Chinese Journal of Aeronautics, (2023), 36(5): 406–420

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

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Performance improvement of licklider transmission protocol in complex deep space networks based on parameter optimization

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Received 24 April 2022; revised 21 July 2022; accepted 27 September 2022
Available online 23 December 2022

KEYWORDS

Complex deep space networks;
File delivery time model;
Licklider Transmission Protocol (LTP);
Network Performance;
Network Protocols;
Parameter optimization;
Performance improvement

Abstract A reasonable parameter configuration helps improve the data transmission performance of the Licklider Transmission Protocol (LTP). Previous research has focused mainly on parameter optimization for LTP in simplified scenarios with one to two hops or multihop scenarios with a custody mechanism of the Bundle Protocol (BP). However, the research results are not applicable to communications in Complex Deep Space Networks (CDSNs) without the custody mechanism of BP that are more suitable for deep space communications with LTP. In this paper, we propose a model of file delivery time for LTP in CDSNs. Based on the model, we propose a Parameter Optimization Design Algorithm for LTP (LTP-PODA) of configuring reasonable parameters for LTP. The results show that the accuracy of the proposed model is at least 6.47% higher than that of the previously established models based on simple scenarios, and the proposed model is more suitable for CDSNs. Moreover, the LTP parameters are optimized by the LTP-PODA algorithm to obtain an optimization plan. Configuring the optimization plan for LTP improves the protocol transmission performance by at least 18.77% compared with configuring the other parameter configuration plans.

1. Introduction

Delay/Disruption Tolerant Networks (DTNs) can solve deep space communication problems such as path loss, excessive delay, and link interruption that are faced in deep space exploration; hence, DTNs have become the main protocol architecture of deep space networks.[1–2] The Licklider Transmission Protocol (LTP) is designed for point-to-point connections with extremely long propagation delays and frequent interruptions. LTP has become the main transport protocol of deep space

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Peer review under responsibility of Editorial Committee of CJA.

Production and hosting by Elsevier

https://doi.org/10.1016/j.cja.2022.12.011
1000-9361

networks that are based on DTNs, owing to its satisfactory performance in deep space communication scenarios[3–5].

LTP provides reliable and unreliable transmission modes completed by red and green segments, respectively. LTP is transmitted in blocks. During data transmission, a file to be transmitted is divided into multiple LTP blocks, and each block is divided into multiple LTP segments that are transmitted to the lower layer protocol for data transmission. The last red segment is marked with a Check Point (CP) to request ACKnowledgement (ACK) from the receiver. Every time the receiver receives a CP segment, it sends a Report Segment (RS) to the corresponding sender to inform the sender of the loss of the data segments, and the sender retransmits the lost data segments according to the notification result of the RS. After all red data segments of a block are transmitted and CP segment is sent, the link has a period of idle time while waiting for an RS from the receiver. At this time, the sender does not send any data that wastes link resources. In order to improve the link utilization, LTP sets up a multi-session mechanism. A session transfers an LTP block. When the previous session has not ended, the next session can be started for data transmission. This mechanism also improves the data transmission efficiency of LTP to a certain extent, and can save the file delivery time of LTP.

The block, segment, and session involved in the LTP data transmission task described above are configurable parameters of LTP. LTP parameters must be configured before data transmission. The parameter configuration for LTP is not defined in any related specification. However, experimental studies show that it has a significant impact on LTP performance.[6–7] Therefore, to ensure that the deep space networks with LTP as the transport protocol may achieve the highest possible performance during data transmission, it is necessary to optimize the configuration of parameters for LTP.

Attempts to optimize parameters for LTP have been reported. However, research has focused on determining the optimal plan for the configuration of LTP parameters in simple networks for scenarios with one to two hops.[8–10] The models of data transmission were established according to the theoretical analysis method of the transmission mechanism for LTP in simple scenarios that were proposed in Refs.[10–12] Based on the established models, the optimal plans of LTP parameters were deduced by simulation experiments. However, since the models based on simple scenes cannot be applied to complex scenes, such research conclusions may not be applicable to Complex Deep Space Networks (CDSNs) with multihop transmission. Moreover, the optimization method is not general owing to the lack of theoretical work. Although a parameter optimization method for multihop scenarios was proposed in Ref.[13] through theoretical analysis, it was based on a data transmission with a custody mechanism of the Bundle Protocol (BP). The theoretical model established in Ref.[13] is the data transmission model of BP, rather than that of LTP. However, the mechanism of bundle custody is redundant when the underlying protocol can achieve reliable transmission. It was suggested that if the lower-layer protocol has a reliable transport mechanism, the custody mechanism of BP should be inactivated, and the responsibility for reliable transport of the BP layer is transferred to the lower-layer protocol.[14] Hence, the parameter optimization of LTP must be based on the data transmission model of LTP. Notably, the parameter optimization method that has been studied in Ref.[13] is not applicable in the current deep space communications with LTP. Herein, we propose a theoretical model of file delivery time for LTP in CDSNs. Based on this model, we propose a Parameter Optimization Design Algorithm of LTP (LTP-PODA) for configuring reasonable parameters for LTP in CDSNs to improve the transmission performance of LTP in complex scenarios. Our main contributions are as follows:

