1998 NASA Review

Center for Space Telemetering and Telecommunications Systems

March 31, 1998

8:30 – 9:00  Welcome and Introductions
9:00 – 9:30  Program Overview - Stephen Horan
9:30 – 10:30 Coding and Carrier Recovery Techniques - William Ryan
10:30 – 10:45 Break
11:00 – 12:00 Carrier Frequency Estimation Under Unknown Doppler Shifts - Phillip De Leon

12:00 – 1:30  Lunch
1:30 – 2:30  Small Satellite Experiments - Stephen Horan and Thomas Shay
2:30 – 2:45  Break
2:45 – 3:45  Bandwidth Efficient Modulation/Equalization Techniques - James LeBlanc
3:45 – 4:00  Lab Tour
4:00 – 5:00  Faculty and NASA Review

5:00    Adjourn
<table>
<thead>
<tr>
<th>Name</th>
<th>Address</th>
<th>Phone</th>
<th>Fax</th>
<th>Email</th>
</tr>
</thead>
</table>
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Telemetering and Telecommunications Research: Program Review

Lujan Space Tele-Engineering Program
Klipsch School of Electrical and Computer Engineering

March 31, 1998
Program Overview

• Topics
  – NMSU Background
  – Telemetering and Telecommunications Program
  – Grant History
  – Faculty & Staff
  – Facilities
  – Review Program
NMSU Background

• NMSU is the Land Grant University and NASA Space Grant University for New Mexico
  – NMSU is #9 in NASA University commitments and New Mexico is #10 nationally in NASA commitments (FY 1997)

• NMSU is a designated minority-serving university
NMSU Background

• NMSU is a Carnegie-I Research University
• Statistics (Fall 1997):
  – enrollment = 15067 students
  – ABET-accredited College of Engineering
  – Student Ethnicity
    • African American - 2%
    • American Indian - 3%
    • Asian American - 1%
    • Hispanic - 36%
    • Other - 58%
Telemetering, Telecommunications & Signal Processing

- Senior-level courses in Analog & Digital Communications, Digital Signal Processing
- Graduate-level courses in Communications Theory, Digital Communications, Coding (Channel & Source), Personal Communications Systems, Telemetering Systems
- M.S.E.E. & Ph.D. degree programs
Telemetering, Telecommunications & Signal Processing

• Full-time & part-time students, distance-education programs at KAFB, NTU, Boeing
• Average 6 M.S.E.E. degrees and 2 Ph.D. degrees awarded each year
• Recent graduates at Lockheed-Martin, Motorola, Stanford Telecommunications, etc.
Telemetering, Telecommunications & Signal Processing

- Research Programs with
  - NASA (Telemetering & Telecommunications, Space Grant, ACTS Propagation)
  - NSF (tape recording technology)
  - Sandia National Laboratories (bandwidth-efficient modulation)
  - Rome Labs (signal processing)
Telemetering, Telecommunications & Signal Processing

• Chaired Professorship in Telemetering & Telecommunications funded by IFT, State of New Mexico, and industry

• Designated Center of Excellence in Telemetering Systems by the IFT
Grant History

• Major research funding comes from NASA NAG 5-1491
  – Continuous since 1990
  – Frank Carden and William Osborne were previous lead investigators

• Related funding from
  – NSF, SNL, IFT, Rome Labs
Faculty & Staff

- Faculty
  - Stephen Horan, Director
  - William Ryan, Associate Director
  - Phillip DeLeón
  - James LeBlanc
  - Thomas Shay
Faculty & Staff

- Janice Apodaca, Secretary
- Lawrence Alvarez, Technician

Students
- 3 Undergraduates
- 17 Graduate Students (all projects)
Facilities

- Faculty Offices in Thomas & Brown Hall and Goddard Hall
- Student Offices in Thomas & Brown Hall and Goddard Hall
- Telemetering Center is a central suite
  - Director’s Office
  - Research Laboratory
  - Secretary
  - Technician
Facilities

• Laboratory
  – hardware development and testing area
  – software simulation area

• Future
  – Telemetering and Telecommunications will take over the bulk of the re-modeled Goddard Hall one-story area
Facilities

- Future (continued)
  - Leave academic laboratories in Thomas & Brown Hall
    - Equipment for laboratory to come from industry and IFT donations already in hand
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<td>4:00 - 5:00</td>
<td>Wrap-up</td>
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<td></td>
<td>Review</td>
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Stanford Telecom / New Mexico State University

ACTS Propagation Measurements Program

Data Analysis Summary

Julie H. Feil
Louis J. Ippolito
Stephen Horan
Jennifer Pinder
Frank Paulic
Atle Borsholm

NAPEX XXI & APSW XI
June 11-13, 1997
Los Angeles, CA
Agenda

- Introduction
  - Experiment objectives & configuration

- NM ACTS $K_A$ band measurements and analysis
  - Three year (12/93-11/96) propagation statistics
  - Annual model comparisons
  - Seasonal statistics

- Summary and future activities

- New Mexico State University: Station status and wet antenna measurements
STel ACTS Propagation Experiment
Objectives

- Measure and evaluate $K_A$ band propagation effects and link performance for New Mexico

- Develop long-term statistics and prediction modeling techniques for New Mexico climate region for advanced satellite system planning and design
New Mexico APT

- Elevation angle: $51^\circ$

- Measured parameters
  - Beacons: 20.185 GHz and 27.505 GHz
  - Radiometers: 20 GHz and 27.505 GHz
  - Rain rate (CRG, TBG)
  - Temperature, Relative Humidity, Wind Vector, Barometric Pressure
New Mexico ACTS $K_A$ Band
Measurements Summary

- Three years of data processed
- Three year weather statistics
- Comparison of old and new processing techniques for three year propagation measurements
- Annual model comparisons
- Statistical attenuation ratio
- Fade duration
- Seasonal statistics
- Worst actual month (in three years): July 1996
Three Year Weather Effects

Temperature December 1, 1993 - November 30, 1996

Relative Humidity December 1993 - November 1996

Location: Las Cruces, NM
Elevation Angle: 51°
Comparison of Processing Techniques

  ➢ From *.pv0 processing (ACTSEDIT)
  ➢ From *.pv2 processing (ACTSPP)

- Minor differences between two processing techniques
  ➢ Monthly Statistics are within 1 dB
  ➢ Gaseous absorption is less for *.pv2 than for *.pv0 processing
Definition of Attenuation Terms

- **AFS**: Attenuation wrt Free Space
  Difference between the received beacon level and the received level if in a vacuum. AFS includes attenuation due to atmospheric absorption, rain, clouds, and scintillation.

- **ARD**: Radiometrical Derived Attenuation
  Attenuation measurements from radiometers. Comparable to AFS.

- **ACA**: Attenuation wrt Clear Air
  The difference between the received beacon level and the expected level due to atmospheric absorption (AGA). ACA includes rain, clouds, and scintillation. ACA=AFS-AGA.

- **ARS**: Statistical Attenuation Ratio
  Ratio of equiprobable attenuation levels at two frequencies of interest.
Three Year Attenuation wrt Free Space (AFS) via ACTSPP

AFS for December 1993 - November 1996

Location: Las Cruces, NM
Elevation Angle: 51°

Percent of Time Attenuation is Equalled or Exceeded

Attenuation (dB)

From *.pv2 files
Three Year Attenuation w.r.t Free Space (AFS) via ACTSEDIT

![Graph showing the attenuation over time and frequency]
Three Year Radiometric Derived Attenuation (ARD) via ACTSPP

ARD for December 1993 - November 1996

Location: Las Cruces, NM
Elevation Angle: 51°

Percent of Time Attenuation is Equalled or Exceeded

From *.pv2 files
Three Year Radiometric Derived Attenuation (ARD) via ACTSEDIT

ARD for December 1993 - November 1996

Location: Las Cruces, NM
Elevation Angle: 51°

- 20 GHz
- 27 GHz

From *.pv0 files
2 Year Rain Rate Statistics

Comparison of Rain Rates for October 1994 - September 1996

The first six months of the NM ACTS experiment the rain gage did not work.
Three Year Comparison of 27 GHz Cumulative Distribution

Comparison of 27.5 GHz Dec 1993 - Nov 96 ACA Cumulative Distributions

Percent of Time Attenuation is Equal to or Exceeded

Attenuation (dB)

Las Cruces, NM
Elevation Angle: 51°

From *.px2 files
Three Year Comparison 20 GHz Cumulative Distribution

Comparison of 20 GHz Dec 1993 - Nov 96 ACA Cumulative Distributions

From *.pv2 files
Three Year Attenuation w.r.t Clear Air (ACA) via ACTSPP

ACA for December 1993-November 1996

Location: Las Cruces, NM
Elevation Angle: 51°

Percent of Time Attenuation is Exceeded

From *.pv2 files
Comparison of 2 Year ACA and Global Model with Local Rain Statistics

2 Years: October 1, 1994 through September 30, 1996

20 GHz

27.5 GHz

From *.pv2 files
10/1/94-9/30/96
Comparison of 2 Year ACA and ITU Model with Local Rain Statistics

