The Center for Space Telemetering and Telecommunications Systems at New Mexico State University - Annual Report 2000-2001
by
S. Horan, P. DeLeon, T. Shay, D. Borah, C. Creusere, and R. Lyman

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The Center for Space Telemetering and Telecommunications Systems at New Mexico State University - Annual Report 2000 - 2001

S. Horan, P. DeLeon, T. Shay, D. Borah, C. Creusere, and R. Lyman

Manuel Lujan Space Tele-Engineering Program
New Mexico State University

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March 21, 2001

Klipsch School of Electrical and Computer Engineering
New Mexico State University
Box 30001, MSC 3-O
Las Cruces, NM 88003-8001
1) Technical Reports
   c) Jiang, Hui and Stephen Horan "Wireless Telemetry and Command (T&C) Program", NMSU-ECE-00-003, April 2000.
   d) Fan, Jin and Stephen Horan, “Implementing Real-Time Radio Propagation Measurements over the Internet”, NMSU-ECE-00-004
   g) Ghrayeb, Ali and William Ryan "Concatenated Coding and Equalization of Data Transmission and Storage", NMSU-ECE-00-008, June 2000.
   h) Anderson, Bobby and Stephen Horan "Three Corner Sat Communications System", NMSU-ECE-00-009, June 2000.

2) Presentations


3) Degrees Awarded
   a) Jin Fan – MSEE
   b) Hui Jiang – MSEE
   c) Bobby Anderson - MSEE
   d) Julio Castro – PhD
   e) Yunsheng Ma – MSEE
   f) Stephan Berner – PhD

4) Patent Applied For
   a) T. Shay, D. Hazzard, S. Horan, and J. Payne, Light Wire Communications System
Communications, Signal Processing and Telemetering Research: Program Review

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

March 8, 2001
Program Overview
Topics

- NMSU Background
- Communications, Signal Processing, and Telemetering Program
- Facilities
- Goddard Hall Remodeling
- Faculty & Staff
- Review Program

March 8, 2001

Program Overview
NMSU Background

- NMSU is the Land Grant University and NASA Space Grant University for New Mexico
- NMSU is a federally-designated minority-serving university
- NMSU is a Carnegie-I Research University
Communications, Signal Processing, and Telemetering Program

• Leverage and Spin-offs
  – Air Force Nanosatellite Program
  – Air Force Speech Processing Program
  – Navy Data Compression Program
  – Wireless Communications Laboratory
  – Digital Signal Processing Laboratory
  – Star Tracker Development (NMSU & AFRL)
Facilities

• Thomas & Brown Hall
  – Hardware development Laboratory
  – Software simulation Laboratory
  – Digital Signal Processing Laboratory

• Jett Hall
  – Optical Communications Laboratory
Goddard Hall Remodeling

- Goddard Hall to be remodeled
  - NSF, State of New Mexico, private donations to fund renovation
  - Annex Space (~13,000 ft²) to be used exclusively for research: electro-optics, communications, digital signal processing, and telemetry
  - Completion target: April 2001 (occupy in May)
Goddard Hall Remodeling
Faculty & Staff

- NMSU Faculty
  - Dr. Stephen Horan - Director
  - Dr. Phillip DeLeon - Associate Director
  - Dr. Deva Borah
  - Dr. Charles Creusere
  - Dr. Raphael Lyman

- NMSU Staff
  - Mr. Lawrence Alvarez
  - Ms. Patricia Anderson
Faculty & Staff

• University of Arizona
  – Dr. William Ryan

• University of New Mexico
  – Dr. Thomas Shay
Review Program

Small Satellite User
- TDRSS
- Channel Coding
- DSP Receiver
- Data Protocols
- Laser Communications
- Laser Transmit/Receive

Modulation & Equalization

Improve access by
- new techniques for antenna configuration
- improved access requests
- improved transmission throughput by using more efficient modulation and equalization techniques
- improved performance by using improved channel coding techniques
- improved data throughput by using data packaging protocols
- efficient telemetry transmission through low-power laser communications

March 8, 2001
Program Overview
Review Program

- 8:30 - 8:45 Welcome & Introductions
- 8:45 - 9:00 Overview
- 9:00 – 9:45 – Error Correcting Coding
- 9:45 – 10:15 – Video Compression Techniques
- 10:15 - 10:30 Break
- 10:30 - 11:15 – Parallel DSP Techniques for SS Receivers
- 11:15 – 12:00 – FQPSK Modulation
- 12:00 - 1:30 Lunch
- 1:30 – 2:15 – Space Protocol Testing
- 2:15 – 2:45 – Channel Equalization
- 2:45 – 3:00 – Break
- 3:00 – 3:45 – LOWCAL
- 4:00 – 4:30 – Tours
- 4:30 - 5:00 Wrap-up Review
- 5:00 -- Adjourn
SO YOU WISH TO PLACE

YOUR SATELLITE ON THE INTERNET...

Stephen Horan
Telemetering and Telecommunications Program
Klipsch School of Electrical and Computer Engineering
New Mexico State University
Topics

- Networking Questions
- Development Efforts
- Options Investigations
- Current Experiments
- LEO Telecom Access
- Next Steps
- Future Possibilities
Networking Questions

Satellite developers wish to operate satellites using the same software, protocols, and techniques as are used in ground testing and in-laboratory development.
Networking Questions

• Pros
  - aids in operational confidence
  - leverage off commercial standards, features, and capabilities
  - interoperability over commercial networks for distributed operations

• Cons
  - overkill in many applications since the link from space to ground is a single-user link
  - protocol overhead in flight computer
  - protocol overhead on link
  - security
Networking Questions

- Assumed User Profile for Small Satellite Networking
  - 2400 bps forward; < 115 kbps return
  - BER < 0.00001 on both links
  - file sizes in 1 kB through 1 MB range
  - short transfer opportunities (~ 5 minutes)
  - short propagation delays
Networking Questions

• Questions to be answered
  – is there an advantage of SCPS over TCP/IP in the satellite channel
  – do protocol options such as congestion control, header compression, etc. help performance
  – do the protocols work in limited flight computer configurations
Networking Questions

- TCP/IP
  - use commercial land lime and wireless products
  - Internet-ready single-board computers that can be used as a flight computer
  - willing to assume risk of space channel

SBC with embedded Linux and networking support
Protocols

• Space Communications Protocol Specification (SCPS)
  – funded by NASA and DoD
  – designed around TCP/IP
  – optimized for the space channel
  – has option to treat packet loss as errors and not congestion
  – reference implementation available for Linux/Unix platforms
Development Efforts

- NMSU Telemetry laboratory testbed
  - model small satellite links
    - $R_b \leq 115200$ bps in each direction
    - BER selectable
    - delay < 5 seconds on each link
    - configure each link independently

Space Protocols/NASA Review/March 2001
Development Efforts

LabVIEW-based channel error simulator for small satellite links

Space Protocols/NASA Review/March 2001
Development Efforts

• Since last review
  – completed bi-directional data flow in simulator
  – added link delay up to 5 seconds
  – continued to work with MITRE on understanding SCPS reference implementation and how it interacts with operating system and link-level protocols
Development Efforts

- Simulator Validation
  - MITRE spent one week here last summer working with us on validating SCPS and our simulator
  - Ran special tests to validate error generation at request of Will Ivancic @ GRC
Preliminary Results

• Investigations to date
  – look at SCPS vs. TCP/IP with different congestion control modes and
    • variable link delays
    • variable BER settings
    • equal and unequal forward and return data rates
    • effects of operating system and link layer protocol on effectiveness
Preliminary Results

(a) symmetric links

(b) unsymmetric links

TCP/IP results as a function of file size and channel BER

Space Protocols/NASA
Review/March 2001
Preliminary Results

(a) symmetric links

(b) unsymmetric links

SCPS fp with VJ congestion control results as a function of file size and channel BER

