Fox-1 Low Speed Telemetry

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Requirements

- Analog satellite, digital telemetry
  - This will get a *lot* easier if we finally go all digital...
- One nonlinear RF power amplifier
  - And it's (almost) always carrying FM audio
- Telemetry must co-exist with repeated voice
  - No interruptions of repeated voice
  - No reliable uplink squelch/switching

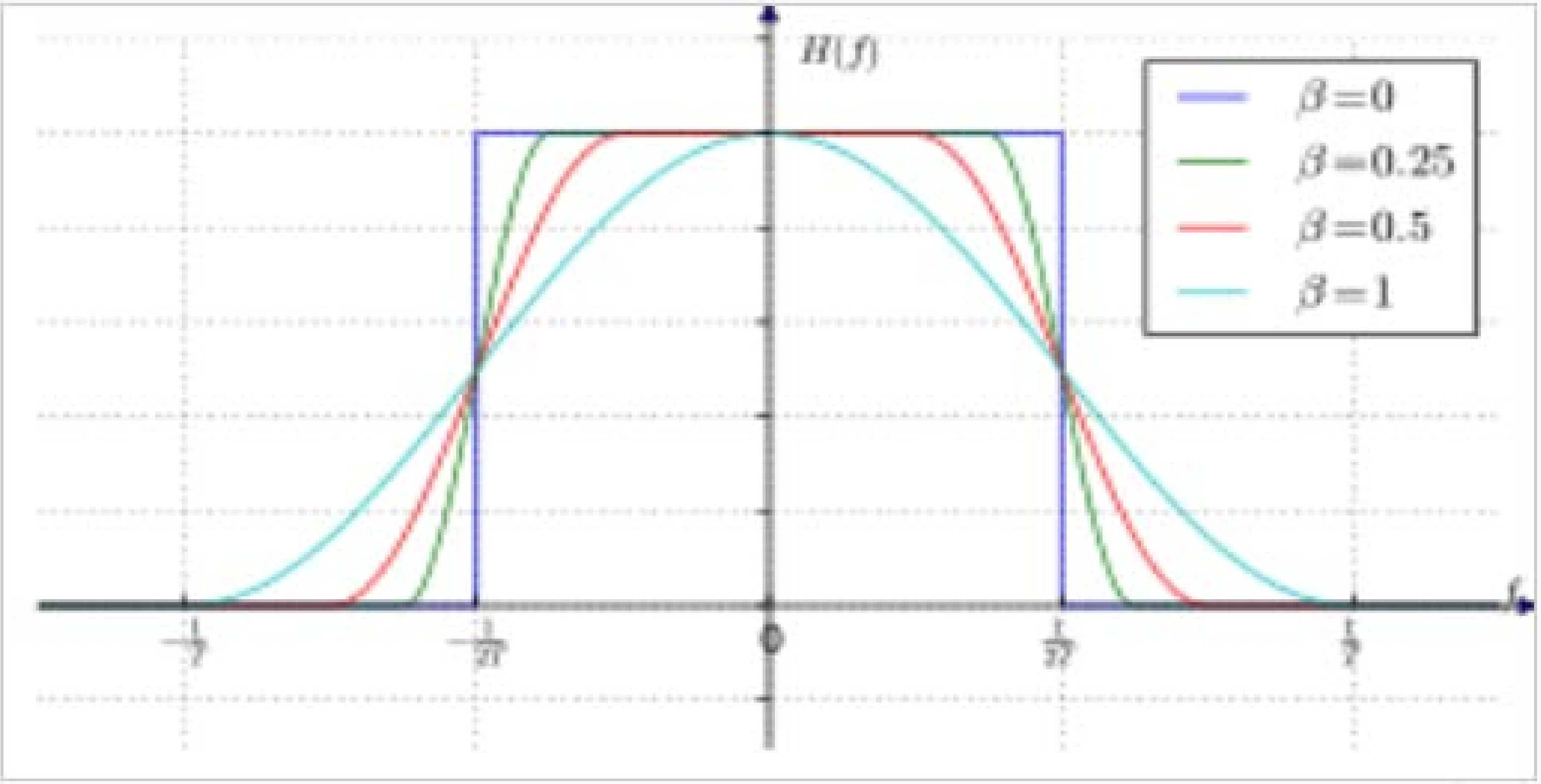
Modulation

- Channel is noncoherent analog FM
  - Rules out efficient digital modulation on a separate carrier, e.g., PSK/DPSK as on AO-40 a
  - Data must be combined with voice
  - No voice, then no data (except for brief fades corrected by coding)
- Two options:
  - Data under voice
  - Data over voice (i.e., on subcarrier)
    - Greater bandwidth available, but:
    - Noise increases with baseband frequency
    - Don't want to increase RF channel bandwidth

