty Channels

Bit Error Accumulation History
ARTM flight 78, frequency diversity, 5 m antenna, high altitude corridor, easterly, 20k ft. altitude

Figure from Robert Jefferis, Tybrin, Edwards AFB. Reprinted by permission of the author.
Performance Metrics

- **Link Availability (LA)** – % of the time that the instantaneous BER over 1 sec blocks is less than 10^{-5}.

- **Video Availability (VA)** - % of time video is available (picture on time/ total time x 100)

- These two metrics are not the same. Video system sensitivity and its response to bit errors can have significant impact on VA performance.
Which Bandwidth?

- **Fixed level**
  - -60 dBC is common
  - -25 dBm is “standard” in IRIG-106

- **Fractional out-of-band power**
  - 99%, 99.9%, 99.99% are all used

- **Minimum frequency separation**
  - Accounts for receive-side effects
    - Receiver IF filtering
    - Demodulator interference tolerance
    - Relative levels of interfering signals
    - Depends on application
Power Spectral Density (PSD)
Fractional Out-of-band Power

2017 International Telemetering Conference
Terry Hill - thill@quasonix.com
Bandwidth-Power Plane

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

![Graph showing modulation comparisons]

- **PCM/FM, single-symbol detection**
- **PCM/FM, multi-symbol detection**
- **SOQPSK-TG, trellis detection**
- **SOQPSK-TG, single symbol detection**
- **ARTM Tier II**
- **SOQPSK with LDPC (4096, 1/2)**
- **SOQPSK with LDPC (4096, 2/3)**
- **SOQPSK with LDPC (4096, 4/5)**
- **SOQPSK with LDPC (1024, 1/2)**
- **SOQPSK with LDPC (1024, 4/5)**
- **SOQPSK with LDPC (1024, 2/3)**

99.99% Bandwidth (Bit Rates)

$\frac{E_b}{N_0}$ (dB) required for BER = $1E-5$
Continuous Phase Modulation
The Modulation Universe

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

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

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

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

- Where \( \alpha_i \) represents an M-ary symbol sequence
  - \( \alpha_i \) 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

![Diagram of phase tree representation with time in bits on the x-axis and phase in cycles on the y-axis. The graph shows sinusoidal waves representing phase changes over time.]
M=2, h=1/2, 1REC (MSK)

PSD vertical axis is dBC per FFT bin
1 FFT bin = 1/64 * symbol rate
M=4, h=1/4, 1REC

PSD vertical axis is dBc per FFT bin
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

CPM Phase Tree

CPM PSD

Quasonix
Multi-h CPM

- Cyclically rotates through multiple “sets” of FSK tones
- Increases minimum distance in trellis
  - Improves BER performance
- Widely proposed for high-performance nonlinear channels
  - MIL-STD-188-181B
M=2, h_1=1/4, h_2=1/2, 1REC

PSD vertical axis is dBC per FFT bin
1 FFT bin = 1/64 * symbol rate
M=4, h₁=4/16, h₂=5/16, 3RC

**ARTM Tier II Waveform**

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

![Diagram of CPM Phase Tree and PSD](image_url)
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)

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

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

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

- 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

![Graph showing fractional out-of-band power over 2-sided bandwidth/bit rate](image)
PCM/FM Summary

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

<table>
<thead>
<tr>
<th>M</th>
<th>$\alpha_i$</th>
<th>h</th>
<th>g(t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>{-1, +1}</td>
<td>0.7</td>
<td>Normalized impulse response of a high order Bessel filter with 3 dB bandwidth = 0.7 * bit rate</td>
</tr>
</tbody>
</table>
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 \( (\rho, B, T_1, T_2) \)
  - 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

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

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

- 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

\[ g(t) = n(t) \times w(t), \text{ where} \]

\[ n(t) = \frac{A \cos(\pi \rho \frac{Bt}{T})}{1 - 4(\rho \frac{Bt}{T})^2} \times \frac{\sin(\pi \frac{Bt}{T})}{(\pi \frac{Bt}{T})}, \]

\[ w(t) = \begin{cases} 
1, & \text{for } |t/T| < T_1 \\
\frac{1}{2} + \frac{1}{2} \cos \frac{\pi(\frac{|t/T|}{T_2} - T_1)}{T_2}, & \text{for } T_1 < |t/T| < T_1 + T_2 \\
0, & \text{for } |t/T| > T_1 + T_2 
\end{cases} \]
Frequency Pulse Shape, $g(t)$

