

# **STANDARD METHODS FOR TELEMETRY AND TELECOMMAND CHANNEL CODING**

**M. L. MacMedan  
Jet Propulsion Laboratory  
California Institute of Technology  
Pasadena, California**

## **ABSTRACT.**

Channel coding is a well-established method for improving the performance of a channel, or link, between space and earth. Until recently, the types of codes and their parameters were frequently tailored to optimize the performance of the data through a channel for a specific application. Furthermore, lack of coordination led to a situation where different developing bodies pursued slightly different schemes with essentially the same performance. This resulted in a proliferation of coding schemes which inhibits interoperability (among centers as well as agencies) and cross support.

Work has been done by two recently-established standards coordinating bodies, the NASA-ESA Working Group for Space Data Systems Standardization (NEWG) and the Consultative Committee for Space Data Systems (CCSDS), to standardize on a few high-performance codes for general applicability. These codes, which are described in the NEWG Telemetry Channel Coding Guideline (Reference 1), can provide up to 6.8 dB of coding gain. They may not be perfectly optimized for every mission, but they can, in most cases, provide satisfactory performance at low cost through amortization of development costs. This leads to affordable inter-center and inter-agency cross support, and cooperative missions.

Error protection is similarly needed for telecommanding, and work has been under way in the CCSDS to establish a Telecommand Channel Coding Recommendation. Status of this work, and methods of synchronization and telecommand frame error protection, are discussed.

This paper may also be of interest to other non-NASA space communication channel users.

## **INTRODUCTION.**

The radio link between space and ground (the “Channel”) may be prone to errors resulting from a poor signal-to-noise ratio. Corruption of the received signal by noise may exist when the signal is very weak because it has travelled over immense distances as in deep space applications, or it may be observed in shorter links (such as through earth-orbiting relays) subjected to noise or severe interference. In either case, the result is improper data transfer.

Channel coding may be applied to the data being transmitted from the spacecraft which will enable a decoder at the receiving end to correct a limited number of errors. If the code is chosen carefully, “clean” (relatively error-free) data may be recovered even though the channel itself is very “noisy.”

Many studies and experiments have been carried out over the past ten to fifteen years in search of suitable error-correcting codes for space communications to efficiently provide much protection for little penalty. This has led to a multiplicity of approaches to accomplish similar ends among different NASA centers as well as among different space agencies of the world. The standardization efforts now under way are attempting to reduce the proliferation of precisely-tailored schemes for each application, and instead adopt a few well-supported, “standardized” schemes that will serve most needs for a reasonable period into the future. The cost savings in repeated new equipment design, fabrication, test, qualification, operations and training are as obvious as the improved opportunities for cross support between agencies and between centers.

It should be pointed out that such standardization is not intended to inhibit advanced coding studies or even the adoption of better coding schemes in the future. It is merely intended to provide an affordable solution for a majority of users. If a project’s needs cannot be satisfied by these standardized approaches, it must pay, as in the past, the price of new development.

In this paper, Telemetry Channel Coding will be discussed first, then Telecommand Channel Coding.

## **CURRENT STATUS.**

Work has been progressing over the past two years within the NEWG to establish a set of guidelines upon which each of the two agencies could base its internal standards to ensure coordination and interoperability for cooperative missions. The NEWG Guideline has been published as a “Review Draft” (Reference 1). This same book has recently been submitted to the multi-agency Consultative Committee on Space Data Systems (CCSDS) to become

its Coding Recommendation “Review Draft.” Finalization of the book is planned at the May, 1984 plenary meeting of the CCSDS.

## **THE NEED FOR CODING.**

Coding is one of several alternative ways of improving the effective performance of the channel. Older, more familiar alternatives such as increasing power level, increasing antenna gain, improving the precision of antenna pointing and the use of lower-noise amplifiers have been largely exploited to their limits. Further improvements by these means are very expensive. However, coding is a cost-effective alternative, and when very low error rates are desired, may be the only affordable means.

