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Error-Control Coding in Satellite Communication

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Abstract: This paper provides survey of the progress made in applying error control coding techniques used in deep space and satellite communication over the last five decades and see the great advances that have occurred in designing practical systems that narrow the gap between real system performance and channel capacity.

Keywords: Error-Control, Coding techniques, Satellite Communications

Introduction

The error control coding applications are in six areas:
1- Space and Satellite Communications
2- Data Transmission
3- Data Storage
4- Digital Audio/Video Transmission
5- Mobile Communications
6- File Transfer

Included among the applications are the Consultative Committee on Space Data Systems (CCSDS) standard coding scheme for space and satellite communications, trellis coding standards for high-speed data modems, the Reed-Solomon coding scheme used in compact discs, coding standard for mobile cellular communication, and the CRC codes used in HDLC protocols.

Applications to Space and Satellite Communications: Most of the early work in coding theory was directed at the low spectral efficiency, or power-limited, portion of the capacity curve. This was principally due to two factors. First, many early applications of coding were developed for the National Aeronautics and space administration (NASA) and the European Space Agency (ESA) deep space and satellite communication systems, where power was very expensive and bandwidth was plentiful. Second, no practical coding schemes existed that could provide meaningful power gain at higher spectral efficiencies. Thus we start with a survey of applications of error-control coding to space and satellite communication systems.

Deep-Space Channel and Power of Coding: The deep-apace channel turned out to be the perfect link on which to first demonstrate the power of coding. There were several reasons for this, most notably those listed below.

The deep-space channel is almost exactly modeled as the memoryless AWGN channel that formed the basis for Shannon's noisy channel coding theorem. Thus all the theoretical and simulation studies conducted for this channel carried over almost exactly into practice.

Plenty of bandwidth is available on the deep-space channel, thus allowing the use of the low-spectral-efficiency codes and binary-modulation schemes that were most studied and best understood at the time.

Because of the large transmission distances involved, which caused severe signal attenuation, powerful, low-rate codes, with complex decoding methods, were required, resulting in very low data rates. However, since a deep-space mission is by nature, a very time-consuming process, the low data rates realized in practice did not present a problem.

A deep-space mission is also by nature, a very expensive undertaking, and thus the additional cost of developing and implementing complex encoding and decoding solutions can be tolerated, especially since each decibel of coding gain realized resulted in an overall savings of about $1,000,000 (in the 1960's) in transmitting and receiving equipment.

Thus it is no surprise that Massey, in a recent paper (Massey), called deep-space communication and coding a "marriage made in heaven."

BPSK Coding for Deep-Space Channel: As a starting point to understand the gains afforded by coding on the deep-space channel, we consider an uncoded BPSK system with coherent detection. Throughout this discussion we assume BPSK modulation, which transmits uncoded information at a rate of 1,0 information bit per signal. If coding is used, the code rate r, in information bit per BPSK signal, then represents the spectral efficiency of the coded system.

Simulation results and analytical calculations have shown that uncoded BPSK achieves a BER of 10^{-5}, considered "reliable" in many applications at an **Eb/No** = 9.6 dB. This point is plotted in Fig. 1 with the label BPSK. All the points in Fig 1 are plotted for a BER of 10^{-5}. Actual BER requirements vary from system to system in deep-space applications depending on several factors, such as the nature and sensitivity of the data and whether it has been compressed on the spacecraft prior to transmission.

From the capacity curve in Fig. 1 it can be seen that the minimum E_b/N_0 required to achieve error-free communication at a code rate r =1/2 bit per signal is 0.0 dB, and thus a power savings of 9.6 dB is theoretically possible with an appropriate rate r=1/2 coding scheme. Looking at the BPSK capacity curve, however, reveals that to achieve a rate r = 1/2 with BPSK modulation requires only a slightly larger E_b/N_0 = 0.2 dB. Thus for code rates r = 1/2 or less, very little in potential coding gain is sacrificed by using BPSK modulation. This, combined with the difficulty in coherently detecting signal sets with more than two points and the relative abundance of bandwidth on the deep-space channel, resulted in the choice of BPSK modulation with code rates r = 1 /2 bit/signal or below for deep-space communication.

