A Novel High Efficiency Distributed UEP Rateless Coding Scheme for Satellite Network Data Transmission

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Abstract. As the satellite networks can provide Internet access services, there are more and more kinds of data are transmitted on it. To ensure all kinds of data can be transmitted satisfied their own reliable requirements and obtain high transmission efficiency, a novel UEP transmission scheme based on distributed LT codes was proposed in this paper. In which scheme, the sub-codes on each node in the satellite network are performed with EEP property. By assigned different output degree distributions for the sub-codes, different kinds of data transmitted under the proposed scheme can be recovered by different reliable levels with nearly optimal transmission efficiency. On other hand, compared with the traditional distributed LT codes based transmission schemes, the relay nodes in proposed scheme do not have to know the reliable level of each source node, hence the security of the data can be guaranteed. We also make the asymptotic and finite-length analysis of proposed coding scheme, and the numerical results shows that the proposed scheme can provide UEP property between different kinds of data with low overhead performance, which can ensure the efficiency of data transmission.

Keywords: Satellite networks · LT codes · Unequal error protection
Low overhead · Asymptotic analysis · Finite length evaluation

1 Introduction

Satellite networks providing a global coverage area, which can provide ubiquitous Internet access services [1]. As a growing number of users expect access these services in different areas, this wide coverage requirement could be achieved by using the satellite networks [2]. To satisfy the various requirements of the users, there are many kinds of data have to be transmitted on the satellite networks, it is worth to note various kinds of data always lead to various reliability requirements. Satellite systems always with long transmission distances, especially for geosynchronous orbits (GEO), and the lossy and possible disruption channels [3].

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To transmit multi-kinds of data on such complex channel and dynamic network structure conditions, make sure all kinds of data can be recovered with their own reliability requirements and ensure the overall transmission efficiency, many previous work have been proposed in the past decade.

Rateless codes were proposed for efficient data transmission over multi users with different channel conditions. As the decoder of rateless codes can recover original message packets (i.e., input symbols) by collecting a little larger number of encoded message packets (i.e., output symbols), which codes can provide capacity-achieving property on channels with various conditions, it worth noting that in most scenarios the encoder of rateless codes continuously generate output symbols until received a feedback message. LT codes were developed by Luby [4] as the first practical realization of rateless codes, although LT codes is capacity-achieving, but which is designed for scenarios with single source node. To ensure the data transmission efficiency in network scenarios with multi-source nodes, the distributed LT codes is invented in [5,6], by encoded the input symbols on different source and relay nodes, the capacity-achieving property can be obtained in the network systems.

To transmit multi kinds of data with different reliability requirements, a class of rateless codes with unequal error protection (UEP) property are first proposed by Rahnavard *et al.* [7–9]. In which codes, the input symbols are divided into different sets, as the encoder assigned different selection probabilities of these sets, the input symbols in different sets can be recovered with different error probabilities. To face for the network scenarios in which there are multi kinds of data with different reliability requirements have to be transmitted, the distributed UEP LT codes also been proposed [10]. Different with the distributed LT codes, the input symbols of distributed UEP LT codes are only encoded on source nodes, the relay nodes only forward the output symbols to destination node with two rules. The first rule is forward a part of output symbols and forward to destination node directly, the other one is forward the XOR of two incoming output symbols to destination. It is clear that the feedback messages of distributed UEP LT codes would passed by both the destination-relay and relay-source channels. By using the distributed UEP LT codes to transmit multi kinds of data on satellite networks, the long transmission distances would lead to large delay times and extremely influence the data transmission efficiency. To overcome the influences, we proposed a novel distributed UEP rateless coding scheme to transmit multi kinds of data on satellite networks. In the proposed distributed UEP rateless coding schemes, both the source and relay nodes would perform LT codes, the feedback message of each encoder would sent from the next node, hence the influence of delay times can be reduced and thus improve the transmission efficiency.

This paper is organized as follows. Section 2 illustrate the related works. The proposed codes are proposed in Sect. 3, and then we derive the asymptotic analysis of proposed codes. In Sect. 4, we give the finite length analysis of proposed codes and then the criteria of output degree distributions and overheads for subcodes are also given. The numerical results are given in Sect. 5, which shown that the proposed codes can provide better overhead property than traditional distributed UEP rateless codes. Finally, we summarized conclusions in Sect. 6.

2 System Model

To propose the distributed UEP rateless codes, a system model of satellite networks is proposed in this section.