The dramatic improvement coding provides for very low error rates may be seen from Figure 1, where an uncoded channel, is compared to two of the recommended codes. At bit error rates (BER) of  $10^{-2}$  or  $10^{-3}$  the advantage of coding over no coding is small. When very low BER are required (e.g.,  $10^{-5}$  or  $10^{-6}$ ) the alternative uncoded methods for a given improvement in signal to noise ratio do not provide as effective an improvement in actual BER as the coded methods. For a performance of  $10^{-5}$  BER, for example, a coding gain of 4.7 dB may be achieved by using the recommended convolutional code, or 6.8 dB with the concatenated convolutional and Reed-Solomon code. At lower error rates, the improvement is even more pronounced.

Errors in received data have been tolerated up to now primarily because the quantities of data we have had to deal with have been relatively small. Since errors in the data were expected, we became accustomed to the high cost of correcting the errors by human intervention. Newer generation spacecraft and more ambitious missions will demand more and more data of better quality from space. However, we are becoming strangled in our ability to get this data back to the ground. Limitations that go beyond channel SNR performance include regulatory bandwidth restrictions, regulatory limitations on earth-received power flux densities, and the high cost of transporting and processing the data once it arrives on the ground. Solutions to overcome these limitations are being developed in three areas, each of which demands a very low error rate to be effective.

The first area of development is on-board data compression, where the redundancies in the telemetry data are extracted, and only the essence of the information is transmitted through the channel. This reduces the quantity of data transmitted, but requires a nearly error-free channel to reconstitute the original data. An error in the compressed data could propagate into many errors in the reconstituted data set depending on the amount of compression, the algorithm being used, and the location of the bit error.

The second reason for needing low error rates is adaptive telemetry. The spacecraft we have built up to now may have had instruments with selectable modes, formats and rates, all of which have been programmed by ground controllers ahead of time, according to a plan. Format changes in the received telemetry, since they have been planned, can be anticipated on the ground at any given moment. New generation instruments will use their on-board microprocessors to do a first-level analysis of the data, and determine if a mode, format or data rate change is needed, capturing many transient scientific observations that would be impossible otherwise. When an adaptive change is required, the instrument executes it on-board without knowledge or planning from the ground controllers. The changes are signalled by flags in the headers of the packets, which trigger the proper ground processing routing and processing algorithms. It is clear that ground processors, when driven by the data they are processing, would be susceptible to even occasional bit errors in these key fields.

The third reason is that future ground processing of great volumes of data must be done automatically - that is, with as little human intervention as possible. In the past, errors were frequently corrected manually or by rerouting selected data sets through correcting and smoothing programs. While this may have been cost-effective for the relatively small amounts of data involved, this type of overhead will no longer hold true for large amounts. The only affordable solution is to recover clean data on the ground before automated processing begins.

## **APPLICATION OF THE CODING GUIDELINES**

The NEWG and CCSDS have tentatively adopted several specific channel coding schemes for international cross-support of missions. The first is a specific convolutional code which will serve as the basic coding scheme for earth orbiters (whether or not they utilize the Tracking and Data Relay Satellite System - TDRSS,) as well as for deep space missions. Because of a highly specific RFI problem, a periodic convolutional interleaving scheme is required in addition to this convolutional code, but only for spacecraft using the TDRSS S-band single access channel at channel symbol rates above 300 ks/s. Finally, when a more powerful code is desired than the convolutional code alone, it is recommended that the convolutional code be concatenated with a specific Reed-Solomon code. Highly elliptical earth orbiters and deep-space missions are examples of missions which may require the latter.

The NEWG guideline is intended to be incorporated into the official NASA and ESA Standards. It carries no formal enforcement power by itself. It applies mainly to cooperative missions between NASA and ESA but it is being adopted as a baseline for a similar agreement by the Consultative Committee on Space Data Systems for future cooperative missions among other space agencies. It should be recognized that by virtue of

the forward-looking focus of this work, it provides guidance to each of the participating agencies for their own internal standards development work. In particular, it should help reduce the proliferation of nearly equivalent but not quite compatible alternatives that frequently accompany highly technical but uncoordinated work. The standards help to furnish the necessary coordination.

To clarify a common misconception, the Coding Guideline does not require that coding be used on any mission; but, if it is found that coding is necessary to achieve the required mission performance, then the recommended affordable schemes for cross support are those described in the guideline.

