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Novel distributed UEP rateless coding scheme for data transmission in deep space networks

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Abstract In deep space data transmission systems, deep space networks can be constructed on different orbits, and the data from each orbit are always associated with the different reliability requirements. In this study, a novel UEP (unequal error protection) transmission scheme based on distributed LT codes is proposed in order to ensure that all the data can be transmitted according to their own reliability requirements and obtain high transmission efficiency property. In the proposed scheme, the sub-codes on each node (orbits) were performed by a classic LT encoding process. By assigning different degree distributions to the sub-codes, all types of data can be transmitted with better transmission efficiency in comparison to the traditional scheme, and can be recovered at the destination with their own reliability requirements. Moreover, the design of the proposed scheme is much easier than that of the traditional scheme, and is also suitable to the strictly limited processing capacity property of deep space networks. By carrying out asymptotic analysis on the proposed scheme, and by obtaining the numerical and simulation results, it can be seen that the proposed scheme can approximately achieve the same UEP property and much better transmission efficiency than the traditional scheme. Additionally, the results demonstrate that the proposed scheme is much more suitable to deep space network data transmission, in comparison to the traditional scheme.

Keywords deep space networks, distributed rateless codes, UEP, encoding overhead, asymptotic analysis, design complexity

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1 Introduction

With the increasing frequency of space science projects, the body of data related to deep space communication systems is growing fast [1]. Since traditional point-to-point (P2P) systems are facing difficulties in meeting the demand for the amount of big data and multi-orbit data transmission, deep space communications networks need to be considered [2]. As the number of orbits expecting access to deep space networks grows, multiple types of data are obtained from existing orbits. Since various types of data always lead to various reliability requirements, it is necessary to transmit such data in order to satisfy the various requirements of orbits [3]. Deep space networks always entail long transmission distances and lossy channels prone to disruptions [4]. In order to transmit multiple types of data over such complicated channels and dynamic network structure conditions, many previous studies over the last decade have proposed methods to ensure that all kinds of data can be recovered with their own reliability requirements, and also to ensure the overall transmission efficiency [5].

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Rateless codes have been proposed for efficient data transmission over multi-users with different channel conditions [6]. The decoder of rateless codes can recover original input symbols (where an input symbol can be a bit, frame, packet or any other data group) by collecting a few larger numbers of output symbols, where an output symbol is the encoded data group which generated by the sum of several input symbols under Mod 2. Some codes can provide the capacity-achieving property on channels under various conditions. Actually, in most cases, the encoder of rateless codes can continuously generate output symbols until a feedback message is received. The LT codes have been invented by Luby [7] as the first class of rateless codes that could be used in practice. However, although the LT codes were capacity-achieving, they were designed for P2P systems. To provide high data transmission efficiency in networks, the distributed LT codes that have been proposed in [8,9] by encoding the symbols on different sources and relay nodes, the capacity-achieving property should be provided in the network systems.

To transmit multiple types of data with various reliability requirements, the LT-based rateless coding scheme with the UEP (unequal error protection) porperty over P2P systems has been proposed in [10–12]. With these codes, the input symbols are divided into different sets. By assigning the different selection probabilities of these sets in the encoding process, the input symbols in different sets can be recovered with different symbol error rates. The distributed UEP rateless coding scheme was invented in order to accommodate the networks in which the data are in different nodes and with different reliability requirements [13]. Unlike the distributed LT codes, the input symbols in the distributed rateless coding scheme are only encoded on source nodes, while the relay nodes us two approaches for forwarding the collected encoded symbols to the destination node. By the first approach, the relay node forwards a part of the collected encoded symbols to the destination node directly, while by the second approach the relay node forwards the XOR of two incoming encoded symbols to destination. It is clear that the feedback messages of the distributed UEP LT codes would be passed through both the destination-relay and relay-source channels. In practice, due to the long transmission distances, the distributed UEP LT codes to transmit multi-type of data on deep space networks would lead to large delay times and dramatically influence the transmission efficiency. To overcome this drawback, we propose a novel distributed UEP rateless coding scheme. By this scheme, both the source and relay nodes would perform the LT codes; then, the feedback message of each node would be sent from the next node; therefore, the influence of the delay times could be reduced while improving the transmission efficiency in deep space data transmission networks.