(1) We propose a theoretical model of file delivery time for LTP in CDSNs. The model is established without the custody mechanism of BP that meets the provisions of the latest standards. Moreover, the model considers both aggregation and non-aggregation for bundles. When predicting the file delivery time in CDSNs, our model has higher accuracy than the models based on simple scenes. In addition, it also makes up for the defect that the application scenario of the models based on simple scenes is relatively single. Therefore, it is more suitable for CDSNs with multihop transmission than the existing latest theoretical models based on simple scenarios.

(2) Based on the proposed model of file delivery time for LTP in CDSNs, we design the optimization basis for LTP protocol parameters.

(3) Because the models based on simple scenes cannot be applied to complex scenes, the parameter optimization methods based on those models cannot be applied to parameter optimization in complex scenes. Therefore, we propose an LTP-PODA based on the optimization basis of LTP parameters. Encountering different complex deep space communication scenarios, we can use the algorithm to obtain an optimized parameter configuration plan suitable for the communication environment. Configuring the plan to LTP can improve the data transmission performance of LTP.

The remainder of the paper is organized as follows. In Section 2, related research on LTP parameters is described. Section 3 introduces complex deep space network scenes. A theoretical model of file delivery time for LTP in CDSNs is established in Section 4. Section 5 presents a parameter optimization method for LTP. Section 6 evaluates the model and the algorithm and presents the results. Section 7 discusses the conclusions of this study.

2. Related work and comparisons with our work

LTP comprises some key parameters. The configuration of these parameters for LTP has a certain impact on the transmission performance of LTP. The research on the configuration of protocol parameters for LTP is extensive.

In a previous research, experimental simulation is used to analyze the impact of different protocol parameter configurations on protocol performance. For example, experimental simulation is used to analyze the impact of the size of bundle and block, and the number of segment on the overhead, file delivery time, and memory occupation of LTP,[7,15] and the impact of LTP window size composed of the number of sessions and block size set for LTP on protocol performance.[6] However, these studies focus on the impact of parameter configuration on protocol performance, but do not provide suggestions on how to optimize the parameter configuration to improve the protocol transmission performance in different communication environments. The current study provides a simple method to configure the optimal parameter configuration plan for different space communication environments.

The subsequent research focuses on determining the method of configuring the optimal protocol parameter configuration plans for different communication environments, and most of them are based on the theoretical modeling of LTP transmission mechanism. The research on the theoretical modeling mostly focuses on how to establish the model of file delivery time for LTP. The methods used to calculate the number of data transmission rounds are different. Yu et al.[11] assumed that the link packet loss is in an ideal situation, that is, the ratio of lost data to transmitted data during each data transmission is the same as the packet loss rate of the link. Therefore, the number of rounds required for the completion of data transmission is calculated in the ideal situation. The model of file delivery time for LTP is established based on the number of rounds of data transmission. Wang et al.[12] used probability calculation to calculate the expected value of the number of data transmission rounds, in order to calculate the file delivery time for LTP. Lent[10] used the Markov model to express the LTP data transmission process and provided the exact solution and approximate solution of the number of data transmission rounds to calculate the delivery time of an LTP block. In addition to the above research on the basic transmission time model, some researchers had also established other relevant models based on the analysis of LTP transmission mechanism, such as the memory dynamic model of LTP in the scenarios with extremely long link delays,[16] the models of BP/LTP transmission mechanism with BP custody mechanism[17–18]; the model of queuing time based on BP/LTP[19] and the model of file reliable transmission time[20] in the case of random link interruptions, and the RTT estimation model considering the influence of delay caused by channel asymmetry and channel damage during BP/LTP transmission.[21] However, the aforementioned studies[10–12,19–21] focused on analyzing the LTP transmission mechanism of deep space communication networks in the simplified scenarios of one to two hops. The research conclusions may not be applicable in the complex scenarios with multiple relay communication nodes. Lu et al.[13] studied the theoretical model in complex scenes. However, this model was the BP transmission model with the custody mechanism of BP, rather than the LTP transmission model. Bundle protocol version 7[14] stipulates that if the lower layer protocol has a reliable transmission mechanism, the custody mechanism of BP will be inactivated, and the reliable transmission responsibility of the BP layer will be completed by the lower layer protocol. The BP transmission model is based on BP custody mechanism, while the LTP transmission model is without BP custody mechanism. The two models are completely different owing to different transmission mechanisms. Therefore, the BP transmission model established by Lu et al.[13] cannot be applied to the CDSNs with LTP as the transmission protocol. However, the theoretical model that our parameter optimization research relies on is the model of file delivery time for LTP established based on the CDSNs with multihop transmission without BP custody mechanism. The model can be applied to both simple and complex communication networks. It has wider application scenarios than the existing models, and meets the requirements of the latest standards.

