The BPSK1000 Format for ARISSat-1

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BPSK1000

- Framing, coding & modulation designed for ARISSat-1 telemetry downlink
- Fits in SSB bandwidth, CW beacon as pilot
- Optimized for severe fading $\rightarrow$ 16 sec delay
- 500 b/s user rate, variable size frame
- rate $\frac{1}{2}$ FEC, Viterbi decoding $\rightarrow$ 1 kbaud
- DBPSK, $\alpha = 1.0$ $\rightarrow$ BW = 2 kHz
- $E_b/N_0 \geq 6.7$ dB on AWGN channel
BPSK1000 Spectrum with CW Beacon

1 kbaud BPSK with raised cosine spectrum, 100% excess bandwidth
(Nyquist BW = 1 kHz, we use 2 kHz)
BPSK spectral nulls @ 500 & 2500 Hz
ARISSat Requirements

No special receiving equipment
  • Just a generic SSB receiver & computer
• Efficient use of spacecraft power
• Tolerate deep, slow fading
• Easy manual Doppler tuning
  • Do not assume satellite experience
  • Automatic tracking nice but not required
• Simple generation by IHU and SDX
BPSK1000 Summary

- HDLC framing with 32-bit CRC
- R=1/2, k=7 convolutional FEC with Viterbi decoding
- 128-way convolutional interleaving with bit-reversed delay line ordering
- Differentially coherent binary phase shift keying
  - Noncoherent detection (implementation choice)
BPSK1000 Encoding

Data frames in

HDLC encoder

FEC encode, r=1/2 k=7

128:1 Convolutional interleaver

Differential encode

BPSK modulator

CRC-32

Ye olde Voyager code

Bit-reversed delay ordering

1 → no change
0 → 180° change
HDLC Frame Format
HDLC with CRC-32

- HDLC with 16-bit CRC part of AX.25 Layer 2
  - Basis of amateur packet radio since 1982
  - Variable length frames
- CRC-32 essentially eliminates spurious frames
  - allows Viterbi decoding without Reed-Solomon
Convolutional FEC

- Rate $\frac{1}{2}$, $k=7$ with Viterbi decoding
  - Same as in AO-40 FEC
- Like all convolutional codes, requires interleaving to tolerate burst errors
- Very fast vectorized software decoders
  - 20-40 Mb/s on reasonably modern PCs
Convolutional encoder
Convolutional Interleaving

- Not to be confused with convolutional coding
  - Vs block interleaving on AO-40FEC
- Operates on a continuous bit stream
  - De-interleaver priming required
- Half the delay and memory for given depth
  - Usual rule: maximum fade < 10% of depth
- BPSK1000 uses 128:1; \(128^2=16,384\)
  - Delay of 16.384 sec at 1 kbaud
Convolutional Interleaver

Sample 4:1 interleaver
Delays: 0, 1, 2, 3
Convolutional De-interleaver

Delays: 3, 2, 1, 0
Bit-reversed ordering

- The delay elements can be in any order
  - As long as sum of delays constant for each row
- Bit-reversed ordering seems to improve distance properties
  - 000 001 010 011 100 101 110 111 → 000 100 010 110 001 110 011 111
  - i.e., 0, 1, 2, 3, 4, 5, 6, 7 → 0, 4, 2, 6, 1, 5, 3, 7
Demodulating BPSK1000

Rx audio in

Estimate carrier freq & symbol timing

Demodulate DBPSK

De-interleave

Viterbi decode

HDLC decode

Decoded frames

Brute force during acquisition, then track

128 copies during acquisition, 1 for each interleaver phase
Demodulating DBPSK

- No carrier phase tracking needed!
  - Impossible on fading channels
- Still need:
  - symbol timing
  - approx carrier frequency
Dot Product Detection

Detected symbol = $S_n \cdot S_{n-1}$

Dot product $\therefore |S_n| |S_{n-1}| \cos \theta$

$|I_n^* I_n + Q_{n-1} Q_n$  

Symbol '1' $\rightarrow$ no change $\rightarrow$ + dot product
Symbol '0' $\rightarrow$ 180° change $\rightarrow$ - dot product