Space Protocols/NASA
Review/March 2001
Preliminary Results

(a) symmetric links

(b) unsymmetric links

SCPS fp with Vegas congestion control results as a function of file size and channel BER
Preliminary Results

- Findings to date
  - Both TCP/IP and SCPS work about the same when the channel error rate is small and both treat errors as congestion
  - Van Jacobson congestion control works a bit better than Vegas congestion control
  - No real link delay penalty for these “slow” links out to GEO orbits
Preliminary Results

• Findings to date
  – PPP does not recognize the SCPS protocol configuration so it will not support some of the internal link layer compression options. TCP can utilize these options and achieve a better throughput.
LEO Telecom Access

- Investigated the potential for small satellites to access LEO telecommunications constellations for T&C or scheduling
  - Globalstar, Iridium, Orbcom, Final Analysis investigated for orbital access and potential problems
  - Contacted all at one time for possible experiment
LEO Telecom Access

• Regulatory
  – No allocations for space-to-space services on a regular basis for LEO satellites and telecommunications communications satellites
  – For now, we will assume that this is an issue that can eventually be worked out
LEO Telecom Access

- Initial Proposal
  - Look at Iridium to service 3 Corner Satellite
- Constellations Used in the Analysis
  - Globalstar
  - Orbcomm
- Alternative Constellation
  - Final Analysis
LEO Telecom Access

- Globalstar Access
  - 350 km alt.
  - 28.5° inclin.
LEO Telecom Access

- Orbcomm Access
  - 350 km alt.
  - 28.5° inclin.
LEO Telecom Access

- Orbcomm Doppler Shifts

![Graph showing frequency offset from 2:42:43 to 2:49:55 with VHF and UHF lines]

Space Protocols/NASA Review/March 2001
LEO Telecom Access

- File transfer times for 1 kB and 1 MB files over PPP link

4800 bps ftp File Transfer

Transfer Time (sec)

0 1 10 100 1000 10000

Bit Error Rate

0 0.00001 0.0001

1000 1000000

Space Protocols/NASA Review/March 2001
Next Steps

- In-lab tests
  - conduct tests of SCPS reference implementation with lost packets treated as errors and not congestion
  - measure any advantage over standard TCP which still treats errors as congestion
- Upgrade simulator to 921600 bps on each link
Next Steps

• Satellite Tests
  - validate simulator results over a satellite link at Navy Research Laboratory
  - investigate > 1 Mbps response of TCP and SCPS
  - investigate SCPS with loss treated as errors and not congestion
Future Possibilities

- Satellite Clusters (Formation Flying)
  - Needs a method to interconnect satellites without prior synchronization
  - Need to allow clusters to grow and shrink
  - Base technology on something like the upcoming Bluetooth or wireless LAN standards
Future Possibilities

• Many unanswered questions related to access security, data integrity, data distribution
• There are regulatory and engineering issues involved with accessing LEO telecommunications from LEO satellites for T&C and scheduling communications
Future Possibilities

- Integrating the satellite with the wireless industry is an exciting concept if regulatory problems can be overcome
- Terrestrial wireless technology may provide a good road map for formation flying development
- Internet world will be a big help in addressing protocol issues
Recent Results on Coding and Nonlinear Equalization at the University of Arizona

William Ryan
University of Arizona

March 8, 2001
Outline

- early turbo code designs (serial and parallel)
- more recent turbo code designs: double turbo DPSK
- initial work on low-density parity-check codes
- combined nonlinear equalization and decoding
Bandwidth-Efficient Parallel and Serial

Concatenated Codes for QPSK Modulation:

Consideration for the CCSDS Near-Earth Standard

William E. Ryan, University of Arizona
Omer Acikel, New Mexico State University

March 4, 2001
OUTLINE

- Bandwidth-efficient signaling with MPSK
- The proposed codes - parallel and serial concatenations
- Performance results for the codes
BANDWIDTH-EFFICIENT SIGNALING

• bandwidth-efficiency for coded QPSK ($r = \text{code rate}$):

$$\mathcal{E}_{QPSK, \text{coded}} = 2r \text{ (bits/sec)/Hz}$$

• bandwidth-efficiency for coded 8PSK ($r = \text{code rate}$):

$$\mathcal{E}_{8PSK, \text{coded}} = 3r \text{ (bits/sec)/Hz}$$

Example

• rate 2/3 trellis coded 8PSK:

$$\mathcal{E}_{8PSK, \text{coded}} = 2 \text{ (bits/sec)/Hz}$$

• rate 15/16 turbo coded QPSK:

$$\mathcal{E}_{QPSK, \text{coded}} = 1.875 \text{ (bits/sec)/Hz}$$

• but, the coded QPSK scheme is more power efficient and has a more robust receiver
THE PROPOSED CODES

The Parallel Concatenated Convolutional Codes

Diagram of PCCC encoder.

- we consider rate 3/4, 7/8, and 15/16 PCCCs, with memory $m = 3$ component recursive systematic convolutional codes
The Serial Concatenated Convolutional Codes

SCCC encoder with differential encoder as rate 1 inner code.

SCCC encoder with two rate 1/2 RSC encoders.
(1) **Top Diagram:** a punctured outer rate $r_o = k/(k + 1)$ RSC encoder and a $r_i = 1$ (2-state) differential encoder

(2) **Bottom Diagram:** two $m = 3$ RSC encoders, with the inner and outer RSCs punctured to achieve rates $r_i = 2k/(2k + 1)$ and $r_o = (2k + 1)/(2k + 2)$, respectively

- We consider rate 3/4, 7/8, and 15/16 SCCCs.
PERFORMANCE RESULTS

PCCC Performance

- decoder: iterative BCJR-APP algorithm with 15 iterations
- information word size: 10,000 bits
- code rates: 3/4, 7/8, and 15/16
Rate 3/4 PCCC bit error rate performance.
Rate 7/8 PCCC bit error rate performance.
Rate 15/16 PCCC bit error rate performance.
SCCC Performance

- decoder: iterative BCJR-SISO algorithm with 15 iterations
- information word size: 10,000 bits
- code rates: 3/4, 7/8, and 15/16
Rate 3/4 SCCC bit error rate performance.
Rate 7/8 SCCC bit error rate performance.
Rate 15/16 SCCC bit error rate performance.
Performance Comparisons: PCCC, SCCC, Convolutional, and Trellis-Coded 8-PSK

Comparision of rate 3/4 codes: PCCC, 8/2 SCCC, and a memory 6 convolutional code.
Comparision of rate 7/8 codes: PCCC, 8/2 SCCC, and a memory 6 convolutional code.
Comparision of the rate 15/16 PCCC and 8/2 SCCC codes, and rate 2/3 trellis-coded 8PSK.
Comparison to QPSK Capacity Curve

- the $E_b/N_0$ required to achieve a bit error rate of $10^{-5}$ is plotted against the QPSK capacity curve.