One of the earliest attempts to improve on the performance of uncoded BPSK was the use of a rate r = 6/32 biorthogonal, Reed-Muller block code, also referred to as the (32, 6) RM code. This code was used on the 1969 Mariner and later Viking Mars missions in conjunction with BPSK modulation and soft-decision maximum-likelihood decoding. The code consisted of 64 codewords, each 32 bits long, with a minimum Hamming distance between codewords of $d_{min} = 16$. The 64 codewords can be viewed as a set of 32 orthogonal vectors in 32-dimensional space, plus the complements of these 32 vectors, and thus the name "biorthogonal." Full soft-decision maximum-likelihood decoding (decoding using unquantized demodulator output) was achieved by using a correlation decoder, based on the Hadamard Transform, developed by Green at the Jet Propulsion Laboratory (JPL) that subsequently became known as the "Green Machine" (Green, 1966). The Mariner system had code rate r = 6/32 =0.1875 bit/signal and it achieved a BPSK of 10^{-5} with an E_b/N_0 = 6.4 dB.

This point is plotted in Fig. 1 with the label "Mariner." From Fig.1, it is seen that the Mariner code requires 3.2 dB less power than uncoded BPSK for the same BER, but it requires more than five times the bandwidth and is still 7.5 dB away from the BPSK capacity curve at the same spectral efficiency. It is important to note that even with its significant bandwidth expansion, the coding gain actually achieved by the Mariner code was rather modest. This is due to the fact that this code, as is typical of block codes in general, has a relatively large number of nearest neighbor codewords, thus substantially reducing the available coding gain at moderate BER' s. (At lower BER' s. a coding gain of up to 4.8 dB is achievable, but this is reduced to 3.2 dB at a BER of 10^{-5} by the code's 62 nearest neighbors.) In fact, most of the coding gain achieved by the Mariner code was due to the extra 2-3 dB obtained by using full soft-decision decoding, a lesson that has carried over to almost all practical coding implementations where coding gain is a primary consideration.

A significant advance in the application of coding to deep-space communication systems occurred later in the 1960's with the invention of sequential decoding (Mozencraft and Reiffen, 1961) for convolutional codes and its subsequent refinement (Fano, 1963). It was now possible to use powerful long-constraint-length convolutional codes with soft-decision decoding. Thus for the first time, practical communication systems were capable of achieving substantial coding gains over uncoded transmission.

Sequential Decoding: Sequential decoding was first used in 1968 on an "experimental" basis. (This was actually a deliberate stratagem to circumvent lengthy NASA qualification procedures (Massey). The pioneer 9 solar orbit space mission used a modified version of a rate r = ½ systematic convolutional code originally constructed by Lin and Lyne , but the coding scheme was changed for subsequent missions. (A Convolutional code is said to be in systematic form if the information sequence appears unchanged as one of the encoded sequences.) It is interesting to note that, even though the Mariner coding system was designed first, the Pioneer 9 was actually launched earlier, and thus the Lin-Lyne code was the first to fly in space. The Pioneer 10 Jupiter fly-by mission and the Pioneer 11 Saturn fly-by mission in 1972 and 1973, respectively, both used a rate r = ½, constraint length K = 32, i.e., a (2,1,32) nonsystematic, Quick-Look-In (QLI) Convolutional code constructed by Massey and Costello (Lin and Iyne, 1967). The two32-bit code generator sequences used for this code are given in octal notation by.

$g^{(1)} = 733533676772$

$g^{(2)} = 53353367672$

The code was chosen to be nonsystematic in order to give it a larger minimum free Hamming distance d_{free}, in this case $d_{free} = 21$, compared to the best systematic code of the same constraint length. This is true for Convolutional codes in general, i.e., for a given constraint length, a measure of decoding complexity more free distance, and thus better performance, can be achieved using a nonsystematic rather than a systematic code. The fact that the two generators differ in only one bit position gives the code the "quick-look" property, i.e., the capability of obtaining a reasonably accurate quick estimate of the information sequence from the noisy received sequence prior to actual decoding. Thus is an important capability in some situations that is always available with systematic codes, but not, in general, with nonsystematic codes. Requiring this capability does result in some reduction in free distance, however, and thus represents a compromise between choosing the best possible code and retaining the "Quick-Look" property. Nevertheless, the above code has had a long and distinguished career in space, having been used, in addition to the above two missions, on the Pioneer12 Venus orbiter and the European Helios A and Helios B solar orbiter missions.

