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Erasure Channel Coding for Future Space Missions

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ABSTRACT: Data unit losses in deep space communications are currently faced using retransmission techniques which are however inefficient due to the large round trip delays. For this reason, the Consultative Committee for Space Data Systems (CCSDS) has recently considered packet erasure correcting codes for inclusion in its recommendations for space data system standards. Erasure correcting codes are expected to replace (or drastically reduce) retransmission requests. Erasure codes operate on packets instead of bits and are usually implemented above at the upper layers of the communication stack. These codes operate at the upper layers of the space link protocol and constitute an attractive new frontier for zero packet loss in future space communications. In this paper a novel framework for packet loss recovery in the Consultative Committee for Space Data Systems (CCSDS) telemetry downlink is presented. The framework relies on packet-level LDPC erasure correcting codes and on low complexity maximum likelihood (ML) pivoting decoding. The code is characterized in this work.

KEYWORDS: Erasure channel, Low density parity check codes, Maximum-likelihood decoding.

I. INTRODUCTION

In communication and information processing, coding is system of rules to convert information in one form into another shortened or secret, form or representation for communication through a channel or storage in a medium. Our focus is on channel coding which adds redundant stream of bits to the data before it is sent through the channel, so that it can detect and possibly correct the errors. In general the channel encoder will divide the input message bits into blocks of k messages bits and replaces each k message bits block with a n-bit code word by introducing (n-k) check bits to each message block.

The Consultative Committee for Space Data Systems (CCSDS) has included a number of channel coding schemes in its protocol stack. Current coding option represents a mix between classical schemes like Reed–Solomon (RS) and convolutional codes and iteratively decoded schemes. These schemes are characterized by low code rates, which induce large bandwidth expansions. Thesis not a problem for traditional deep-space missions, which requires only low data rates and low bandwidth since the operational signal-to-noise ratio (SNR) is extremely low.

New foreseen scenarios are now more demanding in terms of spectral efficiency and data rates. For example, the future Earth-observation TM links will have strong bandwidth constraints together with high data rates required (up to a few gigabits/second). Furthermore, the foreseen Mars exploration TM links will be both bandwidth and power constrained, with information data rates up to 20 Mbit/s(reference [2]). As a consequence, there is an urgent need for new bandwidth-efficient, near Shannon limit (theoretical maximum information rate of the channel), low-complexity channel codes for updating the CCSDS recommendations and covering these new missions. The above requirements therefore suggest the use of coding at higher layers (at packet level) along with the bit-oriented channel codes operating at the synchronization and channel coding sub layer of the space link protocols.

The paper is organized as follows. In Section II provides brief background information on Long erasure correcting codes and introduces new algorithm. In Section III shows simulation results, and in Section IV concludes the paper.

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II. ERASURE CORRECTING CODES

The bit-oriented channel codes operate at the synchronization and channel coding sub layer of the space link protocols model. If the employed channel code performs error correction but does not provide frame validation information (e.g., convolutional code or turbo code), then a cyclic redundancy check (CRC) is computed and appended to each data frame, before the data frame enters the channel encoder. At the receiver side, after completing decoding, a frame validation test is performed via the CRC. The CRC is not used if the channel code provides the frame validation information (e.g., RS code, convolutional code concatenated with RS code, or LDPC code). Only those data frames passing the validation test are delivered to the upper layers: the un-correctable data units, which are not delivered, are "lost".

An appropriate channel model for the end-to-end communication between upper layers is then a packet erasure channel (PEC). According to the PEC model, whole packets of bits are either correctly received or lost. The "traditional" solution implemented at the upper layers to face data unit erasures is the well-known automatic repeat request (ARQ). However, in space communications, ARQ is not always a recommended solution. This is certainly true for the deep-space link, where the long round-trip delay (hours or substantial fractions of the hour, e.g., 40 min for the Earth-to-Mars distance) introduces heavy drawbacks with respect to both the data latency (time needed to request and receive the lost data) and the onboard memory requirements at the transmitter side in order to ensure the buffering of a very large amount of data. The mentioned problems affect any ARQ strategy like the go-back-N ARQ, selective-repeat ARQ, etc.

