Enhanced Decoding for the Galileo Low-Gain Antenna Mission

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Due to a malfunctioning high-gain antenna, the Galileo spacecraft is transmitting all its data through a low-gain antenna, and the data rate will seldom exceed 100 bits per second during its two-year tour of Jupiter's satellites. To offset some of the performance loss, the spacecraft's computer will be extensively reprogrammed to include new data compression and coding algorithms [1],

The baseline coding system for the low gain antenna mission uses a Reed-Solomon (RS) outer code of block length 255 concatenated with a (14, 1/4) convolutional inner code, and interleaves the RS symbols to depth eight, The convolutionally encoded symbols are decoded by a maximum likelihood (Viterbi) decoder, and each RS codeword is decoded algebraically. Two types of decoding enhancements were proposed as feasible due to the low data rate. Both of these enhancements involve "redecoding" some of the data [2, 3]. The first type of redecoding is confined to the RS decoder and utilizes information from neighboring codewords within the same interleaved block to erase unreliable symbols in undecoded words. The second type involves redecoding by the Viterbi decoder, using information fed back from codewords successfully decoded by the RS decoder.

Reed-Solomon redecoding using erasure declarations is possible when at least one but fewer than eight of the codewords within a block of eight interleaved words is decodable (correctable). The RS decoder can then extrapolate the locations of corrected errors in the decodable word(s) to neighboring locations in adjacent undecodable word(s), and declare the corresponding symbols to be erased. If the erased symbols are likely to be erroneous, then the undecoded words might be decoded by a second try at RS decoding that utilizes the erasure information,

Viterbi redecoding starts with an extra pass through a maximum likelihood decoder now constrained to follow only paths consistent with known symbols from previously decodable RS codewords, The Viterbi redecoder is much less likely to choose a long erroneous path because any path under consideration is pinned to coincide with the correct path at the location(s) of the known symbols. The output of the Viterbi redecoder is fed to the RS decoder and, if necessary, the whole process may be repeated,

With both types of redecoding, it usually pays to put different amounts of redundancy in neighboring RS codewords, Words with high redundancy can be counted onto decode during an initial decoding try, and the information from these decoded words can be used to assist the decoding of codewords with lower redundancy later.

The objectives of the analysis were to quantify the amount of coding gain achievable relative to the baseline system for both types of redecoding, allowing up to four stages of Viterbi decoding, and to specify redundancy profiles for implementation on the spacecraft that would achieve these gains. The requirement on final decoded bit error rate was 1 x 10-7, and the predicted coding gain should be accurate within a few hundredths of a dB. These stringent requirements led to the development of two novel analytical tools.

Verification of 10-7 bit error rate by direct simulation for codewords interleaved to depth eight was infeasible even without redecoding. The small loss relative to infinite interleaving (about 0.07 dB) was still several times the desired overall accuracy. However, each performance curve for depth-8 interleaving becomes nearly parallel to a member of a family of curves for infinite interleaving but varying RS codeword redundancies; 10-7 performance for depth-8 interleaving may be inferred by extrapolating along an "equivalent" infinite interleaving curve, The ratio of the actual depth-8 error correction capability to the equivalent infinite interleaving error correction capability is called the depth-8 error magnification factor. The error magnification factor is a way of measuring the propensity for one long Viterbi decoder error burst to contribute more than one symbol error to a given RS codeword whenever the codewords are only finitely interleaved. The error magnification factors vary smoothly and slowly as a function of decoded error rate, and serve as the bases for very accurate extrapolations of decoder performance.

Analysis of the first decoding stage was based on 2 gigabits of simulated decoded data at signal-to-noise ratios spaced 0.10 dB apart. These long decoding runs were obtained from the hardware Big Viterbi Decoder (BVD) [4]. For the second, third, and fourth decoding stages, the Viterbi redecoder had to be simulated in software and much smaller decoded data sets were available. The smaller data sets were sufficient for accurately estimating performance with infinite interleaving, but estimates of depth-8 interleaving performance had to be made by substituting BVD data at an equivalent average error rate for 8-bit RS symbols. These performance estimates are slightly conservative because the error bursts from a decoder presented with known symbols are shorter and thus more benign than those for a decoder operating at the same average symbol error rate without any known symbols,

Several conclusions were drawn from the analysis and delivered to the Galileo mission planners, These comparisons are valid for the Galileo system using a (14, 1/4) convolutional code and depth-8 interleaving of RS symbols, and achieving a final decoded bit error rate of 1 x 10-7, A second stage of Viterbi decoding without any RS erasure declarations is worth about 0.37 dB relative to the baseline system. Adding two more stages of Viterbi decoding is worth an additional 0.19 dB for a total gain of 0.56 dB. The marginal improvement from utilizing erasure declarations was shown to be around 0.19 dB for one-stage decoding (no Viterbi redecoding), but only 0.02 dB for two-stage decoding and essentially nil (0,00 dB) for four-stage decoding. Reed-Solomon codeword redundancy profiles that achieve these gains are (64, 20, 20, 20, 64, 20, 20, 20) for two-stage decoding and (94, 10, 30, 10, 60, 10, 30, 10) for four-stage decoding. The latter is being implemented for Galileo.

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