Improving Rosetta's Return-Link Margins

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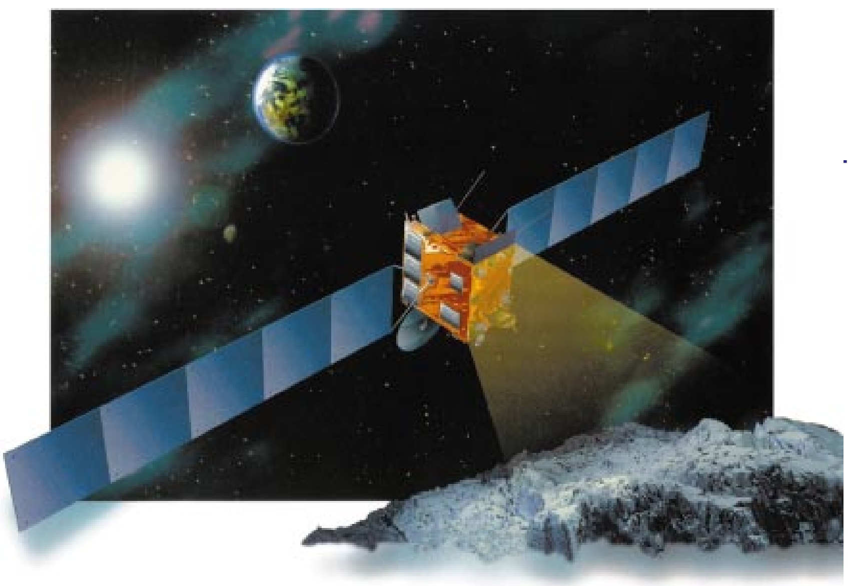
The Rosetta mission is designed to study in-situ a cometary nucleus' environment and its evolution in the inner Solar System. To be launched in January 2003 by an Ariane-5, Rosetta will rendezvous with Comet P/Wirtanen in 2011, after one Mars- and two Earth-gravity assists, and two asteroid fly-bys. The near-comet operations, which are scheduled to last about 1.5 years, will require a minimum return-link telemetry data rate of 5 kbit/s to meet the scientific goals, with about 14 hours of daily coverage.

Rosetta will operate in the frequency bands allocated by the Geneva-based International Telecommunications Union (ITU) to deep-space missions operating 2 million kilometres or more from Earth. These bands enjoy stringent protection requirements, making them virtually free of radio-frequency interference from other services. Moreover, the limited number of such missions makes it acceptable to adopt coding and modulation schemes that are optimum for power-limited as opposed to bandwidth-limited systems. This article describes the efforts currently being made to optimise Rosetta's communications capabilities in this respect.



Artist's impression of the Rosetta mission

Introduction

Rosetta will be ESA's most demanding mission to date in terms of its ground-station requirements (Fig. 1). In order to be able to support the mission using the Agency's own facilities, development of the first ESA deep-space antenna, to be sited at Perth in Western Australia, has been initiated (Fig. 2). Despite the high performance of such a state-of-the-art antenna — with its diameter of 34 m, cryogenically cooled low-noise amplifiers, and receivers with bandwidths as narrow as 0.3 Hz, etc. — the return-link margins needed for Rosetta can only just be satisfied, with little contingency for performance degradation during a mission with a nominal lifetime of about 11 years, operating some 5.8 AU from Earth. In extreme situations in which only Rosetta's Low-Gain Antenna (LGA) can be used, even low-rate telemetry cannot be supported using existing systems.

In 1993, a new signal-coding concept known as 'turbo coding'* was introduced by Berrou et al. It attracted much attention by promising greatly improved communications performance as close as 0.5 dB to the Shannon limit, which represents the theoretical optimum. Following regulatory discussions at the May 1996 Meeting of the Consultative Committee for Space Data Systems (CCSDS), ESA decided to place a study contract with the Communications Group at Politecnico di Torino to investigate the technique further. One aspect of interest stemmed from the fact that the end-product is the received frame instead of the received bit. It was therefore decided to investigate whether the Frame Error Rate (FER) performance would be as good as the Bit Error Rate (BER) performances being cited in the turbo-code-related papers appearing in the literature at the time. The real goal was to develop design criteria aimed at finding turbo codes with gains about 1.5 dB (at an FER = 1×10^{-4}) higher than that of the CCSDS standard concatenated code adopted as the baseline for Rosetta.