A. Coding For Erasure Channels

Erasure codes are typically employed in the upper layers of communication systems to counteract packet losses. Hence, it is assumed that lower layers implement an entity detecting transfer frames as either correct or wrong (in this case transfer frame are actually erased), depending on whether the code words composing each transfer frame are decoded correctly or not. Erasure codes are particularly appealing in scenarios where the data integrity plays a crucial role (as complement to lower layer coding schemes), in scenarios where long delays make ARQ schemes impractical, or when complexity limitations prevent the use of long Physical Layer codes.

Low-Density Parity-Check (LDPC) codes for recovering packet erasures were considered in reference [1]. Through the use of a (nearly) ideal decoding algorithm and an optimized code design, performances close to theoretical limits may be achieved, while decoding complexity is kept low. This is mainly due to the sparse nature of the proposed codes.

B. Erasure Coding Protocol

The erasure coding protocol is to be implemented within a shim layer positioned above the CCSDS Encapsulation Service, so as to improve the transmission robustness of LTP segments and bundles forwarded from upper layers. And it should also be close to CCSDS Space Data Link Protocol (SDLP) layers, where actually transfer frame erasures originate and are detected. Further, such a positioning allows avoiding or at least limiting the propagation of information erasures upwards in the CCSDS protocol stack. For LTP segments containing red-parts, the use of erasure codes complements the ARQ mechanisms used by the LTP protocol entity to recover the missing LTP segments by retransmission.

The interaction of the Erasure code (EC) Service with the other adjacent layers of the CCSDS protocol stack is depicted in figure 1.

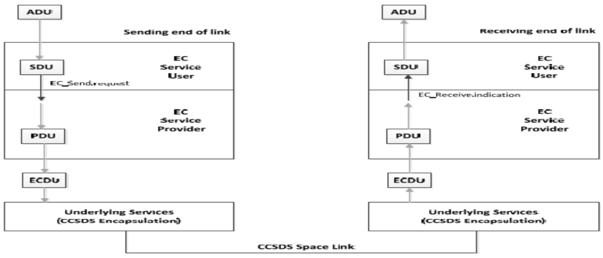

Fig.1: Layered Approach for Implementing Erasure Codes

The Service data units (SDU) of the EC Service is the Application data units (ADU) received from the upper protocol

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layer, such as LTP,BP, IPoC, or CFDP: an LTP segment, a bundle, an IP datagram, or CFDP Protocol data unit (PDU) respectively. The PDU of the EC Service is the ECDU generated during the erasure coding process at the sender side and submitted to the erasure decoding process at the receiver side.

Architectural Elements

The erasure coding and decoding functionalities shall be implemented in the erasure coding protocol entity with respect to: The sender peer shall get the ADUs (LTP segments or bundles) from the upper layer as input and generate the ECDUs (according to encoding algorithms); the receiver peer shall reconstruct by means of erasure decoding algorithms the ADUs that were erased during the transmission over the space links.
The encoding (decoding) protocol entity shall comprise the following elements:

Encoding matrix:

Encoding (decoding) engine, this carries out the encoding (decoding) processes, according to the algorithms and the parity check matrices. The encoding process takes as input the ADUs, which are copied in the encoding matrix for the consequent generation of redundancy symbols, referred to as data redundancy units. Protocol engine, which processes the native ADUs and the generated DRUs, performs the packetization service consisting in the composition of ECDUs, to be forwarded to the CCSDS Encapsulation Service.