A sequential decoder using a modified version of the Fano tree-searching algorithm with 3-bit soft decisions (3-bit quantized demodulator outputs) was chosen for decoding. For lower speed operation, in the Kilobit-second (kbps) range, decoding could be done in software. Faster hardware decoders were also developed for operation in the megabit-per-second (Mbps) range. This scheme had code rate r = ½ = 0.5 bit/signal and achieved a BER of 10^{-5} at an E_b/N_0 = 2.7 dB (Fig 1: Pioneer), thus achieving a 6.9-dB coding gain compared to uncoded BPSK, at the expense of a doubling in bandwidth requirements. This represented a significant improvement compared to the Mariner system and resulted in performance only 2.5 dB away from the BPSK capacity went into the design of these early deep-space coding systems is included in the paper by Massey .

Sequential decoding algorithms have a variable computation characteristic that results in large buffering requirements, and occasionally large decoding delays and/or incomplete decoding of the received sequence. In some situations, such as when almost error-free communication is required or when retransmission is possible, this variable decoding delay property of sequential decoding can be an advantage. For example, when a long delay occurs in decoding, indicating a very noisy and therefore probably unreliable frame of data, the decoder can simply stop and erase the frame, not delivering anything to the user, or ask for a retransmission. A so-called "complete" decoder, on the other hand, would be forced to deliver a decoded estimate, which may very well be wrong in these cases, resulting in what has been termed a "fools-rush in where angels fear to tread" phenomenon (Lin and Iyne, 1967). However, fixed delay is desirable in many situations, particularly when high-speed decoding is required. In addition, the performance of Convolutional codes with sequential decoding is ultimately limited by the computational cutoff rate **Ro** (the rate at which the average number of computations performed by a sequential decoder becomes unbounded), which requires

SNR' s higher than capacity to achieve reliable communication at a given code rate as shown in Fig 1. For example, to achieve reliable communication at a code rate of r = 0.5 bit/signal using sequential decoding and BPSK modulation on the AWGN channel requires an E_b/N_o = 2.4 dB, whereas the capacity bound only requires an E_b/N_o = 0.2 dB. The E_b/N_o at which the pioneer code achieves a BER of 10^{-5} is only 0.3 dB away from the cutoff rate, and thus there is little to be gained with longer constraint length codes and sequential decoding at this code rate and BER.

Viterbi Decoding for Deep-Space Communication: These undesirable characteristics of decoding and the possibility of higher decoding speeds led to the use of maximum-likelihood Viterbi decoding in the next generation of deep-space communication systems. The Viterbi algorithm, like sequential decoding, is compatible with a variety of modulation and quantization schemes. Unlike sequential decoding, though, the Viterbi algorithm has a fixed number of computations per decoding branch and thus a fixed number of computations per decoding branch and thus does not suffer from incomplete decoding and, ultimately, is not limited by a computational cutoff rate.

The Voyager 1 and 2 space mission were launched in 1977 to explore Jupiter and Saturn. They both used a (2, 1, 7) nonsystematic Convolutional code with generator polynomials

$$\mathbf{G}^{(1)}(D) = 1 + D + D^3 + D^4 + D^6$$
$$\mathbf{G}^{(2)}(D) = 1 + D^3 + D^4 + D^5 + D^6 \qquad (1)$$

And d_{free} = 10. This code and a companion (3, 1, 7,) code with generators

$$\mathbf{G}^{(1)}(D) = 1 + D + D3 + D^4 + D^6$$
$$\mathbf{G}^{(2)}(D) = 1 + D^3 + D^4 + D^5 + D^6$$
$$\mathbf{G}^{(3)}(D) = 1 + D^2 + D^4 + D^5 + D^6 \qquad (2)$$

And d_{free} = 15, were both adopted as NASA/ESA Planetary Standard Codes by the Consultative Committee on Space Data Systems (CCSDS). The (2,1,7) code has also been employed in numerous other applications, including satellite communication and cellular telephony, and has become a de facto industry standard.

The above codes were decoded using a 3-bit soft-decision maximum-likelihood Viterbi decoder. Since the complexity of Viterbi decoding grows exponentially with code constraint length, it was necessary to chose short constraint length codes rather than the long constraint length Pioneer codes used with sequential decoding. The K = 7 codes chosen have a decoding trellis containing 64 states, considered reasonable in terms of implementation complexity. The performance of these codes is plotted in Fig. 1 with the label "Planetary Standard". The (2, 1, 7,) code requires an E_b/N_o = 4.5 dB to operate at a BER of 10^{-5}. Though this code results in a 5.1 dB power advantage compared to uncooded transmission, its performance is 1.8 dB worse than the Pioneer system, due to the short constraint length used. However, its decoder implementation complexity is simpler than a sequential decoder, it does not suffer the long buffering delays characteristic of sequential decoding, and because of its regular trellis structure, it is adaptable to parallel implementation, resulting in decoding speed in the 100's of Mbps.