This paper is organized as follows. Section 2 highlights the related work. The proposed coding scheme is proposed in Section 3, and the asymptotic analysis of the proposed scheme is derived. In Section 4, we provide the criteria of encoding overheads and the degree distributions for each sub-code. The numerical and simulation results are presented in Section 5, and it is demonstrated that the proposed codes can provide an approximately optimal overhead property in comparison to the traditional distributed UEP rateless coding scheme. Finally, this paper is concluded in Section 6.

2 Related work

The traditional distributed UEP rateless coding scheme has been proposed in [13], for the distributed ensembles, in which the input symbols in different source nodes have various reliability requirements. In this scheme, the UEP property is mainly determined by the relay nodes. Consider a network with two sources and single relay node: the source nodes generate encoded symbols and deliver them to the relay node; then, the relay node is directly forward, or summed and then forwards these encoded symbols to the destination.

The forward methods on the relay node is given as follows: the encoded symbols from source nodes S_1 and S_2 are directly sent to the destination with probabilities p_1 and p_2. For the probability $p_3 = 1-p_1-p_2$, the relay node selects two encoded symbols in order to generate an output symbol and send it to the destination, where the two selected encoded symbols are generated from different source nodes.

It is obvious that the forward methods on the relay node can be considered as an LT-based UEP code,

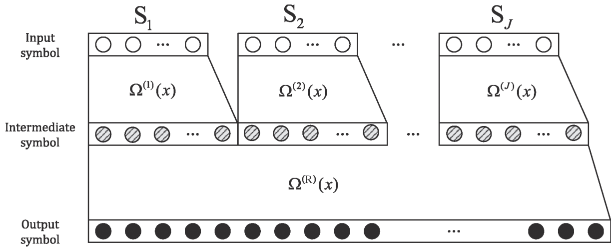

Figure 1 Encoding structure of proposed scheme.

in which the degree distribution only includes two degrees, namely, "1" and "2", while the encoding overhead is $\frac{1}{2}p_3 + p_1 + p_2 < 1$. In deep space networks, as the erasure probabilities of the channels are pretty large, the low encoding overhead on the relay node would lead to extremely larger encoding overheads on the source nodes. Additionally, because the feedback messages of the source nodes should be sent by the destination through the relay node to the source nodes, the transmission delay would also influence the transmission efficiency of deep space networks. In order to avoid these drawbacks and to improve the deep space data transmission efficiency, a novel distributed UEP rateless coding scheme for deep space network data transmission is proposed in Section 3.

3 Proposed coding scheme

In this section, a distributed UEP rateless coding scheme for deep space network data transmission is proposed. The proposed scheme shares the same coding structures with the distributed LT codes, and by assigning different coding parameters to the sub-codes on each node, this scheme can provide the UEP and high transmission efficiency properties in deep space networks.

3.1 The encoding process of proposed coding scheme

The encoding process of the proposed scheme can be seen in Figure 1. The encoding process is divided into two steps: in the first step, the encoders on the source nodes generate intermediate symbols and deliver these symbols to the relay node "R", while in the second step, the relay node encodes the intermediate symbols into output symbols and transmits them to the destination node "D".

In the first step, each source node S_i generates intermediate symbols by selecting the input symbols on this node by using the degree distribution $\Omega^{(i)}(x) = \sum_d \Omega^{(i)} x^d$. By assuming the number of input symbols on S_i is k_i, the encoding overhead as γ_i, and that the erasure probability of the source channel between S_i and R is e_i, there are totally $\frac{\gamma_i k_i}{1-e_i}$ intermediate symbols generated on S_i. In the second step, there are $\sum_{i=1}^{J} \gamma_i k_i$ intermediate symbols collected by the relay node R, while the encoder on the relay node generates output symbols with the selected intermediate symbols by using the degree distribution $\Omega^{(\mathrm{R})}(x)$. In both steps, the encoders carry out processing in the same way as the classical LT encoder [7]. The total number of input symbols is k, where $k_i = \alpha_i k$; then, we have $k = \sum_i k_i = \sum_i \alpha_i k$.