Bandwidth-/Power-Efficiency operating points for the codes presented in this paper.
Convolutional Double Accumulate Codes (or Double Turbo DPSK)

Rajeev Ramamurthy and William E. Ryan
ECE Department, University of Arizona

November 15, 2000

Encoder

Decoder

\[ \Pi = N \cdot r_b \text{ bit pseudo-random interleaver} \]
\[ E_o = \text{Outer convolutional code (rate } r_o < 1) \]
\[ E_{i1}, E_{i2} = \text{Inner accumulate codes (rate } r_{i1}, r_{i2} = 1) \]
\[ \Pi^{-1} = N \cdot r_b \text{ bit pseudo-random de-interleaver} \]
\[ D_o = \text{Outer APP decoder}. \]
\[ D_{i1}, D_{i2} = \text{Inner APP decoders}. \]

Encoder and decoder for double turbo DPSK.
BER's of rate $\frac{1}{2}$ and $\frac{8}{9}$ serial and parallel codes.
FER's of rate $\frac{1}{2}, \frac{8}{9}$ serial, parallel codes.
BER's of rate $\frac{4}{5}$ and $\frac{16}{17}$ serial and parallel codes.
FER's of rate $\frac{4}{5}$, $\frac{16}{17}$ serial, parallel codes.
Initial Results on Low-Density Parity-Check Codes

Michael Yang and William Ryan
University of Arizona

March 2001
- low-density parity-check codes were invented by Gallager circa 1960 at MIT for his doctoral dissertation

- approximately five years ago, they were independently re-invented by MacKay (Cambridge University) and others

- the idea behind these codes (we assume binary codes):

  1. recall all codewords in a linear code form the nullspace of a so-called parity-check matrix $H$:

     $$Hc^T = 0 \quad \text{whenever } c \text{ is a codeword}$$

  2. we say the binary matrix $H$ is low-density if it is sparse, that is, if it contains only a small fraction of ones

  3. the low-density property leads to very powerful codes with decoders lower in complexity than turbo decoders
• the initial designs on LDPC codes (Gallager and MacKay) involved random designs with certain row and column constraints (e.g., # 1’s per column \( k_c > 2 \) and the # 1’s per row \( k_r > k_c \) )

• the problem with randomly generated codes is that the encoder is now complex: \( c = uG = u [ I \mid P] \) (imagine if \( G \) was 9000 x 10000 so that \( P \) was 9000 x 1000)

• more recently, Shu Lin and others have been looking at algebraic and combinatoric designs

• we have been examining both approaches for CCSDS near-earth standards work
A rate $r = 0.82$ MacKay LDPC code with BPSK/QPSK signaling on an AWGN channel, with and without RFI bursts.
A rate $r = 7/8 (= 0.875)$ quasi-cyclic LDPC code based on difference sets for BPSK/QPSK signaling on an AWGN channel, with and without RFI bursts.
RAM Search Viterbi Detector Performance Over Nonlinear Channels

Alejandro Lima Pérez
William E. Ryan
March 5, 2001

University of Arizona
Department of Electrical and Computer Engineering
Amplifier

![Graph showing TWT characteristics with Amp/Radians on the y-axis and Amp on the x-axis, comparing AM/AM and AM/PM.]
Constellation

dk - Signals at the output of the TWT constellation
$\lambda_k = [r_{1k} - b_{1k} - RAM (b_{2,k-1}, b_{1k}, b_{2k})]^2 + [r_{2k} - b_{2k} - RAM (b_{1,k}, b_{2k}, b_{1,k+1})]^2$
RS-VD Performance

BPSK, 1/2 encoder, nonlinear channel

- Coded AWGN sim.
- MLSD
- RS-VD
- VD

Pb vs Eb/No
Wireless Channel
Solid State Power Amplifier
RS-VD Performance
Scalable Motion Compensated Video Compression with Reduced-Complexity Encoding for Remote Transmission

Prof. Charles Creusere
Klipsch School of Electrical & Computer Engineering
New Mexico State University
Introduction

• Remote Transmission implies:
  – Limited weight and volume are available for video encoder
  – Antenna gain and transmission power are limited
  – Therefore, the communications channel has limited bandwidth and may be error prone
Introduction

- Space and power limitations on the remote platform imply that the encoder should be low complexity

- Channel bandwidth limitation suggest that the encoder should be highly efficient
  - i.e., it must be very sophisticated and thus probably highly complex
Introduction

• To achieve maximum performance on video, one must use both transformations and motion compensation

• Existing standardized encoders such as MPEG 1 & 2 and H.263+ are not well suited to remote transmission
  – The motion compensation process makes the complexity of their encoders considerably higher than that of their decoders
Background

- Hybrid DPCM-transform video compression:

![Diagram of Encoder and Decoder for video compression](attachment:image.png)
Hybrid DPCM-Transform Methods

- **Encoder Complexity Issues:**
  - Encoder contains the complete decoder
  - Transform complexity is double that of the decoder
  - Motion estimation must be performed by encoder
In-Subband Motion Compensation

Encoder

Video In

Subband Analysis

Motion Estimation

Motion Compensate

Butler

Unquantize

Quantize

Bits Out
In-Subband Motion Compensation

• Advantage:
  – No inverse transform is required in encoder => reduced complexity

• Disadvantage:
  – Motion compensation does not work well in subbands because filter bank/transform is decimated => shift varying
Out-of-Loop Motion Compensation

(a) is encoder; (b) is decoder
Out-of-Loop Motion Compensation

• Salient Features:
  – Motion compensation is performed in spatial domain
    • Eliminates problems associated with shift-varying transforms
  – Differencing is performed in the transform domain
    • Eliminates need for expensive inverse transform in the encoder
  – Supports resolution scalability with appropriate transform (e.g., wavelet) coefficient encoding
    • Heterogeneous communications networks
    • Channels with time-varying capacity
Out-of-Loop Motion Compensation

- **Limitation**: Motion compensation algorithm *must* be invertible
  - This is not required for conventional DPCM-transform encoding

- Simplest invertible method: periodic pan compensation (PPC):

\[
\text{PPC}\{F(x, y)\} = F((x - \Delta m) \mod X, (y - \Delta n) \mod Y)
\]
Out-of-Loop Motion Compensation

- PPC can be viewed as a window into an infinitely periodic image plane:
Out-of-Loop Motion Compensation

- To handle more complex motion:
  - PPC can be applied in blocks
  - PPC can be generalized to handle skewing motion: G-PPC (allows for rotational compensation)
  - PPC and G-PPC can be designed to compensate for subpixel motion
Frame-Rate Scalable Motion Compensation

(a) is encoder; (b) is decoder
Frame-Rate Scalable Motion Compensation

- Buffer Update Switch:
  - Always closed => single frame rate
  - Alternately open/close => 2 frame rates
    - Full and half
  - Closes every 4th frame => 4 frame rates
    - Full, 3/4, 1/2, and 1/4

- Wavelet transform and resolution-embedded encoding provides resolution scalability within this framework
Results

- Averaging over 5 video sequences
  - 50 to 500 frames
  - Sizes from 176x144 (QCIF) to 352x288 (CIF)
  - Bit Rates: 0.05 to 3.5 bits/pixel (bpp)
- Average result:
  - Encoder speed: 33% faster
  - Bit rate: 9.2 % lower
  - Mean Squared Error (MSE) in reconstruction: 29.6% lower
Results

Original

Frame Differencing

0.39 bpp, MSE= 382
Results

Conventional Pan Compensation

OOL Pan Compensation

0.38 bpp, MSE= 494

0.32 bpp, MSE= 383
Results

**OOL: 4 Blocks**

- 0.29 bpp, MSE = 386

**OOL: 16 Blocks**

- 0.33 bpp, MSE = 409
Results: Scalability

Scalable video decoding of *amb.256* sequence using OOL-Pan compensation. The average bit rate of the encoded sequence is 0.955, the average MSE is 2.42, and the residual update rate is 4