Based on the theoretical model of LTP transmission mechanism, researchers had studied the optimization of protocol parameters. Wang et al. studied the bundle aggregation size in the environment with asymmetric channel rate ratio.[22] Wang et al.[8] and Yang[9] studied the optimal selections of the sizes of bundle, block, and segment and the value of session by means of experimental simulation. However, they were based on the theoretical models established in the simplified scenarios of two hops; thus, the results cannot be applied to the complex scenarios of multi hops. The methods of parameter optimizations using experimental simulations in these previous studies lack theoretical support and are not general and universal. Hu et al.[23] proposed a minimum bundle aggregation model to avoid ACK delay. By establishing the theoretical model of additional transmission overhead, Wang et al.[24] calculated the sizes of segment and bundle that minimize the additional transmission overhead. Lent calculated and analyzed the size of segment that minimizes the block delivery time.[10] This work confirmed that setting the segment to the same size as the Maximum Transmission Unit (MTU) does not always minimize the block delivery time. He also optimized the maximum number of retransmissions of a block.[25] However, those previously mentioned studies[10,23–25] are based on the research of parameter optimizations in the simple scenarios of one hop, and the research results cannot be applied to the CDSNs. In addition, only the optimal selections of the sizes of segment or bundle were studied; thus, the selection of optimization parameters is not comprehensive. Lu et al.[13] studied the optimal selections of the LTP protocol parameters, segment, and block, with the BP custody mechanism in multihop scenarios. However, because the parameter optimization method proposed by them[13] is based on the BP transmission model with BP custody mechanism rather than the LTP transmission model without BP custody mechanism, the conclusion cannot be applied to the current CDSNs with LTP as the transmission protocol. Based on the theoretical model of LTP transmission mechanism established with BP custody mechanism in complex scenarios, this paper proposes an optimization method of LTP protocol parameters for block, segment, and session through theoretical analysis. The optimization method considers the protocol parameters comprehensively and is suitable for CDSNs. It conforms to the latest standards and specifications and is more universal.

3. Complex deep space network scenes

In actual deep space communication, owing to the long distance, multiple relays may be required between the source and the destination. Obviously, the entire communication cannot be completed by one-hop data transmission, and the source, the destination, and all the relays in the middle constitute a complex communication scene.

In deep space communication, the rate of data transmission from deep space to the Earth will be greatly reduced because of the extremely long communication distance. In order to shorten the communication distance between source and destination, reduce the signal attenuation in the communication process, and achieve a higher data rate in deep space communication, the relay constellation is considered to be deployed between the Earth and the deep space detector.

A deep space communication network based on the Universal Interplanetary Communication Network (UNICON)[26] proposed by National Space Science Center has deployed a Geosynchronous-Earth-Orbit (GEO) constellation and a UNICON constellation between earth and Mars. UNICON constellation consists of 6 satellites uniformly distributed in heliocentric orbit between the earth orbit and Mars orbit. GEO constellation is composed of 2 GEO satellites with opposite positions. The diagram of the orbit of the deep space communication network based on UNICON is shown in Fig. 1. Thus, it passes through multiple relay nodes when data is transmitted between ground stations and Mars probes on the deep space network based on UNICON. Therefore, a ground station, a Mars probe, GEO and UNICON relay constellations constitute a complex deep space network based on UNICON (UNICON-CDSN). Moreover, the addition of GEO and UNICON constellations improves the data transmission performance of Mars-Earth[26].

A simulation model of UNICON-CDSN is built using STK, in which Odyssey (Ody) is selected for the Mars orbiter and Kashi is selected for the ground station. According to STK simulation results and the design principle of UNICON-CDSN,[26] the link distance and data rate of each link of UNICON-CDSN in 2020 are shown in Table 1. In addition, there are three possible paths of data transmission for the Mars orbiter in UNICON-CDSN in 2020, which are shown in Fig. 2. Let the number of UNICON satellites along the path be denoted by N_U, U1-U6 constitute the UNICON constellation. Fig. 2 (a) shows the data transmission path forwarded by only one UNICON satellite ($N_U = 1$). Fig. 2 (b), Fig. 2 (c) show the data transmission paths forwarded by two ($N_U = 2$) and three ($N_U = 3$) UNICON satellites.