2 Years: October 1, 1994 through September 30, 1996

20GHz

27.5 GHz

From *.pv2 files
10/1/94-9/30/96
Statistical Attenuation Ratio for ACA

ARS for ACA
December 1993-November 1996

- Drufuca
- ITU-R P.N. 838
- Attn. Coef. 4km (838)
- ITU-R P.N. 618-3

New Mexico
Elevation Angle: 51°

Best Fit: ITU-R P.N. 618-3
Error: 1.0 rms
First Order Regressive Fit
Δ27/Δ20 = 1.54

From *:pv2 files
Statistical Attenuation Ratio for AFS

ARS for AFS
December 1993 - November 1996

New Mexico
Elevation Angle: 51°

First Order Regressive Fit 1.53

27.5 GHz Attenuation (dB)

20 GHz Attenuation (dB)

From either *.pv2 or *.pv0 files
Three Year Winter AFS Statistics


Location: Las Cruces, NM
Elevation Angle: 51°

Percent of Time Attenuation is Equaled or Exceeded

From *.pv2 files
Three Year Spring AFS Statistics

AFS for Spring (March, April, May) 1994, 1995, 1996

Location: Las Cruces, NM
Elevation Angle: 51°

Percent of Time Attenuation Is Equalled or Exceeded

0.0100
0.0010
0.0001
0.0000
0.0000
0.0010
0.0100
10.0000
100.0000

Attenuation (dB)

From *.pv2 files
Three Year Summer AFS Statistics

AFS for Summer (June, July, August) 1994, 1995, 1996

Location: Las Cruces, NM
Elevation Angle: 51°

Percent of Time Attenuation is Exceeded

From *.pv2 files
Three Year Fall AFS Statistics

AFS for Fall (September, October, November) 1994, 1995, 1996

Location: Las Cruces, NM
Elevation Angle: 51°

From *.pv2 files
Actual Worst Month: July 1996

Attenuation wrt Free Space (AFS)
New Mexico ACTS Statistics Summary

- Comparison of pv0 and pv2 processing for 36 months have minor differences (< 1 dB) in attenuation distributions
- Measured link performance for three year period (*.pv2)

<table>
<thead>
<tr>
<th>Annual Link Availability (%)</th>
<th>20 GHz (dB)</th>
<th>27.5 GHz (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>99</td>
<td>1.6</td>
<td>1.8</td>
</tr>
<tr>
<td>99.5</td>
<td>2.1</td>
<td>2.8</td>
</tr>
<tr>
<td>99.9</td>
<td>5.4</td>
<td>8.1</td>
</tr>
<tr>
<td>99.95</td>
<td>8.3</td>
<td>13.1</td>
</tr>
<tr>
<td>99.99</td>
<td>20.8</td>
<td>&gt; 25</td>
</tr>
</tbody>
</table>
Coding and Related Studies

Part I
Turbo Code Through TDRS Test Results

Part II
Design of High Rate Turbo Codes

Part III
Carrier Synchronization at Low SNRs
TURBO CODES OVER TDRS:

TEST RESULTS

William Ryan
New Mexico State University

March 1998

Acknowledgments
Warner Miller
Jack Osborn
Franklin Hartman
Lawrence Alvarez
A BRIEF INTRODUCTION TO TC

- TCs are a class of Forward Error Control (FEC) Codes.
- TC's comprise a paralleled concatenation of convolutional codes.

\[ \Pi : \text{Interleaver} \]

Serially Concatenated

Parallel Concatenated

\[ u \rightarrow \text{outer CC} \rightarrow \Pi \rightarrow \text{inner CC} \]

\[ u \rightarrow \Pi \rightarrow \text{CC} \rightarrow \text{CC} \]
**NONRECURSIVE CONVOLUTIONAL CODES**

**Example:** rate, $r = 1/2$, memory size $m=2$.

$G(D) = [g_1(D) \quad g_2(D)]$

$g_1 = 1 \ 1 \ 1 = 1 + D + D^2$

$g_2 = 1 \ 0 \ 1 = 1 + D^2$

![Diagram showing the convolutional code structure](image)
RECURSIVE SYSTEMATIC CC (RSCC)

Remember $G(D) = [g_1(D) \ g_2(D)]$ from non-recursive CC

Example: $G(D) = [1 \ \frac{g_2(D)}{g_1(D)}]$ for recursive CC

- same set of code sequences $c(D) = u(D) G(D)$
- different $u(D) \leftrightarrow c(D)$ mapping
ITERATIVE DECODER FOR TC
TEST DESCRIPTION

The Codes
\[ r = \frac{1}{2}, \frac{3}{4}, \frac{4}{5} \]
polynomials: (31,33)
\[ N = 10,000 \]
15 iterations

Rate 4/5 Performance
The Test Setup

- Files consisting of 1000 codewords each are transmitted at 100k cbps (code bits/sec), where each codeword contains 10,000 data bits. Thus, each file corresponds to $10^7$ data bits.

- Codewords are separated by a 63-bit frame sync word, a 63-bit pseudo-random sequence.

- Decoding is performed “off line”.

Phase I Test - End to End

Phase II Test - Through TDRS
PHASE I (ASP) TEST RESULTS

- We observed no problems with carrier recovery at the low SNRs seen by the turbo codes, but the symbol timing recovery circuit was overwhelmed at low SNRs.

- The symbol sync loop bandwidth was tightened only for the rate 1/2 case to avoid bit deletions/insertions. (It was tightened to 0.12% of the symbol rate, as compared to a nominal value of 0.36%.) This improved tracking, but acquisition appeared to take thousands of bits.

- Sync word detection was very difficult at the low SNRs seen by the rate 1/2 code.

- The Eb/No measurements imply an implementation loss on the order of 1.3 dB, but both measurement types have errors/biases.

<table>
<thead>
<tr>
<th>File</th>
<th>Hardware-measured Eb/No (dB)</th>
<th>Software-measured Eb/No (dB)</th>
<th>Decoding Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate 1/2 - File 1</td>
<td>2.2</td>
<td>1.0</td>
<td>bit slips - undecodable</td>
</tr>
<tr>
<td>Rate 1/2 - File 2</td>
<td>2.3</td>
<td>1.2</td>
<td>0 errors</td>
</tr>
<tr>
<td>Rate 1/2 - File 3</td>
<td>2.4</td>
<td>1.3</td>
<td>0 errors</td>
</tr>
<tr>
<td>Rate 1/2 - File 4</td>
<td>2.5</td>
<td>1.3</td>
<td>0 errors</td>
</tr>
<tr>
<td>Rate 1/2 - File 5</td>
<td>2.6</td>
<td>1.3</td>
<td>0 errors</td>
</tr>
<tr>
<td>Rate 3/4 - File 1</td>
<td>3.4</td>
<td>1.9</td>
<td>bit slips - undecodable</td>
</tr>
<tr>
<td>Rate 3/4 - File 2</td>
<td>3.5</td>
<td>2.0</td>
<td>2 errors</td>
</tr>
<tr>
<td>Rate 3/4 - File 3</td>
<td>3.6</td>
<td>2.2</td>
<td>0 errors</td>
</tr>
<tr>
<td>Rate 3/4 - File 4</td>
<td>3.7</td>
<td>2.3</td>
<td>0 errors</td>
</tr>
<tr>
<td>Rate 3/4 - File 5</td>
<td>3.8</td>
<td>2.4</td>
<td>0 errors</td>
</tr>
<tr>
<td>Rate 4/5 - File 1</td>
<td>4.0</td>
<td>2.6</td>
<td>2 errors</td>
</tr>
<tr>
<td>Rate 4/5 - File 2</td>
<td>4.1</td>
<td>2.7</td>
<td>4 errors</td>
</tr>
<tr>
<td>Rate 4/5 - File 3</td>
<td>4.2</td>
<td>2.8</td>
<td>0 errors</td>
</tr>
<tr>
<td>Rate 4/5 - File 4</td>
<td>4.3</td>
<td>2.9</td>
<td>0 errors</td>
</tr>
<tr>
<td>Rate 4/5 - File 5</td>
<td>4.4</td>
<td>3.2</td>
<td>0 errors</td>
</tr>
</tbody>
</table>
PHASE II (TDRS) TEST RESULTS

- Again, we observed no problems with carrier recovery, but had trouble with symbol timing recovery. In fact the situation worsened.

- For both code rates, the symbol sync loop bandwidth was tightened to 0.12% of the symbol rate.

- We noticed that the noise was not always stationary or white (i.e., occasional RFI). Also, the files were collected over several days - it was snowing (!) one day.

