Rate-Compatible Shortened LDPC Codes for Deep Space Fading Channel

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Abstract —Accumulate-Repeat-4-Jagged-Accumulate (AR4JA) code is the special class of LDPC codes which has great error correcting capability for deep space communications. Nevertheless, it is quite not suitable to create rate-compatible scheme from AR4JA code due to its high decoder implementation complexity. This paper presents the construction of rate-compatible shortened LDPC codes for deep space application which can facilitate the decoder implementation. The high rate regular quasi-cyclic LDPC code which has low implementation complexity is utilized to construct the rate-compatible code. According to the parameters from CCSDS standards, simulation results show that the proposed rate-compatible codes exhibit the BER performance almost identical to the well-designed AR4JA codes at any code rate under deep space environment modelled by Rician fading channel.

Index Terms—LDPC codes, rate-compatible codes, deep space communications, Rician fading channel

I. Introduction

Deep space communication system is the ultra-long distance communication between spacecraft and ground control station [1]. This very long distance can lead to severe signal degradation and poor system performance. Moreover, this type of communication has strictly limited resources [1] such as transmission power of spacecraft and space to install repeater. So the implementation of error correcting code is necessary.

Low-Density Parity-Check (LDPC) codes were first introduced by Gallager in early 1960s [2]. LDPC code is one of the most powerful error correcting codes widely adopted in many communication standards including deep space communications [3]. The error correcting performance of this code with iterative decoding is very close to the theoretical limit i.e., the Shannon limit [4]. Furthermore, its iterative decoding can be easily and parallelly implemented in hardware [5].

It is known that one of the most important parameters of LDPC code is the code rate. The code rate is defined as the number of message bits divided by the number of coded bits. The error correcting capability is inversely proportional to this parameter. Typically, LDPC code is designed for a specific code rate to deal with specific noise level. For example, low rate code is used to maintain reliability of communication systems with low SNR while medium and high code rates suit well with better channel conditions. In order to appropriately handle rapidly changing environmental conditions, the code rate should be flexible and adaptive. This means that many channel codes with different rates must be employed. And it is quite expensive in the practical point of view.

Rate-compatible (RC) code is a solution to the previous mentioned problem. This kind of code uses only a single pair of encoder-decoder to support different code rates. Puncturing and shortening are the main techniques for the construction of RC codes [6]–[8]. The Consultative Committee for Space Data Systems (CCSDS) states that a family of LDPC codes of rates 1/2, 2/3 and 4/5 with message lengths 1024, 4096 and 16384 bits must be employed to combat error arisen in deep space communication systems [3]. Typically, rate-1/2 code will be punctured to form RC codes for these systems.

AR4JA code, which is a modified LDPC code proposed by D. Divsalar et al [9], is specially designed to achieve a very good BER performance in deep space applications [9]. In order to obtain an RC scheme, AR4JA code with rate 1/2 is punctured to construct a family of codes according to CCSDS standard. However, puncturing of AR4JA code is not suitable due to its high decoding complexity [10]. This is because the excessive decoding iterations are needed for puncturing scheme [6]. Therefore, we avoid this problem by constructing RC code based on shortening technique [11]. Noting that this topic has never been mentioned before in deep space communication. In contrast to puncturing technique, shortening is a technique to construct a family of lower code rates from the original high-rate code (also-called daughter code).

It is worth to mention that most of researches about RC-LDPC codes in deep space application were performed over an AWGN channel model [9], [12] or a Rayleigh fading channel model [13], [14]. In fact, deep space environment should be appropriately modelled as a Rician fading channel [15]. By using the parameters from CCSDS standard, shortened RC-LDPC codes are investigated under Rician fading environment.

The remainder of this paper is organized as follows. Section II describes an introduction to the basics and backgrounds about LDPC codes, AR4JA codes and

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shortening scheme. Deep space channel model is explained in section III. The simulation results are discussed in section IV. Finally, the conclusion is presented in section V.

II. Basics and Backgrounds

This section briefly describes the backgrounds for LDPC codes and AR4JA codes. The construction of RC-LDPC codes based on shortening scheme used in this paper is introduced.

