Shannon Lecture XXVI

June 30, 2004
Chicago, Illinois
“If I have seen further it is by standing on the shoulders of giants.”
“If I have seen further it is by standing on the shoulders of giants.”
Four Giants

Hall  Posner  Solomon  Rumsey
Marshall Hall, Jr.
Ed Posner
Gus Solomon
Howard Rumsey, Jr.
And Now For Something Completely Different.
Summary
Summary

- Of the 35 patterns of three erasures:
Summary

• Of the 35 patterns of three erasures:
  • 25 are correctable
Summary

- Of the 35 patterns of three erasures:
  - 25 are correctable
  - 7 are uncorrectable (codewords)
Summary

• Of the 35 patterns of three erasures:
  • 25 are correctable
  • 7 are uncorrectable (codewords)
  • 3 are ambiguous (stopping sets, but not codewords)
In General:

**Theorem.** The number of weight 3 **codewords** in a Hamming code of length \( n = 2^m - 1 \) is

\[
\frac{1}{6} \left( 4^m - 3 \cdot 2^m + 2 \right) \sim \frac{1}{6} n^2.
\]

**Theorem.** The number of weight 3 **stopping sets** in a Hamming code of length \( n = 2^m - 1 \) is

\[
\frac{1}{6} \left( 5^m - 3^{m+1} + 2^{m+1} \right) \sim \frac{1}{6} n^{2.322}.
\]
Feature Presentation
Feature Presentation

“The fundamental problem of communication is that of reproducing at one point either exactly or approximately a message selected at another point.”
Feature Presentation

“The fundamental problem of communication is that of reproducing at one point either exactly or approximately a message selected at another point.”

“Frequently the messages have meaning”
“The fundamental problem of communication is that of reproducing at one point either exactly or approximately a message selected at another point.”

“Frequently the messages have meaning”

“... [which is] irrelevant to the engineering problem.”
**Staff Scientist**  
Dr. S. W. Golomb (PT)  
Admin. Assistant  
J. C. Kelly

### Communications Projects

<table>
<thead>
<tr>
<th>Name</th>
<th>Role</th>
</tr>
</thead>
<tbody>
<tr>
<td>W. S. Baumgartner</td>
<td>Engineer</td>
</tr>
<tr>
<td>D. V. Brown</td>
<td>Engineer</td>
</tr>
<tr>
<td>R. L. Lundsberg</td>
<td>Engineer</td>
</tr>
<tr>
<td>R. C. Mullik</td>
<td>Engineer</td>
</tr>
<tr>
<td>J. Shatskin</td>
<td>Engineer</td>
</tr>
<tr>
<td>R. W. Bibe</td>
<td>Technician</td>
</tr>
<tr>
<td>C. F. Fontar</td>
<td>Technician</td>
</tr>
<tr>
<td>E. C. Oakley</td>
<td>Technician</td>
</tr>
<tr>
<td>R. C. Starr</td>
<td>Technician</td>
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</table>

### Transmitters

<table>
<thead>
<tr>
<th>Name</th>
<th>Role</th>
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<tbody>
<tr>
<td>C. F. Wiggins, Supvr.</td>
<td>Engineer</td>
</tr>
<tr>
<td>R. S. Arnold</td>
<td>Engineer</td>
</tr>
<tr>
<td>D. L. Lanham</td>
<td>Engineer</td>
</tr>
<tr>
<td>R. L. Weber</td>
<td>Engineer</td>
</tr>
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</table>

### Technicians

<table>
<thead>
<tr>
<th>Name</th>
<th>Role</th>
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<tr>
<td>R. A. Luese</td>
<td>Technician</td>
</tr>
<tr>
<td>G. N. Morris</td>
<td>Technician</td>
</tr>
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</table>

### Goldstone Staff

<table>
<thead>
<tr>
<th>Name</th>
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<tbody>
<tr>
<td>K. T. Mihale, Supvr.</td>
<td>Engineer</td>
</tr>
<tr>
<td>S. A. Gregg</td>
<td>Engineer</td>
</tr>
<tr>
<td>G. A. Morris, Jr.</td>
<td>Engineer</td>
</tr>
<tr>
<td>J. W. Brown</td>
<td>Engineer</td>
</tr>
<tr>
<td>R. L. Price</td>
<td>Engineer</td>
</tr>
</tbody>
</table>
### Communications Systems
Research Section 331,
October 25, 1963

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**Staff Scientist**

Dr. S. W. Golomb (PT)