<table>
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<th>File</th>
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<th>Software-measured Eb/No (dB)</th>
<th>Decoding Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate 1/2 - Files 1-3</td>
<td>about 2.3</td>
<td>-</td>
<td>bit slips - undecodable</td>
</tr>
<tr>
<td>Rate 1/2 - File 4</td>
<td>3.0</td>
<td>2.4</td>
<td>0 errors</td>
</tr>
<tr>
<td>Rate 1/2 - File 5</td>
<td>2.7</td>
<td>2.1</td>
<td>0 errors</td>
</tr>
<tr>
<td>Rate 1/2 - File 6</td>
<td>3.1</td>
<td>3.0</td>
<td>0 errors</td>
</tr>
<tr>
<td>Rate 1/2 - File 7</td>
<td>3.3</td>
<td>3.1</td>
<td>Pb = 0.15 for first 6 cwds, then Pb=0</td>
</tr>
<tr>
<td>Rate 1/2 - File 8</td>
<td>3.4</td>
<td>3.2</td>
<td>Pb = 0.13 for first 16 cwds, then Pb=0</td>
</tr>
<tr>
<td>Rate 1/2 - File 9</td>
<td>3.5</td>
<td>3.3</td>
<td>0</td>
</tr>
<tr>
<td>Rate 3/4 - File 1</td>
<td>3.5</td>
<td>-</td>
<td>bit slips - undecodable</td>
</tr>
<tr>
<td>Rate 3/4 - File 2</td>
<td>3.2</td>
<td>2.1</td>
<td>122 errors (one event)</td>
</tr>
<tr>
<td>Rate 3/4 - File 3</td>
<td>3.4</td>
<td>-</td>
<td>bit slips - undecodable</td>
</tr>
<tr>
<td>Rate 3/4 - File 4</td>
<td>3.5</td>
<td>2.2</td>
<td>0 errors</td>
</tr>
<tr>
<td>Rate 3/4 - File 5</td>
<td>3.5</td>
<td>2.2</td>
<td>0 errors</td>
</tr>
<tr>
<td>Rate 3/4 - File 6</td>
<td>3.2</td>
<td>3.1</td>
<td>Pb = 0.12 for first 4 cwds, then Pb=0</td>
</tr>
<tr>
<td>Rate 3/4 - File 7</td>
<td>3.2</td>
<td>2.0</td>
<td>0 errors</td>
</tr>
<tr>
<td>Rate 3/4 - File 8</td>
<td>3.5</td>
<td>2.1</td>
<td>4 errors</td>
</tr>
<tr>
<td>Rate 3/4 - File 9</td>
<td>3.4</td>
<td>2.1</td>
<td>0 errors</td>
</tr>
<tr>
<td>Rate 3/4 - File 10</td>
<td>3.6</td>
<td>2.2</td>
<td>Pb = 0.18 for first 13 cwds, then Pb=0</td>
</tr>
</tbody>
</table>
CONCLUSIONS AND RECOMMENDATIONS

We made the following observations:

- The integrated receiver symbol sync had difficulty acquiring lock and maintaining lock at the low SNRs where turbo codes operate.

- We had difficulty with the detection of the 63-bit sync words for the lowest SNR case (rate 1/2 case).

We recommend a detailed study of:

- Low-SNR symbol-timing recovery.

- Performance of 63-bit sync words for rate 1/2 frame sync (more generally, (32/r)-bit sync words).
HIGH RATE TURBO CODES
FOR BPSK/QPSK CHANNELS

Omer F. Acikel
Advisor: William E. Ryan

New Mexico State University
Electrical and Computer Engineering Department
March 31, 1998
OUTLINE

1. Punctured High Rate \( r = \frac{k}{k+1} \) Turbo Codes
   a. general puncturing structure
   b. design parameters and algorithm
   c. constraints on the algorithm

2. Simulation Results
   a. rate 3/4, 14/15 and 16/17 for m=3
   b. rate 3/4, 5/6 and 16/17 for m=4
A RATE $5/6$ ($k=5$) TC ENCODER WITH PUNCTURING SCHEME $P(2,1)$

input data

- Recursive Convolutional Encoder 1
- N-bit Interleaver
- Recursive Convolutional Encoder 2

10 data bits
1 parity bit

$v = \frac{10}{10+2} = \frac{5}{6}$

S: Saved bits.
DESIGN PARAMETERS OF RATE $k/(k+1)$ TC

• **goal:** rate 2/3, 3/4,..., 16/17 TC's with large $d_{2,\text{min}}^{TC}$ and $d_{3,\text{min}}^{TC}$.

• **design parameters:**
  
  • poly. sets ($g1,g2$)
  
  • the interleaver, I ($S_i^2$ and $S_i^3$)
  
  • puncturing scheme $P(x,y)$
DESIGN ALGORITHM

The algorithm can be described as

\[ d_{2, \text{min}}^{TC^*} = \max_{g_1, g_2} \max_{S^2} \max_I \max_{P(x, y)} d_{2, \text{min}}^{TC} \]

\[ d_{3, \text{min}}^{TC^*} = \max_{g_1, g_2} \max_{S^3} \max_I \max_{P(x, y)} d_{3, \text{min}}^{TC} \]
CONSTRANTS ON THE DESIGN ALGORITHM

- We limited the number of polynomial set choices.

- for m=3

  \[ g_1 \in \{13, 15\}_{octal} \]
  \[ g_2 \in \{11, 13, 15, 17\}_{octal} \]

- for m=4

  \[ g_1 \in \{23, 31\}_{octal} \]
  \[ g_2 \in \{21, 23, 25, 27, 31, 33, 35, 37\}_{octal} \]
SOME COMMENTS ON THE RESULTS

- For \( m = 3 \) case, almost all the polynomials showed the similar performance.

- For \( m = 4 \) case,
  - for \( r = \frac{2}{3} \) and \( \frac{3}{4} \) the set \((23,31)\) was the best.
  - for \( r = \frac{4}{5} \) the set \((31,25)\) was the best. The set \((23,31)\) performance was close to \((31,25)\)'s.
Rate 3/4 Simulation Result
(m=3)
Rate 14/15 Simulation Result
(m=3)
Rate 16/17 Simulation Result (m=3)
Rate 3/4 Simulation Result
(m=4)

Capacity limit for rate 3/4, 1.62 dB

N=10000
P(3,5)
15 iter.
Rate 5/6 Simulation Result
(m=4)

![Graph showing the simulation results for rate 5/6 with Eb/No in dB on the x-axis and Pb (BER) on the y-axis. The graph includes a curve for the uncoded performance and a point for rate 5/6 (23,31) with N=10000 and 15 iterations.]
Rate 16/17 Simulation Result
\( (m=4) \)

\[ P_b (\text{BER}) \]

\[ \text{Eb/No (dB)} \]

Capacity limit for rate 16/17, 3.96 dB

rate 16/17 (23,31)

N=10000
P(2,2)
15 iter.
Rate 1/2 Convolutional Code
Decoded by Viterbi Algorithm
(m=6)
FUTURE WORK

We are currently working on serially concatenated punctured turbo codes (SCPT codes). Our goal is to design near optimal high rate SCPT codes for BPSK/QPSK channels.

- Selection of generator polynomials.
- Interleaver design.
- Finding the puncturing scheme that maximizes the turbo codeword weight.
LOW SNR CARRIER
PHASE ESTIMATION

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April 1998
OUTLINE AND MOTIVATION

MOTIVATION

- Operating SNR's moving lower e.g. $E_s/N_0 < 0$ dB
  - higher data rates
  - major improvements in channel coding
    - Turbo codes

OUTLINE

- Review basics of coherent demodulation
- Review basics of phase estimation
- Examine low SNR tracking of approximate MAP BPSK phase estimator
- Examine low SNR acquisition of approximate MAP BPSK phase estimator
- Examine low SNR cycle slip of CW signal PLL
- Conclusions and future work
BPSK Approximate MAP carrier phase estimation

- Used to investigate high SNR tracking
- e.g. replace gain and hyperbolic tangent with hard limiter

\[ \hat{\phi} = \arg \phi \max P(\phi|\bar{r}) = \frac{P(\bar{r}|\phi)p(\phi)}{p(\bar{r})} \]

\[ r(t) = \sqrt{\frac{2E}{T}} \cos(\omega_c t - \theta_m(t) + \phi) + n(t) \]

Figure 1. MAP carrier phase estimation loop for BPSK.

Notes: 1. Linear Approximation of phase detector, passband model (sim. with baseband), hardlimiter
Some estimation theory results

- What is the "best" estimate of the phase
  - Quality measures

  a. Phase error

  \[ e = \hat{\phi} - \phi \]

  b. Mean Square Error (MSE)

  \[ \phi^2_e = E[(\hat{\phi} - \phi)^2] \]

  c. Cramer-Rao Bound (CRB)

  - In general MSE difficult to compute
  - CRB provides lower bound on MSE

Page 4 - J. Drake, W. Ryan, New Mexico State University, 03/25/98
Tracking Simulation Results

BPSK Variance of Phase Estimate

High SNR \( B/S_r = 0.19\% \) Damping Factor = 0.85

- **CRB\(_{cw}\)** - Cramer-Rao lower bound on mean square phase error for continuous wave phase estimation
- **CRB\(_{bpsk}\)** - CRB lower bound on mean square phase error for BPSK estimation
- **B/Sr** = High SNR loop bandwidth / symbol rate (%)
- **zeta** = loop damping factor

Figure 2. Phase error variance approximate MAP estimate, \( B/S_r = 0.19\% \), \( \text{zeta} = 0.85 \)
DEFINITION OF CARRIER PHASE ACQUISITION

Figure 3. Typical phase error trajectories with noise.