A. *Low-Density Parity-Check Codes*

It is well known that LDPC code is a class of linear block codes [16]. LDPC code is defined by the parity check matrix **H**. Unlike other linear block codes, **H** is a low-density matrix, i.e., the number of non-zero entries is less than that of zero entries. There are two subclasses of LDPC codes: regular LDPC codes and irregular LDPC codes. For regular LDPC codes, the number of non-zero entries in each row, known as row weight (w_r), is the same and the number of non-zero entries in each column, known as column weight (w_c), is also the same. Irregular LDPC codes can have different row weights or column weights. Therefore, a useful design freedom is flexibly provided with irregular LDPC codes. Generally, irregular LDPC codes tend to outperform regular LDPC codes [17].

A typical block diagram of communication system that utilizes LDPC codes of rate of $R=k/n$ is shown in Fig.1. This system can be described as follows. A message **m** of length k bits is firstly encoded into a codeword **c** of length n bits. The encoder generates n-k parity bits and combines them with the message. After that, the codeword **c** is mapped by the modulator to form the modulated signal **x** which is then sent through the noisy channel. At the receiver, the received signal **y** is demodulated and the demodulator output is **c′**. The signal **c′** is normally transformed into a probabilistic value before preforming the decoding step. Finally, the LDPC decoder outputs the estimation of message **m′**.

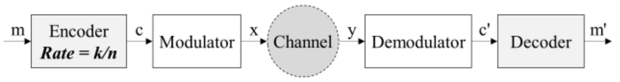

Fig. 1. Block diagram of communication system encoded with LDPC code of rate $R=k/n$.

B. *AR4JA Codes*

AR4JA code is a special class of LDPC codes designed for deep space applications. According to the deep space communication standard established by CCSDS organization, this class of code has three code rates and three lengths. These parameters are summarized in Table I [3].

TABLE I: CODEWORD LENGTHS FOR SUPPORTED CODE RATES

Message length k	Codeword length n		
	Rate = 1/2	Rate = 2/3	Rate = 4/5
1024	2048	1536	1280
4096	8192	6144	5120
16384	32768	24576	20480

The parity-check matrix **H** of AR4JA code of rate 1/2 is specified by the matrix given below [3].

$$\mathbf{H}_{1/2}=\begin{bmatrix} 0_M & 0_M & I_M & 0_M & I_M\oplus\Pi_1 \\ I_M & I_M & 0_M & I_M & \Pi_2\oplus\Pi_3\oplus\Pi_4 \\ I_M & \Pi_5\oplus\Pi_6 & 0_M & \Pi_7\oplus\Pi_8 & I_M \end{bmatrix}$$

where 0_M means the zero matrix of size $M\times M$, I_M is an $M\times M$ identity matrix, $\oplus$ operation is to produce block circulant and Π_1 through Π_8 are permutation matrix. The length of code is directly related to the parameter M.

Similar to the parity check matrix for AR4JA code of rate 1/2, the parity check matrices for AR4JA codes of rate 2/3 and rate 4/5 are shown below [3].

$$\mathbf{H}_{2/3}=\left[\begin{array}{cc|c} 0_M & 0_M & \\ \Pi_9\oplus\Pi_{10}\oplus\Pi_{11} & I_M & \mathbf{H}_{1/2} \\ I_M & \Pi_{12}\oplus\Pi_{13}\oplus\Pi_{14} & \end{array}\right],$$

$$\mathbf{H}_{4/5}=\left[\begin{array}{cc|c} 0_M & 0_M & \\ \Pi_{21}\oplus\Pi_{22}\oplus\Pi_{23} & I_M & \mathbf{H}_{3/4} \\ I_M & \Pi_{24}\oplus\Pi_{25}\oplus\Pi_{26} & \end{array}\right],$$

where

$$\mathbf{H}_{3/4}=\left[\begin{array}{cc|c} 0_M & 0_M & \\ \Pi_{15}\oplus\Pi_{16}\oplus\Pi_{17} & I_M & \mathbf{H}_{2/3} \\ I_M & \Pi_{18}\oplus\Pi_{19}\oplus\Pi_{20} & \end{array}\right].$$

The AR4JA code family has a very low error floor performance but its decoding complexity is very high due to several factors, e.g., a large number of average iterations [10].

