A Reliable Data Transmission Service for Tiansuan Constellation

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***Abstract*—Existing satellite constellations typically lack on-orbit processing capabilities, and on-orbit data backhaul face to reliability and effiency challenges. Tiansuan constellation is with the capability of providing satellite edge computing services, which can support complex data coding transmission methods. To effectively support effective data backhaul for existing satellite constellations, we propose a reliable data transmission service in Tiansuan constellation. The service adopts the adaptive coding transmission strategy to adjust the optimal size of the encoded data packet according to real-time satellite network conditions. An adaptive encoding transmission approach is proposed to reduce end-to-end delay. Experimental results based on the ground simulation platform demonstrate that the proposed method can effectively reduce end-to-end delay and improve effective data transmission rate.**

***Index Terms*—Tiansuan constellation, fountain code, satellite network, satellite edge computing**

I. Motivation

The rapid expansion of satellites has result in a dramatic increase in on-orbit satellite data. Satellite data backhaul faces significant challenges [1]. Due to the unstable and unreliable transmission environment of the satellite network, it is difficult to transmit a large amount of data to the ground efficiently and reliably.

To effectively support the existing various forms of satellite constellations, we designed and planned Tiansuan constellation – a new type of satellite application that mainly provides on-orbit computing power[1]. Tiansuan constellation has implemented a lightweight 5G core network and an edge computing platform [2], which can perform coding transmission services to improve reliability and efficiency of satellite data backhaul.

The application of fountain code technology such as LT code [3] in satellite network transmission can ensure reliable communication and improve throughput. Fountain codes are used in many data transmission studies. Reference [4] developed a fountain-coding-based scheme, which dynamically adjusts the coding strategy based on outage prediction and limited feedback to secure communications over fading wiretap channels. Reference [5] proposed a fountain-coding aided secure transmission approach for fading wiretap channels, which can determine the number of source packets participating and the selection of source data packets in the fountain coding process to prevent information leakage and reduce the decoding delay at the legitimate receiver. However, these research works are insufficient to adapt to the network state, and the algorithm performance may be affected when the satellite-ground link state changes drastically.

To effectively improve data transmission reliability, we design a reliable data transmission service in Tiansuan constellation. This service adopts an adaptive coding transmission strategy to determine the optimal packet size. Based on this strategy, we develop an adaptive encoding transmission approach to reduce end-to-end delay.

II. The Proposed Reliable Transmission Service

A. Application Scenario

In this section, we present a reliable transmission service for Tiansuan constellation. The application scenario is shown in Fig. 1. Tiansuan constellation offers open access of reliable transmission service for other satellites. At first, Remote sensing satellites initiate data transmission requests to Tiansuan constellation. Then, Tiansuan constellation receives the original remote sensing data and encodes these data. After that, Tiansuan constellation transmits the encoded data to the Tiansuan ground station. At last, the Tiansuan ground station receives and decodes the encoded data to obtain the source remote sensing image.

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[1]http://www.tiansuan.org.cn/

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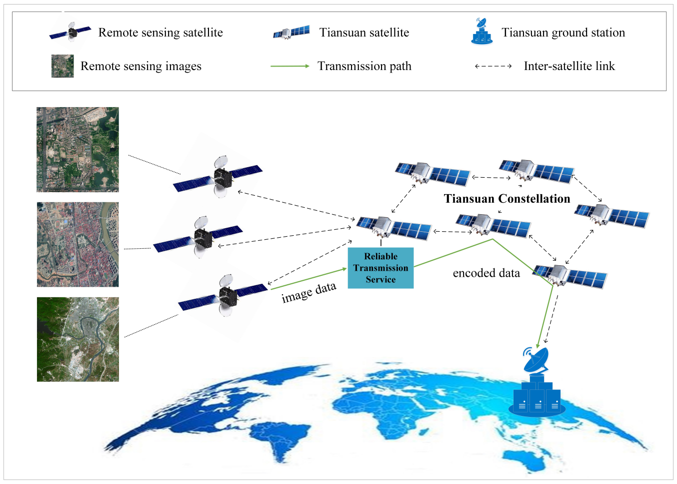

Fig. 1. Scenario of reliable data transmission service

B. Adaptive Coding Transmission Strategy

We define the size of the transmitted data file as M, the number of original packets after segmentation is denoted by n, and then the size of each original packet m is denoted by $\lceil \frac{M}{n} \rceil$. The encoding parameter value of a single original packet is denoted by a, and the check code size is denoted by b. The size of each encoded packet should meet:

$$m + an + b \leq h, \quad (1)$$

where h denotes the maximum value of the data part in a single data frame in the MAC layer protocol. In practical applications, the end-to-end delay is mainly determined by the transmission delay. The transmission delay of each encoded packet is expressed as $T_t = \frac{m+an+b}{r}$, where r represent the data transmission rate between the sender and the receiver.