3.2 The decoding process of proposed coding scheme

In the proposed coding scheme, there is only one decoder on the destination. This decoder implements a belief propagation decoding algorithm in order to recover the input symbols. Although the input symbols are delivered from different source nodes, these input symbols and the collected output symbols can be considered as an independent LT code in the destination. The bipartite graph of the decoding process is shown in Figure 2.

To analyze the decoding process of the proposed coding scheme, the overall output degree distributions $\Omega(x)$ have to be known. Let $\Phi(x)$ represent the degree distribution of intermediate symbols, that are given by the following Lemma.

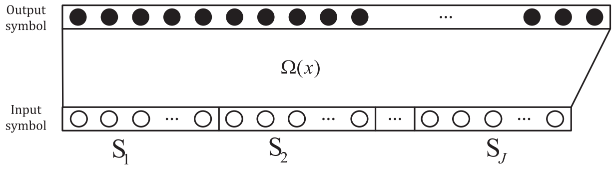

Figure 2 Decoding structure of proposed scheme.

Lemma 1. The degree distribution of intermediate symbols $\Phi(x)$ is computed by

$$\Phi(x) = \sum_{i=1}^{J} \frac{\gamma_i k_i \Omega^{(i)}(x)}{\sum_{j=1}^{J} \gamma_j k_j}. \tag{1}$$

Proof. Since the amount of intermediate symbols is $\sum_{j=1}^{J} \gamma_j k_j$, and the number of intermediate symbols with degree d is $\sum_{i=1}^{J} \gamma_i k_i \Omega_d^{(i)}$, then, the probability of an intermediate symbol with degree d is

$$\Phi_d = \frac{\sum_{i=1}^{J} \gamma_i k_i \Omega_d^{(i)}}{\sum_{j=1}^{J} \gamma_j k_j}. \tag{2}$$

Hence Eq. (1) is obtained.

Since $\Phi(x)$ and $\Omega^{(\mathrm{R})}(x)$ are given, the overall output degree distribution $\Omega(x)$ can also be given.

Theorem 1. The overall degree distribution for the output symbols $\Omega(x)$ of the proposed scheme is given by

$$\Omega(x) = \Omega^{(\mathrm{R})}(\Phi(x)). \tag{3}$$

Proof. Because the number of the intermediate symbols $\sum_{i=1}^{J} \gamma_i k_i$ and degree distribution $\Phi(x)$ are given, we can begin to calculate the overall output degree distribution. For the output symbols generated with degree 1, these output symbols are generated by selecting only one intermediate symbol. Thus, the output degree distribution of these output symbols is $\Phi(x)$. For the output symbols generated with degree d $(d > 1)$, these output symbols are generated by XORed d intermediate symbols, and the output degree distribution of these output symbols is $(\Phi(x))^d$. Since the degree distribution on the relay node is $\Omega^{(\mathrm{R})}(x)$, then the output degree distribution $\Omega(x)$ can be calculated as

$$\Omega(x) = \Omega_1^{(\mathrm{R})}(\Phi(x)) + \Omega_2^{(\mathrm{R})}(\Phi(x))^2 + \cdots + \Omega_d^{(\mathrm{R})}(\Phi(x))^d + \cdots . \tag{4}$$

By summarizing this equation, we obtain (3).

Consider an intermediate symbol with degree d. The probability of this symbol is generated by S_i is

$$q_{d,i} = \frac{\gamma_i k_i \Omega_d^{(i)}}{\sum_{l=1}^{J} \gamma_l k_l \Omega_d^{(l)}}. \tag{5}$$

Since the encoder on the relay node performs an LT encoding process, the probability of an input neighbor to each output symbol coming from the source node S_i is

$$q_i = \frac{\sum_d d\Phi_d \frac{\gamma_i k_i \Omega_d^{(i)}}{\sum_{l=1}^{J} \gamma_l k_l \Omega_d^{(l)}}}{\Phi'(1)} = \frac{\sum_d d\gamma_i k_i \Omega_d^{(i)}}{\gamma k \Phi'(1)}. \tag{6}$$

To quantify the UEP properties of source nodes, the definition K_i is the priority disparity of the source S_i, where $K_i = \frac{q_i}{\alpha_i}$. This implies the difference between the average degrees of the input symbols on different nodes.