Data Under Voice

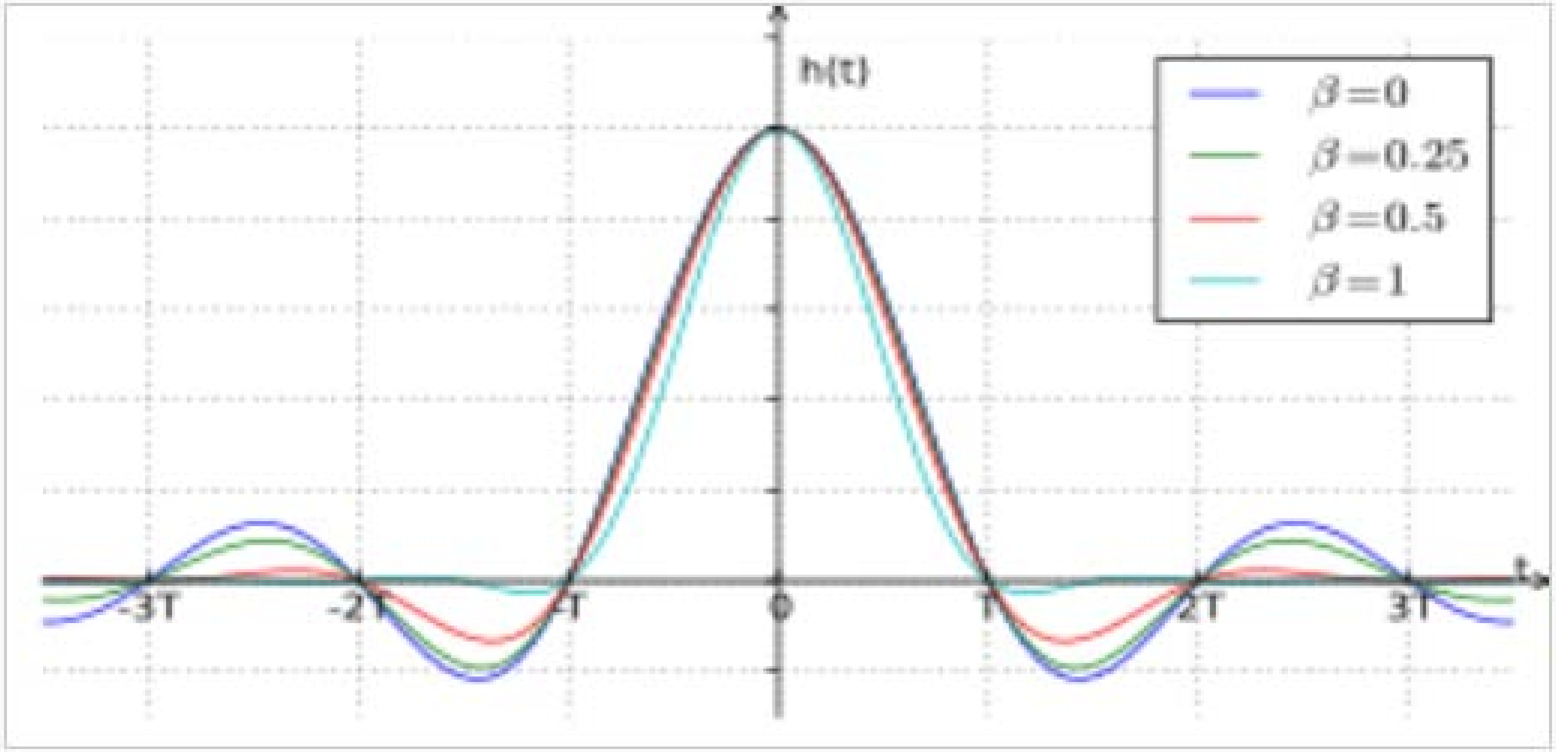
- Comm-quality voice ~300 to ~3000 Hz
- <300 Hz widely used by CTCSS (PL)
    - Tones from 67-257 Hz
    - Highest tone in California repeater directory: 203 Hz
    - Most below 150 Hz
- Select 200 Hz as upper limit for telemetry
  - Nyquist: 400 baud max (0% excess bandwidth)
    - Sharp filter and linear channel required
    - Substantial increase in peak/average ratio due to overshoot
  - 200 baud (100% excess bandwidth)
    - NRZ has first null at baud rate
    - Simple raised-cosine filter removes lobes > 200 Hz
    - Peak/average ratio ~1