1. Phase acquisition time $T_{acq}$ is a random variable

   - Define acquisition to be complete when trajectory first enters one of intervals $[-e, +e]$ or $[\pi-e, \pi+e]$

2. The matter of most interest is the probability distribution of this random variable

   - We denote by $P[T_{acq} \leq x]$ probability that phase error process reaches either of the two boundaries

   - We simulate the acquisition process to obtain $P[T_{acq} \leq x]$
Acquisition Simulation Results

Figure 4. Probability of acquiring lock during first $x$ symbols
Left figure SNR=9.5 dB, Right figure SNR=-2 dB

<table>
<thead>
<tr>
<th>$B/Sr$ (%)</th>
<th>zeta</th>
<th>$SNR_{if}$ (dB)</th>
<th>$X_{0.95}$ (symbols)</th>
<th>$E[x]$ (symbols)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.19, 0.85</td>
<td></td>
<td>9.5</td>
<td>775</td>
<td>508</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-2</td>
<td>1416</td>
<td>709</td>
</tr>
<tr>
<td>0.33, 1.2</td>
<td></td>
<td>9.5</td>
<td>472</td>
<td>302</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-2</td>
<td>849</td>
<td>430</td>
</tr>
</tbody>
</table>

Table 1. Acquisition results

where:

$x_{0.95}$ is $x$ such that $Pr[T_{acq} < x] = 0.95$
Introduction to Cycle Slips

- PLL linear approximation (high SNR) assumes phase error variance small $\Rightarrow \sin(\text{error}) = \text{error}$
- When phase error variance too large a phenomenon occurs that is inherent to the nonlinearity of the loop.
  - At random points in time the noise increase phase error from tracking value $\phi$ to $\phi \pm 2\pi$.
  - This means the loop has slipped a cycle.
- $T_{\text{slip}} \gg T_{\text{symbol}}$ (typical $B_{\text{IF}}/B_{\text{I}} > 100$)
  - Many symbols can be affected by slip
- Cycle slips difficult to analyze due to
  - Non-linear differential equations
  - Random driving function (noise)
  - Hardware or simulation required for analysis
CYCLE SLIP SIMULATION

- Simulation of unmodulated carrier

**Phase error and phase plane plots for two cases**

■ High SNR  +20 dB
  - No cycle slips
  - Convergence to single stable lock point
  - Slightly noisy trajectory in phase plane

■ Low SNR -5 dB
  - Cycle slips present
  - Convergence to 3 different stable lock points
  - Very noisy trajectory in phase plane
HIGH SNR +20 dB

Phase Error - SNRif = 20dB, B1=750 Hz, Bif=15000 Hz, B=Wn=1170 Hz

Figure 5. Phase error verse normalized time

Figure 6. Phase plane plot
LOW SNR -5 dB

Phase Error - SNRif = -5dB, Bi=750 Hz, Bif=15000 Hz, B=Wn=1170 Hz

Figure 7. Phase error verse normalized time

Figure 8. Phase plane plot
CONCLUSIONS

• TRACKING JITTER VARIANCE IS CLOSE TO LOWER BOUND USING APPROXIMATE MAP ESTIMATOR → GOOD PERFORMANCE BPSK

• ACQUISITION PERFORMANCE IS RELATIVELY LONG AT LOW SNR
e.g. TWICE $T_{acq}$ for 9.5 dB SNR

• THIS MAY BE UNACCEPTABLE IN SOME APPLICATIONS
e.g. BURST MODE

• CYCLE SLIP SIMULATION WILL BE VALUABLE IN ASSESSING LOW SNR SYNCHRONIZATION PERFORMANCE AS SLIPS ARE LIMITING TRACKING ISSUE AT LOW SNR
FURTHER AREAS OF RESEARCH (low SNR)

• MPSK TRACKING, CYCLE SLIP and ACQUISITION PERFORMANCE

• MAP ESTIMATOR PERFORMANCE

• LOOP MATCHED FILTERING
  -implement filter matched to channel spectrum in carrier estimation block

• COMBINED PHASE ESTIMATION AND EQUALIZATION FOR ISI CHANNELS
  -implement a linear equalizer (combats ISI)

• ACQUISITION ENHANCEMENT
  - e.g. preamble, variable loop bandwidths

• JOINT CARRIER AND SYMBOL SYNCHRONIZATION

• USE CODING TO IMPROVE THE DECISION MAKING PROCESS
<table>
<thead>
<tr>
<th>Coding Type</th>
<th>Throughput Relative to Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable Rate CC-RS</td>
<td>0.77</td>
</tr>
<tr>
<td>Punctured Turbo Codes</td>
<td>0.93</td>
</tr>
</tbody>
</table>
Carrier Frequency Estimation under Unknown Doppler Shifts

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Center for Space Telemetering and Telecommunications
Space-to-Ground Communications Techniques

- Proprietary Ground Station(s)
  - expensive
  - access only when satellite is above GS horizon
  - typical 5 minutes pass and not always available on every orbit
  - require network of GSs for full coverage

- NASA’s Space Network
  - TDRS satellites provide telecommunication services between LEO spacecraft and NASA customer control and/or data processing facilities (near 100% coverage) via WSC
  - Commercial networks connect WSC to user
DAMA Concept

- Desire to allow users to request TDRSS access "at will" (usually a SMA service)
- Current scheduling takes 3 weeks for full process to run its course (emergencies can be processed quicker)
- Spacecraft currently cannot request a service
- Center proposes:
  - orderwire channel to listen to all users all the time
  - requires 4 new receivers for each WSC ground station
  - uses Aloha protocol on orderwire
DAMA Concept (con’t)

◆ Assume
  – no knowledge of spacecraft position and therefore no knowledge of
    Doppler shift associated with carrier—must estimate shift
  – DAMA carrier located at first null in TDRS spectrum (2287.5MHz +
    6MHz) with a 200kHz main lobe
  – BPSK modulation (Spread Spectrum), $R_b=1$kbps, $R_c=10$kChips/s
  – Chip rate is much less than that of other prescheduled users
  – Doppler shift up to $\pm 50$kHz (exceeds current capabilities of receiver)
  – Doppler shift changes at a rate between $-31$Hz/s and $-60$Hz/s over
    contact period

◆ Required
  – Carrier frequency estimation ($\pm 3$kHz) over 300kHz bandwidth
  – Doppler shift estimation should keep pace with service request rate
DAMA Spectrum
Proposed Solution

- Compute 512-point windowed, discrete Fourier transform (DFT) on input signal (sampled at $f_s = 800$kHz)
- Compute average of eight magnitude-squared spectra (estimated periodogram)
- Search periodogram for peak component index, $k$
- Output locking tone proportional to frequency estimate
Simulation Results

- DAMA signal modelled according to specs
- Add noise to simulate channel and other users
- Estimate frequency according to algorithm
Implementation

- Analog signal pre-processing section
  - Bandpass filter and frequency-shift DAMA signal spectrum into range (300kHz-wide band)

- Digital signal processing section
  - 80MHz Motorola DSP56303 processor (7-level deep pipe, 1 instruction/clock)
  - Program + data both stored in on-chip RAM (2K + 1/1K)
  - Burr-Brown 800kHz, 12 bit A/D
  - Crystal-Semiconductor 32kHz, 24 bit D/A
  - Miscellaneous ICs for address decode logic, 3.3V conversion, etc...

- Analog signal post-processing section
  - 25x frequency multiplier applied to synthesized locking tone after D/A
Implementation

Doppler Shift Estimator

\[
\cos(2\pi f_1 t)
\]
Program Notes

- A/D interrupts are disabled during FFT and magnitude-squared data accumulation calculations
  - Code simplification
  - Approximately 3 samples are dropped between data blocks which has negligible effect on frequency estimate

- Locking tone synthesized on DSP using wavetable synthesis
  - spectral peak index, $k$ becomes decimation factor in wavetable (length $L$) lookup
    \[ fout = \frac{k \cdot f_s}{L} \]
  - D/A interrupts are disabled (no locking tone) for new round of estimation
Performance

- Data acquisition + calculation time takes ~10ms
- Frequency estimation of pure sinusoid over 400kHz bandwidth is exact to within FFT resolution (1562.5Hz)
- Frequency estimation of sinusoid in noise (used to simulate spread carrier and additional MA users) mirrors simulation data
Further Work

- Complete analog sections (minor)
- Implementation of additional features
  - continuous Doppler shift estimates
  - multiple DAMA requests
  - possible DAMA receiver integration on DSP
- Testing on actual signal data
- WSC interfacing/testing
Conclusions

- Most critical component (accuracy real-time Doppler shift estimation) of proposed DAMA service is near completion.
- Hardware design is based on low-cost DSP and A/D.
- Estimation of carrier is possible only if the chip rate of the DAMA user is much less than that for the MA user.
Development of Signal Processing Algorithms and DSP Hardware for Parallel Processing

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Preliminary Investigation Objectives

- Examine state-of-the-art pipelined DSPs, FPGAs, and UNM Microelectronic’s DSP (under development) for parallel SP computation
- Examine implementation strategies of standard signal processing algorithms for on-board parallel signal processing
- Examine critically- and over-sampled filterbanks in providing a signal decomposition for parallel processing.
- Goal: utilize multiple, low-cost processors operating in parallel for complex signal processing/high bandwidth applications for on-board signal processing
Program Models