## **CONVOLUTIONAL CODE.**

The convolutional code chosen for the Guideline is characterized by having a constraint length of 7 bits, and a code rate of 1/2 bit per symbol. The decoding process uses Viterbi's maximum-likelihood algorithm. Complete details of the recommended code are given in the Guideline (Reference 1) At the earliest meetings of the NEWG coding panel, this code was recognized as an existing standard at JPL, GSFC and ESA, and a prime candidate to become a NEWG standard for interoperability.

It was not until the more detailed specifications were carefully scrutinized that it was discovered that each of the three organizations (ESA, GSFC and JPL) had implemented seemingly minor differences in the code, in some cases making compatibility impossible. The reasons were obscure, since in each case the performance was identical. The comparison of the three conventions can be seen in Figure 2 viewed in terms of an on-board convolutional encoder.

It was quickly agreed that even though the ultimate objective would be to pick one of the three for a universal standard, ongoing and already committed missions would still need support with the different codes for a considerable period - perhaps ten years. Therefore, a near-term approach was agreed wherein each organization would support its own convention as a primary service, while accepting the other conventions as a secondary service. (Here, "secondary" means that full capability might not be available, but some limited means of cross support could be provided.) For future missions over the long term, the GSFC convention was tentatively adopted because it was apparent that if a different single convention were chosen, GSFC would incur the greatest cost to change.

## **CONVOLUTIONAL CODE WITH PERIODIC CONVOLUTIONAL INTERLEAVING.**

Spacecraft using the TDRS S-band single access channel at channel rates above 300 ks/s are required to follow the convolutional encoding with a synchronized periodic convolutional interleaver of depth 30. This spreads the information in such a way that the pulsed radio frequency interference on this channel should not corrupt a contiguous set of symbols beyond the correcting capability of the convolutional code. Since interleaving is a unilateral requirement of the TDRSS project, it was decided to specify detailed parameters of the interleaving by reference to the TDRSS Users' Guide. (Reference 3)

It is also recommended that TDRSS-supported missions which may have some need for non-TDRSS support, (such as cooperative missions or those desiring emergency ground support) must incorporate an ability to bypass the spacecraft interleaver. Direct links to the ground are not subjected to this interference, and therefore do not need interleaving; but more importantly, de-interleavers do not exist in such stations!

## **CONVOLUTIONAL CODE CONCATENATED WITH REED-S NON CODE.**

The most powerful code contained in the recommendation is the concatenation of the convolutional code specified above with a Reed-Solomon (R-S) code. In this case, the convolutional code is the "inner code" and the R-S code is the "outer code." This means that the data on the spacecraft is encoded first by the R-S encoder, and then this encoded stream is further encoded by the convolutional encoder. The opposite sequence is used for decoding on the ground.

The R-S code is a block code; its parameters are specified in detail in Reference 1. The recommended R-S symbol length is 8 bits, and an R-S codeword is thus 255 symbols long. The symbol error-correcting capability is 16 symbols. When interleaved to the recommended depth of 5, the resulting 10,200 bit codeblock consists of an 8920-bit "transfer frame" followed by 1280 bits of R-S check symbols.

This transfer frame length is identical to that recommended in the Packet Telemetry guideline, and it is required that the R-S codeblock be synchronous with the telemetry frame. It is currently necessary that codeblock synchronization be accomplished using the transfer frame sync word. Advanced development in self-synchronized R-S codes may permit these to be separated in the future.

The low overhead of the code (less than 15%) provides excellent performance with very little added bandwidth, and the code parameters have been tailored to minimize on-board hardware and complexity.

The R-S code, being systematic, places all the information bits (i.e., the transfer frame) intact at the beginning of the codeblock and the R-S check symbols at the end. Thus, during system test or other times when the error-correcting capability of the code is not needed, telemetry may be read directly without a decoder, and without disabling the spacecraft encoder.

While not encouraged, it should be noted that this coding scheme can also be used with non-packetized telemetry systems, and can be used with transfer frame lengths shorter than 8920 bits by utilizing the concept of “virtual fill.” Both encoder and decoder are initialized to expect a fewer number of leading bits per transfer frame than allowed by the maximum codeblock, and the missing (non-transmitted) bits are set to be all zeros. Frame lengths incrementally shorter than 8920 bits may be accommodated as long as the increments are in multiples of 8 bits times the depth of interleaving. The user must be cautioned that using virtual fill changes the overall performance of the code to a degree dependent on the amount of fill used.