Figure 3 illustrates the evolution of coding for space applications. It shows how, from the first missions of 1958 until the end of this century, higher coding gains have brought increasing

* Turbo code: licence France Télécom & Télédiffusion de France

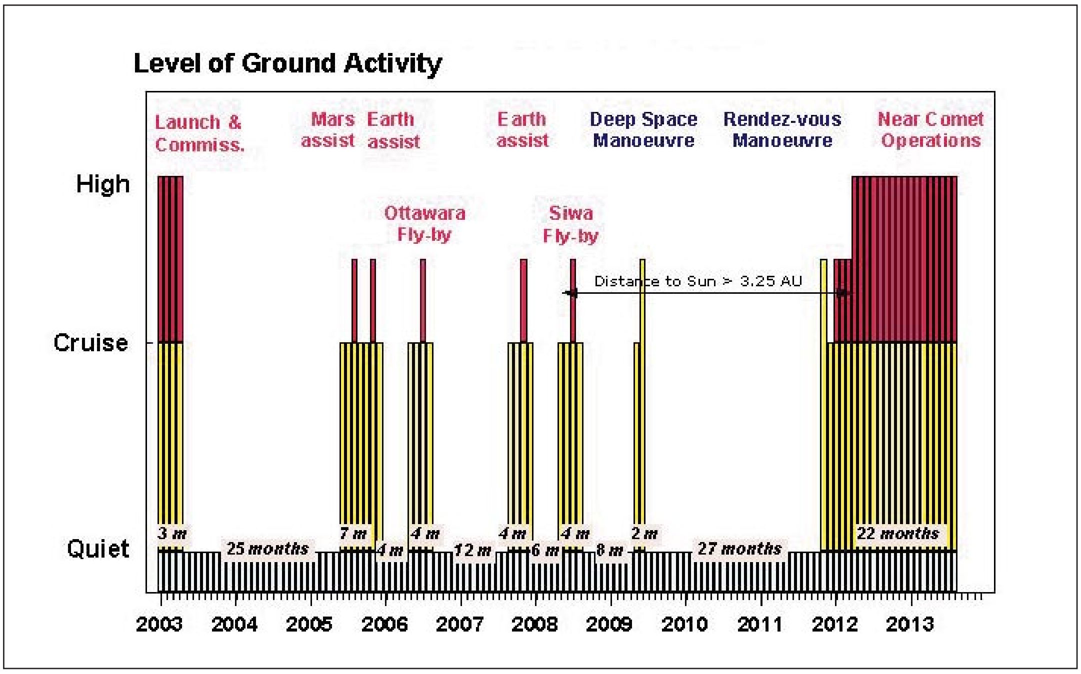


Figure 1. Rosetta mission-activities chart

decoding complexity, and how turbo codes offer the prospect of high gains with still moderate complexity. The concatenated code currently baselined for all ESA and NASA missions was first used in 1981 on Voyager, while the first ESA mission to use it was Giotto, launched in 1985. It is currently being used for ESA's Cluster-II and is presently also baselined for Rosetta. The convolutional code used on ESA's recent ISO mission was first flown on Voyager in 1977. It can be seen that these codes lay on a straight line in the complexity versus gain domain. Large deviations from this line were necessary due to the problems with the Galileo antenna. The so-called long constraint length (14, 1/4) convolutional code needed for the Galileo missions is shown to produce an extra margin of 2 dB over the concatenated code at the expense of a three orders of magnitude increase in complexity! The turbo codes considered here are potentially on the straight line again, yet achieve better performance than the Galileo codes and closely approach the theoretical limit predicted by Shannon.