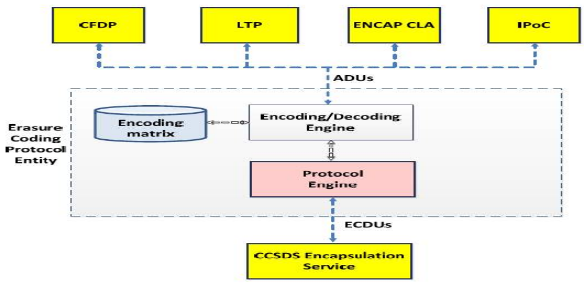

Fig. 2: Diagram of the Erasure Coding Protocol Entity

Protocol Procedures Sending End

The erasure coding operations carried out by the protocol entity shall consist of the following steps: The encoding engine is configured according to the Coding parameter (CP), specifying the coding scheme(e.g., k, n) and the coding family characteristics (e.g., random seed generator). A number k of ADUs are fed into the encoding matrix. ADUs are copied bitwise so to fill each row of the matrix, which is therefore denoted as LW;

The number of columns corresponds to the maximum size acceptable for the specific coding strategy. The value must be known by the sender and receiver peers either by pre configuration (statically) or through dedicated signalling (erasure coding protocol header).In case the matrix is not filled completely, padding bytes are added to fill the in complete rows, in order for the encoding process to perform properly;

Each LW is given a dedicated counter, LWC to be used afterwards for signalling purposes. A number n-k DRUs are generated according to the selected coding strategy applied to the data stored in the Encoding matrix. The native k ADUs and the generated n-k DRUs, generally termed LSes, are assigned a common counter that uniquely identifies the set of LSes generated during that specific encoding round; LSes are forwarded to the protocol engine, which appends to each of them the EC Header, carrying the information necessary (e.g., LWC, LSC, CP) to the receiver peer decoding engine to correctly perform the decoding process.

A CRC-32 code is computed on each data unit constructed at step f, composed of EC Header and LS, and eventually appended as trailer. The newly generated data units constructed at step i are termed erasure coding data units and are forwarded to the underlying layer.

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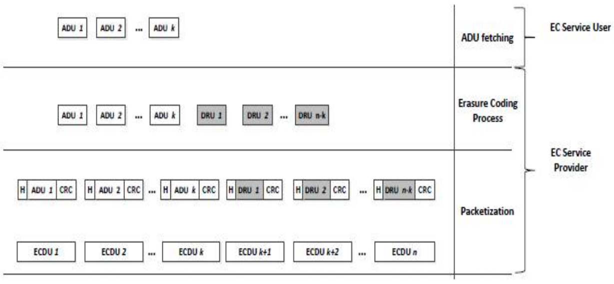

Fig. 3: Overall protocol procedures at the sending side

Receiving End

The erasure decoding operations carried out by the protocol entity shall consist of the following steps:
A number t of ECDUs are received by the erasure decoding protocol entity; the protocol engine processes the EC Header and forwards the information there in contained to the decoding engine in order to eventually start the decoding procedure; the LSes are extracted from the received ECDUs and forwarded to the decoding engine. LSes belonging to the same LSC range are stored in a temporary buffer and processed according to associated LWCs:

In case of consecutive LWC values less than k, LSes are recognized as native ADUs and immediately forwarded to the LTP layer; In case of non-consecutive LWC values less than k, LSes are stored in the decoding buffer before the decoding process actually starts;
In case of LWC values greater than k−1:
If the decoding buffer is empty, the decoding process is not started and the temporary buffer is flushed,
If the decoding buffer is not empty, the decoding process is started;
In the case of successful decoding process (if initiated), the reconstructed ADUs are forwarded to the LTP protocol layer and all buffer flushed.

Essentials

A binary linear block code is designated by C(n, k) where n is the codeword(or block) length and k the information length (or code dimension). The resulting code rate is given by R = k / n . LDPC codes, i.e., a class of linear block codes having sparse parity-check matrices, are considered here.

The (m×n) parity-check matrix H fully defines the LDPC code, where in the following only the case where m = n − k is taken into account. An LDPC code may also be represented via a bipartite Tanner graph, i.e., a graph with two types of nodes, Variable Nodes (VNs) and Check Nodes (CNs), such that each edge connects two different types of nodes. While the VNs correspond to the code symbols (associated with the columns of H) the CNs corresponds to the constraints on the code symbols (i.e., the rows of H). Whenever a VN Vi is connected to a CN Cj the corresponding entry hj,I of the parity check matrix H is different from zero.