For simplicity, consider a multi-source and single-relay satellite network, in which network the source nodes are low earth orbits (LEO) satellite and the relay node is a geosynchronous orbit (GEO) satellite. The data (input symbols) on different LEO satellites with the different reliability requirements. By using the error control codes on the physical layer, the channels in this system can be considered as erasure channels.

The satellite network is shown as Fig. 1, where the data are transmit from J LEO satellites (source nodes) S_1, S_2, …, S_J to ground station (destination) D through the GEO satellite (relay node) R. Where the channels between LEOs and GEO are named *source channel*, which between GEO and ground station is called *relay channel*. The erasure rates of the source channel between S_i and R is e_i, and for relay channel is e_{R}.

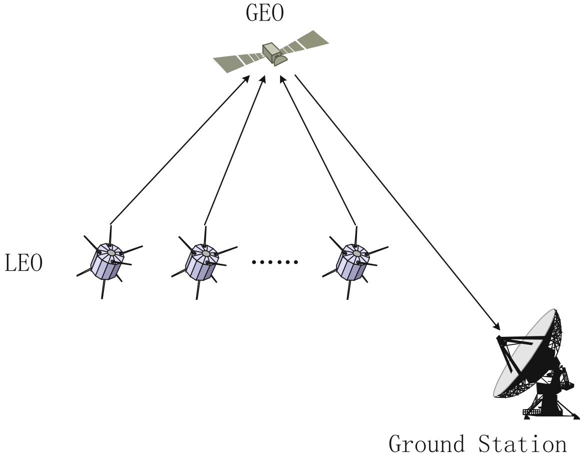

Fig. 1. The structure of multi source and single relay satellite network.

3 Proposed Coding Scheme

In this section, we proposed the coding scheme for satellite network data transmission, which scheme is based on the distributed LT codes, by assign the different coding parameters of sub-codes on each nodes, the proposed scheme can provide UEP property between the data from different source nodes.

3.1 The Encoding Process of Proposed Coding Scheme

The encoding process of proposed scheme is shown in Fig. 2. Where the encoding process is divided into 2 steps: In the first step, the encoders on source nodes generate intermediate symbols and then these symbols are transmitted to the relay node. In the second step, the encoder on GEO select intermediate symbols to generate output symbols and transmit to ground station D.

In the first step, each node S_i generate intermediate symbols by selected input symbols and using the output degree distribution $\Omega^{(i)}(x) = \sum_d \Omega^{(i)} x^d$. Assuming the number of input symbols on S_i is k_i, and encoding overhead of this sub-code is γ_i, which means there are $\frac{\gamma_i k_i}{1-e_i}$ intermediate symbols are generated on the node S_i. In the second step, there are $\sum_{i=1}^{J} \gamma_i k_i$ intermediate symbols are collected by the relay node R, and the encoder on R generate output symbols by selected intermediate symbols using output degree distribution $\Omega^{(\mathrm{R})}(x)$. In the both two steps, the encoders all process as the classical LT encoder [4]. Define the total number of input symbols is k, where $k_i = \alpha_i k$, then we have $k = \sum_i k_i = \sum_i \alpha_i k$.

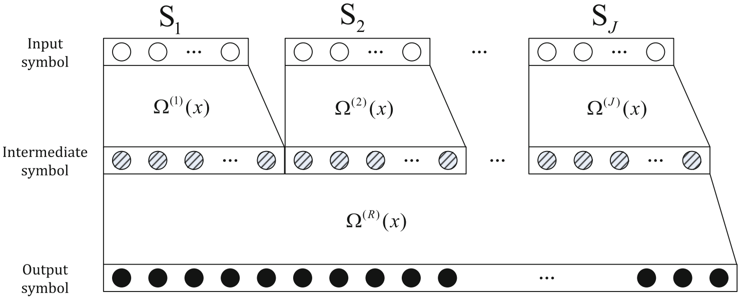

Fig. 2. The encoding structure of proposed codes.

3.2 The Decoding Process of Proposed Coding Scheme

There are only one decoder on the destination in proposed coding scheme, which decoder implement belief propagation (BP) decoding algorithm to recover the input symbols. Although the input symbols came from different source nodes, these input symbols and the collected output symbols can be considered as a independent LT code in the destination, the bipartite graph of the decoding process is shown in Fig. 3.