<table>
<thead>
<tr>
<th>Frame Rate</th>
<th>Resolution</th>
<th>Avg. Bit Rate</th>
<th>Avg. MSE</th>
<th>Decoding Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full</td>
<td>Full</td>
<td>0.955</td>
<td>2.42</td>
<td>48.64</td>
</tr>
<tr>
<td>Full</td>
<td>1/4</td>
<td>0.462</td>
<td>2.34</td>
<td>14.16</td>
</tr>
<tr>
<td>Full</td>
<td>1/16</td>
<td>0.164</td>
<td>0.308</td>
<td>5.05</td>
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<tr>
<td>1/2</td>
<td>Full</td>
<td>0.513</td>
<td>2.39</td>
<td>24.77</td>
</tr>
<tr>
<td>1/4</td>
<td>Full</td>
<td>0.289</td>
<td>2.38</td>
<td>12.72</td>
</tr>
<tr>
<td>1/2</td>
<td>1/4</td>
<td>0.250</td>
<td>2.24</td>
<td>7.47</td>
</tr>
<tr>
<td>1/2</td>
<td>1/16</td>
<td>0.089</td>
<td>0.250</td>
<td>2.82</td>
</tr>
<tr>
<td>1/4</td>
<td>1/4</td>
<td>0.142</td>
<td>2.359</td>
<td>3.92</td>
</tr>
<tr>
<td>1/4</td>
<td>1/16</td>
<td>0.050</td>
<td>0.243</td>
<td>1.55</td>
</tr>
</tbody>
</table>
Conclusion

- OOL Compensation provides the expected benefit of reducing encoder complexity: 33% on average
- In addition, it also supports the creation of both rate and resolution scalable bit streams
- An unexpected benefit: it achieves better rate-distortion performance than conventional DPCM-transform pan compensation when used with the same transform and encoder.
Future Research

• Adding robustness to the bit stream
  – ‘Leaky’ prediction
  – Coefficient Partitioning

• Developing new invertible motion compensation operators
Parallel Digital Architectures for Direct Sequence Spread Spectrum Receivers

Stephan Berner and Phillip De Leon
New Mexico State University
Center for Space Telemetering and Telecommunications
Las Cruces, NM 88003
Outline

- Why?
- Part I: Review of Parallel QAM Receivers
  - (JPL/GSFC 1995, 1998)
- Part II: Proposed Parallel Adaptive DSSS Receiver
- Part III: Analysis of Proposed Parallel Receiver
- Conclusions
Receivers: Why Implement Digitally?

- It is highly desirable to implement as many receiver functions digitally
  - Possible reduction in size and power consumption
  - Potential for single IC solution and better reliability
  - Adaptable, e.g. analog equalizers difficult; reconfigurable
  - Potential to replace costlier analog components with cheaper digital equivalents
  - Possibly better performance
Receivers: Why Parallelize?

- With digital implementations of serial receivers, we can only handle sample rates up to clock frequency of hardware.
- One approach to overcome this limitation is to parallelize the receiver, i.e. decompose the high rate input signal into many, parallel lower rate signals which can be handled digitally.
Part I: Review of Parallel QAM Receivers (JPL 1995)
Serial Implementation of QAM Receiver

- Intermediate Frequency (IF) signal is digitized
- Translation from IF to baseband, matched filtering, symbol rate sampling, and symbol decision are all performed digitally

\[
\begin{align*}
    r_{RF}(t) & \xrightarrow{\text{ADC}} \cos(\Omega_{LO} t) \xrightarrow{\text{matched filter}} \exp(\omega_{IF} n) \xrightarrow{\text{symbol decision}} \hat{a}(n)
\end{align*}
\]
Parallel Implementation of QAM Receiver

- High rate input signal is divided into parallel, lower rate signals. Several implementation possibilities for serial-to-parallel converter
Possibility #1: Parallel QAM Receiver Based on Filterbanks (JPL, 1995)

- Serial-to-parallel conversion by analysis filterbank (implemented in polyphase form)
Possibility #1: Parallel QAM Receiver Based on Filterbanks (cont.)

- Delay line runs at high rate, everything else at lower rate
  - IF to baseband translation, matched filtering performed digitally
- In filterbank implementation, require high order filters and careful design near crossover frequencies
- As will be shown, performance (BER) degrades with increasing number of subbands (not well scalable)
Possibility #2: Parallel QAM Receiver Based on Frequency Domain Filtering (GSFC, 1998)

- Matched filtering (convolution) is performed by multiplication in the frequency domain
Comparison of the Two Parallel Approaches

- Simulated both receivers for AWGN

Frequency Domain Filtering Approach

Filterbank Approach
IC Implementation

- ASIC implementations of BPSK, QPSK, QAM parallel receivers have been reported (A. Gray at JPL/Caltech, P. Ghuman at NASA/GSFC)
  - Bandpass sampling of IF at 4x data rate
  - 75MHz ASIC
  - 16 parallel subbands for 300M symbols/sec data rate
Part II: Proposed Parallel Adaptive DSSS Receiver
Review of Adaptive DSSS Receivers (Fractionally Spaced)

- Features/properties
  - Adaptive filter spans at least over one symbol, contains samples of received signal
  - Filter coefficients are updated at symbol rate using LMS, NLMS, RLS adjustment algorithms
    - Convergence depends on initialization
Review of Adaptive DSSS Receivers
(cont.)

- Filter taps after training (AWGN case) are equal to pulse-shaped PN sequence (matched filter coefficients)
- Adaptive DSSS receiver can suppress interference and equalize channel; also performs code acquisition
- Operating conditions of adaptive DSSS receivers are different from typical adaptive filtering applications
  - Signals are cyclostationary, however, due to sampling at symbol rate they appear stationary for filter
  - For AWGN, correlation matrix is Hermitian (but not Toeplitz as usual)

\[
\mathbf{s} = \begin{bmatrix} s_1 & s_2 & \cdots & s_N \end{bmatrix}^T
\]
\[
\mathbf{R} = \mathbf{s}\mathbf{s}^T + \sigma^2 \mathbf{I}
\]
Parallel Implementation of Adaptive DSSS Receiver: 1st Approach (trivial)

- Apply polyphase decomposition to serial adaptive DSSS receiver
  - Equivalent to serial receiver, same performance
  - Input signal decomposed into parallel lower rate signals

\[ d(n) \]

\[ x(n) \]

\[ w_1 \]

\[ y_1 \]

\[ T_s \]

\[ u_1 \]

\[ \sum \]

\[ \sum \]

\[ e(n) \]

\[ \tilde{a}(n) \]

\[ \text{Decision} \]

\[ \text{Calculate update} \]

\[ \text{Training} \]

\[ \text{Decision directed} \]

Berner, De Leon: Parallel Digital Architectures for DSSS Receivers
Parallel Implementation of Adaptive DSSS Receiver: 2nd Approach

- Apply classic subband adaptive filtering architecture
  - Filterbanks decompose input, desired signals; single adaptive filter replaced by several shorter filters
  - Used in acoustic echo cancellation (AEC) problems

- Simplify architecture, exploiting special operating conditions of adaptive receivers
  - As a first step, replace filterbanks by general transforms (matrices), $T$ and $T^{-1}$
Parallel Implementation of Adaptive DSSS Receiver, 2nd Approach (cont.)

Berner, De Leon: Parallel Digital Architectures for DSSS Receivers
Parallel Implementation of Adaptive DSSS Receiver, 2nd Approach (cont.)

- Simplify and improve architecture
  - Assume symbol length is multiple of $M$
  - Inverse transform reduces to summation
  - Employ adaptive gain factors, $\alpha$
Parallel Implementation of Adaptive DSSS Receiver, 2nd Approach (cont.)

Berner, De Leon: Parallel Digital Architectures for DSSS Receivers
Comparison of Serial and Parallel Receiver by Simulation using NLMS

BER

MSE of Serial Receiver
Comparison of Serial and Parallel Receiver by Simulation using NLMS (cont.)

MSE of Parallel Receiver without Adaptive Gain Factors

MSE of Parallel Receiver with Adaptive Gain Factors
Remarks to NLMS Simulation

- Convergence rate comparison is based on same BER for serial and parallel receivers (can be achieved by step size variation)

- Simulation parameters
  - Interference by 4 other users and 3 sinusoids, each 6 dB stronger than desired signal
  - Training at 6 dB SNR
  - Length 31 PN sequence used, 4 samples per chip, SRRC pulse, 50% excess bandwidth
  - Parallel receiver has 4 “subbands” and length 32 subband filters

- Observations
  - Gain factors speed up filter convergence
  - DCT, Hadamard transforms perform well, DFT poor
Comparison of Serial and Parallel Receiver by Simulation using RLS

BER

MSE of Serial Receiver
Comparison of Serial and Parallel Receiver by Simulation using RLS (cont.)