Parameter | SOQPSK-A | SOQPSK-B  
---|---|---
$\rho$ | 1.0 | 0.5 
B | 1.35 | 1.45 
$T_1$ | 1.4 | 2.8 
$T_2$ | 0.6 | 1.2
SOQPSK Variants

Bandwidth Efficiency of SOQPSK (99.99% BW)

- Optimum Viterbi
- 3rd order Butterworth
- Integrate & Dump

Eb/No (dB) to achieve 10^-5 BER

99.99% Bandwidth
Optimal SOQPSK Variants

99.99% Bandwidth

Viterbi curve
SOQPSK-A (1,1,35,1,4,0,6) (Viterbi)
SOQPSK-B (0,5,1,45,2,8,1,2)(Viterbi)
SOQPSK (0,7,1,25,1,5,0,5) (Viterbi)
Butterworth curve
SOQPSK-A (1,1,35,1,4,0,6) (Butterworth)
SOQPSK-B (0,5,1,45,2,8,1,2)(Butterworth)
SOQPSK (0,7,1,25,1,5,0,5) (Butterworth)
Integrate & Dump curve
SOQPSK-A (1,1,35,1,4,0,6) (I&D)
SOQPSK-B (0,5,1,45,2,8,1,2)(I&D)
SOQPSK (0,7,1,25,1,5,0,5) (I&D)
Unshaped Offset QPSK
Slightly Shaped OQPSK
MIL-STD SOQSPK
SOQPSK-TG
SOQPSK-TG

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

Phase in Cycles

Time in bits
Power Spectral Density
SOQPSK-TG Eye Patterns

- Single-symbol detection is sub-optimal, but practical
Wait! I thought SOQPSK was constant envelope…
Measured PSD (Tier 0 & 1)
Fractional Out-of-band Power
**Shaped Offset QPSK Summary**

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

<table>
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<th>$\alpha_i$</th>
<th>h</th>
<th>g(t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>{-1, 0, +1}</td>
<td>0.50</td>
<td>Normalized windowed impulse response of a spectral raised cosine</td>
</tr>
</tbody>
</table>
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

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

\[ \phi(t, \bar{\alpha}) = 2\pi h \int_{-\infty}^{t} \sum_{i=0}^{+\infty} \alpha_i g(\tau - iT) d\tau \quad -\infty < t < +\infty \]

- \( M = 4 \) (quaternary)
- \( \alpha_i = 2 \left[ 2d_{1i} + d_{0i} \right] - 3 \)
  - \( \alpha_i = \{-3, -1, +1, +3\} \)
  - \( d_i = \{0, 1\} \)
- \( h = \{4/16, 5/16\} \), 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

LENGTH 3 RC FREQUENCY PULSE AND CORRESPONDING PHASE PULS

TIME (SYMBOLS)

NORMALIZED FREQUENCY/PHASE

0 0.5 1 1.5 2 2.5

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1

0 50 100 150 200 250 300 350 400 450 500 550 600

-400 -300 -200 -100 0 100 200 300 400
PSD (Tier 0, I, & II)
Fractional Out-of-band Power

- PCM/FM
- SOQPSK-TG
- ARTM CPM

2-Sided Bandwidth / Bit Rate

0 0.5 1 1.5 2 2.5 3

1.00 1.00 1.00 1.00 1.00 1.00 1.00

90% 99% 99.9% 99.99%
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

<table>
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<th>$\alpha_i$</th>
<th>h</th>
<th>g(t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>{-3, -1, +1, +3}</td>
<td>{4/16, 5/16}</td>
<td>Normalized raised cosine, 3 symbols (6 bits) long</td>
</tr>
</tbody>
</table>
## Side by Side Summary

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

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

\[ \phi(t, \alpha) = 2\pi \hbar \int_{-\infty}^{t} \sum_{i=-\infty}^{t} \alpha_i g(\tau - iT) d\tau \]

- 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

![Tier 0 Frequency Detection](image_url)
SOQPSK-TG Eye Patterns

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

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

● Tier 0
  ◆ Invented in 1974, introduced in 2001
  ◆ 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
A multi-symbol detector finds the data sequence that best fits the observed phase trajectory.
Why Does It Matter?