Admin. Assistant

J. C. Kelly

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<table>
<thead>
<tr>
<th>RADIO RESEARCH</th>
<th>INFORMATION PROCESSING</th>
<th>DIGITAL COMMUNICATIONS</th>
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<tr>
<td>Dr. R. M. Dahlquist</td>
<td>Dr. R. G. Foss</td>
<td>Dr. N. G. Fitzpatrick</td>
</tr>
<tr>
<td>Engineers</td>
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</tr>
<tr>
<td>Dr. W. F. Gilmore</td>
<td>Dr. T. O. Anderson</td>
<td>Dr. R. C. Poehl</td>
</tr>
<tr>
<td>Dr. E. L. Rydor</td>
<td>Dr. L. D. Bäumler (PT)</td>
<td>Dr. R. S. Farnsworth</td>
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<tr>
<td>G. C. Thompson</td>
<td>Dr. I. R. Brown</td>
<td>Dr. W. S. Baugher (PT)</td>
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<tr>
<td>R. A. Winklerstein</td>
<td>Dr. M. F. P. Rosen</td>
<td>Dr. R. A. E. Farnsworth</td>
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<tr>
<td>Dr. S. Zovar</td>
<td>Dr. H. C. Pansey</td>
<td>Dr. R. A. E. Farnsworth</td>
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<tr>
<td>Vacancy 81273</td>
<td>Dr. R. J. Mullins (PT)</td>
<td>Dr. R. A. E. Farnsworth</td>
</tr>
<tr>
<td>A. Kish</td>
<td>Math Assistant</td>
<td>Dr. R. J. Mullins (PT)</td>
</tr>
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<table>
<thead>
<tr>
<th>TECHNOLOGICAL PROJECTS</th>
<th>DIGITAL COMMUNICATIONS</th>
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<tr>
<td>W. S. Baugher (PT)</td>
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</tr>
</tbody>
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P. H. Schottler
Dr. A. J. Viterbi (PT)
C. C. Wang

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1. Starting on 10-7-63
2. Starting on 10-21-63

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Goldsmith Hall
2. K. Minkes, Supvr.
R. A. Gregg
G. A. Morris, Jr.
J. W. Newton
R. L. Price
INFORMATION PROCESSING

Dr. E. C. Posner

Engineers
T. O. Anderson
L. D. Baumert (PT)
I. Eisenberger
H. Fredrickson (LOA)
W. Lushbaugh (PT)
Dr. H. C. Rumsey
Dr. G. Solomon
E. A. Yerman

Math Assistant
R. J. McEliece (PT)
Are There Turbo-Codes on Mars?

Robert J. McEliece
California Institute of Technology
Are There Turbo-Codes on Mars?

Robert J. McEliece
California Institute of Technology
Are There Turbo-Codes on Mars?

Robert J. McEliece
California Institute of Technology
• The source, “Mars,” produces a sequence of image bits. This is the message.
• The source, “Mars,” produces a sequence of image bits. This is the message.

• The object is to communicate these i-bits reliably from Mars to Earth, as rapidly as possible.
• The source, “Mars,” produces a sequence of image bits. This is the message.

• The object is to communicate these i-bits reliably from Mars to Earth, as rapidly as possible.

• All compression algorithms being considered are (subjectively) noiseless.
Example: Mariner 4 (1965)
Example: Mariner 4 (1965)

- $F = 2.3 \, \text{GHz} \, (S\text{-band})$
Example: Mariner 4 (1965)

- $F = 2.3$ GHz (S-band)
- $R = 8.33$ ibps
Example: Mariner 4 (1965)

- $F = 2.3$ GHz (S-band)
- $R = 8.33$ ibps
- No Coding (rep twice)
Example: Mariner 4 (1965)

- F = 2.3 GHz (S-band)
- R = 8.33 ibps
- No Coding (rep twice)
- No Compression
Example: Mariner 4 (1965)

- $F = 2.3 \text{ GHz (S-band)}$
- $R = 8.33 \text{ ibps}$
- No Coding (rep twice)
- No Compression

This is our baseline system.
Mariner 4

The First Close-Up of Mars
Mariner 4

First close-up image of Mars, before and after image processing
Mariner 4

A Memento
Mariner 4

Another Mariner 4 Picture
Mars  

Normalized Rate $R^*$  

Earth
We normalize the data rate $R$ to $R^*$, the rate in $\text{i-bits/sec}$ at $D = 215 \text{ Gm}$ (the Mariner 4 distance).
• We normalize the data rate $R$ to $R^*$, the rate in $i$-bits/sec @ $D = 215$ Gm (the Mariner 4 distance).