- **MIMD (multiple instruction, multiple data)**
  - multiple instruction threads executing concurrently

- **SIMD (single instruction, multiple data)**
  - all processors operate in lock step, executing same instructions simultaneously but processing different data
  - well suited to algorithms which can be partitioned in spatial or frequency domain
Filter Bank Overview

- Filter bank is composed of analysis and synthesis banks
- Analysis bank decomposes signal into $M$ subbands
  - spectral decomposition by bandpass filtering ($1/M$ bandwidth)
  - downsample by $D \leq M$
- Synthesis bank reconstructs fullband signal from subband signals
  - upsample to original rate
  - bandpass filter to remove spectral images
Filter Banks for Parallel Signal Processing

- Transform the algorithm operating on the fullband on a single processor to a set of algorithms operating on the subbands on multiple processors
- Ideally suited for parallel signal processing since spectral decomposition can be matched to number of parallel hardware units (scalable)
- Subbands are independent and may be processed independently
- Some subbands can be optionally bypassed as in subband coding
Example: Subband Adaptive Filters

- Transform a single, fullband adaptive filter with 1000’s of coefficients to multiple subband adaptive filters with 100’s of coefficients
- Performance is increased due to faster convergence for shorter filters
- Subband system has reduced total complexity (even including filter bank operations)
- Potential for parallel processing using very inexpensive hardware
Example: High Bandwidth Processing

- **Fullband case**
  - $fs$-sampled input signal
  - execute $N$ instructions/sample
  - DSP required to maintain $Nfs$ instructions/s

- **Subband case ($M$ subbands)**
  - assume 2x oversampled subbands, 10% overhead for filter bank operations
  - each subband requires $1.1Nfs/D$ instructions/s

- **Example**
  - $fs = 10$MHz, $M = 256$, $D = 128$, $N = 10$
  - single DSP on fullband requires 100MIPs
  - single DSP on subband each requires 0.86MIPs
State-of-the Art Architectures and Application

- **TI TMS320C62xx**
  - VLIW architecture
  - two 16-bit multipliers, six ALUs (up to 1600MIPs)
  - two data paths, 32 registers

- **Univ. of New Mexico (G. Maki)**
  - reconfigurable data path processor
  - 16 ALUs

- **Starfire Optical Range (941 channel adaptive optics system)**
  - 1024 DSP elements for wavefront reconstruction at 1kHz refresh
Algorithms for Parallel Processing (1998)

- Parallel FFT implementations (C. Ju)
  - Sharp LH9124, Butterfly DSP DSPMAX-V4
  - Distributed Arithmetic
  - data latency due to poor data addressing sequences

- Parallelized version of LMS Adaptive Filter (S. Douglas)
  - no delay in coefficient update or excessive hardware overhead but delay in filter output
  - architecture is independent of filter length

- High-speed multirate FIR filters (B. Newgard)
  - FPGA implementation using Distributed Arithmetic
  - 10MHz sample rate
Distributed Arithmetic

- Efficient for vector \((N \times 1)\) inner products (filtering)
- 2's complement binary, \(K\)-bit word size

\[
y = \sum_{n=0}^{N-1} h(n)x(n)
= \sum_{n=0}^{N-1} h(n) \left[ b_{0,n} - b_{0,n} + \sum_{k=1}^{K-1} b_{k,n} 2^{-k} \right]
= \sum_{k=1}^{K-1} \left[ \sum_{n=0}^{N-1} h(n)b_{k,n} \right] 2^{-k} + \sum_{n=0}^{N-1} h(n)(-b_{0,n})
\]

- Use input signal data to address a \(2^N\) ROM which stores all possible combinations of sums of bit-weighted coefficients
- Output is computed in \(K\) clock cycles independent of \(N\)
Conclusions

- Subband decompositions (filter banks) provide a natural mechanism for parallelizing signal processing
- Parallel signal processing can be exploited
  - employ multiple, lower cost DSPs
  - more complex processing than allowable on a single DSP operating on the fullband
  - high bandwidth applications
- Possibility for new on-board signal processing applications at reduced cost
Small Satellite Experiments

Stephen Horan

and

Thomas Shay

March 31, 1998
Topics

• Goals of Research Program
• Program Components
• Recent Experiment Results
• Hitchhiker Payload Development
  – RF Experiments
  – Optical Communications Experiments
Goals of Research Program

• To assist the small satellite community in utilizing the SN for communications services rather than proprietary ground stations
  – reduce costs and risks associated with communications system design
  – assist users in gaining access when high-priority users are being supported
Program Components

• Small Satellite Access of the Space Network
  – use fixed antenna system to communicate as satellite sweeps past the TDRS

• DAMA Concept Design
  – use orderwire channel to request services

• RF Testbed
  – "virtual satellite" on campus
Recent Experiment Results
Recent Experiment Results

- Performed fixed antenna pointing experiment using the TOPEX to communicate through TDRS
- TOPEX stowed high-gain antenna towards local zenith and communicated through TDRS when near the TDRS subsatellite point
Recent Experiment Results

Sample ground tracks during day 178 of 1997 for the TOPEX experiment runs

March 31, 1998
Recent Experiment Results

Sample BER status measurements during day 178 of 1997 for the TOPEX experiment runs
Recent Experiment Results

Sample estimated antenna pointing loss and receiver lock status during day 178 of 1997 for the TOPEX experiment runs

March 31, 1998

Small Satellite Experiments
Recent Experiment Results

- Pass Duration

- Pass Quality

- Maximum Data Rate

- Pre-experiment predictions validated for receiver lock up

- 16-kbps data were received “error free” during receiver lock time

- Estimate > 350 kbps @ 10^{-5} BER
Recent Experiment Results

- Implications for Fixed Antenna Pointing
  - fixed pointing can provide an equivalent to 10 kbps continuous
  - works more efficiently by using high-gain antennas; e.g., 17 dB antenna gain and 11 dBW source

![Figure 1 - Available EIRP for axial-mode helical antennas as a function of available transmitter power. Available data rates for the EIRP are also shown.](image-url)
Recent Experiment Results

<table>
<thead>
<tr>
<th>No. Turns</th>
<th>Average Contact Duration (min.)</th>
<th>Required Data Rate (kbps)</th>
<th>AOS/LOS EIRP (dBW)</th>
<th>Required Xmit Power (dBW)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Single TDRS</td>
<td>Constellation</td>
<td>Single TDRS</td>
<td>Constellation</td>
</tr>
<tr>
<td>3</td>
<td>12.8</td>
<td>38.6</td>
<td>1125</td>
<td>373</td>
</tr>
<tr>
<td>5</td>
<td>9.78</td>
<td>29.4</td>
<td>1472</td>
<td>490</td>
</tr>
<tr>
<td>10</td>
<td>7.00</td>
<td>21.0</td>
<td>2057</td>
<td>686</td>
</tr>
<tr>
<td>21</td>
<td>4.83</td>
<td>14.5</td>
<td>2981</td>
<td>993</td>
</tr>
</tbody>
</table>

Table 22. Required Performance Using a Helical Antenna System
Hitchhiker Payload Development

• Goal
  – to demonstrate the fixed antenna, DAMA, and low-power telemetry concepts in an actual space environment with realistic components

• Method
  – Develop a Hitchhiker Payload containing experiments that can be run during a Shuttle flight
Hitchhiker Payload Development

- S-Band Antennas
- DAMA
- Fixed
- Optical Port
- Modulator
- Corner Cube Reflector
- Hitchhiker Payload Canister
- RF Modulator & Amplifier
- Power/ Ground
- Control Lines
- Controller
- Data Source

March 31, 1998
Hitchhiker Payload Development

• Progress
  – Held a design class during fall 1997 semester
  – Identified potential components for RF experiments
  – Identified positions in shuttle orbit when experiments can be conducted (referenced to ascending and descending node positions)
Hitchhiker Payload Development

TDRS

Data Source

Controller

Modulator

Power Amplifier

S-Band Antenna

Hitchhiker Payload

Initiate Test

Status

Status Output → Control Input ← Internal Status & Control

Data Flow

GSFC

March 31, 1998

Small Satellite Experiments
Hitchhiker Payload Development

• Progress (continued)
  – Vetted concepts to Omitron and PSL for critique of methodology and plans
    • no problems foreseen by either group
  – Preparing final version of baseline Customer Payload Requirements document for submission to GSFC
Hitchhiker Payload Development

• Testing Plan
  – Test with RF testbed under development in the laboratory and with TDRS prior to Hitchhiker launch
    • Use amplifiers previously developed
    • Use one previously-developed antenna; get antenna design class to design another antenna
    • Considering Microdyne modulator and demodulator
RF Testbed

---

March 31, 1998
Small Satellite Experiments
LIGHTWEIGHT OPTICAL COMMUNICATIONS WITHOUT A LASER IN SPACE. (LOWCAL)

Carrier beam

R

Modulated signal beam
LOWCAL GOALS

• First Laser Communications to LEO without a Laser in Space
• Lightweight on board optical communications system.
• Data rates of 20 kbs.
• Daylight as well as, at nighttime operation.
• Monostatic operation
On Board Components