The Rosetta telecommunications

As is customary with deep-space missions, Rosetta's down-link modulation scheme will be binary PCM/PSK/PM* on a square-wave subcarrier. The CCSDS-recommended coding

* PCM / PSK / PM = Pulse-Code Modulation / Phase-Shift Keying / Phase Modulation

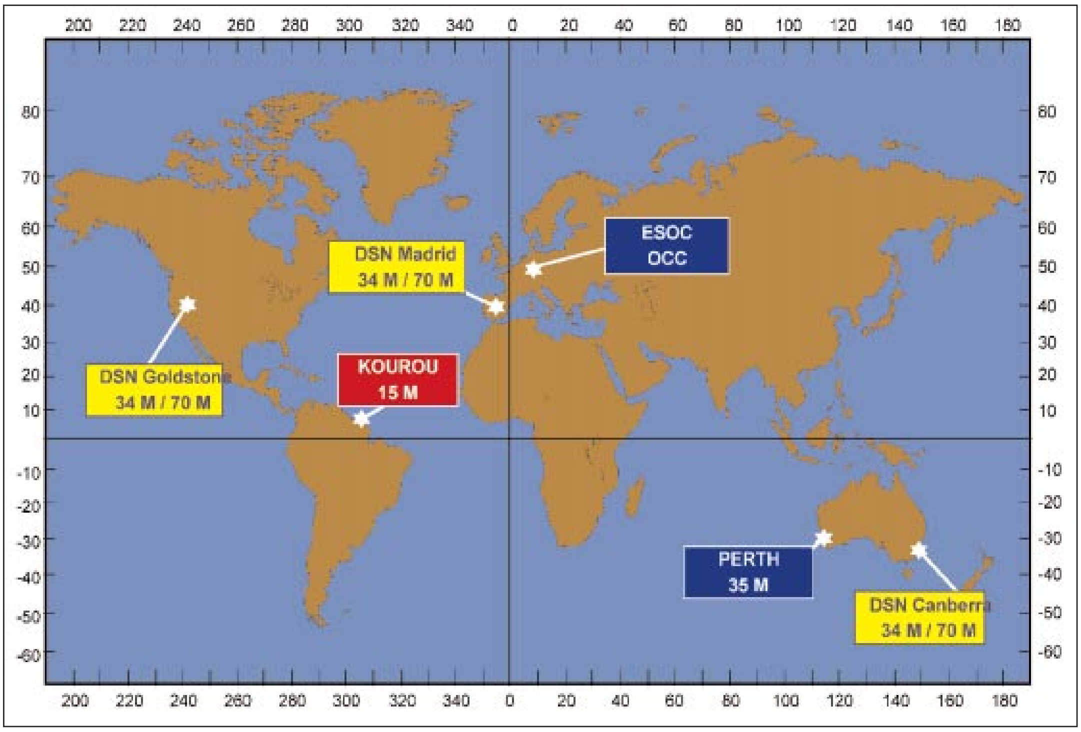


Figure 2. The Rosetta ground-station network

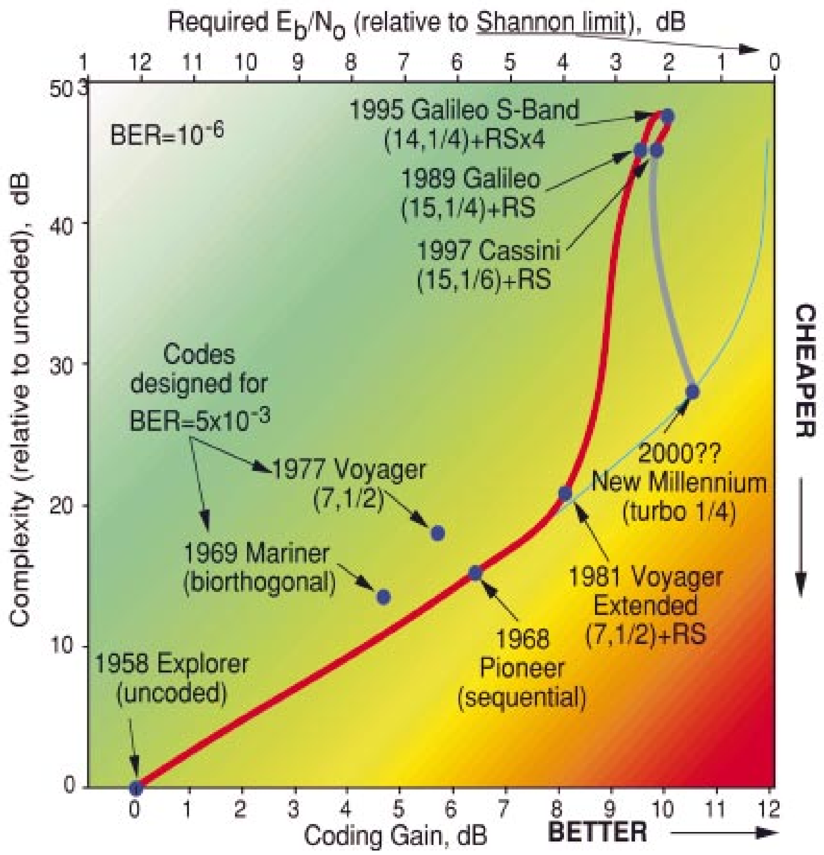


Figure 3. Historical evolution of coding for deep-space missions
(Courtesy of NASA/JPL; Copyright JPL/Caltech)

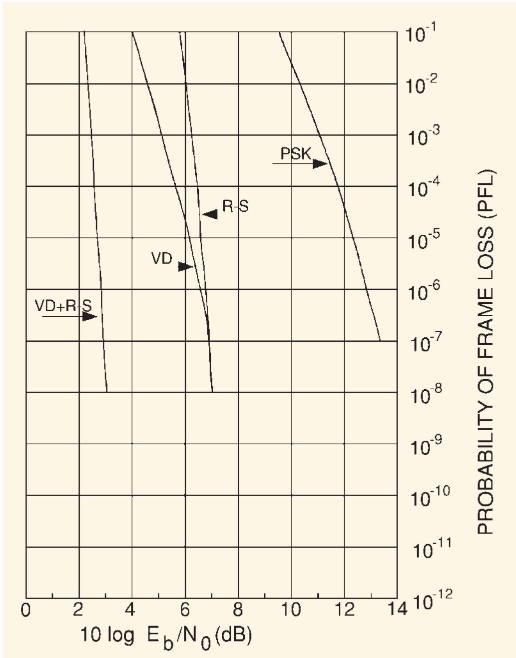


Figure 4. Frame Error Rate (FER) performances of the various CCSDS codes

Turbo Encoding

A turbo code, which functionally is a Parallel Concatenated Convolutional Code (PCCC for short), is formed by two convolutional encoders and one interleaver (Fig. 5). The information sequence u enters the first encoder C1, which generates the coded sequence x1. At the same time, u is permutated by the interleaver into a new sequence uP, which is successively encoded by the second encoder C2, giving rise to the coded sequence x2. The code sequence x of the PCCC code CP is obtained through the concatenation of the two encoded sequences x1 and x2. Designing a PCCC involves optimising the two convolutional encoders and the interleaver.

To be compatible with one of the existing frame lengths allowed by the current standard concatenated coding scheme, the interleaver length N was chosen equal to 8920 bits, corresponding to 5 input words of a (255,223) Reed-Solomon code with 8 bits per symbol (N=8920=5*223*8). The development effort has therefore been decoupled into two separate design stages, the first optimising the two convolutional encoders, and the second seeking a suitable interleaver with length N=8920.

To perform the first step, the presence of an 'average' interleaver, called the 'uniform' interleaver has been assumed, so that the two convolutional encoders can be optimised as those offering the best performance averaged with respect to the whole class of interleavers.