The performance of this scheme without virtual fill, is shown in Figure 1. The steepness of the curve leads one to expect either “clean data” (to the right of the curve) or data so corrupted with uncorrectable errors as to be unusable (to the left of the curve.) One of the most profound attributes of the Reed-Solomon code is that the decoder can flag the user when the data is so bad as to be uncorrectable, instead of merely trying to correct as best it can. Under these circumstances, a user can specify that he wants to have delivered to him (and possibly pay for) only good, corrected data; uncorrectable data may be discarded before transporting.

When the NEWG Coding Panel began this coordination, it found different agencies and centers working on different, incompatible versions of Reed-Solomon coding schemes as solutions to nearly the same problem. Fortunately, early exposure of the problem allowed a single approach to be agreed upon for future applications, achieving commonality and the ability to provide interoperability without having to retrofit equipment as in the case of the convolutional code.

## **TELECOMMAND CHANNEL CODING.**

Work on international standardization of coding for the telecommand channel is not as advanced as that for the telemetry channel but significant progress has been made recently within the CCSDS. As with telemetry, common standards for telecommand permit affordable cross-support and reduce the proliferation of arbitrary command coding schemes for each mission.

The requirement for a low error rate in telecommand is more demanding than for telemetry, so error checking is performed at more than one layer. Coordination work in the NEWG and CCSDS has focussed on the physical layer coding algorithm and link layer data structures. The telecommand channel coding function is at these lower levels.

The Telecommand Guideline will require telecommands to be formatted into Command Link Transmission Units (CLTUs) each of which carries a buffer load of user command bits, typically between several hundreds and several thousands of bits long. The CLTU contains a variable-length preamble needed for bit synchronization, followed by an 8-bit Barker code and then a set of telecommand frames. These frames may be 48, 56, or 64 bits long, but all must be the same length for a particular mission. The Barker code delimits the preamble from the contiguous set of telecommand frames which follow, and establishes the sense of a “1” and “0”. Once the start of the first frame is located, and the one-zero ambiguity is resolved, each frame of the CLTU is individually checked for errors.

Each telecommand frame contains a parity byte consisting of 7 bits of parity followed by a “zero” (to maintain the byte structure). The code, which is a (63, 56) expurgated BCH code, has a maximum overall length of 63 bits and a Hamming distance of 4. A shortened version of this code is used with shorter (48- or 56-bit) telecommand frames.

The chosen code may be decoded on the spacecraft in the error-detection mode as well as the error-correction mode. In the error-detection mode, one or two bit errors in the frame causes the frame to be rejected, after which steps must be taken to re-transmit the command. If the spacecraft decodes in the error-correcting mode, a single bit error in the frame will be corrected and loaded as if it were received error-free. An even number of bits-in-error triggers an on-board protocol to reject the command. The precise recovery procedures are the subjects of higher level protocols.

This coding scheme is well established, as it is based on similar codes in use by GSFC and JPL for some time. GSFC uses the error-detecting mode, which is suitable for earth-orbiter missions, while JPL uses the code in both error-detecting and error-correcting modes. The error-correcting mode is more suitable for deep-space missions with long round-trip light time. The CCSDS is about to adopt the code for its “recommendation,” which will help provide the basis for inter-center and inter-agency cross support at this level. Work is in progress to achieve a compatible error control standard at the higher levels.