Generally, a code word is formed by multiplying message bits with the generator matrix G. Since, we have already defined a parity check matrix H, we form the generator matrix G from H. For that row column transformation is done. I.e. G=$[I_k P_{n-k}]$is transformed into H=$[-P^T I_{n-k}]$ which is a complex process. So here we use H to form the code. Parity check matrix H is formed using irregular repeat accumulate code (IRA).

LDPC codes offer lower complexity decoding than turbo codes. However, a disadvantage of LDPC codes is an encoding complexity which can be quadratic in the code length. A recent addition to the family of turbo-like codes, repeat accumulate (RA) codes, provides a solution to this problem. Repeat-accumulate codes were first presented as a class of simple turbo codes for which coding theorems could be developed. However it was soon realized that, although simple, RA codes are powerful turbo codes in their own right. When viewed as a serially concatenated turbo code, the two constituent codes of an RA code are a rate- 1/q repetition code and a rate-1 1/1+D convolutional code, called an accumulator, with a standard inter-leaver between them (reference [5]). RA codes can also be designed with an irregular degree distribution by using an irregular repetition code.

For the binary erasure channel, Jin et al. have established that IRA code ensembles exist which can be decoded reliably

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in linear time at rates arbitrarily close to channel capacity. Alternatively, IRA codes can be represented as a class of LDPC codes. When viewed as an LDPC code, the accumulator corresponds to weight two columns in the parity-check matrix of the code while the inter leaver determines the structure of the remaining columns in the parity-check matrix, whose weight is determined by the repetition code. The power of this interpretation of IRA codes is that they can be encoded using serial concatenation of the two constituent codes, as for turbo codes, but decoded using ML-P decoding on the code's Tanner graph, as for LDPC codes, thus gaining both the low encoding complexity of turbo codes and the decoding power and parallelization of LDPC codes. It is these codes we consider in this paper.

C. Code Specification

The proposed scheme is a concatenation of two codes: the outer code: a short random code and the inner code: an IRA LDPC code obtained by a random permutation-based construction (see reference [1]).The overall code is referred to as Flexible IRA (F-IRA) code. Both component codes are discussed in detail in the following subsections.

Outer Code

The outer code is specified by the $((n_o - k_o) \times n_o)$ parity-check matrix , $H_o = [H_{o,u}\ H_{o,p}]$,where k_o is the information length; no the block length of the outer code; $H_{o,u}$is a random matrix of size $((n_o - k_o) \times k_o)$, whose elements are set to zero or one with uniform probability;$H_{o,p}$is the $((n_o - k_o) \times (n_o - k_o))$identity matrix.

Inner Code

The inner code is specified by the $((n_i - k_i) \times k_i)$parity-check matrix, $H_i = [H_{i,u}\ H_{i,p}]$, where Ki is the information length; ni the block length of the outer code; $H_{i,p}$is the $((n_i - k_i) \times (n_i - k_i))$dual diagonal matrix that ensures low-complexity encoding.

$$\mathbf{H}_{i,p} = \begin{bmatrix} 1 & 0 & 0 & \cdots & 0 & 0 \\ 1 & 1 & 0 & \cdots & 0 & 0 \\ 0 & 1 & 1 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 1 & 0 \\ 0 & 0 & 0 & \cdots & 1 & 1 \end{bmatrix};$$

The matrix $((n_i - k_i) \times k_i)$,$H_{i,u}$is the binary matrix obtained by random-permutation based construction.

Overall Code

The overall concatenated code is given by the $((n - k)\times n)$ parity-check matrix:

$$\mathbf{H} = \begin{bmatrix} \mathbf{H}_o & \mathbf{0} \\ \mathbf{H}_{i,u} & \mathbf{H}_{i,p} \end{bmatrix};$$

k_o= k and n_i= n ;It consists of a small but dense part $H_o$and a sparse part$H_i = [H_{i,u}\ H_{i,p}]$.