If this bit is different, the phase trajectory is forever shifted...

Therefore, later bits can help make decisions about earlier bits.

Noise-corrupted trajectory

Single-symbol detector decides “zero”

Multi-symbol detector decides “one” – correcting the error
Multi-Symbol Detector Example

Brute force approach – yields performance gain, but leads to extreme hardware complexity
Brains over brawn – Efficient computation yields the same performance as the brute force approach, with far less hardware.

Generic Trellis Demodulator

Diagram:
- CPM SIGNAL
- IF BPF
- COHERENT DOWNCONVERTER
- METRIC CALCULATOR
- SURVIVOR PATH UPDATE
- TRACEBACK
- RECOVERED DATA
- SYNCHRONIZATION
- TRACKING ADJUSTMENTS
- WINNING STATES
Tier 0 BER Performance

![Graph showing Tier 0 BER Performance with various data points and labels for different symbol generations.](image-url)
Legacy PCM/FM Transmitters

h = 0.8
h = 0.7
h = 0.6
Effect of TX Deviation Error

![Graph showing the effect of TX deviation error on Eb/N0 for different modulation indices and symbol generations.](image)

- **Conventional Single-Symbol (1990's)**
- **First Generation Multi-Symbol (2001)**
- **Second Generation Multi-Symbol (2004)**
- **MLSE (Theoretical Limit)**
What About Phase Noise?

- **No phase noise:** The entire trellis is helpful
- **Minimal phase noise:** Several bits of the trellis are helpful
- **Significant phase noise:** A few bits of the trellis are helpful
- **Severe phase noise:** Not a candidate for trellis demodulation
Phase Noise

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

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

SOQPSK-TG
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

![Graph showing BER performance comparison for different tiers and encoding methods.](image-url)
Synchronization
Telemetry Channels are Bursty

In a typical flight test, the vast majority of bit errors occur at dropouts.

Synchronization is important!
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

PCMF, 5 Mb/s, BER = 1E-5

Synchronization Time, Bits

Frequency

Cumulative %
SOQPSK Synchronization, No Noise
SOQPSK Synchronization, 6 dB
SOQPSK Synchronization, 3 dB
SOQPSK Synchronization, 1 dB

Frequency

Synchronization Time (Bits)

Cumulative %

10 Mbps, 1 dB Eb/N0
SOQPSK Synchronization, -1 dB
Synchronization Summary

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

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

DATA → BITS TO SYMBOLS → CPM MODULATOR → HP ESG D4000A RF Signal Generator

DATA → BITS TO SYMBOLS → CPM MODULATOR

DATA → BITS TO SYMBOLS → CPM MODULATOR

Rohde & Schwarz AMIQ

Noise Source

Microdyne 700-MR L-Band Receiver

Σ

Σ

Fireberd 6000A BER Analyzer

Nova Engineering CPM Trellis Demodulator

SYMBOLS TO BITS → TRELLIS DEMODULATOR → IF FILTER
9 Mbps Multi-h CPM, Multichannel
BER as a Function of $\Delta F$

From Gene Law, “Recommended Minimum Telemetry Frequency Spacing With CPFSK, CPM, SOQPSK, and FQPSK Signals”, ITC 2003
Degradation as a Function of $\Delta F$

Figure 5. 5 Mbps SOQPSK-TG.

Figure 6. 5 Mbps multi-h CPM.