Data Stream

Carrier Detector

Corner Cube

Temperature Controlled

Carrier Beam

Modulated signal beam
COMMUNICATIONS FORMAT

CARRIER TRANSMISSION

On
Off

\[ T_{\text{Talk}} = \frac{R}{c} \]

\[ T_{\text{Listen}} = \frac{R}{c} \]

SIGNAL RECEIVER

On
Off

DATA

\[ T_b = 25 \, \mu s \]

where \( c \) represents the speed of light
LOWCAL SIGNAL MODEL

The received signal, $P_s$, is,

$$P_s = P_T \cdot \eta_T \cdot T_{Atm} \cdot \frac{A_{retro}}{R^2 \cdot \Delta \Omega_{up}} \cdot \eta_{mod} \cdot \eta_{retro} \cdot T_{Atm} \cdot \frac{A_r}{R^2 \cdot \Delta \Omega_{down}} \cdot \eta_T \cdot T_{FA DOF}$$

where:

- $P_T$ represents the transmitter laser power.
- $T$, $\eta$, and retro represent the telescope, the modulator, and the retro-reflector efficiencies, respectively.
- $T_{Atm}$ and $T_{FA DOF}$ represent the atmospheric and the FADOF transmissions, respectively.
- $A_r$ and $A_{retro}$ represent the receiver and retro-reflector areas respectively.
- up and down represent the carrier and signal beam solid angles, respectively.
- $R$ represents the range to the satellite.
LOWCAL LINK EQUATION

\[ P_s (dB) = P_T (dB) + 2 L_T + 2 L_{Atm} + L_{mod} + L_{CIE} + L_{SIE} \]

where:

\[ L_T = -10 \log(\eta_T) \]

\[ L_{Atm} = -10 \log(T_{Atm}) \]

\[ L_{FADOF} = -10 \log(T_{FADOF}) \]

\[ L_{mod} = -10 \log(\eta_{mod}^2 \eta_{retro}) \]

\[ L_{CIE} = -10 \cdot \log \left( \frac{A_{retro}}{R^2 \cdot \Delta \Omega_{up}} \right) \]

\[ L_{SIE} = -10 \cdot \log \left( \frac{A_{retro}}{R^2 \cdot \Delta \Omega_{down}} \right) \]

Margin = \[ P_T + 2 L_T + 2 L_{Atm} + L_{mod} + L_{CIE} + L_{SIE} - P_{min} - M_{scintillation} \]

where:

\[ M_{scintillation} \] represents the margin required to compensate for beam scintillation.
RECEIVER NOISE EQUIVALENT POWER ANALYSIS I

The NEP is,

\[ \text{NEP} = \sqrt{\text{NEP}^2_{PD} + \text{NEP}^2_{shot} + \text{NEP}^2_{sky}} \]

where:
\[ \text{NEP}_{PD}, \text{NEP}_{shot}, \text{and} \text{NEP}_{sky} \]
represent the noise equivalent power of the photodetector, the signal shot noise, and the background sky radiation, respectively.

Assuming that the receiver noise equivalent power is determined by the PMT noise,

\[ \text{NEP}_{PD} = \frac{1}{\eta} \cdot \frac{h \cdot c}{\lambda} \cdot \frac{\sqrt{I_{dark} \cdot 2}}{e \cdot G} \]

where:
\[ \eta \]
represents the quatum efficiency of the PMT.
\[ h \text{ and } c \]
represent Planck’s constant and the speed of light, respectively.
\[ I_{dark} \text{ and } G \]
represent the PMT’s dark current and gain, respectively.
\[ e \]
represents the electron charge.
RECEIVER NOISE EQUIVALENT POWER ANALYSIS II

The shot noise equivalent power is,

$$NEP_{\text{shot}} = \sqrt{\frac{P_s}{\eta}} \cdot \frac{h \cdot c}{\lambda}$$

The sky background power, $P_{\text{sky}}$, that reaches the photodetector, produces

$$NEP_{\text{sky}} = \sqrt{\frac{P_{\text{sky}}}{\eta}} \cdot \frac{h \cdot c}{\lambda}$$

$$P_{\text{sky}}(\Delta \Omega) = L_{\text{sky}}(\lambda) \cdot \Delta \Omega \cdot \Delta \lambda \cdot A_r \cdot T_{\text{FADOF}} \cdot \eta_f$$

where $L_{\text{sky}}(\lambda)$ represents the spectral radiance of the blue sky and $\Delta \lambda$ represents the equivalent noise bandwidth of the FADOF.

For a BER of 1 ppm the received optical signal must equal,

$$P_{\text{min}} = 3.1 \, \text{NEP} \, (2 \, \text{DR}_{\text{max}})^{1/2}$$

where $2 \, \text{DR}_{\text{max}}$ represents $1$ over the bit period.
Accuracy expected (~ 0.2 km).

<table>
<thead>
<tr>
<th>Acquire</th>
<th>Comm</th>
<th>4 7 10.10</th>
<th>4 7 10.10</th>
<th>4 7 10.10</th>
<th>4 7 10.10</th>
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</thead>
<tbody>
<tr>
<td>Acquire</td>
<td>4 7 10.10</td>
<td>48</td>
<td>72</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Acquire</td>
<td>4 7 10.10</td>
<td>54</td>
<td>33</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Mode</td>
<td>Avn</td>
<td>L-ze (db)</td>
<td>L-ce (db)</td>
<td>9.4</td>
<td>SUM</td>
</tr>
</tbody>
</table>

Beam Intercept Losses

<table>
<thead>
<tr>
<th>MODULATOR APERTURE INDEPENDANT LOSSES</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.4</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2*0.5</td>
</tr>
<tr>
<td>2*3</td>
</tr>
<tr>
<td>1.4</td>
</tr>
</tbody>
</table>

Modulator Aperature Independent Losses

<table>
<thead>
<tr>
<th>MODULATION</th>
<th>ACQUISITION INTEGRATION TIME</th>
<th>1 sec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 Kbps</td>
<td>Maximum data rate</td>
<td>60 cm</td>
</tr>
<tr>
<td>60 cm</td>
<td>Receiver diameter</td>
<td>3 db</td>
</tr>
<tr>
<td>3 db</td>
<td>TRANSMITTER POWER</td>
<td></td>
</tr>
</tbody>
</table>
**LINK MODEL SUMMARY**

**COMMUNICATIONS MODE**

<table>
<thead>
<tr>
<th>$D_{retro}$ (inches)</th>
<th>Margin (dB)</th>
<th>$P_{min}$ (dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-5.4</td>
<td>-80</td>
</tr>
<tr>
<td>2</td>
<td>6.7</td>
<td>-74</td>
</tr>
<tr>
<td>4</td>
<td>18.6</td>
<td>-68</td>
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</tbody>
</table>

**ACQUISITION MODE**

<table>
<thead>
<tr>
<th>$D_{retro}$ (inches)</th>
<th>Margin (dB)</th>
<th>$P_{min}$ (dBm)</th>
<th>Day/Night</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.5</td>
<td>-117</td>
<td>Night</td>
</tr>
<tr>
<td>2</td>
<td>19.6</td>
<td>-112</td>
<td>Night</td>
</tr>
<tr>
<td>4</td>
<td>31.6</td>
<td>-106</td>
<td>Night</td>
</tr>
<tr>
<td>1</td>
<td>5</td>
<td>-110</td>
<td>Day</td>
</tr>
<tr>
<td>2</td>
<td>17</td>
<td>-109</td>
<td>Day</td>
</tr>
<tr>
<td>4</td>
<td>29</td>
<td>-105</td>
<td>Day</td>
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</table>
## COMPARISON WITH OTHER EXPERIMENTS

<table>
<thead>
<tr>
<th></th>
<th>NASA/NMSU</th>
<th>AF/PL/USU</th>
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<tbody>
<tr>
<td><strong>PLATFORM</strong></td>
<td>Space Shuttle</td>
<td>Balloon</td>
</tr>
<tr>
<td><strong>ALTITUDE</strong></td>
<td>320 km</td>
<td>32 km</td>
</tr>
<tr>
<td><strong>DATA RATE</strong></td>
<td>20 kb/s</td>
<td>1.2 kb/s</td>
</tr>
<tr>
<td><strong>RECEIVER DIAMETER</strong></td>
<td>0.6 m</td>
<td>1.5 m</td>
</tr>
<tr>
<td><strong>MODULATOR FOV</strong></td>
<td>$\pm \pi/4$</td>
<td>$\pm \pi/4$</td>
</tr>
<tr>
<td><strong>MODULATOR WT.</strong></td>
<td>1-2 kgm</td>
<td>28 kgm</td>
</tr>
<tr>
<td><strong>MODULATOR AREA</strong></td>
<td>20 cm$^2$</td>
<td>1-10 cm$^2$</td>
</tr>
<tr>
<td><strong>24 HOUR CAPABILITY</strong></td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td><strong>TRANSMITTER POWER</strong></td>
<td>1/2 W</td>
<td>5 W</td>
</tr>
</tbody>
</table>
LOWCAL PROGRESS 97-98

• LINK MODEL DEVELOPED
• RECEIVER NOISE MODEL DEVELOPED
• SYSTEM CONCEPTUAL DESIGN WELL ALONG
• DETECTOR SYSTEM DESIGNED AND PARTS ORDERED
• MODULATOR ORDERED

LOWCAL DELIVERABLES FY 98-99

• MODULATOR SYSTEM REPORT AUGUST 98
• TRANSMITTER OPTICS REPORT NOV. 98
• FINAL REPORT FOR FY 98-99
SUMMARY

- A LOWCAL LINK TO LEO IS FEASIBLE
- ONLY A 1/2 WATT TRANSMITTER IS REQUIRED
- THE 60 CM WSMR ADVANCED POINTING TELESCOPE WILL BE USED IN THIS WORK
- THIS WILL BE THE FIRST OPTICAL LINK TO LEO WITHOUT A LASER IN SPACE
- THE ON BOARD COMPONENTS WILL BE LIGHT AND VERY LOW POWER CONSUMPTION
- A DATA RATE OF 20 Kb/S SHOULD BE POSSIBLE
LOWCAL SCHEDULE

FY 98-99
DESIGN, BUILD AND TEST CRITICAL SUBSYSTEMS.
UPGRADE LINK MODEL AS TESTING PROGRESSES.
GROUND FIELD LINK TEST.