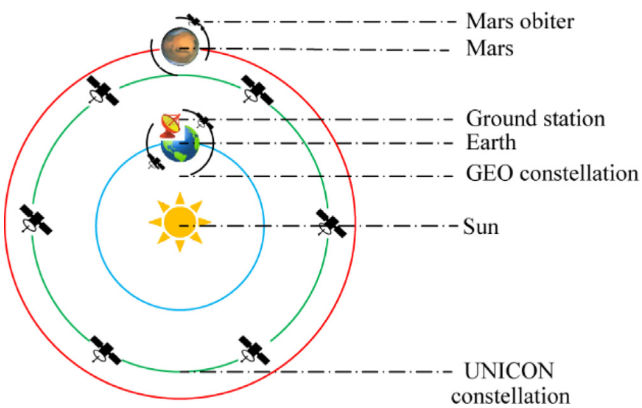


Fig. 1 Diagram of orbits of deep space communication network based on UNICON.

Table 1 Link distance and data rate in UNICON-CDSN.

Communication link	Link distance (km)	Data rate (kbps)
Mars orbiter-UNICON	$(7.33 -12.6) \times 10^7$	1000
UNICON-GEO	$(6.58 -12.6)\times 10^7$	60–172
GEO-Ground station	$(3.72 -4.15) \times 10^4$	60–172
UNICON satellite-UNICON satellite	2.17×10^8	20

4. Theoretical model

The general idea of the common protocol parameter optimization methods for LTP in the existing literature is to establish a theoretical model for LTP data transmission, and subsequently optimize the protocol parameters according to the model. This study also optimizes the protocol parameters for LTP in CDSNs according to this idea. Firstly, the theoretical model of file delivery time for LTP in CDSNs is established.

An excessively small block size L_{block} may cause the ACK transmission of a block on the forward link to experience delay,[27] thereby reducing the data transmission efficiency. To improve the LTP data transmission efficiency as much as possible, the model of file delivery delay in this paper is established with the condition that ACK transmission does not experience delay. When the bundle size L_{bundle} is fixed, the data transmission in case $L_{bundle} > L_{block}$ is equivalent to that in case $L_{bundle} = L_{block}$ with the condition that ACK transmission does not experience delay. Therefore, only the case of $L_{bundle} \leq L_{block}$ is considered here.

A file consists of multiple bundles. During the LTP data transmission in case $L_{bundle} \leq L_{block}$, bundles are aggregated into blocks, and then blocks are divided into segments for data transmission by LTP. Multiple sessions can be started by LTP at the same time, and one session transmits one block. Therefore, in the complex communication scenarios of multihop data transmission, when transmitting the files composed of multiple blocks, the transmission process is more complex than that in the simple scenarios of one or two hops. The transmission process of an LTP file in a complex scenario is shown in Fig. 3. As shown in Fig. 3, a file composed of 3 blocks is transmitted from source to destination through four hops. The first

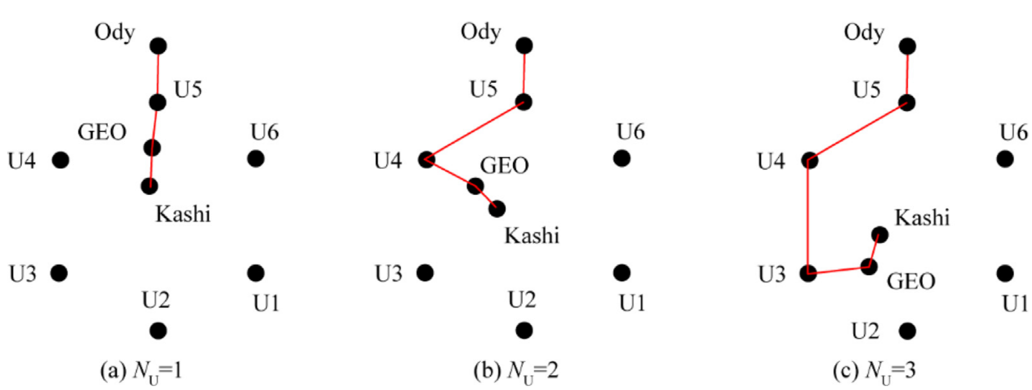


Fig. 2 Possible paths of data transmission for the Mars probe in UNICON-CDSN in 2020.