3.3 Asymptotic analysis of proposed coding scheme

The and-or tree technique was adopted to analyze the asymptotic performance of the proposed scheme. It is worth noting that under the asymptotic conditions, the number of input symbols is considered as infinity.

Additionally, the encoding process of the proposed scheme was divided in two steps, where one was carried out on the source nodes, and the other one was carried out on the relay node. After the first step, the degree distribution of the input symbols on S_i was denoted by $\Lambda^{(i)}(x)$, where

$$\Lambda_d^{(i)} = \binom{k_i(\Omega^{(i)}(1))'}{d}\left(\frac{1}{k_i}\right)^d\left(\frac{k_i-1}{k_i}\right)^{k_i(\Omega^{(i)}(1))'-d}. \tag{7}$$

As is the case in an asymptotic condition, the number of input symbols on S_i satisfied $k_i \to \infty$; then, the degree distribution of the input symbols could be approximated as

$$\Lambda^{(i)}(x) = \exp\left\{\left(\Omega^{(i)}(1)\right)'\gamma_i(x-1)\right\}. \tag{8}$$

Let $\lambda^{(i)}(x)$ be the edge distribution of the input symbols on S_i; then, we have

$$\begin{aligned}\lambda^{(i)}(x) &= \frac{(\lambda^{(i)}(x))'}{(\lambda^{(i)}(1))'}\\ &= \frac{(\Omega^{(i)}(1))'\gamma_i e^{(\Omega^{(i)}(1))'\gamma_i(x-1)}}{(\Omega^{(i)}(1))'\gamma_i e^{(\Omega^{(i)}(1))'\gamma_i(x-1)}\,|_{x=1}}\\ &= \exp\left\{\left(\Omega^{(i)}(1)\right)'\gamma_i(x-1)\right\}.\end{aligned} \tag{9}$$

Since the probability of an intermediated symbol being generated by S_i is q_i, by considering the second step of the encoding process for an output symbol, the probability that its neighbors belong to S_i equals q_i. Since the computational complexity of the second step is $(\Omega^{(\mathrm{R})}(1))'\gamma_\mathrm{R}$, the overall average degree of the input symbols on S_i can be given by

$$\left(\Omega^{(i)}(1)\right)'\gamma_i\left(\Omega^{(\mathrm{R})}(1)\right)'\gamma_\mathrm{R}, \tag{10}$$

and the edge distribution of input symbols is

$$\lambda_{i,\mathrm{overall}}(x) = \exp\left\{\left(\Omega^{(i)}(1)\right)'\gamma_i(x-1)\left(\Omega^{(\mathrm{R})}(1)\right)'\gamma_\mathrm{R}\right\}. \tag{11}$$

According to [12], the symbol error rate of the input symbols on S_i is $y_{i,l}$; then, the symbol error rates of the proposed scheme can be computed by

$$y_{i,l} = \lambda_{i,\mathrm{overall}}\left(1-\omega\left(1-\sum_{i=1}^{J}q_i(y_{i,l-1})\right)\right),\quad l>1, \tag{12}$$

where $\omega(x) = \frac{\Omega'(x)}{\Omega'(1)}$.

4 Parameter design of proposed coding scheme

As the UEP performances of the LT-based UEP codes are mainly determined by their selection probabilities, and as can be seen from (6), the selection probability of each source node S_i is mainly determined by the variables γ_i and $\Omega^{(i)}(x)$, this means that the UEP properties of the proposed scheme are mainly determined by the encoding overheads and degree distributions on each node. In this section, we will analyze the encoding overheads and the degree distributions on each node, and provide the criteria for these parameters in the proposed coding scheme.