MSE of Parallel Receiver (4 Subbands)  MSE of Parallel Receiver (8 Subbands)
Comparison of Serial and Parallel Receiver by Simulation using RLS (cont.)

MSE of Parallel Receiver (4 Subbands)

MSE of Parallel Receiver (8 Subbands)
Remarks to RLS Simulation

- With RLS, parallel receiver converges faster compared to serial receiver due to shorter filter length
- Observations
  - Factor $\delta$, which scales initial correlation matrix is chosen much bigger than usual for convergence
  - Furthermore $\delta$ allows tradeoff between convergence speed and BER, similar to step size of LMS/NLMS
  - Set forgetting factor, $\lambda = 1$ (infinite memory) for best performance
  - Adaptive gain factors have little effect
Part III: Analysis of Parallel Adaptive DSSS Receiver
Optimal Transform Design: General Approach

- We now explore how to design a general transform, \( T \) for better performance (better BER, faster convergence)
- Calculate MSE at receiver output assuming subband filters have converged to their Wiener solutions, i.e. MMSE
  - Assuming error signal after convergence is white and Gaussian (common assumption), BER follows directly from MSE
    \[
    J_{\text{min}} = \frac{1}{d^2} \sum_{m=1}^{M} \sum_{n=1}^{M} \alpha_m \alpha_n [d_m d_n - (|d_m| w_{\text{opt},m}^T s_n + |d_n| w_{\text{opt},n}^T s_m) + w_{\text{opt},m}^T R_{mn} w_{\text{opt},n}^T]
    \]
- Formula gives MMSE for arbitrary transforms and inputs
  - Entries of \( T \) are wrapped up inside \( s, R \)
- Not suitable for minimization of MSE with respect to entries of the \( T \), i.e. transform optimization is difficult
Optimization of Transform, \( T \) for

Maximum Output SNR (AWGN case)

- Calculate and maximize SNR at receiver output, and compute rows of optimal \( T \)
- Major steps of calculation, shown for case of two subbands with subband filters of length two:

\[
\text{SNR} = \frac{P_s}{P_N} = \frac{\sigma^2 ((s_1^T s_1 + t_{12}^2) \alpha_1^2 + (s_2^T s_2 + t_{12}^2) \alpha_2^2)}{8\sigma^2 ((t_{11}^2 + t_{12}^2) \alpha_1^2 + (t_{21}^2 + t_{22}^2) \alpha_2^2)}
\]

Assume absolute value of all elements of pulse-shaped PN sequence and \( T \) are less than 1:
Optimization of Transform, $T$ for Maximum Output SNR (cont.)

- Constrain SNR denominator to be constant
  \[ (t_{11}^2 + t_{12}^2)\alpha_1^2 + (t_{21}^2 + t_{22}^2)\alpha_2^2 = k \]
- Assuming BPSK, drop square in SNR numerator
- Use method of Lagrange multipliers to solve constrained optimization problem
  \[ \nabla f(t) = \lambda \nabla g(t) \]
  \[ f(t) = (s_1^T s_1)\alpha_1 d + (s_2^T s_2)\alpha_2 d \]
  \[ g(t) = (t_{11}^2 + t_{12}^2)\alpha_1^2 + (t_{21}^2 + t_{22}^2)\alpha_2^2 \]
Optimization of Transform, $T$ for Maximum Output SNR (cont.)

- Solution: Rows of the optimal transform matrix, are the eigenvectors of

$$
B = \begin{bmatrix}
     s_1^2 + s_3^2 & s_1 s_2 + s_3 s_4 \\
     s_1 s_2 + s_3 s_4 & s_2^2 + s_4^2
\end{bmatrix}
$$

- For the general case of $M$ subbands with subband filter length $N$, entries of $B$ are given by

$$
b_{mn} = \sum_{i=1}^{M} s_{(i-1)M+m} s_{(i-1)M+n}
$$
Performance Comparison of Parallel Receiver Using Different Transforms

- Optimized transform yields slightly better BER
  - Better performance also for interference case, despite the fact derivation was done for AWGN

AWGN case

Interference case
Optimization of Transform, $T$ for Fast Convergence

- Analyze how transform, $T$ effects convergence speed of receiver
- If LMS or NLMS is used, eigenvalue spread determines convergence speed
- We look at 3 cases
  - Single user
  - Multiuser
  - Sinusoidal interference
Optimization of Transform for Fast Convergence: Single User Case

- For 2 subbands, length 2 subband filter, correlation matrix of subband 1 is:

\[ R_{11} = \begin{bmatrix} (t_{11}s_1 + t_{12}s_2)^2 & (t_{11}s_1 + t_{12}s_2)(t_{11}s_3 + t_{12}s_4) \\ (t_{11}s_1 + t_{12}s_2)(t_{11}s_3 + t_{12}s_4) & (t_{11}s_3 + t_{12}s_4)^2 \end{bmatrix} + \sigma^2 (t_{11} + t_{12})I \]

- Optimization for fast convergence (minimization of EV spread) is in conflict with optimization for SNR maximization: \((t_{11}s_1 + t_{12}s_2)^2 + (t_{11}s_3 + t_{12}s_4)^2\)

\[ \lambda_{max} = \frac{(t_{11}s_1 + t_{12}s_2)^2 + (t_{11}s_3 + t_{12}s_4)^2}{\sigma^2 (t_{11} + t_{12})} \]

\[ \lambda_{min} = \frac{(t_{11}s_1 + t_{12}s_2)(t_{11}s_3 + t_{12}s_4)}{\sigma^2} \]

Optimization for fast convergence is also in numerator of equation for the SNR.
Optimization of Transform for Fast Convergence: Multiuser, Sinusoidal Cases

- Can show similar result for multiuser case
- Sinusoidal case is difficult to analyze because of nonstationarity, e.g. correlation matrix time dependent, however, adaptive filter theory assumes stationary processes
- Transform could attenuate sinusoid, however cannot build good notch filter given the transform sizes of interest, e.g. $M < 16$
Computational Costs

- For LMS/NLMS, cost of updating subband filters is similar for serial receiver (because in both cases update at symbol rate)
- For RLS, we have computational savings because costs for RLS update proportional $N^2$.
  - Fast RLS not usable according to Miller, 1995
- Further computational savings possible by removing subbands which contain only noise
- In all cases need to consider overhead of transform
- Gain factors add very little additional computation
Comparison of Parallel Receivers: Polyphase-Based and Transform-Based

- Advantages of transform-based parallel receiver
  - Computational savings
  - Moderate increase of convergence speed compared to serial receiver with NLMS
  - More significant increase of convergence speed with RLS

- Disadvantages of transform-based parallel receiver
  - Parallel architecture, not fully scalable: for higher number of subbands performance degradation similar to the filterbank architecture
Conclusions

• Architectures for parallel adaptive DSSS receivers have been designed and analyzed
  – Due to parallel nature, we can employ multiple lower speed processing units
• BER performance of parallel receivers close to serial one
  – Novel use of gain factors to speed up convergence
  – Possible increase of convergence speed
  – Possible computational savings
• Future work
  – Synchronization issues, non-square transforms, more realistic channel conditions
EFQPSK versus CERN: A Comparative Study

Presented by

Dr. Deva K. Borah

Assistant Professor,
Klipsch School of Electrical and Computer Engineering,
New Mexico State University, Las Cruces, NM 88003, USA
OVERVIEW

- Introduction
- EFQPSK
- CERN
- Numerical Results
- Future Work and Conclusions
Communication System

Data in → Encoder → Modulator → Power amplifier

Noise

Demodulator (Detector) → Decoder → Data out
Consider an input signal $x(t) = m(t)\cos(\omega_c t + \psi(t))$, where

- $\omega_c$ is the carrier frequency,
- $m(t)$ and $\psi(t)$ are modulated envelope and phase, respectively.