C. *Shortening*

Shortening is a technique to construct a rate-compatible code [11]. Given the original code (known as a fixed-rate daughter code), lower-rate codes can be obtained by inserting known bits to the daughter code. Fig. 2 shows the block diagram that demonstrates the shortening process. At the transmitter side, k_s known bits, that can be zeros or ones, are inserted into the block of k_m message bits before encoding. The total of message bits and known bits are equal to the k message bits of daughter code ($k = k_m+k_s$). After encoding, these k_s known bits are removed and only n-k parity bits and k_m message bits will be sent through the channel. The codeword length for shortened case decreases to n-k_s bits. Code rate of the shortened code is given by

$$R_S=\frac{k-k_s}{n-k_s}$$

At the receiver, the k_s known bits must be inserted back to n-k_s demodulated symbols before decoding. So, the input of the decoding process has n bits. After decoding, the estimation of k message bits is produced.

Finally, the k_s known bits are removed to form the k_m estimated message bits.

In order to clearly illustrate the shortening technique, a simple example is presented. In this example, (8,4) code of rate 1/2 is used as the daughter code and this code will be shortened to form a code of rate 1/3. Firstly, k_s = 2 known bits are inserted into a block of k_m = 2 message bits before encoding. Therefore, the total symbol length before encoding is equal to $k = k_m + k_s = 4$ which is also equal to the message length of daughter code. After encoding, the k_s known bits are removed from the codeword of length n = 8 bits. Only n-k = 4 parity bits and k_m = 2 original message bits will be sent through the channel. This means that the codeword length for shortened case decreases to n-k_s = 6 bits and the code rate is then decreased to R_S = (4-2)/(8-2) = 1/3.

At the receiver, the k_s = 2 known bits are inserted back into the block of n-k_s = 6 received bits before decoding. The n = 8 codeword bits are then decoded and the decoder outputs are the estimated k = 4 message bits. Finally, the k_s = 2 known bits are removed into k_m = 2 original message bits.

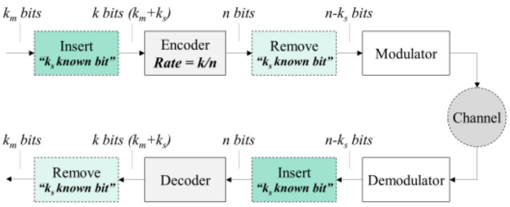

Fig. 2. An example of block diagram of (8,4) LDPC code with rate R = 1/2 is shortened into R_S = 1/3.

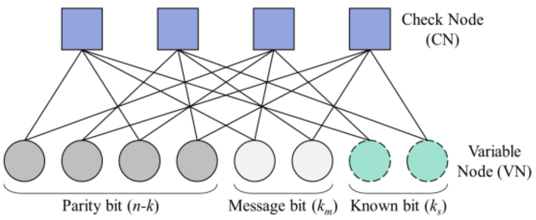

Fig. 3. An example of Tanner graph of (8,4) shortened LDPC code with rate n = 8 bits, k_m = 2 bits and k_s = 2 bits.

It is known that the parity-check matrix of LDPC codes can be graphically represented by a Tanner graph [16]. A Tanner graph is a bipartite graph with two sets of nodes: n-k check nodes (CN) and n variable (bit) nodes (VN). Each bit "1" in the parity check matrix is represented by an edge between the corresponding CN and VN. Fig. 3 shows the Tanner graph of shortened code obtained from (8,4) daughter code in the example. Known bits can be inserted at any positions of message bits. The position of shortening directly affect the performance of the code. LDPC codes are decoded iteratively by passing the information between VN and CN according to their connections in the Tanner graph.

III. Deep Space Channel Model

As stated before, the communication over deep space channel can be appropriately modeled by Rician fading channel. This type of channel will be described in this section. Furthermore, likelihood ratio (LLR) calculation, involving in decoding process, for Rician fading channel is also presented.

A. Generation of Rician Fading Factor

It is known that wireless communication channels which have strong direct line-of-sight (LOS) path between transmitter and receiver can be properly modelled by using Rician fading channel [18]. From the literature review [19], many researches suggest that deep space communication in which LOS path is dominant should be modeled by Rician fading channel. Fig. 4 shows the block diagram of Rician fading channel with additive white Gaussian noise. The received signal at the output of a Rician fading channel is given by $y = \alpha x + n_A$, where x is the transmitted signal, n_A is Additive White Gaussian Noise (AWGN) and α is the Rician fading factor.