CCSDS Telemetry Standard: The Planetary Standard also played a major role in military Satellite Communications well into the 1980's (as incorporated into the Satellite Data Link Standard (SDLS)). In general, Convolutional encoding with Viterbi decoding will continue to be used in earth orbiting satellite communication systems well into the next century. The Globalstar and Iridium systems use K = 9, rate ½ and K = 7, rate ¾ Convolutional codes, respectively. The rationale for the differing constraint lengths and rates lies with the nominal lengths (and consequent space loss) of the satellite-to-ground links for the two Goperates systems. Globalstar satellites operate at altitudes of approximately 1400 km, while Iridium at half that height. Coding gain beyond that provided by the planetary Standard can be achieved using code concatenation. Concatenation is a scheme first introduced by Foreney in which two codes, an "inner code and an outercode" are used in cascade. The inner code should be designed to produce a moderate BER (typically on the order of 10^{-3} to 10^{-4}) with modest complexity. The outer code can be more complex and should be designed to correct almost all the residual errors form the inner decoder, resulting in nearly error-free performance (BER's, on the order of 10^{-10}). The most common arrangement is a combination of a short constraint length inner Convolutional code with soft-decision Viterbi decoding and a powerful nonbinary Reed-Solomon (RS) outer code. This combination was eventually accepted in 1987 as the CCSDS telemetry standard.

In fact, though, several other concatenation schemes had been tried earlier. For example, on the 1971 mariner mission a (6,4) RS outer code with symbols drawn from GF (2^6) was used in conjunction with the (32,6) RM code as an inner code, and on the two 1977 Voyager missions, a (24,12) extended Golay outer code was used together with the (2,1,7) Planetary Standard code as an inner code. In both cases, the data to be transmitted consisted of mostly of uncompressed image information, along with small amounts of sensitive scientific information. The outer codes were used only to give added protection to the scientific information, so that tile overall coding rate was not reduced much below the inner-code rates. In the case of the Mariner system, each 6-bit symbol from tile outer code is encoded into one 32-bit codeword in the inner code. This "matching" between the outer code symbol size and the information block size of the inner code means that each block error from the inner decoder causes only one Symbol error for tile outer decoder, and desirable property for a concatenation scheme consisting of two block codes. Finally, although both inner decoders made use of soft-decision inputs from the channel, the outer decoders were designed to work directly with the "hard decisions" made by the inner decoders. Outer decoders which also make use of soft-decision inputs will be considered later in this section.

The CCSDS Standard concatenation scheme consists of the (2, 1, 7) Planetary Standard Inner code along with a (255, 223) RS outer code, as shown in Fig, 2. (Note that the CCSDS Standard assumes that all the data is protected by both codes, inner and outer, although it is clearly possible to protect some data using only the inner code or to send some data without any protection at all.) The RS code consists of 8-bit symbols chosen from the finite field GF(2^8) based on the primitive polynomial