Raised-Cosine in frequency



Frequency response of raised-cosine filter with various roll-off factors

Raised-Cosine in time



Impulse response of raised-cosine filter with various roll-off factors

What About The Low End?

- Random NRZ data has maximum spectral density at DC
- This is undesirable
  - Doppler appears as very low frequency FM
  - Tracked out by tuning (automatic or manual)
  - Baseline wander if channel does not pass DC
    - Increases error rate

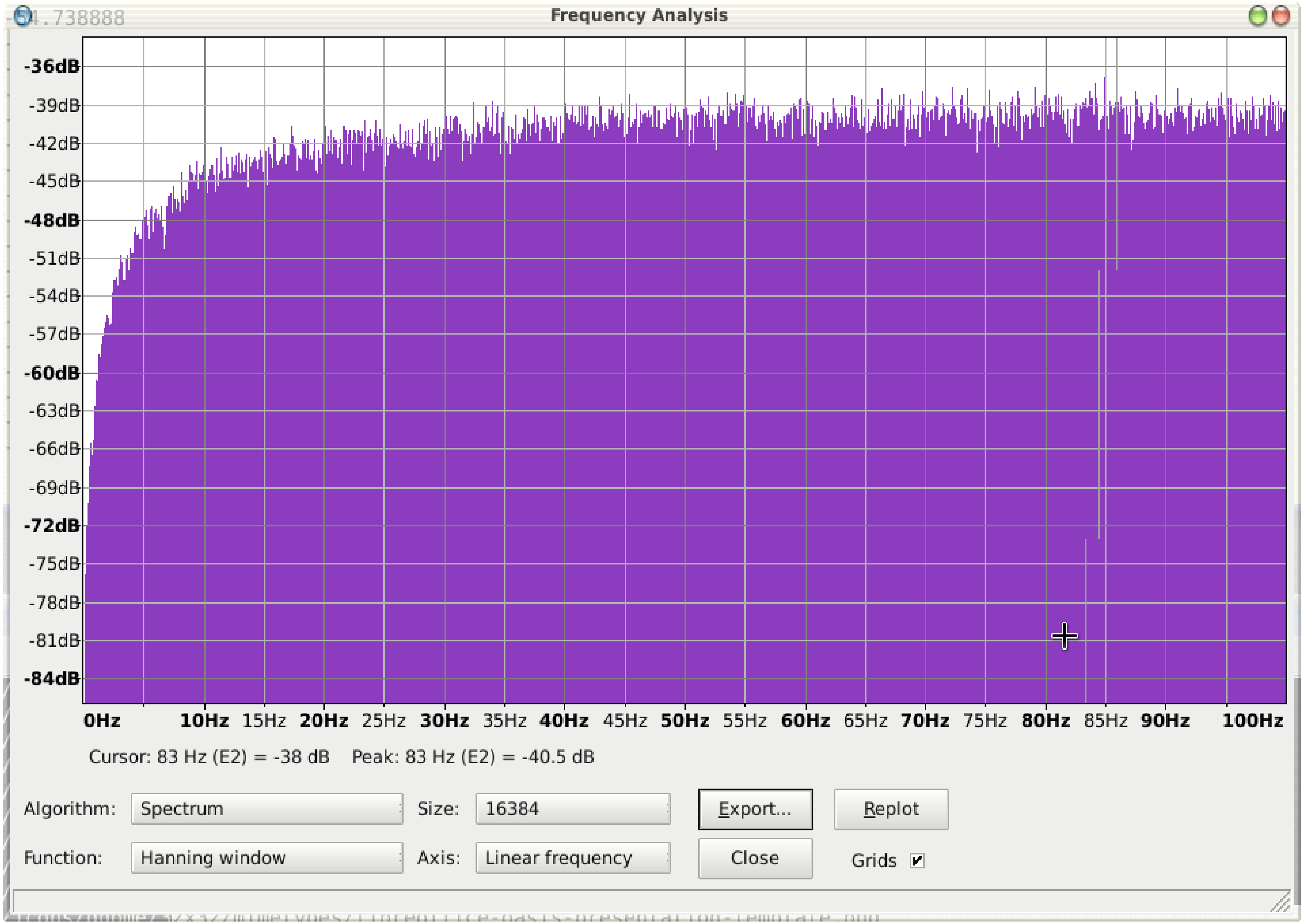
What about scrambling?