The corresponding TWT output is

$$y(t) = A[m(t)]\cos(\omega_c t + \psi(t) + \Phi[m(t)])$$  \hspace{1cm} (1)

where

$$A(m) = \frac{\alpha_a m}{1 + \beta_a m^2}$$

$$\Phi(m) = \frac{\alpha_\phi m^2}{1 + \beta_\phi m^2}$$

We use $\alpha_a = 1.9638$, $\alpha_\phi = 2.5293$, $\beta_a = 0.9945$, and $\beta_\phi = 2.8168$. 
AM/AM Characteristics of a Commercial TWT
AM/PM Characteristics of a Commercial TWT

![Graph showing AM/PM characteristics of a commercial TWT](image-url)
Spectra of Conventional RRC Filtered QPSK
FQPSK Block Diagram

Data in

Serial/Parallel

I(t)

p(t)

IF

LO

90°

T/2

p(t)

90°

Low power
hard limiter

PA

To
antenna

Nonlinear
power amplifier

RF-LO
Waveform Set of EFQPSK

The constant $A$ is $1/\sqrt{2}$ in the following equations.

1. $s_0(t) = A, \quad -T/2 \leq t \leq T/2, \quad s_8(t) = -s_0(t)$

2. $s_1(T) = \begin{cases} 
A, & -T/2 \leq t \leq 0 \\
1 - (1 - A)\cos^2(\pi t/T), & 0 \leq t \leq T/2 
\end{cases}$

$s_9(t) = -s_1(t)$

3. $s_2(t) = \begin{cases} 
1 - (1 - A)\cos^2(\pi t/T), & -T/2 \leq t \leq 0 \\
A, & 0 \leq t \leq T/2 
\end{cases}$

$s_{10}(t) = -s_2(t)$

4. $s_3(t) = 1 - (1 - A)\cos^2(\pi t/T), \quad -T/2 \leq t \leq T/2,$

$s_{11}(t) = -s_3(t)$
5. \( s_4(t) = A \sin(\pi t / T), \quad -T/2 \leq t \leq T/2, \quad s_{12}(t) = -s_4(t) \)

6. \( s_5(t) = \begin{cases} 
\sin(\pi t / T) + (1 - A)\sin^2(\pi t / T), & -T/2 \leq t \leq 0 \\
\sin(\pi t / T), & 0 \leq t \leq T/2 
\end{cases} 
\quad s_{13}(t) = -s_5(t) \)

7. \( s_6(t) = \begin{cases} 
\sin(\pi t / T), & -T/2 \leq t \leq 0 \\
\sin(\pi t / T) - (1 - A)\sin^2(\pi t / T), & 0 \leq t \leq T/2 
\end{cases} 
\quad s_{14}(t) = -s_6(t) \)

8. \( s_7(t) = \sin(\pi t / T) \quad -T/2 \leq t \leq T/2, \quad s_{15}(t) = -s_7(t) \)
Vector Plot of EFQPSK
Spectra of EFQPSK
Spectra of EFQPSK with Unbalanced Data
<table>
<thead>
<tr>
<th>Probability of a bit being a +1</th>
<th>Relative strength at zero frequency (dB)</th>
<th>Relative strength at $f = 1/2T_b$ (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.45</td>
<td>+16.0</td>
<td>-10.0</td>
</tr>
<tr>
<td>0.40</td>
<td>+21.0</td>
<td>-4.0</td>
</tr>
<tr>
<td>0.35</td>
<td>+25.0</td>
<td>-0.5</td>
</tr>
<tr>
<td>0.30</td>
<td>+30.0</td>
<td>0.0</td>
</tr>
<tr>
<td>0.25</td>
<td>+30.0</td>
<td>+0.5</td>
</tr>
<tr>
<td>0.15</td>
<td>+38.0</td>
<td>+1.5</td>
</tr>
<tr>
<td>0.10</td>
<td>+39.0</td>
<td>+2.5</td>
</tr>
<tr>
<td>0.05</td>
<td>+41.0</td>
<td>+1.0</td>
</tr>
</tbody>
</table>

Table 1: Line strengths with unbalanced data. The reference spectrum level is zero frequency for balanced data.
Spectra of EFQPSK

Advantages

- Spectrally efficient compared to conventional QPSK under nonlinear amplification.
- Spectral properties remain intact under nonlinear amplification.

Disadvantages

- Not spectrally efficient compared to conventional QPSK under linear amplification.
- Spectral lines are produced when unbalanced data are used.
Constrained Envelope Root Nyquist (CERN)

Consider a baseband equivalent linearly modulated signal \( s_o(t) \),

\[
s_o(t) = \sum_i a_i p(t - iT)
\]

where \( \{a_i\} \) is the symbol sequence, \( p(t) \) is a pulse-spreading filter, \( T \) is the symbol period. Consider a sampling rate of 2 samples per symbol interval at time instants \( t = 0T, 0.5T, T, 1.5T, 2T, \ldots \).

These are

\[
\{s_o(0T), s_o(0.5T), s_o(T), s_o(1.5T), s_o(2T), s_o(2.5T), s_o(3T), \ldots \}
\]

Divide the signal samples into two groups:

- On-time samples: samples at time instants \( t = iT \).
- Off-time samples: samples at time instants \( t = (i + 0.5)T \).
Magnitude Probability Density Function (8 PSK)
Magnitude Probability Distribution Function
Potential Backoff Improvement

Consider a threshold clipping level of 0.01%.

- Conventional 8 PSK: 1.91
- CERN 8 PSK: 1.36

Back off improvement: \(20 \log_{10}(1.91/1.36) \approx 2.95 \text{ dB}\)
QPSK CERN Spectra with Ideal Clipper

Normalized power spectral density (dB)

\[ f/Rb \]

Without TWT
With TWT (clip at 1.25)

SFCG mask, SR > 2 Mbps
QPSK CERN Spectra with a Commercial TWT
Effect of the Predistorter on AM/AM
Effect of the Predistorter on AM/PM

![Graph showing the effect of the predistorter on AM/PM]

- TWT (without predistorter)
- TWT (with predistorter)
QPSK CERN Spectra with Predistorter

Normalized power spectral density (dB)

SFCG mask, SR > 2 Mbps

IBO=4dB
Conventional RRC QPSK Spectra with Predistorter

Normalized power spectral density (dB)

SFCG mask, SR > 2 Mbps

IBO=4dB
**Spectra of CERN**

**Advantages**

- Improves spectral efficiency over conventional QPSK under nonlinear amplification.
- Does not generate spectral lines for unbalanced data (except a DC line).

**Disadvantages**

- Requires a good predistorter, else much less benefit.
Effect of sampling rate on EFQPSK

![Graph showing BER vs. sampling rate for different methods: Optimal, PWMF, Wiener, and Average MF.](image-url)
BER performance of uncoded EFQPSK

![BER Performance Graph](image-url)
BER Analysis/Simulation for uncoded EFQPSK

![Graph showing BER vs. SNR for various methods: PWMF (analysis), Wiener (analysis), and Average MF (analysis), along with PWMF (simulation), Wiener (simulation), and Average MF (simulation).]
Sensitivity to predistorter phase error (EFQPSK)
BER Performance of Coded EFQPSK

![Graph showing BER performance vs. SNR (dB)]
Convergence of Adaptive Receivers for EFQPSK

![Graph showing convergence of MSE with number of iterations for single filter receiver and per-waveform filter receiver.](image)
BER Performance of QPSK CERN
BER Performance Comparison (TWT:0 dB IBO)
BER Performance of EFQPSK and CERN

- Several receiver structures are available for EFQPSK providing complexity performance trade off. 
- BER performance of EFQPSK is negligibly affected by the nonlinear amplifier. 
- BER performance of CERN is degraded by more than 1 dB due to the nonlinear amplifier. 
- Ignoring other features of the modulation techniques, the EFQPSK is found to provide more than 2 dB performance improvement over CERN.
Possible Future Directions

- Improvement on EFQPSK to suppress the spectral lines for unbalanced data.
- Improvement on CERN technique.
- Adaptive predistorter investigation and realization with improved CERN.
- Efficient detection in intersymbol interference environment.
Conclusions

- A comparative study on EFQPSK and CERN techniques is considered and both the techniques are found to have advantages and disadvantages.