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

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

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

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

\[ \Delta F_0 = a_s R_s + a_i R_i \]

where:
- \( \Delta F_0 \) = 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

<table>
<thead>
<tr>
<th>Modulation Type</th>
<th>( a_s )</th>
<th>( a_i )</th>
<th>( R_s = R_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRZ PCM/FM</td>
<td>1</td>
<td>1.2</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>0.7</td>
<td>1.2</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>1.2</td>
<td>1.7</td>
</tr>
<tr>
<td>FQPSK-B, FQPSK-JR, SOQPSK-TG</td>
<td>0.45</td>
<td>0.65</td>
<td>1.1</td>
</tr>
<tr>
<td>ARTM CPM</td>
<td>0.35</td>
<td>0.5</td>
<td>0.85</td>
</tr>
</tbody>
</table>

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

Let’s Eat, Students!

Commas Save Lives

See you back here at _______ PM
Multipath Propagation
Multipath Propagation

Airborne transmitter

Line-of-sight communications link

Narrow beam receive antenna

Irregular terrain

Dry lake bed = smooth reflecting surface

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

127-PN source → LPF → BPSK mod → linear PA

bipolar NRZ @ 10 Mbits/sec

aircraft fuselage

hemispherically omni-directional antenna

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

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

Power spectral density of transmitted signal

Power spectral density of received signal

Estimate of channel transfer function

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

\[ \hat{H}(\omega) = \frac{R(\omega)}{S(\omega)} \]

- \( \hat{H}(\omega) \): power spectral density of received signal
- \( R(\omega) \): power spectral density of transmitted signal

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

- Nearly static, frequency selective, long delays
Multipath in Flight

- Dynamic, frequency selective and flat fading, various delays
Multipath During Flight

Received Signal Strength History
ARTM flight 78, Cords Road, westerly

Frequency Diversity

Figure from Robert Jeffers, Tybrin, Edwards AFB. Reprinted by permission of the author.
Classic Two-Ray Multipath

Received Signal Strength History
ARTM flight 78, Cords Road, westerly

Figure from Robert Jefferis, Tybrin, Edwards AFB. Reprinted by permission of the author.
Multipath Summary

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

- Maximal ratio combining – optimal against AWGN
  - Polarization diversity
  - Frequency diversity
  - Receive-side processing, no transmitter impact

- Adaptive equalization
  - Powerful tool against multipath
  - Receive-side processing, no transmitter impact

- Best source selection
  - Combats all forms of signal impairment
  - Receive-side processing, no transmitter impact

- Space-time coding (STC)
  - Mitigates “built-in” multipath from dual TX antennas
  - Requires dual transmitters

- Forward error correction
  - Spending bandwidth to buy link margin
  - Requires encoder implemented in transmitter
Maximal Ratio Combining

- Many telemetry systems utilize diversity reception
  - Frequency separation using two transmitter
  - Orthogonal polarizations using cross-polarized antenna feeds

- Combining two (or more) copies of the same signal
  - Diversity combining
  - Creates a third signal to be demodulated
  - BER performance of third signal is better than either of the individual signals

- Special case – the leading use of diversity
  - Linearly polarized transmit antenna on test article – could be at any orientation
  - Left-hand and right-hand circularly polarized receive antennas
  - Each receive antenna loses half the transmit power
  - Diversity combiner puts it all back together, eliminating the polarization loss
  - Frequency diversity works the same way, but uses twice the bandwidth
Maximal Ratio Combining

- Weight each signal in proportion to its SNR and add
- Yields optimum SNR on combined channel in AWGN
- \( \text{SNR}_{\text{combined}} = \text{SNR}_a + \text{SNR}_b \)
Maximal Ratio Combining

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

Signal To Noise Ratio

Bit Error Rate

Average Bit Error Rate
Measured Combiner BER - Tier 0

![Graphs showing measured combiner BER for PCMFM channels Ch 0, Ch 1, and Ch 2 (90°) compared to theory.](image)
Measured Combiner BER - Tier I

SOQPSK
Ch 0 Eb/N0 = Ch 1 Eb/N0

SOQPSK
Ch 0 Eb/N0 = 6
Measured Combiner BER - Tier II

MHCPM
Ch 0 Eb/N0 = Ch 1 Eb/N0

MHCPM
Ch 0 Eb/N0 = 9

BER vs Eb/N0 (dB)

Ch 0
Ch 1
Ch 2 (90°)
Theory
Combiner Summary

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

- Equalization can turn
  
  this into... this.