$$p(x) = x^8 + x^7 + x^2 + x + 1 \qquad (3)$$

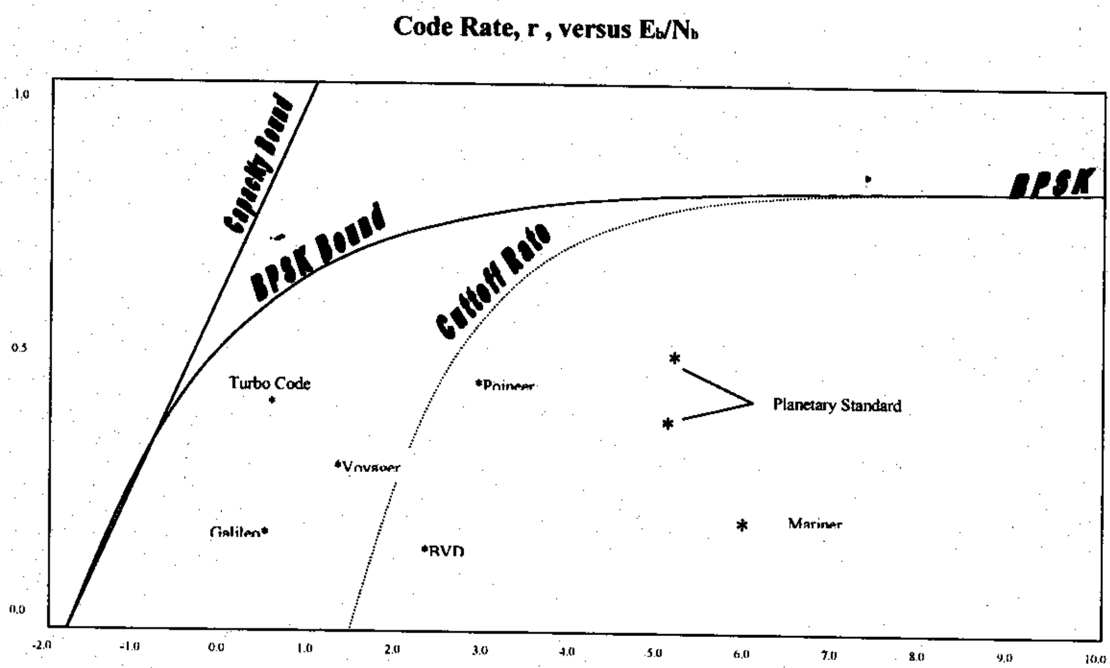


Fig 1: Capacity and Cutoff rate curves and the performance of several coding schemes for deep-space applications