To analysis the decoding process of proposed coding scheme, the overall output degree distributions $\Omega(x)$ are needed. Let $\Phi(x)$ represent the degree distribution of intermediate symbols, which distribution can be given by the following Lemma.

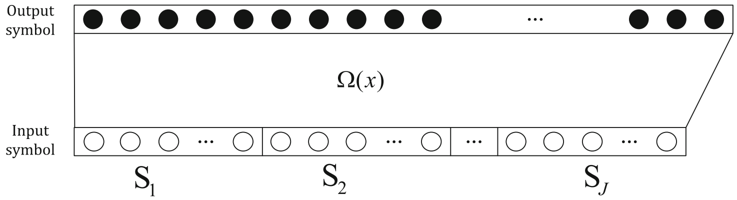

Fig. 3. The decoding structure of proposed codes.

Lemma 1. *The degree distribution of intermediate symbols $\Phi(x)$ can be calculated 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. The number of intermediate symbols is $\sum_{j=1}^{J} \gamma_j k_j$ and the intermediate symbols with degree d is $\sum_{i=1}^{J} \gamma_i k_i \Omega_d^{(i)}$, then we have $\Phi_d = \frac{\sum_{i=1}^{J} \gamma_i k_i \Omega_d^{(i)}}{\sum_{j=1}^{J} \gamma_j k_j}$. Hence Eq. (1) is obtained.

As the $\Phi(x)$ and $\Omega^{(\mathrm{R})}(x)$ are known, the overall output degree distribution $\Omega(x)$ can be obtained.

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

$$\Omega(x) = \Omega^{(\mathrm{R})}(\Phi(x)). \tag{2}$$

Proof. For the intermediate symbols, the number is $\sum_{i=1}^{J} \gamma_i k_i$ and degree distribution is $\Phi(x)$. When the GEO R generate output symbols with degree 1, which means these output symbols are generated by select only one intermediate symbol, then the output degree distribution of these output symbols are $\Phi(x)$. When R generate output symbols with degree d ($d > 1$), which means the output symbols are generated by XORed d intermediate symbols, then the output degree distribution of these output symbols are $(\Phi(x))^d$. As the generate degree distribution of relay node R is $\Omega^{(\mathrm{R})}(x)$, then the output degree distribution $\Omega(x)$ can be calculated as

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

Consider an intermediate symbol with degree d, the probability this symbol generated by the source node S_i is

$$q_{d,i} = \frac{\gamma_i k_i \Omega_d^{(i)}}{\sum_{l=1}^{J} \gamma_l k_l \Omega_d^{(l)}}. \tag{3}$$

As the encoder on relay node perform EEP LT encoding process, the probability that an input neighbor of each output symbol came from source node S_i is

$$q_i = \frac{\sum_d d\Phi_d \frac{\gamma_i k_i \Omega_d^{(i)}}{\sum_{l=1}^{J} \gamma_l k_l \Omega_d^{(l)}}}{\Phi'(1)} = \frac{\sum_d d\gamma_i k_i \Omega_d^{(i)}}{\gamma k \Phi'(1)}. \tag{4}$$

To quantify the UEP properties of source nodes, define K_i is the *priority disparity* of the source S_i, and $K_i = \frac{q_i}{\alpha_i}$.

3.3 Asymptotic Analysis of Proposed Codes

In this section, we use And-Or tree technique to analyze the asymptotic performance of proposed codes.

The encoding process of proposed code are divided in 2 steps, the one is on the source node, the other is on the relay nodes. When first step is finished, the input degree distribution of input symbols on S_i is denoted by $\Lambda^{(i)}(x)$, where

$$\Lambda_d^{(i)} = \binom{k_i(\Omega^{(i)}(1))'}{d} \left(\frac{1}{k_i}\right)^d \left(\frac{k_i - 1}{k_i}\right)^{k_i(\Omega^{(i)}(1))' - d}. \tag{5}$$

In asymptotic conditions, which means $k_i \to \infty$, we have

$$\Lambda^{(i)}(x) = \exp\left\{(\Omega^{(i)}(1))'\gamma_i(x-1)\right\}. \tag{6}$$

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

$$\begin{aligned} \lambda^{(i)}(x) &= \frac{(\lambda^{(i)}(x))'}{(\lambda^{(i)}(1))'} \\ &= \frac{(\Omega^{(i)}(1))'\gamma_i e^{(\Omega^{(i)}(1))'\gamma_i(x-1)}}{(\Omega^{(i)}(1))'\gamma_i e^{(\Omega^{(i)}(1))'\gamma_i(x-1)} \mid_{x=1}} \\ &= \exp\left\{(\Omega^{(i)}(1))'\gamma_i(x-1)\right\}. \end{aligned} \tag{7}$$