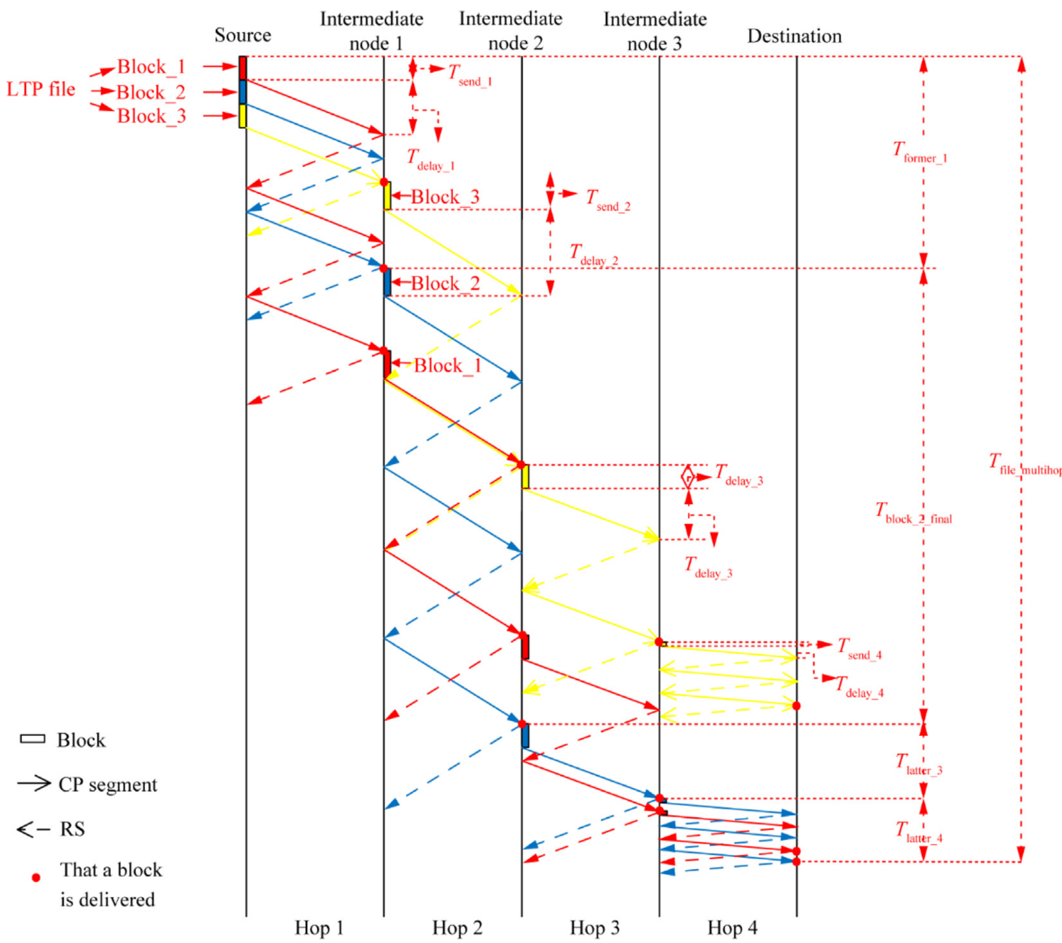


Fig. 3 Transmission process of an LTP file in a CDSN.

to the third blocks of the file are represented by red, blue and yellow in turn. For convenience of description, the first to the third blocks are represented by Block 1, Block 2, Block 3. As shown in Fig. 3, on the Hop 1, Block 1, Block 2 and Block 3 complete data transmission through 3, 2 and 1 transmission rounds, respectively. The order of data transmission completion of the three blocks is Block 3, Block 2 and Block 1. The Hop 2 is the hop with the longest one-way delay in the CDSN. After Block 3 arrives at the sending node of the second hop, Block 2 and Block 1 are sent successively. On the Hop 2, Block 3, Block 2 and Block 1 complete data transmission through 1, 2 and 1 retransmissions, respectively. The data transmission completion order of the three blocks on the Hop 2 is Block 3, Block 1 and Block 2. On the Hop 3, Block 3 completes data transmission first after one retransmission. Block 2 has one less retransmission than Block 1 and reaches intermediate node 3 before Block 1. On the Hop 4, Block 3, Block 1 and Block 2 complete data transmission in sequence after 2, 1 and 2 retransmissions, respectively.

The figure shows that when a file is transmitted in a CDSN, there will be different idle time intervals for block transmission on each hop except that the block can be sent continuously on the first hop. Moreover, because a file is encapsulated into a number of blocks according to the block size in LTP, multi-session mechanism results in transmitting multiple blocks simultaneously at different hops in multihop communication scenarios. In case of multihop scenarios, the efficiency of data delivery of LTP is improved. Therefore, the file delivery time for LTP in CDSNs cannot be calculated by the simple sum of file delivery time on each hop.