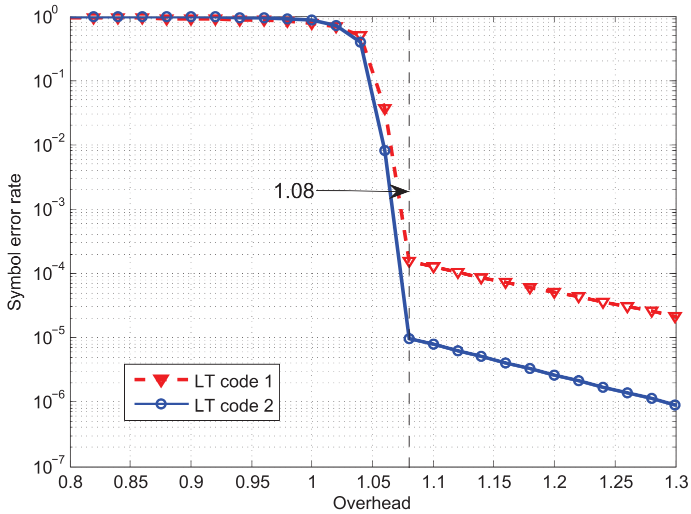

Figure 3 (Color online) Asymptotic symbol error rate of given LT codes.

4.1 Overhead of each sub-code in proposed coding scheme

On each node in the proposed coding scheme, the encoder performs an LT encoding process. The symbol error rates of the LT codes are also mainly determined by their output degree distributions and overheads. Although the encoders of the LT codes can generate as many encoded symbols as required, in order to seek to improve the transmission efficiency, an LT code with given degree distributions will have an optimal decoding overhead corresponding to the highest transmission efficiency.

The BER (bit error rate) curves of the traditional forward error control codes, can be divided into different regions, which are waterfall region and error floor region. The region where the BER dramatically decreases with SNR (signal-noise ratio) growth is termed the waterfall region. On the other hand, the region in which the SNR is larger than the waterfall region, and the BER tends to fixed or decrease very slowly with SNR growth, are termed as the error floor regions. The waterfall and error floor region phenomena are also included in the SER (symbol error rate) curves of the LT codes, the only difference is that the regions are divided by different overheads, but not by the SNRs.

Figure 3 shows the symbol error rate curves of LT codes using the robust soliton distributions with parameters ($k = 1000,\ c = 5,\ \delta = 0.1$) and ($k = 1000,\ c = 0.01,\ \delta = 0.01$), respectively. Additionally, the average degree of the output symbols in LT codes 1 and 2 are 8.282 and 10.761, respectively. Since code 2 had a larger average degree of output symbols in comparison to code1, it could provide better symbol error rate performance than code 1. It can be easily seen that in the region where the overheads satisfied $1 < \gamma \leqslant 1.08$, the symbol error rates of both codes dramatically decreased as the overhead grew, which means that this region is the waterfall region of the two codes. For the region where the overhead was larger than 1.08, the symbol error rates of both codes decreased much slower than those of the waterfall region. Then, this region was the error floor region of these two codes. As is the case in deep space communication networks, a high data transmission efficiency is one of the most important targets. Then, the optimal decoding overheads of the sub-codes in the proposed scheme are defined as the overheads corresponding to the intersection between the waterfall and error floor regions.

4.2 Output degree distribution of sub-codes in proposed coding scheme

The advisable overheads of sub-codes were obtained, and the UEP properties of the proposed coding scheme could be determined by the degree distributions of the sub-codes. To quantify the UEP performance by using priority disparity, the following theorem was obtained.

Theorem 2. Consider each source node S_i. Then, in order to obtain the priority disparity K_i, the