- Common in 9600 bps FSK (G3RUH, K9NG)
- “Randomizes” data
- Breaks up spectral lines
  - Including DC due to 0/1 imbalance
- Maintains transitions for clock recovery
- Does *not* change spectral shape
  - NRZ still has spectral maximum at DC!

Line Coding

- Manchester (biphase)
  - 0 → 01; 1 → 10
  - Simple, formerly popular (Phase III 400 bps)
  - 100% bandwidth overhead!
- AA2TX suggestion: use 8b10b
  - Very popular
    - DAT, DCC, DVI, HDMI, SATA, Firewire 800, PCI-e < 3.0, USB 3.0, many others
  - 25% overhead

8b10b Spectrum, 200 b/s



8b10b Line Code

5b/6b code

Input		RD = −1	RD = +1	Input		RD = −1	RD = +1
	EDCBA	abcdei			EDCBA	abcdei	
D.00	00000	100111	011000	D.16	10000	011011	100100
D.01	00001	011101	100010	D.17	10001	100011	
D.02	00010	101101	010010	D.18	10010	010011	
D.03	00011	110001		D.19	10011	110010	
D.04	00100	110101	001010	D.20	10100	001011	
D.05	00101	101001		D.21	10101	101010	
D.06	00110	011001		D.22	10110	011010	
D.07	00111	111000	000111	D.23 †	10111	111010	000101
D.08	01000	111001	000110	D.24	11000	110011	001100
D.09	01001	100101		D.25	11001	100110	
D.10	01010	010101		D.26	11010	010110	
D.11	01011	110100		D.27 †	11011	110110	001001
D.12	01100	001101		D.28	11100	001110	
D.13	01101	101100		D.29 †	11101	101110	010001
D.14	01110	011100		D.30 †	11110	011110	100001
D.15	01111	010111	101000	D.31	11111	101011	010100
				K.28	11100	001111	110000

3b/4b code

Input		RD = −1	RD = +1	Input		RD = −1	RD = +1
	HGF	fghj			HGF	fghj	
D.x.0	000	1011	0100	K.x.0	000	1011	0100
D.x.1	001	1001		K.x.1 ‡	001	0110	1001
D.x.2	010	0101		K.x.2 ‡	010	1010	0101
D.x.3	011	1100	0011	K.x.3 ‡	011	1100	0011
D.x.4	100	1101	0010	K.x.4	100	1101	0010
D.x.5	101	1010		K.x.5 ‡	101	0101	1010
D.x.6	110	0110		K.x.6 ‡	110	1001	0110
D.x.P7 †	111	1110	0001				
D.x.A7 †	111	0111	1000	K.x.7 †	111	0111	1000

8b10b Properties

- Maps 8 data bits to 10 channel bits
- Actually 5b6b + 3b4b
- Long-term 0/1 balance (no DC)
  - Run disparity (RD) never more than +/-2 over >= 20 bits
- Never more than five 1's or 0's in a row
  - Maintain transitions for clock recovery
- Error propagation: 1 channel bit error → 5 data bit errors max
- Extra control words
  - No bit stuffing or escaping needed for data transparency
  - Unique comma sequences useful for sync
    - 0011111, 1100000 never found in any possible data sequence