Assume that the qth hop has the longest one-way delay and that the last block for completing the delivery on this hop is $\text{block}_{q\_\text{final}}$. It can be seen from Fig. 3 that the total delivery delay is mainly affected by the transmission delay $T_{\text{block}\_q\_\text{final}}$ of $\text{block}_{q\_\text{final}}$ on Hop q. The total delivery time is divided into three parts for calculation in this paper: (A) the elapsed time between the start of file transmission at the first hop and the start of $\text{block}_{q\_\text{final}}$ transmission at the qth hop, T_{former}, (B) the delivery time of $\text{block}_{q\_\text{final}}$ on the qth hop, $T_{\text{block}\_q\_\text{final}}$, and (C) the elapsed time between the completion time of $\text{block}_{q\_\text{final}}$ transmission at the qth hop and the time when the entire file is received by the destination, T_{latter}. To simplify the discussion, Table 2 summarizes the main parameters that we use in the analysis.

Assume that a file with the size of L_{file} is divided into N_{bundle} bundles for transmission and that these bundles are combined into N_{block} blocks after being encapsulated by BP. Each session contains one block; hence, there are $N_{\text{block}} = (L_{\text{file}} + L_{\text{bundle\_head}} N_{\text{bundle}})/L_{\text{block}}$ sessions, where $L_{\text{bundle\_head}}$ is the header length of a bundle encapsulated by BP. Let N_{sess} represent the number of sessions configured for LTP before data transmission. When $N_{\text{sess}} < N_{\text{block}}$, the transmission perfor-

Table 2 Summary of main parameters used in analysis.

Parameter	Meaning
L_{file} (B)	File size
$L_{\text{bundle\_head}}$ (B)	Bundle header length
L_{block} (B)	Size of a block
$L_{\text{seg\_frame\_}i}$ (B)	Frame size of a segment of the ith hop
$L_{\text{seg\_payload\_}i}$ (B)	Payload size of a segment of the ith hop
$L_{\text{RS\_frame}}$ (B)	Frame size of an RS
N_{bundle}	Number of bundles into which a file is divided
N_{block}	Number of blocks constituting a file
N_{sess}	Number of sessions configured by LTP
$k_{\text{max\_}i}$	Number of delivery rounds of the entire file when it is delivered in the ith hop
$k_{\text{min\_}i}$	Number of delivery rounds of a block when it is delivered in the ith hop
$k_{\text{mean\_}i}$	Average number of delivery rounds of a file when it is delivered in the ith hop
f	Red segment fraction of a block
$p_{\text{seg\_}i}$	Segment loss probability of the ith hop
$p_{\text{ber\_}i}$	Bit Error Rate (BER) of a link of the ith hop
$p_{\text{CP\_RS\_}i}$	Loss probability of CPs (the segments with checkpoints) or RSs of the ith hop
$T_{\text{delay\_}i}$ (s)	One-way link delay of the ith hop
$R_{\text{data\_}i}$ (bps)	Data rate of the ith hop
$R_{\text{ACK\_}i}$ (bps)	ACK rate of the ith hop
ω_i (s)	Aggregation time of a block of the ith hop
λ_i (bps)	Data rate at which the sending node of the ith hop processes the aggregation operation
t_{lim} (s)	Maximum aggregation time of LTP configuration

mance of LTP will be significantly reduced.[27] This situation will be avoided when the protocol parameters is configured. Therefore, the file delivery time for LTP in CDSNs is calculated only when the session parameter is $N_{\text{sess}} \geq N_{\text{block}}$ in this paper.

For the same file, $L_{\text{bundle}} \leq L_{\text{block}}$ is equivalent to $N_{\text{bundle}} \geq N_{\text{block}}$. Since only the case of $L_{\text{bundle}} \leq L_{\text{block}}$ is considered here, the case of $N_{\text{bundle}} < N_{\text{block}}$ is not considered here. Therefore, the calculation is divided into two cases of bundle non-aggregation and aggregation. The two cases are when $N_{\text{bundle}} = N_{\text{block}}$ and $N_{\text{bundle}} > N_{\text{block}}$.

For the case of bundle non-aggregation in which $N_{\text{bundle}} = N_{\text{block}}$, a block contains only one bundle. After a file is divided into bundles, bundles do not need aggregation and can be directly packaged into blocks; thus, there is no consumption of aggregation time. Accordingly, the total delivery time for LTP in this case is

$$T_1 = T_{\text{former}} + T_{\text{block\_}q\text{\_final}} + T_{\text{latter}} \tag{1}$$