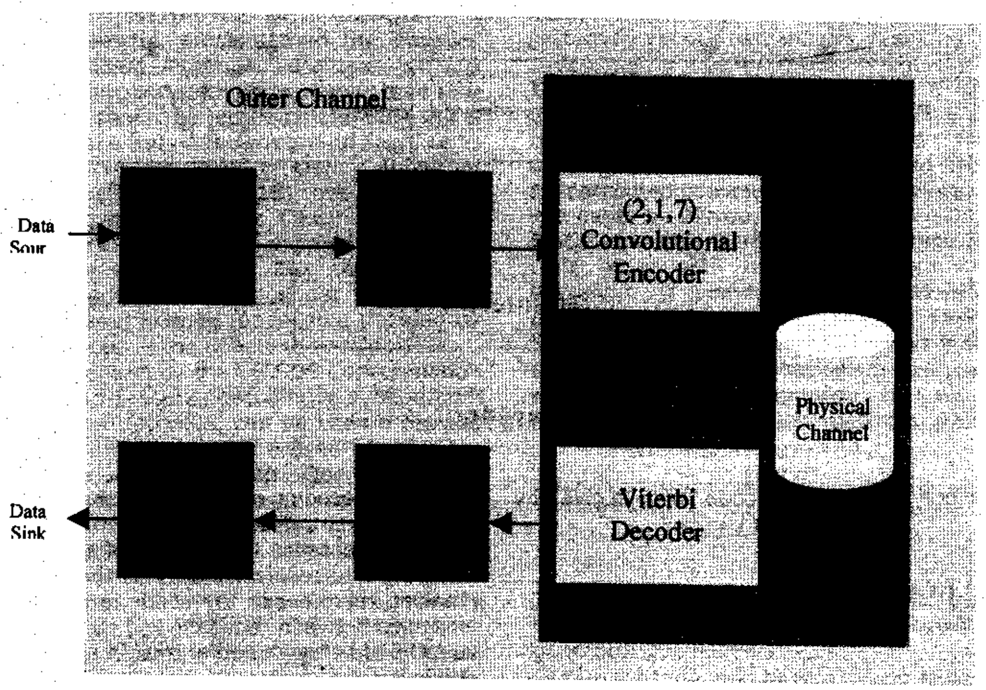
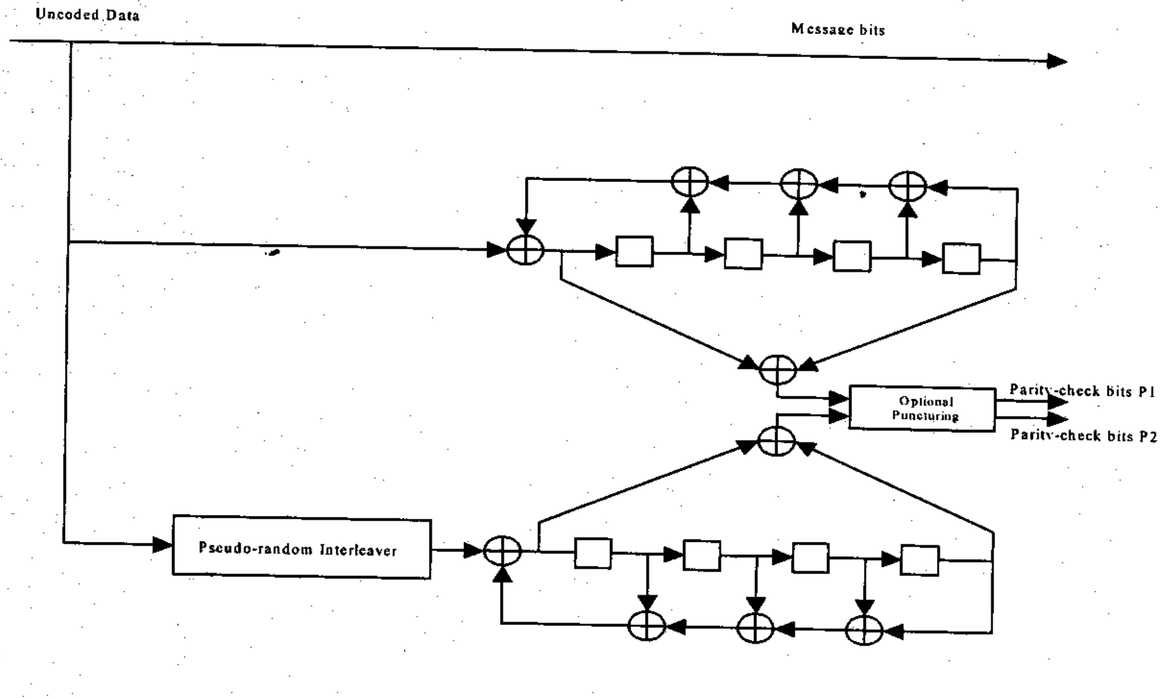
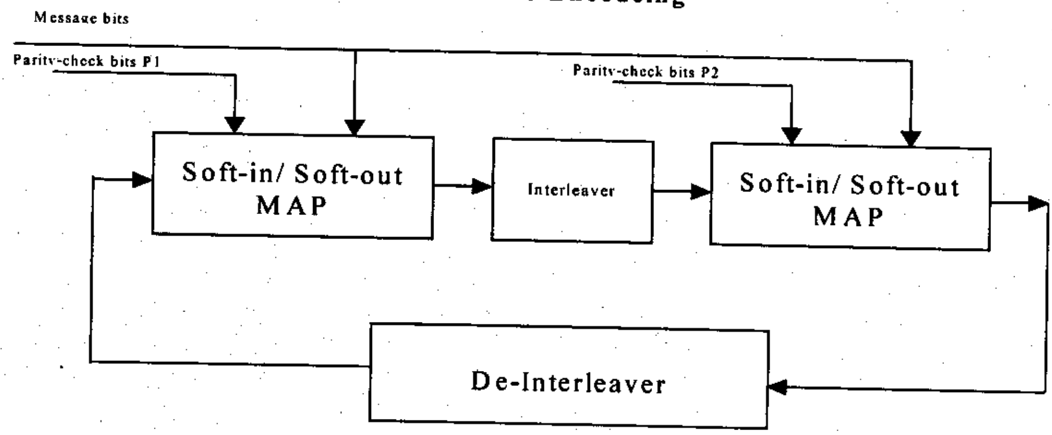


Fig 2: The CCSDS concatenation standard



Turbo Encodeing



Turbo Decoder

The generator polynomial (cyclic code form) is given by

$$g(x) = \prod_{j=112}^{143} (x - \alpha^{11j}) \qquad (4)$$

Where α is root of p(x). From (4) we see that g(x) has 32 first order roots, giving it degree 32, and thus the code contains 32 redundant symbols. Since RS codes are maximum distance separable (MDS), their minimum distance is always one more than the number of redundant symbols. Hence this code has d_{min} = 33 and can correct any combination of 16 or fewer symbol errors within a block of 255 symbols (2040 bits). Hard-decision decoding of the outer code is performed using the Berlekamp-Massey algorithm, Finally, in order to break up possibly long bursts of errors from the inner decoder into separate blocks for the outer decoder, thus making them easier to decode, a symbol interleaver is inserted between the inner and outer codes. Interleaver depths of between two and eight outer-code blocks are typical.