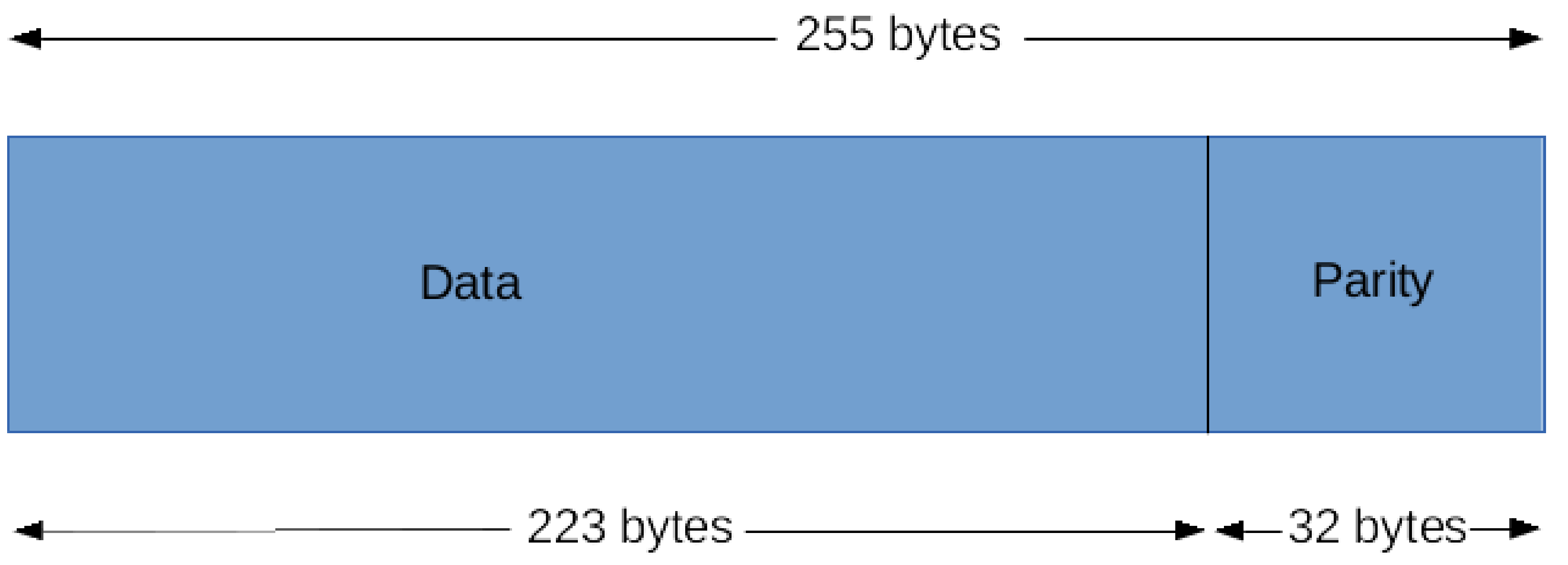
FEC: high vs low altitude

- High altitude satellites:
  - High path loss, weak-signal
  - Slow moving
    - Little or no fading (except spin modulation)
- Low altitude satellites:
  - Low path loss, strong signals (on average)
  - Fast moving
    - Frequent, deep fades from view aspect changes
  - Short passes

FEC choices

- Viterbi Convolutional
  - Better Eb/N0 performance
    - especially with soft decisions
  - Worse fade tolerance (without interleaving)
- Reed-Solomon
  - Good fade/burst error tolerance
  - Worse single-bit error tolerance
  - Well suited to non-binary channels
- Concatenated (RS + Viterbi)
  - E.g., Voyager, ACE, AO-40
  - Space coding of choice until Turbo coding