The optimisation has been performed for PCCCs with rates of 1/2, 2/5, 1/3, 1/4, and 1/6, and upper bounds to the Frame Error Rate (FER) have been evaluated in the presence of the uniform interleaver. Figure 6 shows the FER performance for different interleaver lengths and numbers of states (and therefore complexity) of the convolutional encoders. Figure 7 only shows the performance of the selected 16-state turbo code versus E_b/N_o (signal-to-noise ratio) for three different interleaver lengths (and therefore frame lengths). Looking at these figures, an FER of better than 10^{-4} is obtained by the CCSDS standard at E_b/N_o=2.62 dB, and better than 10^{-6} at E_b/N_o=2.88 dB. Both the rate 1/2 and 1/6 turbo codes achieve a gain with respect to both FER specifications. However, the gain at FER=10^{-6} appears to be marginal, and this can be attributed to the relatively poor performance of the uniform interleaver.

Having optimised the two convolutional encoders, the interleaver has been designed using the so-called 'spread-interleaver' approach, which leads to an interleaver permutation whose integer values are chosen randomly, although this imposes a constraint on the minimum separation of two consecutive interleaver positions.

Figure 8 shows as an example the simulated results and the extrapolated curve for the rate 1/6 PCCC, obtained by concatenating a 16-state, rate 1/4 optimal systematic, recursive convolutional encoder with a rate 1/2 encoder obtained from the optimal 16-state rate 1/3 encoder by eliminating the systematic bit. The curves show a frame error probability of around $4.4x10^{-4}$ at -0.2 dB.

scheme is the concatenated Reed-Solomon (255,223) and convolutional (rate 1/2, 64 states) code, for which both ESA and NASA have coders and decoders available off-the-shelf. With a Reed-Solomon code interleaving depth of 5, the Rosetta Frame Error Rate is met when the bit signal-to-noise ratio (SNR = E_b/N_o) is greater than 2.62 dB. The performance of this code is shown in Figure 4, where it (indicated as VD+R-S) is compared with the uncoded Phase-Shift Keying (PSK), the Reed-Solomon (R-S) and the convolutional (VD) performance. The coding rate, currently set to 1/2.28, could be reduced to 1/6 without problems. Thanks to the coherency between symbol clock and subcarrier frequency, the ESA ground-station demodulators achieve symbol synchronisation down to SNR values much lower than required for concatenated decoding and could therefore accommodate coding schemes with lower rates without needing to redesign the demodulation chain.

The coding improvements

Extracting extra dBs of gain from the Perth antenna is not possible without incurring major costs, as its specifications are state-of-the-art for a 34-m antenna. Increasing its diameter beyond 34 m would require a completely new design and double the cost. Enlarging Rosetta's on-board High-Gain Antenna (HGA) or increasing its transmit power is also not viable, and moreover would not help in emergency situations where the HGA cannot be used. The development efforts have therefore been focused on potential improvements in the coding area, and turbo coding in particular for its promise of approaching the theoretical maximum gain obtainable (the Shannon limit). The details are