With the CCSDS Standard concatenation scheme, the E_b/N_0 needed to achieve a BER of 10^{-5} is reduced by a full 2.0 dB compared to using the Planetary Standard code, alone, with only a slight reduction in code rate (from r = 0.5 to r = 0.44). The performance of the (2, 1, 7) code in a concatenated system with the (255, 223) RS outer code is shown in Fig. 1 with the label "Voyager."

The concatenated Voyager system operates in the same Eb/No region as the Pioneer system, gaining about 0.2 dB with a 12.5% loss in rate. Thus short constraint length convolutional codes with Viterbi decoding in concatenated systems can be considered as alternatives to long constraint length codes with sequential decoding. Variations on the concatenated CCSDS theme continued to be used to the end of the century in near-earth applications. For example in 1998, the DirectTV Satellite system was using a concatenated convolutional-Viterbi/Reed-Solomon System to bring Television Signals to 3 Million Subscribers.

Recently, technological advances have made it practical to build maximum-likelihood Viterbi Decoders for larger constraint lengths convolutional codes. The culmination of this effort was the Big Viterbi Decoder (VBD) designed by Collins to decode a (4, 1, 15) code. The VBD was constructed at JPL for use on the Galileo Mission to Jupiter. The decoder trellis has 2^{14} = 16384 states making internal decoders formidable task. but decoding speeds up to 1 Mbps were still achieved. The code has octal generators

$G^{(1)}$ = 46321

$G^{(2)}$ = 51271

$G^{(3)}$ = 63667

$G^{(4)}$ = 70535 and

D_{free} = 35, clearly a very powerful code. It achieves BER of 10^{-5} at an **Eb/No** = 1.7 dB, only 2.6 dB away from the BPSK capacity curve (Fig 1). Compared to the (2, 1, 7) Planetary Standard Code, it gains a full 2.8 dB. In a concatenated system with the (255, 223) RS outer codes, the (4, 1, 15) requires an **Eb/No** = 0.9 dB to achieve a BER of 10^{-5} is within 2 dB of Capacity, and is 1.6 dB more powerful, efficient than the Voyager System (Fig 1, Galileo). Although the above rate 1/4 Systems are 50% less bandwidth efficient than their rate 1/2 counter parts, it should be recalled that bandwidth is plentiful in deep-space thus it is common to sacrifice to the spectral efficiencey for added efficiency. Infact an even less spectrally efficient (6, 1, 15) code is currently scheduled to be flown abroad the Cassini Mission to Sturn. However further bandwith expansion may be difficult to achieve due to the fact that addition redundancy may reduce the energy per transmitted symbol below the level needed for reliable tracking by the phase-locked loops in the coherent demodulators.

As a further improvement on the CICSDS Concatenation Standard, errors-and-erasures decoding, a suboptimum form of soft-decision decoding, can be used o provide some performance improvement if erased symbols are available from the inner decoding. One method of providing erased symbols is based on two facts mentioned above:

a frame of several RS code block is interleaved prior to encoding by the inner code, and

Decoding errors from the inner decoder are typically bursty, resulting, in strings of consecutive error symbols. Although long stings of error symbols will usually cause problems for an RS decoder, After de-interleaving they are more spread out, making them easier to decode. In addition, once a symbol error has been corrected by the RS decoder, symbols in the corresponding positions of the other codewords in the same frame can be flagged as erasures, thus making them easier to decode. This technique is known as "error forecasting" and has been discussed in a paper by Paaske.

Another method of improving the CCSDS Concatenation Standard makes use of iterative decoding, In one approach, the RS codes in a given frame are assigned different rates, some higher that the (255, 223) code and some lower, such that the average rate is unchanged. After an initial inner decoding of one frame, the most powerful (lowest rate) outer code is decoded, and then its decoded information bits (correct with very high probability) are fed back and treated as known information bits (side information) by the inner decoder in a second iteration of decoding. This procedure can be repeated until the entire frame is decoded, with each iteration using the lowest rate outer code not yet decoded. The use of known information bits by the inner decoder has been termed "state pinning," and the technique is discussed in a paper by Collins and Hizlan. A more general approach to iterative decoding of concatenated codes was proposed by Hagenauer and Hoeher with the introduction of the Soft-Output Viterbi Algorithm (SOVA). In the SOVA, reliability information about each decoded bit is appended to the output of a Viterbi decoder. An outer decoder which accepts soft inputs can then use this reliability information to improve its performance. If the outer decoder also provides reliability information at its output, iterative decoding can proceed between the inner and outer decoders. In general, such iterative decoding techniques for concatenated systems can result in additional coding gains of up to about 1.0 dB. In the CCSDS system, however, the outer RS decoder cannot make full use of such reliability information. Nevertheless, several combinations of error forecasting, state pinning, and iterative decoding have been applied to the CCSDS system by various researchers, resulting in an additional coding gain of about 0.5 dB.