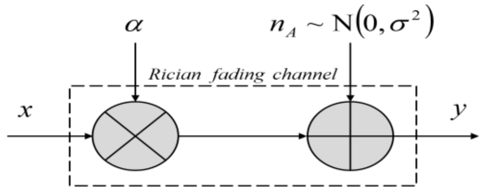

Fig. 4. An illustration of Rician Fading channel model.

The Rician fading factor can be generated by the equation

$$\alpha = \sqrt{\frac{a^2 + \left(b + \sqrt{2K}\right)^2}{2(K+1)}}$$

where a and b are independent and identically distributed Gaussian random variables. Both a and b have zero mean and unit variance. The Rician K-factor is the ratio between the power of LOS component and the power of non-LOS components, i.e., scattering components. Typically, this factor is expressed in dB, e.g., 10 dB which means that the power of LOS is ten times the power of non-LOS. The probability density function (pdf) of Rice distribution in terms of K -factor (dB) is given by [20].

$$f(\alpha) = \frac{2\alpha 10^{KdB/10}}{s^2} e^{-\left(\frac{10^{KdB/10}}{s^2}\right)(\alpha^2 + s^2)} I_0\left(\frac{2\alpha 10^{KdB/10}}{s^2}\right)$$

where $\alpha \geq 0$, KdB = 10log10(K) and I_0 is the modified Bessel function of zero order.

B. LLR Calculation for Rician Channel

A class of message passing algorithms called the min-sum decoding algorithm is often used to decode LDPC codes in practice since it is hardware-friendly [15]. To obtain a good decoding performance, the noisy received signal must be prepared in terms of the log-likelihood ratio (LLR) before performing the decoding process. For the case of a Rician fading channel, if the channel side information is assumed to be known at the receiver, LLR can be expressed as [21].

$$LLR_j = y_j \alpha_j \tag{1}$$

where LLR_j is the log-likelihood ratio of j-th received symbol, j={1,2,3,…,n}, y_j is the received symbol and α_j is the Rician fading factor corresponding to the j-th symbol.

At the first step, j-th VN node uses LLR_j as the initial message for decoding. Each VN node sends this message to the corresponding CN node according to the structure of Tanner graph. After that, each i-th CN calculates an extrinsic message to the connected j-th VN node, denoted by $L_{i\to j}$. This extrinsic message is given by [21]

$$L_{i\to j} = \prod_{j'\in N(i)-j} sign(L_{i\to j}) \cdot c_{atten} \cdot \min_{j'\in N(i)-j} \beta_{j'i} \tag{2}$$

where i={1,2,3,…,n-k}, $\prod$ is the product of array elements, sign is the signum function that extracts the sign of a real number, $0 < c_{atten} < 1$is the attenuation factor and min is the smallest elements in array. Next, this message will be used to update information at the j-th VN node. The messages at both VN and CN nodes will be updated iteratively by using the same formula [21].

IV. Simulation Result

This paper proposes RC-LDPC codes based on the shortening for deep space communication. The BER performances of the proposed codes with different message lengths and rates over deep space Rician fading channel are shown in this section. Regular Quasi-Cyclic (QC) LDPC codes with w_c = 3 are used as the daughter codes for all simulations [22]. Attenuated min-sum is used as the decoding algorithm for all the results. AR4JA codes according to CCSDS standard are used as the benchmark. Binary phase-shift keying (BPSK) modulation is employed. Following the research reported in [15], the Rician K-factor is set to be 10dB. Other simulation parameters used in this paper are summarized in Table II.

TABLE II: Simulation Parameters

Parameters	Specification
Daughter Code Rate	4/5, 2/3
Shortening Code Rate	2/3, 1/2
Message Length (k)	1024, 2048, 16384

As can be seen from equation (2), the attenuation factors play roles in decoding step. For AWGN channel, this factor is recommended to be 0.5 [21]. However, the suitable value of this factor for Rician fading channel has not been reported. Fig. 5 shows the BER performances of the proposed code with different attenuation factors. From the figure, it can be seen that the case of c_{atten} = 0.8 gives identical BER performance to the original SPA decoding with a lower complexity. We also observe the effect of c_{atten} in other cases and the results still hold. Therefore, c_{atten} = 0.8 will be used for all simulations.