D. Code Design

The configuration n = ni = 512is chosen along with an outer random code with parameters (256,246).

Outer Code Design

Outer code length no is chosen to be 256 and the information length k_o is 246. Therefore the number of parity bits $(n_o$-$k_o)$ is m_o = 10. The parity check matrix $H_{o,u}$ is of order (10 x 246) and the identity matrix Hop is of order (10 x 10).The entries of the matrix $H_{o,u}$ is formed using uniform random number generator.

Uniform random number generator

To generate the entries of the matrix $H_{o,u}$ the following Linear Congruential Generator (LCG) may be used:$x_{t+1} = (ax_t + c) \bmod h$, where$x_t$is a pseudorandom number and the next pseudorandom number is denoted as x_{t+1};

a =1103515245, c =12345, h = 2^31;$x_0$is called the seed of the pseudorandom number generator and shall be set such

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that $0 \leq x_0 < h$; In this work x_0 is chosen to be 0. An entry of the matrix $H_{o,u}$ is obtained by generating a pseudorandom number using the LCG and by performing the operation x_t mod 2.

Inner Code Design

Inner code length n is chosen as 512 and rate is chosen to be R_i = ½. Therefore $k_i = R_i*n_i$ = 256. Node oriented Variable node (VN) degree distribution is considered for $H_{i,u}$, Φ(x) = 0.543x^3 + 0.102x ^4+ 0.008x^5 + 0.020x ^6+ 0.008x^7 + 0.008x^8 + 0.047x^9 + 0.266x^8 (see reference [6]).The parity-check matrix $H_{i,u}$ is generated as follows: Inner code-rate, as well as the code dimension k_i (and thus n_i) are selected. The node oriented VN degree distribution for $H_{i,u}$ is denoted by Φ(x) is selected. Based on Φ(x) a vector $u=(u_0, u_1, \ldots, u_{ki-1})$ containing the ki column weights of $H_{i,u}$ is generated. Permutation vector $\pi=(\pi_0, \pi_1 \ldots, \pi_{mi-1})$ is defined and randomly permuted. The random permutation vector $\pi=(\pi_0, \pi_1 \ldots, \pi_{mi-1})$ may be generated according to the following rule: The counter j = 0 is set and π is initialized as an all-zero vector.

A uniform random number p Є [0, j] is generated. The LCG defined in 2.1.1 shall be used to yield x_t. Hence $p = x_t \bmod (j+1)$. $\pi_j = \pi_p$ is set .π_p = j is set. These steps are repeated as long as j ≤ mi.

The u_l non-zero indices of the generic lth column of $H_{i,u}$ are denoted as $q_0, q_1 \ldots, q_{ul-1}$. The zeroth column of $H_{i,u}$ $q_j = \pi_j$ is assigned for $j=0 \ldots u_0 - 1$; i.e., the non-zero entries of the zeroth column are determined from the random permutations. The columns of the matrix $H_{i,u}$ shall be constructed as follows: For the first column: $q_j = \pi_{j+u0}$ for $j=0 \ldots u_1 - 1$. For the second column: $q_j = \pi_{j+u0+u1}$ is obtained for $j=0 \ldots u_2 - 1$, etc.

The process continues l steps until the number of remaining elements π is less than the column weight under consideration. When this happens, a new permutation vector is generated, and the above described procedure restarts from the l-th column. The procedure is iterated until the last column of $H_{i,u}$ has been filled with ones. Finally, the inner code parity-check matrix is obtained by concatenation with a double diagonal matrix $H_i = [H_{i,u} H_{i,p}]$.