T_{former} includes the transfer delay of block$_{q\text{_final}}$ on each hop of the previous $(q-1)$ hop that is recorded as $T_{\text{former\_1}}$, $T_{\text{former\_2}}$, $T_{\text{former\_3}}$, ..., $T_{\text{former\_}a}$, ..., $T_{\text{former\_}q-1}$. Each $T_{\text{former\_}a}$ includes the propagation time of block$_{q\text{_final}}$, the transmission time of all blocks that are sent before block$_{q\text{_final}}$ on the ath hop, and the additional time that corresponds to the expiration of the timers due to the loss of CPs (the segments with checkpoints) or RSs. Because block$_{q\text{_final}}$ is sent with an uncertain order on the ath hop, the transmission rounds that are undergone by block$_{q\text{_final}}$ to complete transmission on the ath hop may be maximum, minimum, or any value in the middle, and the probabilities are the same. In order to obtain the optimal parameter configuration plan in a certain scenario, it is necessary to obtain the average situation of LTP file transmission in this scenario. Therefore, the average value of the propagation time of block$_{q\text{_final}}$ on the ath hop is considered here. Accordingly, the number of transmission rounds experienced by block$_{q\text{_final}}$ when it completes the entire transmission on Hop a is also calculated according to the average method. Assume that all bits on the channel are transmitted independently. Because block$_{q\text{_final}}$ may be the first or the last to complete transmission on the ath hop, or even the block that completes transmission in any order in the middle, the probabilities of being these blocks are the same. The mean number of transmission rounds of block$_{q\text{_final}}$ on the ath hop is the intermediate value between the numbers of the maximum transmission rounds and the minimum transmission rounds. The mean number of transmission rounds of block$_{q\text{_final}}$ on the ith hop is denoted as $k_{\text{mean\_}i}$, $i = a$. Let $k_{\text{min\_}i}$ and $k_{\text{max\_}i}$ indicate the numbers of the maximum and the minimum transmission rounds of block$_{q\text{_final}}$ on the ith hop. They are the numbers of transmission rounds that are undergone when passing one block and the entire file, respectively. Because the number of propagation rounds will have a major impact on the propagation time in deep space communications when the corresponding communication distance and data rate are fixed, the average value of the propagation time of a single block is converted to the average value of $k_{\text{min\_}i}$ and $k_{\text{max\_}i}$. Accordingly, $k_{\text{mean\_}i}$ can be calculated as follows:

$$k_{\text{mean\_}i} = (k_{\text{min\_}i} + k_{\text{max\_}i})/2 \tag{2}$$

Next, the number of transfer rounds $k_{\text{min\_}i}$ experienced when passing a block at the ith hop is calculated. Because a block is divided into multiple segments for transmission, the number of transmission rounds experienced by a block transmission, G_{block}, is determined by the maximum number of transmission rounds experienced by all segments in the block, $G_{\text{seg\_max}}$, that is, $G_{\text{block}} = G_{\text{seg\_max}}$. In this study, the expectation of G_{block} is used to calculate $k_{\text{min\_}i}$. Assuming that all bits on the channel are transmitted independently; thus, $p_{\text{seg\_}i} = 1 - (1 - p_{\text{ber\_}i})^{8L_{\text{seg\_frame\_}i}}$. Let N_{seg} represent the number of red segments of a block. Accordingly, the block comprises $N_{\text{seg}} = (fL_{\text{block}})/L_{\text{seg\_payload}} - 1$ red segments. Therefore, $k_{\text{min\_}i}$ is calculated as follows:

$$\begin{aligned} k_{\text{min\_}i} &= E(G_{\text{block}}) = E(G_{\text{seg\_max}}) = \sum_{m=1}^{\infty} mp(G_{\text{block}} = m) \\ &= \sum_{m=1}^{\infty}\left[1 - \prod_{j=1}^{N_{\text{seg}}} p\left(G_{\text{seg\_}j} < m\right)\right] \\ &= \sum_{m=1}^{\infty}\left[1 - \left(1 - p_{\text{seg\_}i}^{m-1}\right)^{\frac{fL_{\text{block}}}{L_{\text{seg\_payload\_}i}} - 1}\right] \end{aligned} \tag{3}$$

Similarly, $k_{\text{max\_}i}$ is calculated as follows:

$$k_{\text{max\_}i} = \sum_{m=1}^{\infty}\left[1 - \left(1 - p_{\text{seg\_}i}^{m-1}\right)^{\frac{L_{\text{file}} + L_{\text{bundle\_head}} N_{\text{bundle}}}{L_{\text{block}}}\left(\frac{fL_{\text{block}}}{L_{\text{seg\_payload\_}i}} - 1\right)}\right] \tag{4}$$

The propagation time of a block is mainly determined by the number of transmission rounds experienced when all segments of the block are successfully transmitted. Accordingly, the propagation time of T_{former_a} is calculated as follows:

$$T_{\text{prop}\_a\_\text{mean}} = (2k_{\text{mean}\_a} - 1)T_{\text{delay}\_a} + (k_{\text{mean}\_a} - 1)\frac{L_{\text{RS\_frame}}}{R_{\text{ACK}\_a}} \tag{5}$$