Turbo Codes: Now we discuss a significant new discovery called "Turbo Codes," which is currently being considered as a software upgrade for the Cassini mission. Turbo codes, which are also known as parallel concatenated convolutional codes, were first introduces in a paper by Berrou, Glavieux, and Thitimajshima were first introduced. Turbo codes combine a convolutional code along with a pseudorandom interleaver and maximum a posteriori probability (MAP) iterative decoding to achieve performance very close to the Shannon limit. The encoder employs a simple (2, 1, 5) code in systematic feedback form using two copies of the parity generator separated by a pseudorandom interleaver. The generator matrix is given by

$$G(d)=\left[1\;\frac{1+D^4}{1+D+D^2+D^3+D^4}\right] \qquad (5)$$

The code is the same as that generated by a conventional non- systematic feedforward encoder with generator polynomials

$G^1(D) = 1 + D + D^2 + D^3 + D^4$ and

$G^2(D) = 1 + D^4$

But it is important that it be encoded in systematic feedback form because of the way the interleaver combines the two parity sequences. The encoder output consists of the information sequence and two parity sequences, thus representing a code rate of 1/3. Alternately puncturing (deleting) bits from the two parity sequences produces a code rate of 1/2, and other code rates can be achieved by using additional parity generators and/or different puncturing patterns. The pseudorandom interleaver reorders the information sequence before encoding by the second parity generator, thus producing, two different parity sequences. In essence, the interleaver has the, effect of matching "bad" (low-weight) parity sequences with 11 good" (higher weight) parity sequences in almost all cases, thus generating a code with very few low-weight crosswords. For large enough information sequence block lengths, Performance very close to the Shannon limit can be achieved at moderate BER's, even though the free distance of turbo codes is not large. In fact for most interleaver, the free distance of the above code is only dfree=6, even for very long blocklengths. The excellent performance at moderate BER's is due rather to a dramatic reduction in the number of nearest neighbor codewords compared to a conventional convolutional code. In a paper by Benedetto and Montorsi, it was shown that the number of nearest neighbor is reduced by a factor of N, where N blocklength. This factor is refereed to as file "interleaver gain."

The other important feature of turbo codes, is the iterative decoder, which uses a soft-in/soft-out MAP decoding algorithm first applied to convolutional codes by Bahl. Cocke, Jelinek, and Raviv. This algorithm is more complex than the Viterbi algorithm by about a factor of three and for conventional convolutional codes it offers little performance advantage over Viterbi decoding. However, in turbo decoding, the fact that it gives the maximum MAP estimate of" clear individual information bit is crucial in allowing the iterative decoding procedure to converge at very low SNR's. Although the SOVA call also be used to decode turbo codes, significant improvement, can be obtained with MAP decoding.

At almost any bandwidth efficiency, performance less than 1.0 dB away from capacity is achievable with short constraint turbo codes, very long blocklengths, 10^{-20} iterations of decoding.

This is a full 3.8 dB better than the Planetary Standard (2, 1, 7) code, with roughly file same decoding complexity and is also 1.0 dB better, than the very complex BVD code, which operates at 50% less spectral efficiency! Using the same rate of 1/4, the turbo code outperforms the BVD code by 1.9 dB. The major disadvantage of a turbo code are its long decoding delay due to the large blocklengths and iterative decoding, and its weaker performance at lower BER's, due to its low free distance. The long delays are not a major problem except in real-time applications such as voice transmission, and performance at lower BER's can be enhanced by using serial concatenation, so turbo codes seem to be ideally suited for use on many future deep-space missions. A comprehensive survey of the application of coding to deep-space communication is the decade of the 1960's drew to a close was given in a paper by Forney. For a more recent review of the subject, the article by Wicker is all excellent sources.

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