FY 99-00
ASSEMBLE AND TEST REMAINING SUBSYSTEMS.
UPGRADE DESIGN AS NECESSARY.
INSTALL SYSTEM AT WSMR.
DESIGN FLIGHT EXPERIMENT.

FY 00-01
GROUND TEST AT WSMR.
BUILD FLIGHT HARDWARE.

FY 01-02
FLIGHT EXPERIMENT
Bandwidth Efficient Modulation

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Motivation

- High-rate communication thru nonlinear ISI channels is of interest as available spectrum becomes scarce.
- The need for power efficiency often requires the use of saturating power amplifiers.
- Within this bandlimited nonlinear environment, typical methods to increase data rate:
  - faster symbol rates
  - higher order modulation schemes (next talk)

Or,

- Spectral Shaping via filtering to increase frequency utilization.
Possible Filter Placement:

- post-amplifier $\Leftrightarrow$ Heavy, expensive, not compatible
- post-modulator $\Leftrightarrow$ Nonconstant modulus signal $\rightarrow$ spectral spreading through NL amp.
- pre-modulator $\Leftrightarrow$ ? $\Leftrightarrow$ Focus of Study
Pre-modulation Filtering

- Preserves constant modulus property of constellation. → no spectral spreading through NL amp.
- May introduce spectral spikes → ACI issue.
- May introduce ISI → receiver design issue.
Pre-mod Filtering Example Spectra

Spectrum: Rectangular Pulse Shape $- T_s$

Spectrum: Butterworth Filter Pulse Shape

Spectrum: Rect Pulse w/ Raised Cosine Transition $- 3T_s$
Results

- Built software tools and gained analytic understanding of spectral occupancy, signal modulus and ISI effects.
- Results for both spectral occupancy and bit-error rates for a variety of pre-mod filter's (both "classical" and "new").
- There exist tradeoff of ISI and spectral shaping:
  - hold $p(t)$ constant over $T_s$ yields no spikes...
  - ...but allowing support of $p(t) > T_s$ induces ISI.
  - removing discontinuities in $p(t)$ narrows spectrum.
Open Issues

- Develop methodology for design of waveform shaping $p(t)$ which allows tradeoff (and optimization?) of spectral occupancy vs. receiver simplicity (ISI).
- Use of Spike Cancellation Methods (Does cancellation of spectral spikes inherently imply non-constant modulus?)
Nonlinear Equalization for Bandwidth Efficient Modulation

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Motivation

- High-rate communication thru nonlinear ISI channels is of interest as available spectrum becomes scarce.
- The need for power efficiency often requires the use of saturating power amplifiers.
- Within this bandlimited nonlinear environment, typical methods to increase data rate:
  - faster symbol rates
  - higher order modulation schemes

suffer greatly.
Earlier Proposed Solutions

- Predistortion techniques (Saleh, and others).
  - adaptively predistort transmitted signal so desired constellation is achieved after passing through the nonlinearity.
  - effective, but requires additional transmitter hardware.
  - requires feedback from distorting device to transmitter.

- Nonlinear Volterra equalizers
  - may be effective
  - potentially large parameter space and sensitivity to noise remains an issue.
Our proposed technique

RAM-based Equalization

• appears robust to channel noise
• requires no additional transmit hardware,
• has rather modest receiver hardware needs.
• borrows from recent work in the magnetic storage channel and
digital communications communities.
• essentially this is an extension of the RAM-DFE.
• extension allows removal of “pre-cursor” nonlinear ISI components
- Bandlimited, nonlinear channel
  - pre-filtering, $f(n)$
  - saturating amplifier TWT
  - post-filtering, $g(n)$
  - additive Gaussian noise
TWT Nonlinearity

Phase Shift (degrees) - dotted

Input Amplitude

Output Amplitude - solid
Example Distortion - No Noise, ISI only

16-QAM

8-PSK

QPSK
### RAM-Based Compensation Techniques

The basic idea:

- regard the nonlinear channel with memory as a state-machine.
- channel output (neglecting noise) may considered to be an arbitrary function of the (previous and present) channel inputs

\[ x_k - n_k = g(s_{k+n-1}, \ldots, s_k, \ldots, s_{k-m}) \]

- ideal receiver implements a version of this function

\[ \hat{g}(s_{k+n-1}, \ldots, s_k, \ldots, s_{k-m}) \]

- nonlinear ISI components may be subtracted from the received signal to obtain a distortion-free sample in additive noise.
The equalizer which embodies this idea is depicted in Figure 1.

The receiver shown is not implementable, it requires:

\[ \{s_{k-n-1}, \ldots, s_k, \ldots, s_{k-m}\} \]

which is not known.
Family of RAM-based equalizers...

- Use various \textit{local} decisions on values of present and past inputs are used.
- The different ways of obtaining and using these decisions leads to different eq's:
  - RAM-DFE
  - RAM-canceler
  - PERC
- Such equalizers typically work in cooperation with a feedforward fractionally spaced equalizer (FSE) to
  - act as pseudo-matched filter (to maximize SNR)
  - aid symbol synchronization
The RAM-DFE

- RAM-DFE only uses \( \{s_{k-1}, \ldots, s_{k-m}\} \)
- expected to be effective when most of the nonlinear ISI (NL-ISI) is post-cursor.
- estimated NL-ISI is a function only of the post-cursor decisions \( \{\hat{s}_{k-1}, \ldots, \hat{s}_{k-m}\} \).
The RAM-DFE (continued)

- Slow convergence expected due to large number of RAM locations.
- It is not possible to cancel all nonlinear ISI terms with the standard RAM-DFE.
  - terms such as $s_{n+1}s_ns_{n-1}$ are possible
  - RAM-DFE can only remove terms of form $s_{n-i}s_{n-j}s_{n-k}$, for $i, j, k > 0$.

This motivates RAM-Canceler and PERC equalizers which attempts to eliminate all of the nonlinear ISI terms.
The RAM-Canceler

- RAM-Canceler uses both precursor and post-cursor symbol decisions.
- uses tentative symbol decisions
  - tentative decisions are less reliable than the final decisions.
  - final decisions are fed back in the RAM-DFE
The RAM- Canceler (continued)

- Even for relatively poor tentative decision error rates, performance improvement may be possible.
- However, improved results may be obtained by considering a "block cursor" idea,

This idea leads the the PERC ( Pre-Cursor Enhanced RAM-DFE Canceler).
The PERC($n, m$)

- RAM has address lines consisting of
  - $m$ past decisions $\hat{s}_{k-1}$ to $\hat{s}_{k-m}$ (denoted post-address)
  - $n$ present/future potential decisions $\tilde{s}_k$ to $\tilde{s}_{k+n-1}$.
**PERC Training**

- PERC must be "trained" first to learn the channel:
  - all "post" ($\{\hat{s}_{k-1}, \ldots, \hat{s}_{k-m}\}$) components are known.
  - all "pre" ($\{\tilde{s}_{k-1}, \ldots, \tilde{s}_{k-m}\}$) components are known.
- FSE uses standard LMS update relation:
  $$W_{k+1} = W_k + \mu_{ff} X_k e_k^*$$
- FSE is fixed, then RAM component is updated using:
  $$RAM_{k+1}(A_k) = RAM_k(A_k) + \mu_{fb} e_k$$
  - $RAM_k(A)$ denotes contents at time $k$ of address $A_k$.
  - $A_k$ is given by the bit representation of the
    $$[\tilde{s}_{k+n} \ldots \tilde{s}_k | \hat{s}_{k-1} \ldots \hat{s}_{k-m}] = [A_{pre} | A_{post}].$$
PERC Operation

- After training, the PERC may be run in:
  - "fixed mode" with no adaptation or...
  - "decision-directed" mode.