Actual multipath from aircraft on the tarmac at Edwards AFB
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

Generic Adaptive Equalizer

Training Mode
- Training Sequence
- Symbol Statistics

Blind Mode

Decision-Directed Mode
- Tap Weights
- Error Calculation
- Equalizer Adjustment
- Equalized Signal
- Decision Device
- Recovered Data

Transmitted Signal → RF Channel → Received Signal → Equalizer → Equalized Signal → Decision Device → Recovered Data

Tap Weights → Error → Error Calculation → Training Mode → Decision-Directed Mode
Equalizer Adaptation

Click here
Dial-a-Channel
Adaptive Equalizer Summary

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

- Receive and demodulate the same signal at multiple receive sites
- Funnel all the demodulated data to one central location
- Time align the multiple data streams
- Build a better output stream from the multiple input streams
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 $\text{Num\_errors} \div 32$)
  - Useless with encrypted data

- **Log-likelihood ratio**
  - Uses all the bits
  - Works with encrypted data
  - Max-likelihood (optimal) combining scheme
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 assess the impact of all these impairments
- We need to compute $p_n$
  - Quickly
  - Accurately

\[
\hat{x} = 0 \iff \prod_{n \in N_0} p(y_n | x = 0) \prod_{n \in N_1} p(y_n | x = 0) > \prod_{n \in N_0} p(y_n | x = 1) \prod_{n \in N_1} p(y_n | x = 1) \\
\iff \prod_{n \in N_0} (1 - p_n) \prod_{n \in N_1} p_n > \prod_{n \in N_0} p_n \prod_{n \in N_1} (1 - p_n) \\
\iff \log \left( \prod_{n \in N_0} (1 - p_n) \prod_{n \in N_1} p_n \right) > \log \left( \prod_{n \in N_0} p_n \prod_{n \in N_1} (1 - p_n) \right) \\
\iff \sum_{n \in N_0} \log(1 - p_n) + \sum_{n \in N_1} \log(p_n) > \sum_{n \in N_0} \log(p_n) + \sum_{n \in N_1} \log(1 - p_n) \\
\iff \sum_{n \in N_0} \log(1 - p_n) - \sum_{n \in N_0} \log(p_n) > \sum_{n \in N_1} \log(1 - p_n) - \sum_{n \in N_1} \log(p_n) \\
\iff \sum_{n \in N_0} \log \left( \frac{1 - p_n}{p_n} \right) > \sum_{n \in N_1} \log \left( \frac{1 - p_n}{p_n} \right) .
\]

Terminology

- **BER (Bit Error Rate)**
  - *Measured* as (number of errors / number of bits)
  - Assumes you know the data in advance
  - Measuring very low BER requires a long time
  - Converges to BEP if test runs long enough, *and channel is static*

- **BEP (Bit Error Probability)**
  - *Calculated* likelihood that a bit is in error
  - Even very low BEP can be determined from only a few bits

- **DQM (Data Quality Metric)**
  - Derived directly from BEP
  - Expressed as a 16-bit integer

- **DQE (Data Quality Encapsulation)**
  - Process of “bundling” DQM words and payload data
  - Includes a sync word to aid BSS time alignment
Data Quality Encapsulation

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

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

- Start with BEP, derived within demod
- Likelihood Ratio (LR) = (1 - BEP) / BEP
- DQM = min (round (log10 (LR) / 12 * (2^16)), 2^16 -1)
  - 16-bit unsigned integer, ranges from 0 to 65,535

- Easily reversed:
  - LR = 10^(-12 * DQM / 2^16)
  - BEP = 1 / (1 + LR)

- Define “Q” as the “User’s DQM”
  - Q = 12 * DQM / 65535
  - Represents the exponent of 10 in the BEP
  - Examples:
    - Q = 3 ➔ BEP = 1e-3
    - Q = 7 ➔ BEP = 1e-7
  - Arbitrarily cap Q at “a perfect 10”.