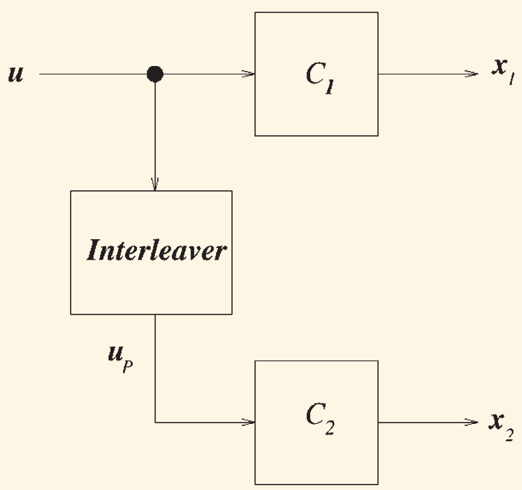


Figure 5. The turbo-encoding concept

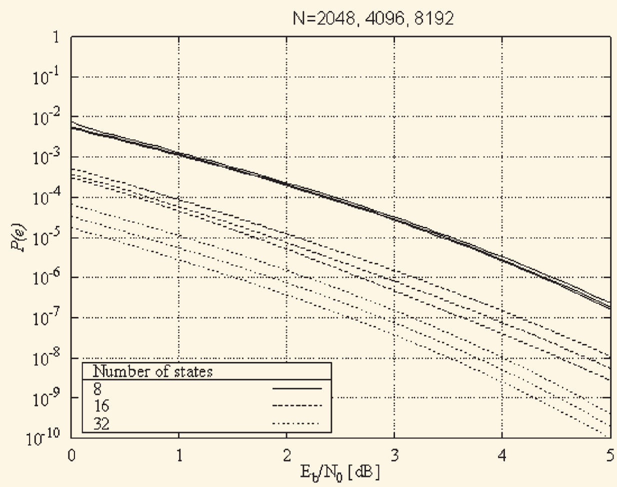


Figure 6. FER versus E_b/N_o bounds for proposed rate 1/2 turbo codes

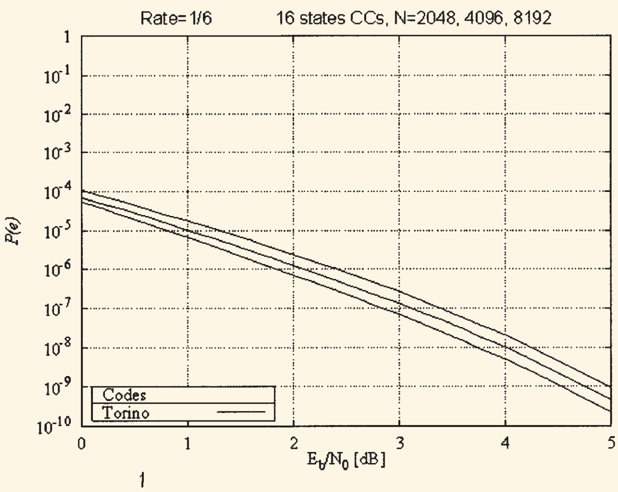


Figure 7. FER versus E_b/N_o bounds for 16-state rate 1/6 turbo code

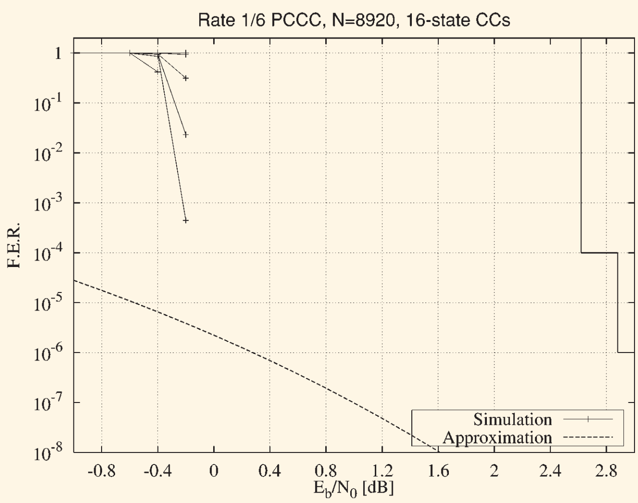


Figure 8. Simulated FER versus E_b/N_o curves for 16-state rate 1/6 turbo code and spread interleaver (N=8920)

given in the accompanying panel.

The coding gains of the proposed 16-state Parallel Concatenated Convolutional Codes (PCCCs) over the present 64-state CCSDS standard are summarised in Table 1 for various code rates and for the two representative values of FER, i.e. 10^{-4} and 10^{-6}. These gains

Table 1. Estimated improvement compared with current CCSDS concatenated coding scheme (Reed-Solomon and 64-state convolutional encoder)

Code Rate	Improvement [dB]	
	@ FER = 10^{-4}	@ FER = 10^{-6}
1/2	1.7	~ 1.2
2/5	2.0	~ 1.6
1/3	2.3	~ 2.0
1/4	2.5	~ 2.0