The probability of successful transmission of a single encoded packet P is computed as follow:

$$P = (1-p)^{8(m+an+b)}, \quad (2)$$

where p denotes the end-to-end network transmission error rate.

The number of encoded packets received by the receiver is denoted by n_s,$n_s = n(1+\varepsilon)$. ε is redundancy. The expected value of the total number of encoded packets can be obtained:

$$\zeta_{n_s} = \frac{n(1+\varepsilon)}{P} \quad (3)$$

The expected value of the total transmission delay is expressed as:

$$\xi_T = \zeta_{n_s} T_t = \frac{n(1+\varepsilon)}{P} T_t \quad (4)$$

The final expression of transmission delay can be obtained from (5).

$$\xi_T = \frac{(1+\varepsilon)n\,(m+an+b)}{r(1-p)^{8(m+an+b)}}. \quad (5)$$

Minimizing the total transmission delay expectation is equivalent to an integer programming problem:

$$\begin{aligned} &\min_n \xi_T, \\ &n, m \in N_+, \\ &mn \geq M. \end{aligned} \quad (6)$$

By calculating the first derivative of (5), we get

$$\frac{d\xi_T}{dn} = \frac{(1+\varepsilon)\left(2an + b + 8\ln P\left(\frac{M^2}{n^2} + \frac{bM}{n} - a^2n^2 - abn\right)\right)}{r(1-p)^{8\left(\frac{M}{n}+an+b\right)}}. \quad (7)$$

To minimize the expected value of the total transmission delay, the optimal value of n is required. Letting $\frac{d\xi_T}{dn} = 0$, we can get (8)

$$\begin{aligned} -8\ln Pa^2n^4 + (2a - 8\ln Pab)n^3 + bn^2 + \\ 8\ln PbMn + 8\ln PM^2 = 0. \end{aligned} \quad (8)$$

Since n is an integer, it is difficult to directly solve (8). We can utilize various methods to find its solution, such as enumeration methods, heuristic algorithms, machine learning.

After the optimal packet size is obtained, original data can be divided into original packets based on the size. After that, the original packets will be encoded through fountain coding approach.

C. Adaptive Encoding Transmission Approach

In this section, we propose an adaptive encoding transmission approach for Tiansuan constellation. A lightweight 5G core network is implement in Tiansuan constellation to provide network access services for on-orbit satellite constellations. Based on the 5G core network, remote sensing satellites can access the network through the Access and Mobility Management Function(AMF) and send the remote sensing images to the Tiansuan constellation. Tiansuan constellation receives remote sensing images and distribute them to the satellite edge computing platform through the User Plane Function(UPF). The adaptive coding transmission strategy obtains optimal packet sizes of received remote sensing images. The adaptive encoding transmission approach is performed based on the satellite edge computing platform to achieve coding transmission. This approach divides each original remote sensing image into several data packets according to the optimal packet size of this image. After that, this approach adopts the LT code [3] to generate encoded packets. Tiansuan constellation also maintains a basic data routing service. The encoded data packet will be transmitted to the ground station by the routing service.

III. Simulation Result

A. Simulation Setup

To verify the effectiveness of the reliable data transmission service proposed in this paper, we first simulated the position, orbit, and visibility of satellites in the Satellite Tool Kit

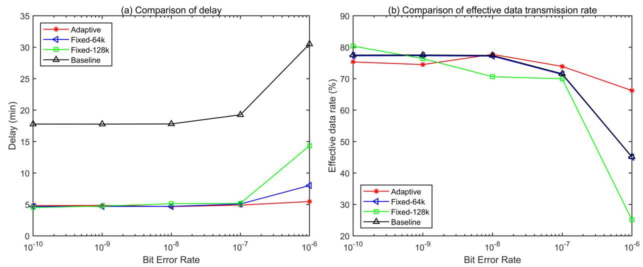

Fig. 2. The comparison on end-to-end delay and effective data rate.