• Example: $R = 256$ bps @ $D = 100$ Gm with 2:1 compression is equivalent to $R^* = 256 \times (100/215)^2 \times 2 = 111$ ibps
Viking Mars Orbiters/ Landers (1976)
Viking Mars Orbiters/landers (1976)

- F = 2.3 GHz (S-band)
Viking Mars Orbiters/Landers (1976)

- $F = 2.3 \text{ GHz (S-band)}$
- $R^* = 3K \text{ ibps}$
Viking Mars Orbiters/Landers (1976)

- $F = 2.3$ GHz (S-band)
- $R^* = 3K$ ibps
- (32,6) Biorthogonal Code
Viking Mars Orbiters/ Landers (1976)

- F = 2.3 GHz (S-band)
- R* = 3K ibps
- (32,6) Biorthogonal Code
- No compression
Viking Lander

Viking I Landscape
Viking Lander

Sunset on Mars
Viking Orbiter

The Great Equatorial Canyon
A 20-Year Gap
and Then:
Mars Global Surveyor (1997)
Mars Global Surveyor (1997)

- F = 8.4 GHz (X-band)
Mars Global Surveyor (1997)

- $F = 8.4 \text{ GHz (X-band)}$
- $R^* = 128K \text{ ibps}$
Mars Global Surveyor (1997)

- $F = 8.4$ GHz (X-band)
- $R^* = 128$ K bps
- $(7, 1/2) CC + (255, 223) RS$
Mars Global Surveyor (1997)

- $F = 8.4 \text{ GHz} (X\text{-band})$
- $R^* = 128K \text{ ibps}$
- $(7, 1/2)CC + (255,223)RS$
- $\sim 2:1$ lossless Rice compression
MGS
The “Face” on Mars (Cydonia)
Earth and Moon from MGS
Mars Pathfinder
(1997)
Mars Pathfinder (1997)

- $F = 8.4$ GHz (X-Band)
Mars Pathfinder (1997)

- $F = 8.4$ GHz (X-Band)
- $R^* = 8K$ ibps
Mars Pathfinder (1997)

- \( F = 8.4 \text{ GHz (X-Band)} \)
- \( R^* = 8K \text{ ibps} \)
- \((15, \frac{1}{6})\text{CC} + (255,223)\text{RS}\)
Mars Pathfinder (1997)

- $F = 8.4\ \text{GHz (X-Band)}$
- $R^* = 8K\ \text{ibps}$
- $(15, 1/6)\text{CC} + (255,223)\text{RS}$
- 6:1 lossy JPEG compression
Pathfinder

Pathfinder on Mars
Pathfinder

“Sojourner”
Simulated view through a telescope of Mars from Earth

Earth to Mars distance: 259 million km

Date: 7 February 2003
Mars Exploration Rovers (2004)
Mars Exploration Rovers (2004)

- F = 8.4 GHz (X-Band)
Mars Exploration Rovers (2004)

- $F = 8.4 \text{ GHz (X -Band)}$
- $R^* = 168K \text{ ibps}$
Mars Exploration Rovers (2004)

- $F = 8.4$ GHz (X-Band)
- $R^* = 168K$ ibps
- $(15, 1/6)CC + (255,223)RS$
Mars Exploration Rovers (2004)

- $F = 8.4 \text{ GHz (X -Band)}$
- $R^* = 168K \text{ ibps}$
- $(15, 1/6)CC + (255,223)RS$
- 12:1 lossy ICER compression
MER

Leaving the Lander
The “Columbia Hills” (Spirit)
Eagle Crater (Opportunity)

Example of composite Pancam image
Progress 1965-2004
Progress 1965-2004

- 1965 (Mariner 4): 8.33 ibps
Progress 1965-2004

• 1965 (Mariner 4): 8.33 ibps
• 2004 (MER-direct to earth): 168K ibps
Progress 1965-2004

- 1965 (Mariner 4): 8.33 ibps
- 2004 (MER-direct to earth): 168K ibps
- This is a 20000-fold increase, or 4.3 orders of magnitude (43 dB).
Progress 1965-2004

- 1965 (Mariner 4): 8.33 ibps
- 2004 (MER-direct to earth): 168K ibps
- This is a 20000-fold increase, or 4.3 orders of magnitude (43 dB).
- How much of the increase is due to Shannon?
Newton vs. Shannon
Newton vs. Shannon

- Newton (Physics)
Newton vs. Shannon

- Newton (Physics)
- Aperture
Newton vs. Shannon

- Newton (Physics)
- Aperture
- Frequency
Newton vs. Shannon

- Newton (Physics)
- Aperture
- Frequency
- Power
Newton vs. Shannon

- Newton (Physics)
- Aperture
- Frequency
- Power
Newton vs. Shannon

- Newton (Physics)
  - Aperture
  - Frequency
  - Power
- Shannon (Mathematics)
Newton vs. Shannon

- Newton (Physics)
  - Aperture
  - Frequency
  - Power
- Shannon (Mathematics)
  - Source Coding
Newton vs. Shannon