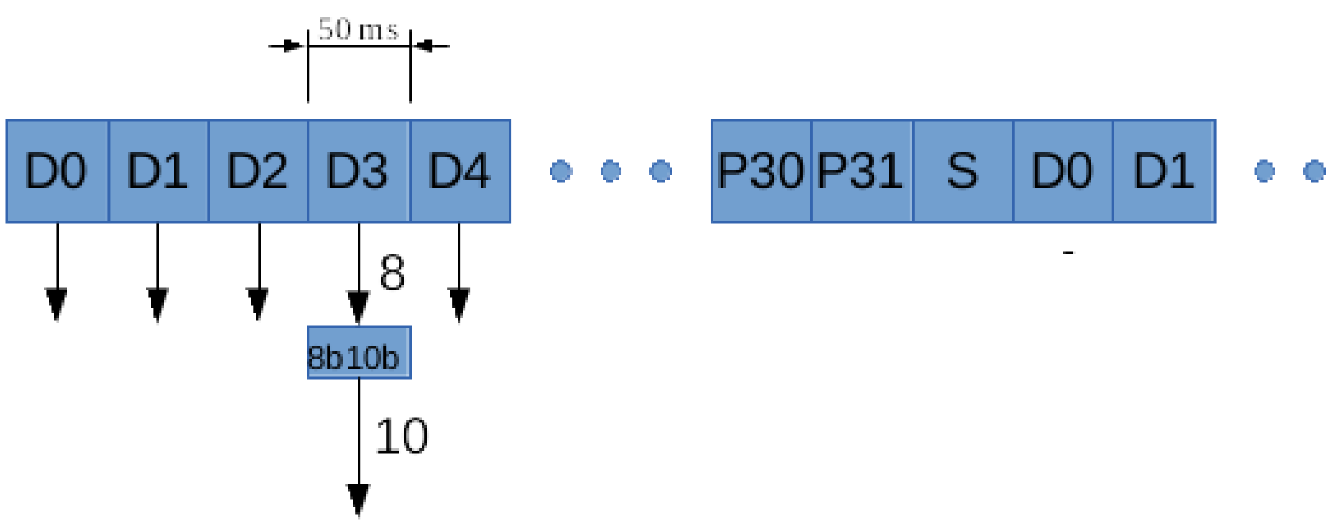
(255,223) CCSDS RS Code



Fox-1 Telemetry Elements

- (255,223) CCSDS-standard Reed-Solomon block code
  - 8-bit symbols – nice match to 8b10b
  - 32 parity symbols/block
  - Error tolerance:
    - All locations unknown: ½ of parity (i.e., 16 symbols)
    - All locations known: as many erasures as parity (i.e., 32 symbols)
    - 8b10b decoder will help by providing some erasures
- Can be shortened to desired data size
  - Beginning of data field padded with 0's, not transmitted
  - All parity bytes must still be sent; otherwise, use a different code
    - e.g., CCSDS-standard (255,239) with 16 parities
- 8b10b encode
  - Each RS symbol becomes a 10-bit channel word
- Append 10-bit control word for synchronization
  - Control word distinct from all data; no need for bit stuffing
  - Could allow variable-sized frames with extra decoder complexity

Fox-1 TLM Frame Format



Timing – 64 byte frames

- 64 data bytes/frame:
  - 512 data bits + 256 parity bits = 768 RS bits
  - / 8b10b = 960 bits
  - +10 bits sync
  - = 970 channel bits / 200 bps
  - = 4.85 sec/frame
  - Net data rate = 512/4.85 = 105.6 b/s

Timing – 128 byte frames

- 128 data bytes/frame:
  - 1024 data bits + 256 parity bits = 1280 RS bits
  - / 8b10b = 1600 bits
  - +10 bits sync
  - = 1610 channel bits / 200 bps
  - = 8.05 sec/frame
  - Net data rate = 1024/8.05 = 127.2 b/s

Timing – 223 byte frames

- 223 data bytes/frame:
  - 1784 data bits + 256 parity bits = 2040 RS bits
  - / 8b10b = 2550 bits
  - +10 bits sync
  - = 2560 channel bits / 200 bps
  - = 12.8 sec/frame
  - Net data rate = 1784/12.8 = 139.4 b/s

Decoding

- Bit sync, 8b10b word sync, frame sync
- Decode 8b10b with maximum likelihood detector
  - Validity of 10 bit word depends on RD state from previous word
  - Try both RD values for several words, pick the best, decode the oldest, and repeat for nex
- Invalid 8b10b words become RS symbol erasures
  - Two erasures good for correction of one additional undetected error