No phase locking, so phase is arbitrary
Frequency error appears as slow rotation
Frequency errors in DBPSK

- Frequency errors cause slow rotation of signal phasor.
- Effective signal loss in dB = $20 \log_{10} \cos(2\pi E/R)$
  - $E =$ frequency error, $R =$ baud rate
  - e.g., 50 Hz error @ 1 kbaud $\rightarrow$ 0.44 dB loss
  - 100 Hz error @ 1 kbaud $\rightarrow$ 1.84 dB loss
## Nonfading channel performance

<table>
<thead>
<tr>
<th>Differential encoding</th>
<th>Demod</th>
<th>FEC</th>
<th>Eb/No $10^{-5}$ BER</th>
<th>Fade tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>non-coherent</td>
<td>None</td>
<td>10.3</td>
<td>Good</td>
</tr>
<tr>
<td>No</td>
<td>coherent</td>
<td>None</td>
<td>9.6</td>
<td>Bad</td>
</tr>
<tr>
<td>Yes</td>
<td>non-coherent</td>
<td>$r=1/2, k=7$</td>
<td>6.7</td>
<td>Good</td>
</tr>
<tr>
<td>Yes</td>
<td>coherent</td>
<td>$r=1/2, k=7$</td>
<td>5.9</td>
<td>Bad</td>
</tr>
<tr>
<td>No</td>
<td>coherent</td>
<td>$r=1/2, k=7$</td>
<td>4.4</td>
<td>Bad</td>
</tr>
<tr>
<td>No</td>
<td>coherent</td>
<td>$R=1/2 k=7, (255,223)RS$</td>
<td>2.5</td>
<td>Bad</td>
</tr>
<tr>
<td>No</td>
<td>coherent</td>
<td>$R=1/6$ turbo, 8920 bit blk</td>
<td>-0.1</td>
<td>Bad</td>
</tr>
</tbody>
</table>
ARISSat-1 vs AO-40

- Faster Doppler
- Stronger average signal
- Random fading
- Variable data frames
- IHU/SDX software

- Slow Doppler
- Weaker signal
- Periodic spin fading
- Fixed frame size
- Hardware restrictions: 400 baud, BPSK, Biphase
## AO40/ARISSat comparison

<table>
<thead>
<tr>
<th></th>
<th>AO40FEC</th>
<th>ARISSat</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Baud rate</strong></td>
<td>400</td>
<td>1000</td>
</tr>
<tr>
<td><strong>Data rate</strong></td>
<td>160</td>
<td>500</td>
</tr>
<tr>
<td><strong>Error control</strong></td>
<td>r=1/2, k=7 convolutional (160,128) Reed-Solomon Overall rate = 0.4</td>
<td>r=1/2, k=7 convolutional CRC-32 Overall rate =~ 0.5</td>
</tr>
<tr>
<td><strong>Baseband</strong></td>
<td>Biphase</td>
<td>NRZI</td>
</tr>
<tr>
<td><strong>Interleaving</strong></td>
<td>Block, 5200 symbols</td>
<td>128:1 convolutional</td>
</tr>
<tr>
<td><strong>Interleaver depth</strong></td>
<td>13 sec</td>
<td>16.384 sec</td>
</tr>
<tr>
<td><strong>Sync vector</strong></td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td><strong>Block size</strong></td>
<td>256 bytes</td>
<td>variable</td>
</tr>
<tr>
<td><strong>Differential coding</strong></td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Modulation</strong></td>
<td>BPSK</td>
<td>BPSK</td>
</tr>
<tr>
<td><strong>Scrambling</strong></td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>
Future Formats

• AMSAT needs a *family* of modulation & coding schemes
  • HEO, LEO, telem, comms, freq, BW, speed...
  • There's no one-size-fits-all!

• Broadcast vs Interactive
  • Broadcast – long interleavers
  • Interactive – short interleavers, hybrid ARQ

• Uplink is a different, unaddressed problem
  • multiple access
  • greater power