10. Then, we simulated data transmission approaches based on Tiansuan constellation ground simulation system. We use encoding transmission approaches with fixed packet size and the proposed adaptive coding transmission strategy to encode and transmit files, respectively. In the encoding transmission approaches with fixed packet size, we set the information packet sizes to be 64 KB and 128 KB, respectively.

B. Comparison on End-to-end Delay and Effective Data Transmission Rate

This section compares end-to-end delays and effective data transmission rates of coding transmission approaches with fixed packet size and the adaptive coding transmission strategy. The non-encoding strategy is represented by the baseline method. The end-to-end delay records the time difference from the sending end to the receiving end. The effective data transmission rate is calculated as the ratio of the total amount of decoded data and the total amount of transmitted data. We assume that each information packet uses 1 bit to mark whether it participates in encoding, i.e., $a = 0.125$. In the simulation, the round-trip time is set to 200 ms. The link transmission speed is set to a Gaussian random number, with an average of 1 $\mathrm{MB/s}$ and a standard deviation of 0.05 $\mathrm{MB/s}$.

Fig. 2 (a) shows the simulation results of end-to-end delay. When the bit error rate is 10^{-6}, the end-to-end delay of the adaptive coding transmission strategy is about one-third of that of the encoding algorithm with the fixed information packet size of 128 K and is about half of the end-to-end delay of coding transmission approaches with fixed packet size of 64 K. This result indicates that coding transmission can reduce end-to-end delay efficiently. Furthermore, the adaptive coding transmission strategy is suitable for various network conditions, especially when the bit error rate of the data backhaul link is high.

Fig. 2 (b) shows the simulation results of effective data transmission rate. It can be seen that the effective data transmission rate of the adaptive coding transmission strategy is better than that of the adaptive coding transmission strategy and remains above 65%. When the bit error rate is 10^{-6}, the effective data transmission rate of the adaptive coding transmission strategy can be about 20% higher than that of the coding transmission approach with the fixed packet size of 128 K, and about 40% higher than that of the coding transmission approach with the fixed packet size of 64 K. This result indicates that the adaptive coding transmission strategy can increase the effective data transmission rate under various network conditions.

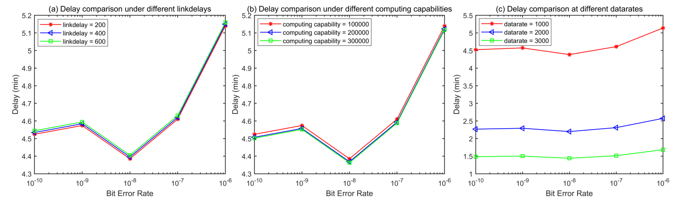

Fig. 3. The comparison on end-to-end delay under different influence factors.

C. Environmental factor analysis

To verify the influence of different satellite network conditions on the algorithm, we compare the end-to-end delay under different influencing factors. The comparison results are shown in Fig. 3. It can be seen that end-to-end delay difference is slight under different link delays and computing capabilities, and they are all maintained at 4.3 min - 5.2 min. The smaller the link delay, the smaller end-to-end delay, and the more substantial the computing capability, the smaller end-to-end delay. In contrast, end-to-end delay difference under different data rates is evident. When the data rate is 1000, end-to-end delay is maintained at 4.3 min - 5.2 min; when the data rate is 3000, end-to-end delay is maintained at 1.4 min - 1.7 min. It can be concluded that the performance of the proposed approach is mainly influenced by the data rate of data backhaul link.

IV. Conclusion

In this paper, we design a reliable data transmission service in Tiansuan constellation to provide reliable and effective satellite data backhaul. We propose an adaptive coding transmission strategy to adjust the optimal packet size of data encoding. An adaptive encoding transmission approach is performed based on satellite edge computing platform of Tiansuan constellation. Existing satellite constellations can access this service for on-orbit satellite data backhaul. The simulation results show that the algorithm proposed in this paper can reduce the end-to-end delay and improve the effective data transmission rate.

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