- Only difficulty becomes what is the proper "pre-cursor" address component $A_{pre}$?
  - idea is to test over all possible symbols of $A_{pre}$
  - choose address that places $z_k$ closest to a valid symbol value (address that minimizes $|e_k|^2 = |z_k - Q(z_k)|^2$).
  - error propagation is possible and MSE in non-training mode is worse.
Simulation Examples: 16-QAM at SNR = 15dB

- Linear Eq. Output
  MSE = -11.65

- Received Signal

- PERC(2,3)
  MSE = -15.63

- PERC(1,3)
  MSE = -13.96

- PERC(0,3)
  MSE = -11.4
Simulation Examples: 16-QAM Bit Error Rates

![Graph showing Bit Error Rate vs. \( E_b / N_o \) for PERC(0,3), Linear Eq, PERC(1,3), AWGN, and PERC(2,3).]
Open Issues and Continued Research

This research implies successful use of higher-order modulation through nonlinear channels (such as the TDRSS channel).

Further work focuses:

- verification using real-world data/hardware tests
  - presently engaged in a phase I hardware verification (random 16-QAM data through bandlimiting filters and TWT)
  - collected data to be run through our computer code implementation of the PERC algorithm.
  - computer generated noise samples used for bit-error rates.
  - phase II hardware verification experiment using actual TDRSS data would follow.
Open Issues and Continued Research (cont.)

- optimizing the performance of PERC equalizers
  - Multiply Free implementations
  - Enhanced training convergence
  - Determination of methods for identifying proper PERC\((n,m)\) parameterization for a given channel.
ACTS Propagation Measurements Program

Data Analysis Summary

Julie H. Feil
Louis J. Ippolito
Stephen Horan
Jennifer Pinder
Frank Paulic
Atle Borsholm

NAPEX XXI & APSW XI
June 11-13, 1997
Los Angeles, CA
Agenda

- Introduction
  - Experiment objectives & configuration

- NM ACTS $K_A$ band measurements and analysis
  - Three year (12/93-11/96) propagation statistics
  - Annual model comparisons
  - Seasonal statistics

- Summary and future activities

- New Mexico State University: Station status and wet antenna measurements
STel ACTS Propagation Experiment

Objectives

☐ Measure and evaluate $K_A$ band propagation effects and link performance for New Mexico

☐ Develop long-term statistics and prediction modeling techniques for New Mexico climate region for advanced satellite system planning and design
New Mexico APT

- Elevation angle: 51°

- Measured parameters
  - Beacons: 20.185 GHz and 27.505 GHz
  - Radiometers: 20 GHz and 27.505 GHz
  - Rain rate (CRG, TBG)
  - Temperature, Relative Humidity, Wind Vector, Barometric Pressure
New Mexico ACTS $K_A$ Band Measurements Summary

- Three years of data processed
- Three year weather statistics
- Comparison of old and new processing techniques for three year propagation measurements
- Annual model comparisons
- Statistical attenuation ratio
- Fade duration
- Seasonal statistics
- Worst actual month (in three years): July 1996
Three Year Weather Effects

Relative Humidity December 1993 - November 1996

Temperature December 1, 1993 - November 30, 1996
Comparison of Processing Techniques

  - From *.pv0 processing (ACTSEEDIT)
  - From *.pv2 processing (ACTSPP)

- Minor differences between two processing techniques
  - Monthly Statistics are within 1 dB
  - Gaseous absorption is less for *.pv2 than for *.pv0 processing
Definition of Attenuation Terms

- **AFS**: Attenuation wrt Free Space
  Difference between the received beacon level and the received level if in a vacuum. AFS includes attenuation due to atmospheric absorption, rain, clouds, and scintillation.

- **ARD**: Radiometrical Derived Attenuation
  Attenuation measurements from radiometers. Comparable to AFS.

- **ACA**: Attenuation wrt Clear Air
  The difference between the received beacon level and the expected level due to atmospheric absorption (AGA). ACA includes rain, clouds, and scintillation. ACA=AFS-AGA.

- **ARS**: Statistical Attenuation Ratio
  Ratio of equiprobable attenuation levels at two frequencies of interest.
Three Year Attenuation wrt Free Space (AFS) via ACTSPP

AFS for December 1993 - November 1996

Location: Las Cruces, NM
Elevation Angle: 51°

Percent of Time Attenuation is Equalled or Exceeded

Attenuation (dB)

0.0100
0.0010
0.0001
0.0000
0.0000

0 5 10 15 20 25

From *.pv2 files
Three Year Attenuation wrt Free Space (AFS) via ACTSEDIT

AFS for December 1993 - November 1996

Location: Las Cruces, NM
Elevation Angle: 51°

Percent of Time Attenuation is Equal to or Exceeded

- 20 GHz
- 27 GHz

From *.pv0 files
Three Year Radiometric Derived Attenuation (ARD) via ACTSPP

ARD for December 1993 - November 1996

Location: Las Cruces, NM
Elevation Angle: 51°

Percent of Time Attenuation is Equalled or Exceeded

Attenuation (dB)

From *.pv2 files
Three Year Radiometric Derived Attenuation (ARD) via ACTSEDIT

ARD for December 1993 - November 1996

Location: Las Cruces, NM
Elevation Angle: 51°

Percent of Time Attenuation is Exceeded or Exceeded

From *.pv0 files
Three Year Attenuation wrt Clear Air (ACA) via ACTSPP

ACA for December 1993-December 1996

Location: Las Cruces, NM
Elevation Angle: 51°

Percent of Time Attenuation is Equaled or Exceeded

- 20 GHz
- 27 GHz

From *pv2 files
Three Year Comparison 20 GHz Cumulative Distribution

Comparison of 20 GHz Dec 1993 - Nov 96 ACA Cumulative Distributions

- Crane Global
- ITU-R
- ACA from Beacon
- USA
- ExCell

Percent of Time Attenuation is Equalled or Exceeded

Attenuation (dB)

From *.pv2 files
Three Year Comparison of 27 GHz Cumulative Distribution

Comparison of 27.5 GHz Dec 1993 - Nov 96 ACA Cumulative Distributions

Las Cruces, NM
Elevation Angle: 51°

From *.pv2 files
2 Year Rain Rate Statistics

Comparison of Rain Rates for October 1994 - September 1996

The first six months of the NM ACTS experiment the rain gage did not work.
Comparison of 2 Year ACA and Global Model with Local Rain Statistics

2 Years: October 1, 1994 through September 30, 1996

20 GHz

27.5 GHz

From *.pv2 files
10/1/94-9/30/96
Comparison of 2 Year ACA and ITU Model with Local Rain Statistics

2 Years: October 1, 1994 through September 30, 1996

20GHz

27.5 GHz

From *.pv2 files
10/1/94-9/30/96
Statistical Attenuation Ratio for ACA

ARS for ACA
December 1993-November 1996

- - - - Drufuca
- - - - ITU-R PN, 838
- - - - Attn. Coef. 4km (838)
- - - - ITU-R PN, 618-3

New Mexico
Elevation Angle: 51°

Best Fit: ITU-R PN, 618-3
Error: 1.0 ms
First Order Regressive Fit
Δ27/Δ20 = 1.54

From *.pv2 files
Statistical Attenuation Ratio for AFS

ARS for AFS
December 1993 - November 1996

New Mexico
Elevation Angle: 51°

First Order Regressive Fit 1.53

From either *.pv2 or *.pv0 files
Three Year Fade Duration

200 GHz

27.5 GHz

Location: Las Cruces, NM
Elevation Angle: 51°
Three Year Winter AFS Statistics


Location: Las Cruces, NM
Elevation Angle: 51°

- 20 GHz
- 27 GHz

Percent of Time Attenuation is Eqaul or Exceeded

Attenuation (dB)

From *.pv2 files
Three Year Spring AFS Statistics

AFS for Spring (March, April, May) 1994, 1995, 1996

Location: Las Cruces, NM
Elevation Angle: 51°

Percent of Time Attenuation is Equalled or Exceeded

From *.pv2 files
Three Year Summer AFS Statistics

AFS for Summer (June, July, August) 1994, 1995, 1996

Location: Las Cruces, NM
Elevation Angle: 51°

From *.pv2 files
Three Year Fall AFS Statistics

AFS for Fall (September, October, November) 1994, 1995, 1996

Location: Las Cruces, NM
Elevation Angle: 51°

Percent of Time Attenuation is Equal to or Exceeded

From *.pv2 files
Actual Worst Month: July 1996
Attenuation wrt Free Space (AFS)

From *p2 files
New Mexico ACTS Statistics Summary

- Comparison of pv0 and pv2 processing for 36 months have minor differences (< 1 dB) in attenuation distributions
- Measured link performance for three year period (*.pv2)

<table>
<thead>
<tr>
<th>Annual Link Availability (%)</th>
<th>20 GHz (dB)</th>
<th>27.5 GHz (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>99</td>
<td>1.6</td>
<td>1.8</td>
</tr>
<tr>
<td>99.5</td>
<td>2.1</td>
<td>2.8</td>
</tr>
<tr>
<td>99.9</td>
<td>5.4</td>
<td>8.1</td>
</tr>
<tr>
<td>99.95</td>
<td>8.3</td>
<td>13.1</td>
</tr>
<tr>
<td>99.99</td>
<td>20.8</td>
<td>&gt; 25</td>
</tr>
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