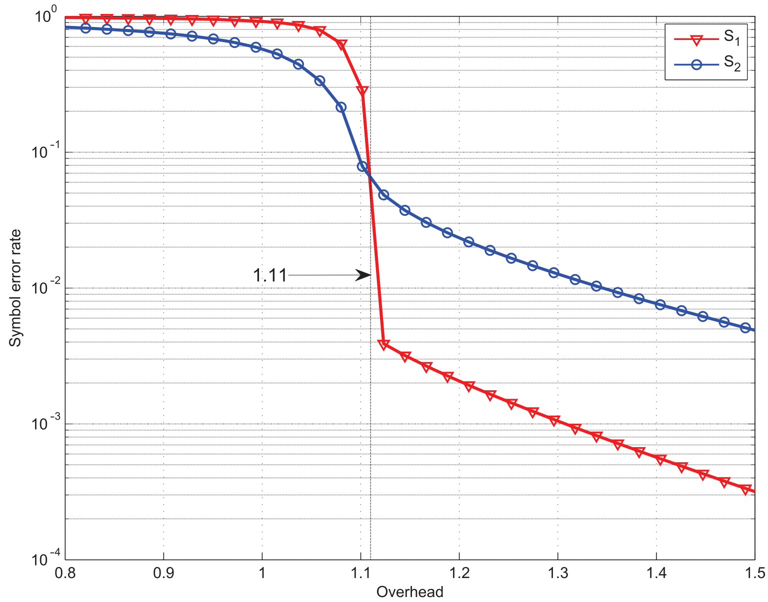

Figure 4 (Color online) Asymptotic performance of proposed code with 2 source nodes and single relay node.

output degree distribution $\Omega^{(i)}(x)$ should satisfy

$$(\Omega^i(1))' = \frac{\gamma\Omega'(1)K_i}{\gamma_i\gamma_{\rm R}\Omega'_{\rm R}(1)}, \tag{13}$$

where γ is the overall overhead, while the left part is the average degree of the intermediate symbols from S_i after the first encoding step.

After the second step of the encoding process, the average degree of input symbols on each source node S_i is increased by times $(\Omega^{(\mathrm{R})}(1))'$. But for each input symbol, the number of its identity neighbors has not been increased. In other words, although the average degrees of input symbols increased after the second step of encoding process, but all the output neighbors of each input symbol are also been neighbors of intermediate symbols which are connected with this input symbol in bipartite graph. For this reason, the LT encoder on relay node was not implemented to improve the symbol error rates but to overcome the erasure probability of the relay channel. For this reason, concerning the limited energy, load and processing capacity of the relay node, the encoding process on relay node would be as good as adopting the degree distribution with lower average degrees.

5 Simulation results

In this section, we first describe the asymptotic evaluation of the proposed scheme; and subsequently describe the comparison between the proposed coding scheme and the traditional distributed UEP rateless coding scheme; at last, the Monte-Carlo simulation results of the proposed coding scheme are also given.

Consider a deep space network with two source nodes and a single relay node, where the number of input symbols and overhead of sub-codes are the same, and the degree distributions for sub codes on source nodes are $\Omega^{(1)}(x) = 0.007969x^1+0.493570x^2+0.166220x^3+0.072646x^4+0.082558x^5+0.056058x^8+0.037229x^9+0.055590x^{19}+0.025023x^{64}+0.003137x^{66}$ and $\Omega^{(2)}(x) = 0.0782x+0.4577x^2+0.1706x^3+0.0750x^4+0.0853x^5+0.0376x^8+0.0380x^9+0.0576x^{19}$, respectively. The degree distribution for the sub-code on the relay node is $\Omega^{(\mathrm{R})}(x) = 0.057x+0.4589x^2+0.17x^3+0.1156x^4+0.0754x^5+0.0575x^6+0.0382x^7+0.0274x^8$, and the assigned encoding overhead on the relay node is 1.05. The asymptotic error performance of the proposed scheme is shown in Figure 4, under the assumption that the erasure probabilities are all zero. The input symbols of S_1 can provide better error performance than those of