- The CERN method is found to have better bandwidth efficiencies, especially when higher modulation formats are used.

- The CERN requires good adaptive predistorter to fully utilize its potential spectral benefits.

- The EFQPSK provides better power efficiencies than CERN.

- Several future research directions in terms of improving the performance of EFQPSK and CERN techniques have been indicated.
Bandwidth-efficient Transmission in Nonlinear Satellite Channels

Raphael J. Lyman
New Mexico State University
Personal Background

• Graduated University of Florida, May 2000
• Dissertation: Linear Prediction of Bandlimited Processes
• Research interests:
  – Channel modeling
  – Estimation theory
  – Wireless communications
Satellite Channel Model

\[ m(t) \rightarrow \text{TWT} \rightarrow \text{BPF} \rightarrow \text{Phased Array} \]
TWT Characteristic

Output Phase in Degrees vs. Normalized Output Amplitude vs. Normalized Input Amplitude

$A(r)$, $\phi(r)$
Distortion of QAM Alphabet
Proposed Solutions

- Adaptive predistortion (demod on TX)
- Volterra filters (noise sensitivity?)
- RAM DFE (training time)
My Focus

- Channel modeling
  - Nonlinear memoryless cascaded with linear ISI
  - Very slow variation of nonlinear characteristic
- Channel estimation
  - Faster convergence than direct adaptation
  - Run TWT in linear region during adaptation
Direct Adaptation

- Equalizer parameters updated directly
- LMS or RLS commonly used algorithms
Indirect Adaptation

LMS and RLS performance nearly identical.
Channel Modeling

- What about the noise?
- Avoid overly general compensation techniques.
- Use adaptation to get you “the last cm”.

Keep it as simple as possible, not simpler.
Examples

- Nonadaptive predistortion
- Ring-type QAM alphabet
Action Items

• Refine channel models.
  – Nonlinearities and dispersion separable?
  – Which elements slowly varying?
  – Can channel types be usefully classified?
• Review proposed compensation techniques.
• Develop or borrow simulation software.
Conclusions

- General approaches are not always general solutions.
- Nonlinear channels may require more case-by-case consideration.
- Choose solutions that fit the particular channel model.
- First step is good channel modeling and estimation procedures.
Lightweight Optical Wavelength Communications a Laser in Space

by

T. M. Shay

University of New Mexico
Center for High Technology Materials
Albuquerque, NM
(505)-272-7818
tshay@chtm.unm.edu


New Mexico State University
Klipsch School of Electrical and Computer Engr.
Las Cruces, NM
CURRENT SPONSORS

- NASA
- New Mexico Space Grant Consortium
LOWCAL vs. RF

LOWCAL Goals
- Data Rate: 10 kbps
- Lightweight: < 2 pound
- Ultra low power consumption: < 500mW
- Day / night operation
- LEO communication without a laser in space

RF Communication
- Data Rate: 10 kbps
- Weight: ~ 10 pounds (heat sink weight)
- Power consumption: ~ 10W
LOWCAL LINKS

852-nm uplink
downlink carrier

Telescope

852-nm downlink
signal beam

LOWCAL: Lightweight Optical Wavelength Communication without A Laser in space
Satellite Acquisition

In-Space Spot Size:
Acquire: ~100m
Locked: 7 m

WSMR APT
## Comparison With Other Experiments

<table>
<thead>
<tr>
<th></th>
<th>LOWCAL</th>
<th>AF/PL/USU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Platform</td>
<td>Space Shuttle</td>
<td>Balloon</td>
</tr>
<tr>
<td>Range</td>
<td>640 km</td>
<td>32 km</td>
</tr>
<tr>
<td>Data Rate</td>
<td>10 kbps</td>
<td>1.2 kbps</td>
</tr>
<tr>
<td>Telescope Diameter</td>
<td>0.6 m</td>
<td>1.5 m</td>
</tr>
<tr>
<td>Modulator Weight</td>
<td>2-4 kg</td>
<td>28 kg</td>
</tr>
<tr>
<td>Retro-Modulator Area</td>
<td>70-180 cm²</td>
<td>1-10 cm²</td>
</tr>
<tr>
<td>24 Hour Capability?</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Transmitter Power</td>
<td>0.2 W</td>
<td>5 W</td>
</tr>
</tbody>
</table>
LOWCAL with Differential Circular Polarization Keying

Diode Transmitter → DMS → λ/4 → ASE → WSMR APT → “0” → “1” → LCS Retro Modulator

Computer → 0.2% Beam Splitter → λ/4 → “0” → “1” → FADOF → Tracking Camera

Receiver → FADOF → FADOF → Receiver

Polarizing Beam Splitter
DCPK COMMUNICATIONS FORMAT

CARRIER TRANSMISSION

On
Off

$T_{\text{Talk}} = \frac{R}{c}$

$T_{\text{Listen}} = \frac{R}{c}$

SIGNAL RECEIVER

On
Off

DATA

$T_b = 50 \, \mu s$

where $c$ represents the speed of light
DOWNLINK LINK EQUATION

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

where:

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

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

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

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

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

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

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

where:

\[ M_{\text{scintillation}} \] represents the margin required to compensate for beam scintillation.
APPROXIMATE SIGNAL

Taking into account dependence of Zenith angle, $\phi$, on the effective retro-modulator area and range to the spacecraft we obtain,

$$P_s = P_T \cdot \eta_T^2 \cdot \eta_{mod}^2 \cdot \eta_{retro} \cdot T_{Atm}^2 \cdot T_{FADOF} \cdot \frac{A_r \cdot D_{retro}^4 \cdot \cos^4(\phi) \cdot \cos^2(\phi - \alpha)}{H_{orbit}^4 \cdot \pi \cdot (1.22 \cdot \lambda)^2 \cdot \theta_{Trans}^2}$$

Where:

- $D_{retro}$ represents the retro-modulator diameter
- $\phi$ represents the spacecrafts angle with Zenith
DCPK SNR

\[ SNR = \frac{(2 \cdot P_s \cdot (1 - \varepsilon) \cdot R_{PD})^2}{2 \cdot q \cdot B \cdot (P_s \cdot (1 - 2\varepsilon) \cdot R_{PD} + I_D) + \left(\frac{4 \cdot k \cdot T \cdot B \cdot F_t}{R_L}\right)} \]

Where:
q represents the electron charge.
B represents the signal bandwidth.
\(R_{PD}\) represents the photodetector responsivity.
\(I_D\) represents the photodetectors dark current.
k represents Boltzmann's constant.
T represents the temperature in degrees Kelvin.
\(R_L\) represents the load resistor.
\(F_t\) represents the noise figure of the amplifier.
\(\varepsilon\) represents the extinction ratio of the LCS
DCPK-SNR