<table>
<thead>
<tr>
<th>BEP</th>
<th>LR</th>
<th>DQM</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>1.00</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>1E-01</td>
<td>1.1111E-01</td>
<td>5211</td>
<td>0.95</td>
</tr>
<tr>
<td>1E-02</td>
<td>1.0101E-02</td>
<td>10899</td>
<td>2.00</td>
</tr>
<tr>
<td>1E-03</td>
<td>1.0010E-03</td>
<td>16382</td>
<td>3.00</td>
</tr>
<tr>
<td>1E-04</td>
<td>1.0001E-04</td>
<td>21845</td>
<td>4.00</td>
</tr>
<tr>
<td>1E-05</td>
<td>1.0000E-05</td>
<td>27307</td>
<td>5.00</td>
</tr>
<tr>
<td>1E-06</td>
<td>1.0000E-06</td>
<td>32768</td>
<td>6.00</td>
</tr>
<tr>
<td>1E-07</td>
<td>1.0000E-07</td>
<td>38229</td>
<td>7.00</td>
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<td>1.0000E-08</td>
<td>43691</td>
<td>8.00</td>
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<tr>
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<td>1.0000E-09</td>
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<td>9.00</td>
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<tr>
<td>1E-10</td>
<td>1.0000E-10</td>
<td>54613</td>
<td>10.00</td>
</tr>
<tr>
<td>1E-11</td>
<td>1.0000E-11</td>
<td>60075</td>
<td>10.00</td>
</tr>
<tr>
<td>1E-12</td>
<td>1.0000E-12</td>
<td>65535</td>
<td>10.00</td>
</tr>
</tbody>
</table>
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, \(128 \leq N \leq 16,536\)
  - Defaults to 4096

| 16-bit Sync Pattern | 8-bit Word | 8-bit Word | 16-bit DQM | N bits of payload data \(128 \leq N \leq 16,536\) |
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

![Graph showing error rate vs. RF signal level for 1850 MHz, PCMFM, 5 Mbps](image)
DQM Step Response

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

One block at each step is a blend of the two states.
DQM Fade Recovery

- Includes UUT synchronization time
DQM Interference Test

- Interference is not AWGN, but it causes bit errors

![Graph showing error rate vs. interferer dB above victim. The graph compares BEP (from DQM value) and BER. The victim is SOQPSK, 2 Mbps, 1850 MHz, -80 dBm, while the interferer is PCMFM, 10 Mbps, 1862.9 MHz.]
DQM in Multipath

- Test run at high signal level – essentially no noise

![SOQPSK, 5 Mbps, Static Multipath, 165° phase, 81.8% Magnitude](image)
Does it work?

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

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

Spatial transmit diversity

Air vehicle maneuvering masks Tx antenna and causes polarization mismatch

Polarization receive diversity

Ground bounce creates multipath interference

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

Spatially Separated Antennas Create Interference Pattern

Antenna 1

Antenna 2
MIMO Communications

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

Space-Time Encoder

H

Space-Time Decoder

Data

H

Data

Potential Benefits:
• Diversity (robust communications)
• Increased data throughput
Alamouti Space-Time Coding

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

Each symbol is simultaneously sent from both antennas

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

Power equally divided between antennas

Received signal energy

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

With the noise energy as \( N_o \), the received SNR is

\[
SNR_T = \frac{1}{2} |h_1 + h_2|^2 \frac{E_s}{N_o}
\]
**Alamouti Space-Time Coding**

**Signal energy over one symbol time:**

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

**Received noise energy:**

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

**Signal-to-Noise Ratio:**

\[
SNR_A = \frac{1}{2} \left( |h_1|^2 + |h_2|^2 \right) \frac{E_s}{N_o}
\]
Symbol Error Rate - QPSK

SER for QPSK in AWGN

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

Using two transmit antennas (traditional signaling)

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

If the aircraft is rotated 360° in the horizontal plane

\[ P(E | \theta) = \frac{1}{2\pi} \int_{0}^{2\pi} 2Q\left( \sqrt{\frac{E_s}{N_o}} \frac{|h_1(\theta, \phi) + h_2(\theta, \phi)|^2}{2} \right) d\phi \]
Symbol Error Rate - QPSK