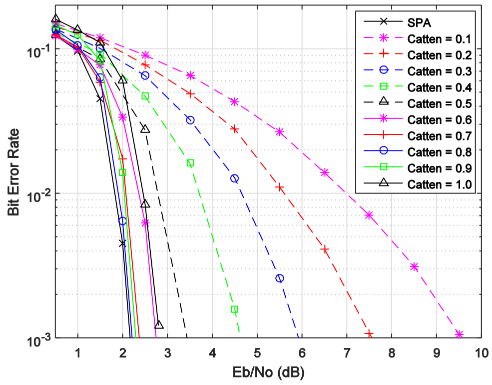

Fig. 5. The BER performances of proposed code with different attenuation factors. Daughter code of R = 4/5 with k = 4096 bits is shortened into R_S = 1/2 with k_s = 1024 bits. The maximum number of iterations is set as 50.

The BER performances of the proposed code with different maximum number of iterations for decoding (I_{max}) are demonstrated in Fig.6. The figure suggests that the appropriate I_{max} should be 20. If I_{max} = 15, the performance is inferior by approximately 0.3dB. In addition, if I_{max} is increased to 50, the performance is not further improved. Therefore, I_{max} = 20 will be used for the rest of all simulations.

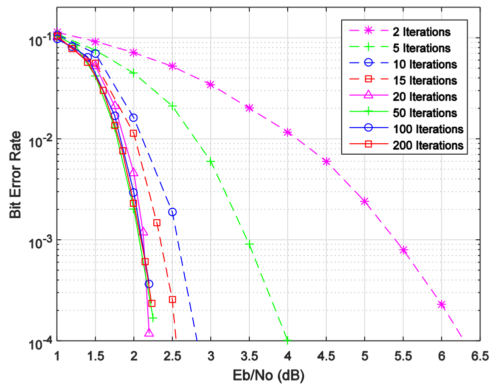

Fig. 6. The BER performances of proposed code with different maximum number of iterations. I_{max} is varied from 2 to 200. Daughter code of R = 4/5 with k = 4096 bits is shortened into R_S = 1/2 with k_m = 1024 bits.

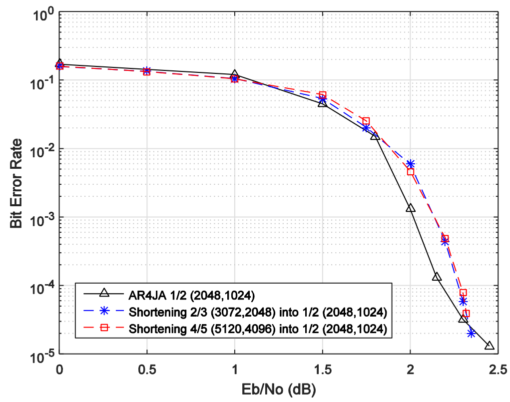

Fig. 7. The performance comparison between AR4JA code and the shortened LDPC codes (in the case of same message length). AR4JA code of R = 1/2 with k = 1024 bits (black triangle). The (3072,2048) LDPC code of R = 2/3 is used as daughter code for the shortened code of R_S = 1/2 with k_m = 1024 bits (blue asterisk). The (5120,4096) LDPC code of R = 4/5 is used as daughter code for the shortened code of R_S = 1/2 with k_m = 1024 bits (red square).

The performance comparisons between shortened LDPC codes and AR4JA code are shown in Fig. 7. Given the AR4JA code with rate $R = 1/2$ and the message length $k = 1024$, the daughter LDPC code with $R = 2/3$ and $k = 2048$ is shortened to have the same rate and the message length. This comparison is fair in the sense of message length. The figure shows that the performance of shortened LDPC code is very close to AR4JA code. The daughter code with $R = 4/5$ and $k = 4096$, is also considered. It can be seen from the figure that the shortened code gives the same performance comparing to AR4JA ($R = 1/2$) and the shortened code constructed from the daughter with $R = 2/3$.

One may think that the previous result is not fair because the daughter codes have larger k and n. Therefore we would like to investigate another case in which the daughter and AR4JA code have the same message length. This means that, for this case, the message length of the shortened codes are lower than AR4JA code. As can be seen in Fig. 8, the performances of shortened LDPC codes are worse than that of AR4JA code.