- Newton (Physics)
  - Aperture
  - Frequency
  - Power

- Shannon (Mathematics)
  - Source Coding
  - Channel Coding
4.3 Orders of Magnitude Improvement in Image Bit Rate, 1965-2004
4.3 Orders of Magnitude Improvement in Image Bit Rate, 1965-2004

Shannon
37%

Newton
63%
4.3 Orders of Magnitude Improvement in Image Bit Rate, 1965-2004
4.3 Orders of Magnitude Improvement in Image Bit Rate, 1965-2004

Shannon: 37%
Newton: 63%
Next Round
Mars Reconnaissance Orbiter (2006)
Mars Reconnaissance Orbiter (2006)

- F = 8.4 GHz (X - Band)
Mars Reconnaissance Orbiter (2006)

- $F = 8.4\text{ GHz (X - Band)}$
- $R^* = 12\text{ M ibps}$
Mars Reconnaissance Orbiter (2006)

- $F = 8.4$ GHz (X - Band)
- $R^* = 12$ M ibps
- (8920, 1/6)CCSDS turbo code
Mars Reconnaissance Orbiter (2006)

- $F = 8.4$ GHz (X - Band)
- $R^* = 12$ M ibps
- $(8920, 1/6)$CCSDS turbo code
- $\sim 2:1$ lossless FELICS compression
Mars Reconnaissance Orbiter (2006)

- F = 8.4 GHz (X - Band)
- R* = 12M ibps
- (8920, 1/6)CCSDS turbo code
- ~2:1 lossless FELICS compression
Mariner 4 vs. MRO
1965-2006
Mariner 4 vs. MRO
1965-2006

- Mariner 4: 8.33 ibps
Mariner 4 vs. MRO
1965-2006

- Mariner 4: 8.33 ibps
- MRO: 12M ibps
Mariner 4 vs. MRO
1965-2006

• Mariner 4: 8.33 ibps
• MRO: 12M ibps
• This is a 6.2 order of magnitude increase (62 dB).
Mariner 4 vs. MRO
1965-2006

- Mariner 4: 8.33 ibps
- MRO: 12M ibps
- This is a 6.2 order of magnitude increase (62 dB).
- How much of the increase is due to Shannon?
6.5 Orders of Magnitude Improvement in Image Bit Rate, Mariner 4 - MRO
6.5 Orders of Magnitude Improvement in Image Bit Rate, Mariner 4 - MRO

Shannon
21%

Newton
79%
6.5 Orders of Magnitude Improvement in Image Bit Rate, Mariner 4 - MRO

Shannon
21%

Newton
79%
LDPC Codes: The Final Frontier?
LDPC Codes: The Final Frontier?

• RA Codes
LDPC Codes: The Final Frontier?

• RA Codes
• IRA Codes
LDPC Codes: The Final Frontier?

- RA Codes
- IRA Codes
- IRPA Codes
LDPC Codes: The Final Frontier?

- RA Codes
- IRA Codes
- IRPA Codes
- ARA Codes
LDPC Codes: The Final Frontier?

- RA Codes
- IRA Codes
- IRPA Codes
- ARA Codes
- ARAA Codes
LDPC Codes: The Final Frontier?

- RA Codes
- IRA Codes
- IRPA Codes
- ARA Codes
- ARAA Codes
- AARP Codes
LDPC Codes: The Final Frontier?

- RA Codes
- IRA Codes
- IRPA Codes
- ARA Codes
- ARAA Codes
- AARP Codes
There's much more to the Solar System than just Mars!
We shall not cease from exploration
And the end of all our exploring
Will be to arrive where we started
And know the place for the first time.
Some Information - Theoretic Anagrams
Some Information - Theoretic Anagrams

- A Sound Channel
Some Information - Theoretic Anagrams

- A Sound Channel
- Brainy Coed
Some Information - Theoretic Anagrams

• A Sound Channel
• Brainy Coed
• Rome Noodles
Some Information - Theoretic Anagrams

- A Sound Channel
- Brainy Coed
- Rome Noodles
- Cubed Roots
Some Information -Theoretic Anagrams

- A Sound Channel
- Brainy Coed
- Rome Noodles
- Cubed Roots
- UCLA Shenanigans
Some Information - Theoretic Anagrams

- A Sound Channel
- Brainy Coed
- Rome Noodles
- Cubed Roots
- UCLA Shenanigans
- Coordinate Spasm
Some Information - Theoretic Anagrams

- A Sound Channel
- Brainy Coed
- Rome Noodles
- Cubed Roots
- UCLA Shenanigans
- Coordinate Spasm
- Momentary Mixup