Traditional signaling

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

Addition of transfer functions leads to reduction in effective SNR

For Alamouti signaling

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

Only magnitudes of transfer functions used in sum
Alamouti Scheme

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

**Time Slot 1:**
Gain Pattern: $G_{t1}(\phi) = 2 \cos^2\left(\frac{kd}{2} \cos \phi\right)$

**Time Slot 2:**
Gain Pattern: $G_{t2}(\phi) = 2 \sin^2\left(\frac{kd}{2} \cos \phi\right)$
Symbol Error Rate

Similar expressions have been derived for:

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

for both Traditional Signaling and Alamouti Signaling
SER Simulations

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

Simple AWGN Channel

\begin{itemize}
  \item Traditional Signaling
  \item Alamouti Signaling
  \item Single Antenna
\end{itemize}
SER Simulations

Results Identical to Single Receive Antenna System

Circular Polarization Diversity Reception
Flight Tests: Airborne Configuration

![Diagram of flight test configuration]

- **STC Transmitter**
  - Quasonix QSX-VLT-110-105-20-6A
  - 10 W
  - L-band isolator
  - Channel Microwave L320I

- **SOQPSK Transmitter**
  - Quasonix
  - 10 W
  - L-band isolator
  - Channel Microwave L320I

- **GPS/AHRS**
  - House keeping link antenna (separate lower antenna)

- **Channel Microwave L320I**
  - L-band isolator

- **Pasternak PE 7016-3**
  - 3 dB
  - 5 W

- **Narda 4322-2**
  - Upper antenna
  - Lower antenna
C-12 Beechcraft: Airborne Platform
Antenna Locations

- Fuselage station = 302”
- Centerline = 9” (right)
- Waterline = 145.5”

- Fuselage station = 222.25”
- Centerline = 10” (left)
- Waterline = 76”
Flight Tests: Idealized Gain Patterns

STC Frequency

Reference Link Frequency

Carrier Frequency = 1485.5 MHz

Carrier Frequency = 1514.5 MHz
Flight Tests: Ground Station Configuration

Bldg 4795: “Antenna 5”
EMT Model 150
5-m parabolic reflector

LNA
RHCP

multi-coupler

MU-Dell 2MDP1425

T/M Receiver
1496.5 MHz
L-3/Microdyne
RCB 2000

AM
AGC

Antenna Tracking

to antenna servo motors

Data

Clock

PC

Housekeeping data logging and display

{ reference link
1514.5 MHz

STC link
1485.5 MHz

20 dB
atten

1:4 split

MU-Dell
2MDA1424D-06

unity gain input-to-each-output

Spectrum Analyzer

spectrum display

to DVD

MU-Dell
2MDA1424D-06
Test Flights: Ground Station Configuration

- **Receiver 1514.5 MHz**
  - M/A Com SMR 5550i
  - IF 70 MHz
  - Tier 1 Demod.
  - RF Networks Model 2120
  - BERT
  - Fireberd 6000A
  - Data to PC data logging

- **Receiver 1485.5 MHz**
  - M/A Com SMR 5550i
  - IF 70 MHz
  - BYU Prototype STC Demod.
  - BERT
  - Fireberd 6000A
  - Data to PC data logging

- **Receiver 1514.5 MHz**
  - Microdyne 700 MR
  - AGC
  - AM
  - Data Acquisition
  - Wideband Systems DRS 3300 (5 Msamples/s)

- **Receiver 1485.5 MHz**
  - Microdyne 700 MR
  - AGC
  - AM
  - Data Acquisition
  - National Instruments DAQ (20 samples/s)
Test Flights: Ground Station Configuration
Test Flights: Ground Station Configuration
M1: Left-Hand Turn @ 10° bank
M2: Right-Hand Turn @ 10° bank
M2: Test Results

Graphs showing the results of a test with time on the x-axis and different metrics on the y-axis.
M3: Left-Hand Turn @ 30° bank
M3: Test Results
M4: Right-Hand Turn @ 30° bank
M4: Test Results
M3 to C2 Transition Test Results
C2: Cords Road West-to-East
C2: Test Results
D2: Cords Road East-to-West
D2: Test Results