Overall Code Design

Parity check matrix H is formed of the order ((n-k) x n) i.e. (266 x 512), by concatenating inner and outer code.

$$\mathbf{H} = \begin{bmatrix} \mathbf{H}_o & \mathbf{0} \\ \mathbf{H}_{i,u} & \mathbf{H}_{i,p} \end{bmatrix};$$

E. Encoding

Encoding consists of generating n code symbols out of the k information symbols at the encoder output. Only systematic codes are considered, i.e., codes for which the information symbols are also transmitted and are thus part of the codeword. Hence the length-n code word can be formally split into a part that corresponds to the k information symbols and a part that is made up by the m parity symbols. By noting that each of the m parity symbols can be expressed as a linear combination of the k information symbols, encoding may be generally described follows:

a) The m parity symbols are considered as erasures, i.e., a received vector y that contains all the k information symbols and m erasures corresponding to the parity symbols is assumed.

b) The Maximum-Likelihood Pivoting (ML-P) decoder is used to recover the erasures by solving $x_{k'} H_{k'}^T = x_k H_k^T$.

Above, encoding of LDPC codes is turned into a pure decoding problem, where the decoder works only with the parity-check matrix Hof the code. A detailed discussion on the ML-P decoder follows in the next subsection.

For some classes of LDPC codes, such as Irregular-Repeat-Accumulate (IRA) LDPC codes, encoding can be further simplified (reference [4]). The parity-parity check matrix H may be formally expressed as H = $[H_u \; H_p]$, where for the IRA codes under consideration H_u is a sparse (unstructured) matrix corresponding to the information symbols and H_p is a double diagonal matrix corresponding to the parity symbols. As a result of the double diagonal structure of H_p, each parity symbol is a sum of a set of information symbols and another already known parity symbol (reference [4]). This is visualized in figure 4, where the upper branch stands for the information symbols and the lower branch for the parity symbols. The double diagonal matrix H_p corresponds to an accumulator with transfer function1/ (1+ D) .

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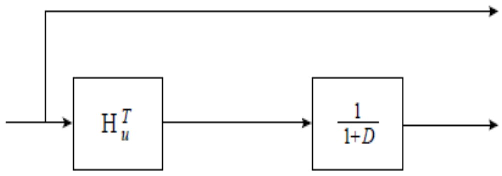

Fig. 4: Encoding of systematic IRA code

F. Decoding

The ML-P decoding of LDPC codes (reference [6]) is considered. ML- P decoding is a reduced complexity decoding algorithm that attempts to solve most of the erasures by applying light ITerative (IT) decoding, whereas only a small number of erasures α (referred to as pivots) is resolved by more complex Maximum-Likelihood (ML) decoding if necessary.

On erasure channels, ML decoding may be well implemented by Gauss-Jordan elimination. The performance of the algorithm ranges from that of IT decoding to that of ML decoding, depending on the computational capabilities of the decoding platform. More specifically, the algorithm performance can be adjusted by properly setting the parameter αmax, i.e., the maximum number of pivots and hence the dimension of the system on which Gauss-Jordan elimination shall be applied. If α_{max}=0 only IT decoding is performed, while for α_{max}=m decoding is done.

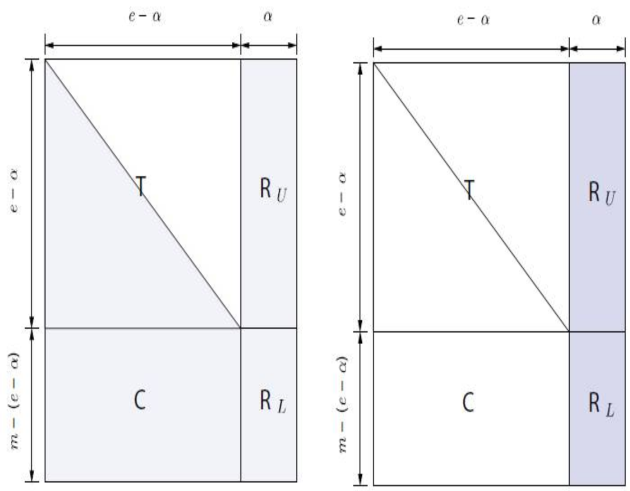

Fig. 5: Matrix HK after Triangulation (Left) and after Nullification (Right)