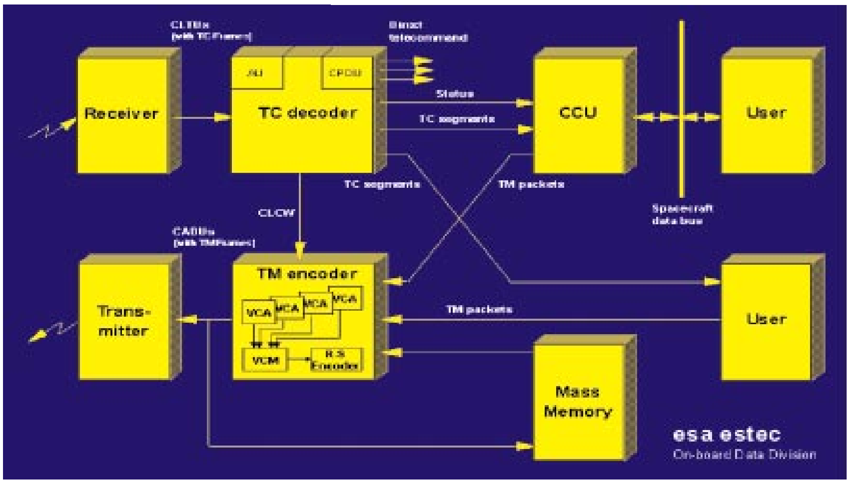


Figure 9. A typical onboard telemetry and telecommand data-processing approach for an ESA spacecraft

are based on the turbo encoders proposed for CCSDS adoption (with the exception of rate 2/5). The extensive simulation results suggest the following conclusions:

– With respect to the CCSDS performance goal, the use of parallel concatenated codes yields a significant saving in E_b/N_o for both frame error probabilities considered (10^{-4} and 10^{-6}).

– For the higher frame error probability, i.e. 10^{-4}, the expected gain ranges from 1.7 dB (for the rate 1/2 code) up to 2.7 dB (for the rate 1/6 code). Note that these coding gains have been obtained by simulating the iterative very reliable.

– For the lower value of frame error probability, i.e. 10^{-6}, the expected gain ranges from 1.2 dB (for the rate 1/2 code) up to 2.0 dB (for the rate 1/3 code). Decreasing the code rate does not seem to yield improvements in this case. These coding gains have been obtained through a semi-analytical extension technique, which implies maximum likelihood decoding, and must therefore be considered good approximations of those obtainable with the iterative decoding algorithm.

– The sensitivity of performance to the phase jitter due to the carrier recovery scheme of a practical receiver has been measured in terms of bit error probability degradation. It has been verified that a carrier-to-noise ratio of 17 dB in the carrier recovery loop (the same as required by the present standard) is sufficient to guarantee a degradation below 0.1 dB in E_b/N_o, for both rate 1/2 and rate 1/6 codes.

The outlook for Rosetta

CCSDS standard concatenated encoding is the baseline for Rosetta and will be implemented on board with the usual ESA data-processing approach based on dedicated hardware, as shown in Figure 9. Since the frame-length values proposed in the turbo-code option of the CCSDS Channel Coding Recommendation (undergoing Agency review) correspond to those allowed for Reed-Solomon encoding, it will be possible to retain the current upper-layer implementations unaltered, still using the standard ASICs for on-board frame generation.

As the data rates needed for Rosetta are comparatively low, the turbo encoding can be implemented in software and used only when required to achieve the necessary link margins. The uncoded frames would always be generated by the VCM ASIC, be encoded by software routines, augmented by the addition of the required synchronisation markers, and then sent to the ‘transmitter’. The only foreseen impact of turbo coding on Rosetta’s on-board telecommunications system is that a different symbol rate has to be accommodated by the transponder’s modulator, unless the information bit rate is properly adjusted.

Since the turbo routines are proposed for software implementation, different coding schemes (potentially even closer to the Shannon limit) could be loaded onto the spacecraft by ground commands during the 11-year mission, for use as required. As the existing ground-station demodulation chains are also compatible with the proposed codes, only replacement or augmentation of the existing decoders and frame synchronisers would be required. It is therefore believed that this choice is the most cost-effective solution for increasing Rosetta’s return-link margins by as much as 2.7 dB.

Acknowledgement

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