![Graphs showing test results over time.](image-url)
**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

<table>
<thead>
<tr>
<th>Information block length $k$</th>
<th>Code block length $n$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>rate 1/2</td>
</tr>
<tr>
<td>1024</td>
<td>2048</td>
</tr>
<tr>
<td>4096</td>
<td>8192</td>
</tr>
<tr>
<td>16384</td>
<td>32768</td>
</tr>
</tbody>
</table>

- 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

A A Ā A 4096 Data Bits  2048 Parity bits
Spectral Characterization

Offset from Center (Bit Rates)

dBm

Tier 0
Tier I
Tier I with LDPC
Fractional Out-of-Band Power

Two-Sided Bandwidth (Bit Rates)

Fraction of Total Power Outside Bandwidth

- Tier 0
- Tier I
- Tier I with LDPC

90%
99%
99.9%
99.99%
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

![Graph showing Measured BER Results]

- Uncoded SOQPSK
- LDPC @ 28 Mbps
- LDPC @ 7 Mbps
- LDPC @ 1.75 Mbps

**Eb/N0 (dB)**

**BER**

1.00
0.10
0.01
0.001
0.0001
0.00001
0.000001
0.0000001

12
11
10
9
8
7
6
5
4
3
2
1
0

Quasonix

2017 International Telemetering Conference
Terry Hill - thill@quasonix.com
LDPC from Appendix 2-D

Table D-11. Bandwidth Expansion Factor

<table>
<thead>
<tr>
<th>Information Block Length, k</th>
<th>Bandwidth Expansion Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rate 1/2</td>
</tr>
<tr>
<td>1024</td>
<td>33/16</td>
</tr>
<tr>
<td>4096</td>
<td>33/16</td>
</tr>
</tbody>
</table>
BER – All Modes

- Tier 0, Single-Symbol
- Tier 0, Trellis
- Tier I, Trellis
- Tier II, Trellis
- Tier I LDPC (1024, 4/5)
- Tier I LDPC (4096, 4/5)
- Tier I LDPC (1024, 2/3)
- Tier I LDPC (4096, 2/3)
- Tier I LDPC (1024, 1/2)
- Tier I LDPC (4096, 1/2)
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

- 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

Site 4
- F1, F2
- Ch1, Ch2, DQE

Site 2
- F1, F2
- Ch1, Ch2

CM4
- F1, F2
- Ch1, Ch2, DQE

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)
Flight 1 – PCM/FM 5 Mbps
Link Availability Summary (PN23 BER)
Flight 2 – SOQPSK 5 Mbps
Link Availability Summary (PN23 BER)
Flight 3 – SOQPSK 20 Mbps
Link Availability Summary (PN23 BER)
Flight 4 – STC/LDPC 5 Mbps
Link Availability Summary (PN23 BER)
The elusive zero-error link.....

- STC/LDPC from 3 sites at 5 MBPS
- 1st pass PN23 -- 34 minutes of helicopter flight across YPG...
- Error-free!
- 2nd pass video with no freeze ups or blackouts!
Performance Comparison and Summary
Power Spectral Densities
Out-of-Band Power
BER Performance Comparison

![Graph showing BER performance comparison with various tiers and LDPC codes.](image)
Bandwidth-Power Plane

- LDPC Modes
- 99.99% Bandwidth (Bit Rates)
- Eb/N0 (dB) required for BER = 1E-5
- PCM/FM, single-symbol detection
- PCM/FM, multi-symbol detection
- SOQPSK-TG, trellis detection
- SOQPSK-TG, single symbol detection
- ARTM Tier II
- SOQPSK with LDPC (4096, 1/2)
- SOQPSK with LDPC (4096, 2/3)
- SOQPSK with LDPC (4096, 4/5)
- SOQPSK with LDPC (1024, 1/2)
- SOQPSK with LDPC (1024, 4/5)
- SOQPSK with LDPC (1024, 2/3)
Acknowledgements

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Questions/Comments