In more detail, the ML-P decoding algorithm attempts to recover the values for $x_{k'}$ by solving $x_{k'} H_{k'}^T = x_k H_k^T$. The algorithm can be summarized as follows:

a) Approximate lower triangulation procedure. The matrix $H_{k'}$ is transformed into an approximate triangular matrix, as depicted in figure 5 (left), by row and column permutations only. Accordingly permutations of x_k and $x_k H_k^T$ are also required. The obtained matrix is composed of a lower triangular matrix T and of the three sparse matrices C, RU, and RL. In the process, some of the columns blocking the triangulation of $H_{k'}$ are moved to the right-most part of $H_{k'}$ and hence form RU, and RL at the end of the procedure. The α unknowns associated with such columns are called reference variables or pivots. The choice of the pivots can be made in different ways. In the sequel, the Maximum Column Weight (MCW) pivoting algorithm from reference [6] is used. The complexity of this stage is O(N2). The complexity of the above described column permutation is O(N).

b) Nullification procedure. T is transformed into an identity matrix by row additions. Moreover, C is made equal to the zero matrixes by row additions, leading to the matrix depicted in figure 5 (right). It should be noted that, because of the row additions, both RU, and RL may not be sparse any more. Corresponding row additions on the known term are also required.

c) Gaussian elimination procedure. Gauss-Jordan elimination is applied to RL to recover the α reference variables. Corresponding manipulations on the known term are also required.

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d) Final IT decoding step. The remaining e −α unknowns are solved by simple IT decoding. Overall complexity of this decoding method is of the order O(N3) (reference[9]).

III. SIMULATION RESULTS

Encoding and decoding of various data was done to study the performance of the algorithm. The number of errors corrected by inputting random and burst errors was examined.

The efficiency of code is computed. It has approximately 90 percentage of efficiency. The results used for computing efficiency are tabulated in the table.

TABLE I: RESULTS BASED ON WHICH EFFICIENCY IS COMPUTED

BURST ERROR	
No. of errors	No. of errors corrected
41	40
48	48
35	35
42	39
50	50
RANDOM ERRORS	
69	50
86	63
99	67
92	69
71	64

The algorithm was compared with existing convolution coding algorithm and the performance was compared. This algorithm showed better performance compared to convolution code.

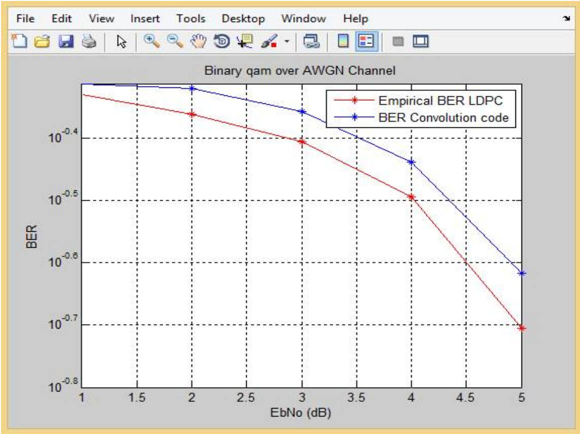

Fig. 6: Comparison of BER performance of convolutional and new coding scheme

IV. CONCLUSION

Data unit losses in deep space communications are currently faced using retransmission techniques which are however inefficient due to the large round trip delays. For this reason, the Consultative Committee for Space Data Systems (CCSDS) has recently considered packet erasure correcting codes for inclusion in its recommendations for space data system standards. Erasure correcting codes are expected to replace (or drastically reduce) retransmission requests. Erasure codes operate on packets instead of bits and are usually implemented above at the upper layers of the

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communication stack. These codes operate at the upper layers of the space link protocol and constitute an attractive new frontier for zero packet loss in future space communications. In this paper a novel framework for packet loss recovery in the Consultative Committee for Space Data Systems (CCSDS) telemetry downlink is presented. The framework relies on packet-level LDPC erasure correcting codes and on low complexity maximum likelihood (ML) pivoting decoding. The code is characterized in this work.

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