Then consider the second step of encoding process, as the probability an intermediated symbol is generated by S_i is q_i, then for an output symbol, the probability its neighbors belong to S_i is also q_i. As the compute complexity of second step is $(\Omega^{(\mathrm{R})}(1))'\gamma_{\mathrm{R}}$, hence the average degree of input symbols on S_i of the overall LT code is $(\Omega^{(i)}(1))'\gamma_i(\Omega^{(\mathrm{R})}(1))'\gamma_{\mathrm{R}}$, and the input edge distribution is $\lambda_{i,\mathrm{overall}}(x) = \exp\{(\Omega^{(i)}(1))'\gamma_i(x-1)(\Omega^{(\mathrm{R})}(1))'\gamma_{\mathrm{R}}\}$.

Following with paper [9], denote the error rate of input symbols in S_i is $y_{i,l}$, then we have

$$y_{i,l} = \lambda_{i,\mathrm{overall}}\left(1 - \omega\left(1 - \sum_{i=1}^{J} q_i(y_{i,l-1})\right)\right),\ l > 1 \tag{8}$$

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

4 Design of Proposed Coding Scheme

The UEP performance of UEP LT codes are mainly determined by the selection probabilities. It is can be seen from Eq. (4), for the proposed distributed UEP LT coding scheme, the selection probability of each source node S_i is mainly determined by the variables γ_i and $\Omega^{(i)}(x)$. As overheads γ_i represent the transmission efficiency of proposed codes, we will mainly focus on the output degree distributions of proposed coding scheme.

4.1 The Output Degree Distributions of Sub-codes

As the advisable overheads of sub-codes are obtained, the UEP properties of the proposed coding scheme should be determined by the output degree distributions of sub-codes.

Consider each source node S_i, to obtain priority disparity K_i, the output degree distribution $\Omega^{(i)}(x)$ should satisfies

$$\left(\Omega^{(i)}(1)\right)'\gamma_i = K_i\gamma\Phi'(1), \tag{9}$$

where γ is the overall overhead, and the left part of Eq. (9) is the average degree of the input symbols on source node 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 are increased by times $(\Omega^{(R)}(1))'$, but for each in put symbol, the number of its identity neighbors has not been increased. In other word, 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 the neighbors of the intermediate symbols which are connected with this input symbol. For this reason, the LT encoder on relay node was not implemented to improve the error performance but to overcome the erasure probability of the relay channel. For this reason, and consider the overall compute complexity, the LT encoder on relay node should be assigned output degree distribution $\Omega^{(R)}(x)$ with low average degree.

As the Robust degree distributions of LT codes can provide nearly optimal decoding performances, and the Robust degree distribution is determined by the variables k, δ and c, where δ is the allowable decoding failure probability and c is a constant, then by assign different value to δ and c, one can obtain different Robust degree distribution. Hence, for the source nodes, the degree distributions should satisfy Eq. (9), and for the relay node.

5 Simulation Results

In this section, we first take the asymptotic and finite length evaluation of proposed codes, then the comparisons between proposed codes and conventional distributed UEP codes are also given.

Consider a proposed code with two LEOs and single GEO, where the number of input symbols and overhead of sub-codes on LEOs are the same, and output degree distributions for sub-codes on LEOs 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 output degree distribution for sub-code on GEO 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 overhead on GEO is 1.05. The asymptotic error performance of the proposed code is shown in Fig. 4, where the input symbols on LEO S_1 can provide better error performance than which on S_2, which means the proposed code can provide UEP property between input symbols on different LEOs. Figure 5 shows the finite length error performances of proposed codes with $k_1 = k_2 = 10000$ and $k_1 = k_2 = 1000$, it is easy to say the overhead and error performances of proposed codes would as better as larger number of input symbols on source nodes.