In our case shot noise dominates, thus the SNR reduces to,

\[
SNR = \frac{2 \cdot P_s \cdot \eta_{PMT} \cdot q}{2 \cdot q \cdot B \cdot h \cdot \nu} = \frac{P_s \cdot \eta_{PMT}}{B \cdot h \nu}
\]

\[
SNR = P_T \cdot \eta_T^2 \cdot \eta_{mod} \cdot \eta_{retro} \cdot T_{Atm}^2 \cdot T_{FADOF} \cdot \frac{A_r \cdot D_{retro}^4 \cdot \cos^4(\phi) \cdot \cos^2(\phi - \alpha)}{H_{orbit}^4 \cdot \pi \cdot (1.22 \cdot \lambda)^2 \cdot \theta_{trans}^2} \cdot \eta_{PMT} \cdot \frac{1}{B \cdot h \nu}
\]
DATA RATE VERSUS POWER

Maximum angle from Zenith 60 degrees
SYSTEM CHARACTERISTICS

Transmitter power  -7 dB
Receiver diameter   60 cm
Maximum data rate  10 kb/s
Acquisition integration time  0.01 sec.
M_{scintillation}  10-dB

<table>
<thead>
<tr>
<th>Description</th>
<th>Loss (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulator</td>
<td>1.4</td>
</tr>
<tr>
<td>Atmospheric</td>
<td>2*3</td>
</tr>
<tr>
<td>Telescope</td>
<td>2*0.5</td>
</tr>
<tr>
<td>FADOF</td>
<td>1</td>
</tr>
<tr>
<td>Carrier Intercept at Spacecraft</td>
<td>46</td>
</tr>
<tr>
<td>Signal Collection at the ground</td>
<td>24</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>79.4</strong></td>
</tr>
</tbody>
</table>

Link margin  20-dB
DOWNLINK SUMMARY

• 10 kbps Data rate planned to LEO with a 20 dB margin

• First Circular Polarization Keying concept. (patent pending)
  – DCPK provides 6 dB SNR increase.

• 24 hour a day operation.

• Lightweight and low power consumption in space.

• With faster modulators data rates of Mb/s are possible
UPLINK SECTION
LOWCAL LINKS

852-nm uplink signal beam

852-nm downlink signal beam

LOWCAL: Lightweight Optical Wavelength Communication without a Laser in space
LIGHTWIRE FORMAT

CARRIER TRANSMISSION

On
Off

FSK subcarrier 10% modulation

T_{Talk} = R/c

T_{Listen} = R/c

SIGNAL RECEIVER

On
Off

DOWNLINK

T_b = 50 \mu s

where c represents the speed of light
Conceptual Block Diagram for Uplink Modulation

\[ P_{mo} \cdot (1 + 0.1) \cos(\omega_{fsk} t) \]

- DC Drive Current
- Semiconductor Master Oscillator
- Amplifier (A)
- BFSK Encoder
- Data
Lightwire FSK Demodulation

Phase-locked loop
FSK Demodulator

Flight Electronics

VCO @ $f_{\text{center}}$

$V_{\text{ref}}$

$\frac{f_u + f_1}{2}$

Transimpedance amplifier in photoconductive mode

FSK input signal

$f_u$
$f_1$
$f_c$

i(t)

C_f
R_f
FSK Demodulation Theoretical

Input

Code
“1” “1” “0” “1” LOST

Phase Comparator
Output (3 states)
FSK Demodulation Experimental

FSK Input Signal

FSK Demodulator

Output
UPLINK SIGNAL

The optical power incident upon the spacecraft $P_r$ is,

$$P_r = I_i A_{PD} [1 + m \cos(\omega_{FSK} t)]$$

where:

- $P_r$ represents the received optical power at the spacecraft.
- $I_i$ represents the intensity incident upon the spacecraft.
- $m$ represents the modulation index.
- $\omega_{FSK}$ represents the subcarrier frequency.
UPLINK SNR CALCULATIONS

\[ SNR = \frac{\frac{1}{2}(m \cdot P_r \cdot R_{PD})^2}{\left(2 \cdot q \cdot B \cdot (P_r \cdot R_{PD} + I_D) + \frac{4 \cdot k \cdot T \cdot B}{R_L} \cdot F_t \right)} \]

Where:
- \( q \) represents the electron charge.
- \( B \) represents the signal bandwidth.
- \( R_{PD} \) represents the photodetector responsivity.
- \( I_D \) represents the photodectors dark current.
- \( RIN \) represents the laser relative intensity noise.
- \( k \) represents Boltzmann's constant.
- \( T \) represents the temperature in degrees Kelvin.
- \( R_L \) represents the load resistor.
- \( F_t \) represents the noise figure of the amplifier.
# Preliminary Uplink Model Results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incident Intensity</td>
<td>50 nW/cm²</td>
</tr>
<tr>
<td>Eye Safety limit</td>
<td>2 mW/cm²</td>
</tr>
<tr>
<td>Photodetector area</td>
<td>4.0 cm²</td>
</tr>
<tr>
<td>Photodetector responsivity</td>
<td>0.6 amp/watt</td>
</tr>
<tr>
<td>modulation index</td>
<td>0.1</td>
</tr>
<tr>
<td>Data Rate</td>
<td>10 kHz</td>
</tr>
<tr>
<td>Load resistance</td>
<td>25 kohm</td>
</tr>
<tr>
<td>FSK Signal to Noise</td>
<td>36 dB</td>
</tr>
<tr>
<td>FSK signal current</td>
<td>89 nA</td>
</tr>
</tbody>
</table>
Summary of Unique Features

- Sunlight insensitive operation
- No laser in space
- All pointing is on the ground
- Very low power consumption
- Very low mass

- 200 mW transmitter
- Full-Duplex by "Lightwire" *
- First Optical DD-CPK *

* Patent pending
LABORATORY
EXPERIMENTS
Lightwire: FSK and Circular Polarization Keying transparent link pair
Subsystem Tests

- **Liquid Crystal Shutter**
  - Rise time 80 $\mu$s
  - Versus frequency
    - 0.035 at 10 kbps
  - Power consumption
    - 14 mW/cm²

- **FADOF**
  - Throughput $\sim$ 0.7
  - Transmission Spectrum

![Graph of transmission spectrum at 91 GHz](image)
Preliminary System Tests

- Downlink receiver
  - PMT
    - Quantum Efficiency = 1.1%
    - Gain = $5.2 \times 10^5$
  - CPK link
    - SNR = 138
    - BER < $1.67 \times 10^{-7}$ (no errors in 10 minutes at 10 kbps)

- Uplink Receiver
  - FSK demodulator
    - Easily operates at 20 kbps
  - FSK Link
    - SNR ~ 1000
    - BER < $1.67 \times 10^{-7}$ (no errors in 10 minutes)

- Lightwire Demonstration
- (Full Duplex on a single beam)
  - BER < $1.67 \times 10^{-7}$ (no errors in 10 minutes at 10 kbps)
SUMMARY OF MAJOR ACCOMPLISHMENTS IN FY 00-01

• First demonstration of DD-CPK optical communications

• First demonstration of Full Duplex on a single optical beam, “Lightwire”

• Demonstration of the Subcarrier FSK uplink receiver system

• All of the critical subsystems have been built and tested

• For the space experiment received signal levels no errors were detected over a 10 minutes period for any of the above link tests
GOALS FOR FY 01-02

• Experimental Tasks
  – Perform short range field test
  – Design, build, and test DSP for uplink receiver
  – Add AGC’s to uplink and downlink receivers
  – Design and implement data storage and data processing hardware for flight system
  – Finalize reflector design

• Design Tasks
  – Structural/thermal modeling and design for flight package
  – Safety review preparations
Inter-Agency collaborations

• Army
  – Proving the WSMR APT ground station at no cost
  – Donating the use of the WSMR APT satellite tracking optical telescope
  – Donating the WSMR manpower required to operate the APT

• Air Force
  – Funding a second ground station at Maui
    • Funding 2.5 Gbps link at 1.5 microns
    • Funding a second NASA type link

• DOE (LANL)
  – Considering funding an additional experiment