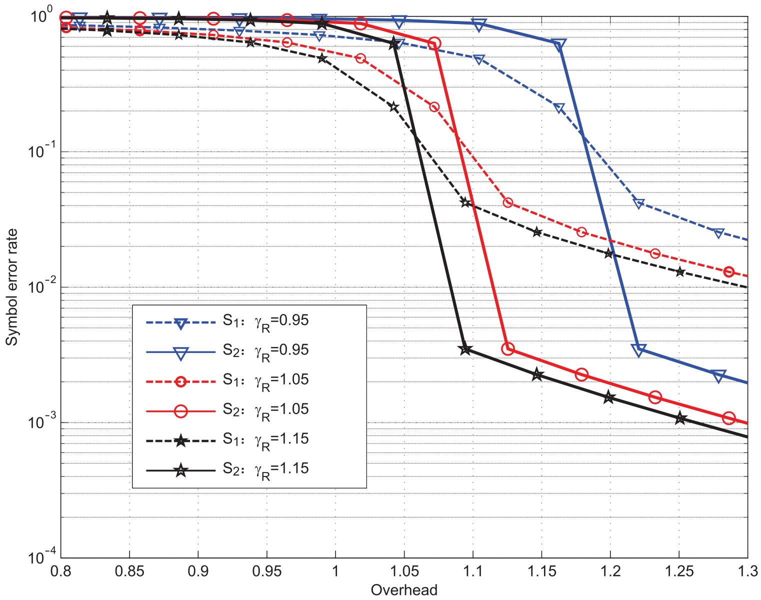

Figure 5 (Color online) Asymptotic performance of proposed code with various encoding overheads on relay node.

S_2, which confirms that the proposed scheme can provide the UEP property between the input symbols on different source nodes.

Figure 5 shows the asymptotic error performances of the proposed scheme with different encoding overheads on the relay node. It can be observed that the decoding performances on both the symbol error rates and encoding overheads for source nodes are all as good as the encoding overhead growth on the relay node. By observing that the margin between the curves corresponds to $\gamma_{\rm R} = 0.95$ and $\gamma_{\rm R} = 1.05$ is larger than that between $\gamma_{\rm R} = 1.05$ and $\gamma_{\rm R} = 1.15$, it can be seen that the overall encoding overheads for each node S_i given by $\gamma_i\Gamma_{\rm R}$ can be assigned an optimal value with a trade-off between the encoding overheads of the source and relay nodes. Actually, the optimal overall encoding overhead should be the product of the optimal overheads of the source and relay nodes.

Subsequently, we compared the proposed scheme to the traditional distributed UEP rateless coding schemes proposed in [13]. We assumed that the sub-codes of traditional scheme source nodes share the same degree distribution, which is the same as the aforementioned $\Omega^{(1)}(x)$. For the relay node, schemes 1 and 2 adopted the different forward probabilities ($p_1 = 0.462$, $p_2 = 0.462$, $p_3 = 0.076$) and ($p_1 = 0.48$, $p_2 = 0.48$, $p_3 = 0.04$), respectively. Additionally, it is worth noting that the forward probabilities of the traditional scheme 2 were optimal. We also assume that the encoding sub-code overheads on the proposed scheme's relay nodes were 1.05, and that a fair the comparison could be made. It can be seen from Figure 6 that the proposed scheme can provide better overhead performance than the traditional scheme 1, while sharing the same overhead performance the scheme 2. As mentioned earlier, in deep space networks, the source node encoders can be terminated until the feedback messages are collected, while the feedback messages in the propose scheme would be delivered through a much shorter distance. Thereby, the proposed scheme could provide better transmission efficiency than both of the traditional schemes. It can also be seen that the proposed scheme could provide the symbol error rates between the two traditional schemes, which means that the cost to improve the transmission efficiency is the symbol error rate performance. As shown in [13], the optimal forward probabilities of the traditional scheme are determined by using a multi-objective genetic algorithm, which means that the forward probabilities have to be designed with much higher computational complexity. As is the case in deep space networks, all nodes are orbits or detectors and are all strictly limited with regard to energy, loading, and processing capacity. Thereby, the design of the forward probabilities would lead to a much longer processing delay than the proposed scheme. This implies that if the relay node of traditional scheme adopted the optimal forward probabilities, the proposed scheme could provide much