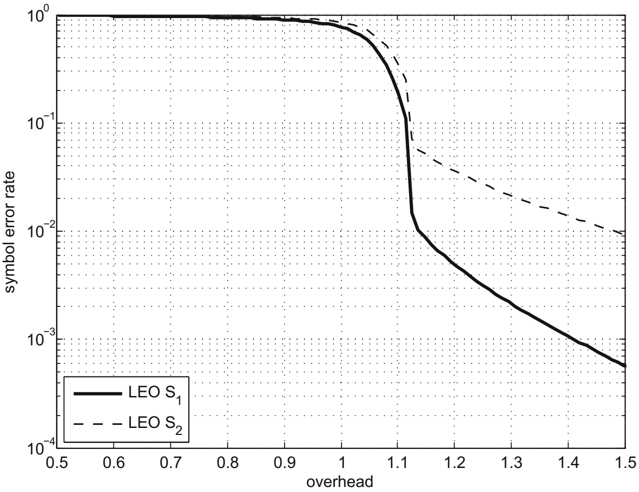

Fig. 4. Asymptotic error performance of proposed code with 2 source nodes and single relay node.

Then we make the comparison between proposed codes and conventional distributed UEP codes. Assume the sub-codes on LEOs of conventional code with the same output degree distribution, which is same as $\Omega^{(1)}(x)$, and the sub-code on GEO also share the same output degree distribution as the proposed code. Different with the proposed codes, the UEP property of conventional codes are mainly determined by the sub-code on relay nodes, then we assume the overhead of both sub-codes on source nodes are 1.05. To compare fairly, the conventional code has been assigned priority disparity $K_M = 1.7$, then the proposed code

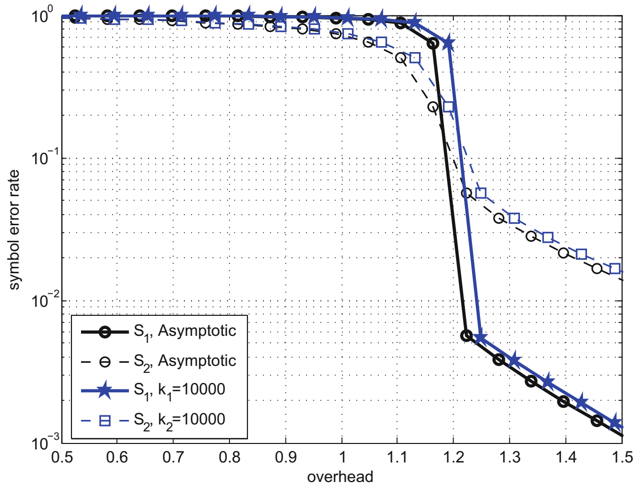

Fig. 5. Finite length error performance of proposed code with two source nodes and single relay node.

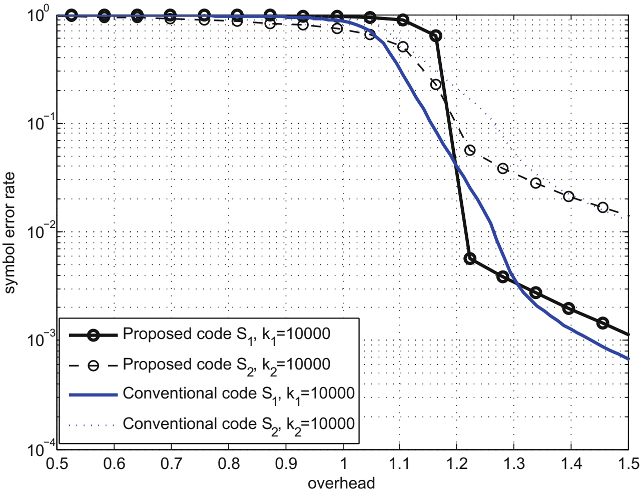

Fig. 6. Finite length error performance of proposed code and conventional distributed UEP rateless code.

and conventional codes would provide the same UEP properties at the finite length condition where the input symbols on both source nodes are $k_1 = k_2 = 10000$, its can be found in Fig. 6, the proposed code can provide better overhead performance than conventional codes, which because of the drawback of the LT-based UEP codes.

6 Conclusion

In this paper, we propose a new class of distributed UEP rateless codes which can be using transmit multi kinds of data with different reliable requirements on satellite networks. All the sub-codes of proposed UEP rateless codes are EEP LT codes, hence the proposed code can provide better overhead property than the conventional distributed UEP rateless codes. As the relay node (GEO) in proposed code provide EEP property, which means the relay node not have to know the reliable requirements of input symbols on different source nodes, hence the security of input symbols can be ensured. We also derive the asymptotic and finite-length analysis of proposed codes. And the numerical results shown the proposed can provide the same UEP property as conventional distributed UEP rateless codes with low overhead performance.

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