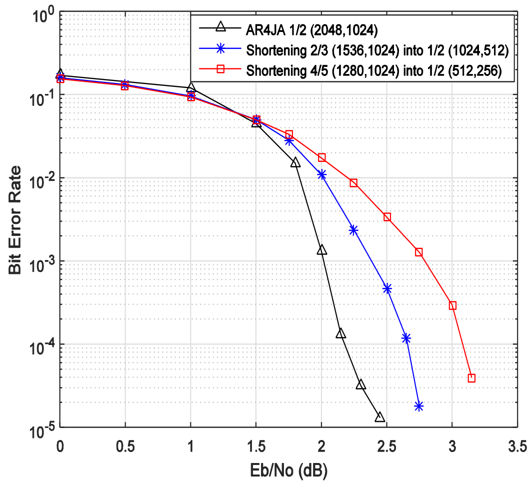

Fig. 8. The comparison of BER performance between AR4JA code and the shortened LDPC codes (the same message length of daughter code). AR4JA code of $R = 1/2$ with $k = 1024$ bits (black triangle). The (2048,1024) daughter code of $R = 2/3$ and the shortened code of $R_S = 1/2$ with $k_m = 512$ bits (blue asterisk). The (2048,1024) daughter code of R=4/5 and the shortened code of $R_S = 1/2$ with $k_m = 256$ bits (red square).

It is well known that the BER performance of good code will be increases as the length increases. Fig. 9 shows the comparison of the proposed codes with various message lengths. The shortened LDPC codes of $R_S = 1/2$ are constructed from the daughter code of $R = 4/5$ with the message lengths of 1024, 4096 and 16384 bits. It is obviously seen that the performance of the proposed codes increase when the message length of the daughter codes increase.

All the results discussed above are restricted to the case of $R_S = 1/2$. Next, the shortened code of different 4/5 is shortened into the code with $R_S = 2/3$. Similar to the results appeared in Fig. 9. The results shown in Fig. 10 have the same trend. If the results between Fig. 9 and Fig. 10 are compared, the performances of $R_S = 2/3$ shortened codes are worse than these of $R_S = 1/2$ shortened codes. This conforms with the coding theory which tells us that the performance of code varies inversely with code rate.

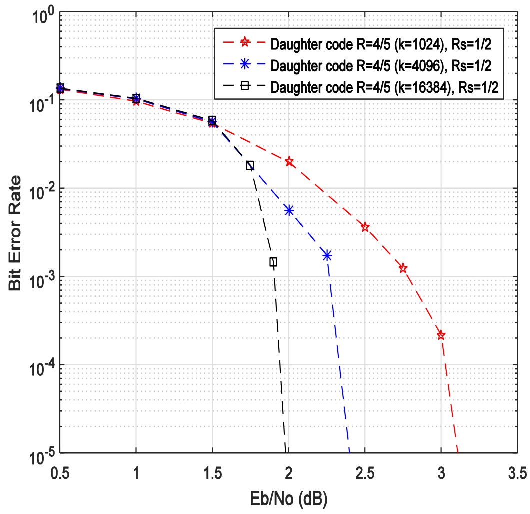

Fig. 9. The comparison of shortened code with various message lengths. The shortened LDPC codes of $R_S = 1/2$ are constructed from daughter code of $R = 4/5$ with message lengths 1024, 4096, 16384 bits.

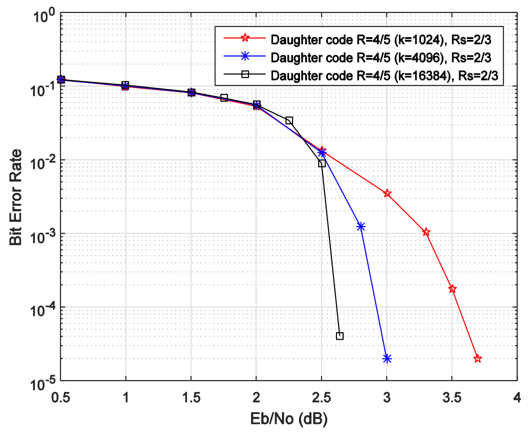

Fig. 10. The comparison of shortened code with various message lengths. The shortened LDPC codes of $R_S = 2/3$ are constructed from daughter code of $R = 4/5$ with message lengths 1024, 4096, 16384 bits.

V. Conclusions

The rate-compatible LDPC code based on shortening for deep space communications is proposed in this paper. The results clearly show that the proposed codes can provide identical BER performance to AR4JA code which is the special class of LDPC code specifically designed for deep space communications. Therefore, the proposed codes can be considered as a promising candidate for deep space communication systems.

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