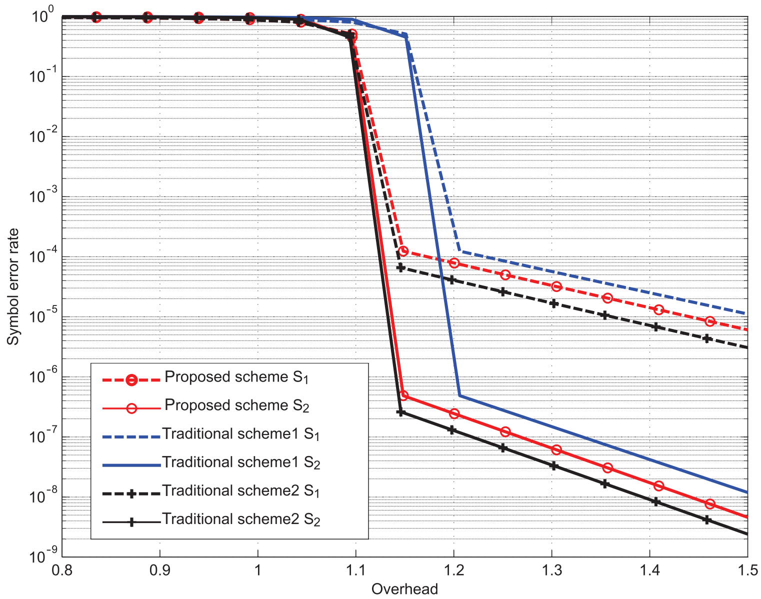

Figure 6 (Color online) Comparison between proposed and traditional distributed UEP rateless coding schemes.

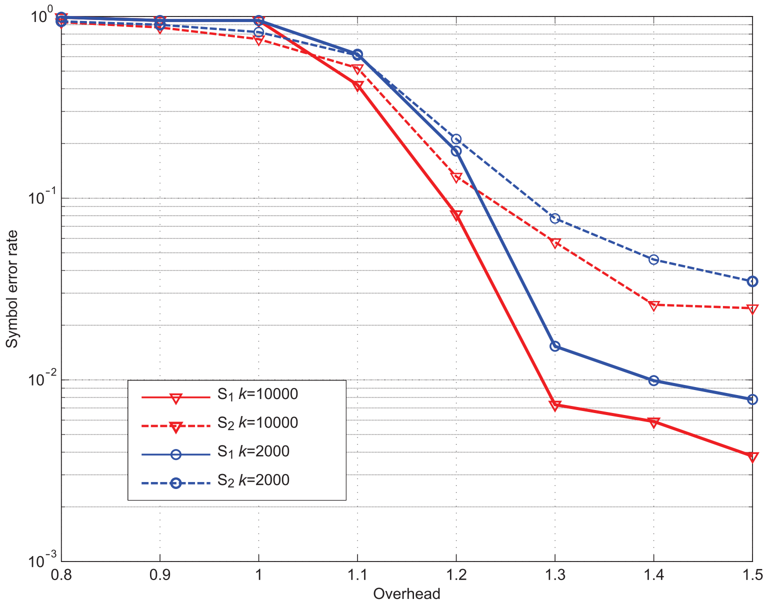

Figure 7 (Color online) Simulation results of proposed scheme on two-source and single relay networks.

better overhead performances than the traditional schemes due to the shorter feedback transmission and processing delays, at the cost of symbol error rate performance deterioration. On the other hand, if the processing delay the of traditional scheme is short enough to be neglected, this means that the forward probabilities are not optimal, the proposed scheme can achieve better overhead performance based on shorter feedback transmission delay, and also achieve symbol error rate performance that will not be worse than that of the traditional scheme. In other words, the proposed scheme can achieve better transmission efficiency in deep space networks, in comparison to the traditional scheme.

Figure 7 shows the Monte-Carlo simulation results of the proposed scheme with $k = 10000$ and $k = 2000$. This means that they could be used to prove that the proposed scheme can provide UEP properties under actual conditions.

6 Conclusion

In this study, we proposed a novel class for a distributed UEP rateless coding scheme that can transmit multi-types of data with different reliability requirements on deep space networks. All the sub-codes of proposed scheme were LT codes; therefore, the proposed code could provide better encoding overhead performance, in comparison to the traditional distributed UEP rateless codes. As the feedback messages in the proposed scheme were delivered through a much shorter distance than those of the traditional scheme, the proposed coding scheme could be used to improve transmission efficiency on deep space networks, in comparison to the transmission efficiency achieved by the traditional scheme. Apart from the transmission delay, the design processing delay of the proposed scheme was also shorter than that of traditional schemes. By summarizing these properties, it can be seen that the proposed scheme is more suitable to deep space network data transmission, in comparison with the traditional scheme.

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