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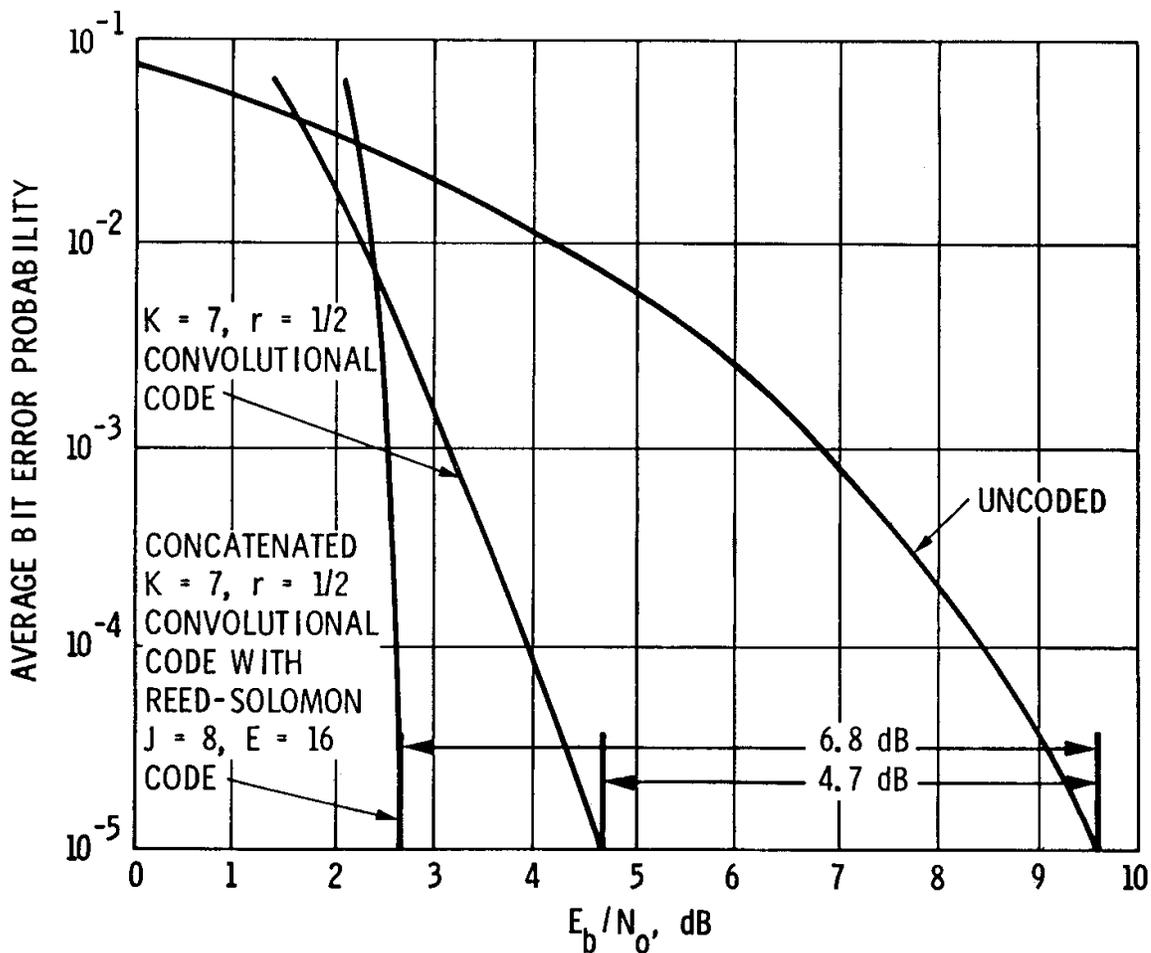
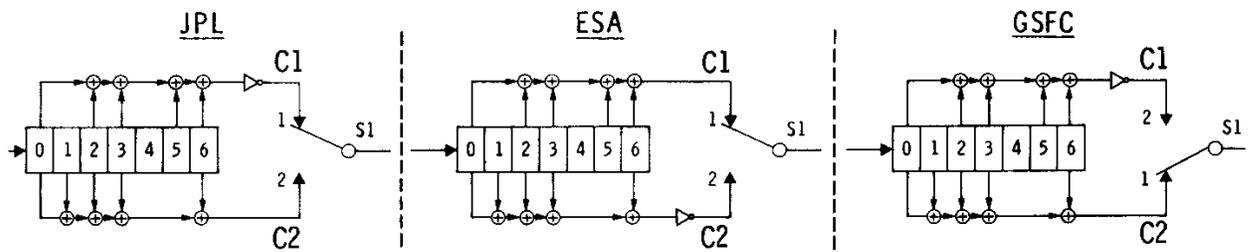


FIGURE 1: PERFORMANCE COMPARISON



- CONNECTION VECTORS ARE IDENTICAL
- INVERTER LOCATION IS TRANSPARENT TO THE DECODER AS LONG AS ONE AND ONLY ONE INVERTER IS PRESENT
- INCOMPATIBILITY LIES IN PHASE RELATIONSHIP BETWEEN STARTING POSITION OF S1 FOR EACH INCOMING BIT

**FIGURE 2: CONVOLUTIONAL ENCODER DIFFERENCES**