The transmission time of each segment of the ith hop is $(L_{\text{seg\_frame}\_i}/R_{\text{data}\_i})$ bps. A block will be divided into multiple segments for transmission at the ith hop, including $N_{\text{R}\_i} = fL_{\text{block}}/L_{\text{seg\_payload}\_i}$ red segments and $N_{\text{G}\_i} = L_{\text{block}}(1-f)/L_{\text{seg\_payload}\_i}$ green segments. It is assumed that a segment obeys the geometric probability distribution during transmission. Accordingly, the transmission time of the ith hop that is required to transfer all data in a single block is $T_{\text{trans}\_i} = (L_{\text{seg\_frame}\_i}/R_{\text{data}\_i})[N_{\text{R}\_i}/(1-p_{\text{seg}\_i}) + N_{\text{G}\_i}]$. Because the sending order of $\text{block}_{q\_\text{final}}$ at the ath hop is uncertain, the transmission time of T_{former_a} is as follows:

$$T_{\text{trans}\_a\_\text{mean}} = T_{\text{trans}\_a}N_{\text{block}}/2 \tag{6}$$

To prevent premature retransmission, the expiration time of the timer for CPs or RSs of the ith hop is $T_{\text{ex}\_i} = 2T_{\text{delay}\_i} + \beta$, where β is equal to at least the sending time of an RS. Assume that p_{CP_i} and p_{RS_i} are the loss probabilities of CPs and RSs of the ith hop, respectively, according to the same calculation approach as for p_{seg_i}. Accordingly, the loss probability of CPs or RSs of the ith hop is $p_{\text{CP\_RS}\_i} = 1-(1-p_{\text{CP}\_i})(1-p_{\text{RS}\_i})$. The additional time is as follows:

$$T_{\text{ex\_time}\_a\_\text{mean}} = \frac{p_{\text{CP\_RS}\_a}}{1-p_{\text{CP\_RS}\_a}}(k_{\text{mean}\_a} - 1)T_{\text{ex}\_a} \tag{7}$$

Therefore, T_{former} is calculated as follows:

$$T_{\text{former}} = \sum_{a=1}^{q-1}\left(T_{\text{prop}\_a\_\text{mean}} + T_{\text{trans}\_a\_\text{mean}} + T_{\text{ex\_time}\_a\_\text{mean}}\right) \tag{8}$$

$T_{\text{block}\_q\_\text{final}}$ contains the transmission time, propagation time, and additional time. Because $\text{block}_{q\_\text{final}}$ is the last block for completing the transmission at the qth hop, the number of transmission rounds is $k_{\max}$. $\text{block}_{q\_\text{final}}$ is sent with an uncertain order at the qth hop; hence, the transmission time is equal to the time consumed to send half the files. $T_{\text{block}\_q\_\text{final}}$ is calculated as follows:

$$\begin{aligned} T_{\text{block}\_q\_\text{final}} &= T_{\text{prop}\_q\_\max} + T_{\text{trans}\_q\_\max} + T_{\text{ex\_time}\_q\_\max} \\ &= \left(2k_{\max\_q} - 1\right)T_{\text{delay}\_q} + \left(k_{\max\_q} - 1\right)\frac{L_{\text{RS\_frame}}}{R_{\text{ACK}\_q}} + \\ &\frac{T_{\text{trans}\_q}N_{\text{block}}}{2} + \frac{p_{\text{CP\_RS}\_q}}{1-p_{\text{CP\_RS}\_q}}\left(k_{\max\_q} - 1\right)T_{\text{ex}\_q} \end{aligned} \tag{9}$$

Suppose the data transmission undergoes n hops. We divide T_{latter} into $(n-q)$ parts, namely, T_{latter_q+1}, T_{latter_q+2}, T_{latter_q+3}, $\ldots$, T_{latter_a}, $\ldots$, T_{latter_n}, and each part contains the transmission time, propagation time, and additional time. Because the link delays of the subsequent $(n-q)$ hops are all shorter than that of the qth hop, the propagation time contained in each T_{latter_a} is the propagation time of the block that was last sent and delivered at the corresponding hop. The last block to be sent is not necessarily the block with the most transmission rounds. Therefore, the number of transmission rounds of the related single block is set to k_{mean}. The transmission time consumed to send the entire file, T_{latter}, is calculated as follows:

$$T_{\text{latter}} = \sum_{a=q+1}^{n}\left(T_{\text{prop}\_a\_\text{mean}} + 2T_{\text{trans}\_a\_\text{mean}} + T_{\text{ex\_time}\_a\_\text{mean}}\right) \tag{10}$$

By substituting Eqs. (8)-(10) into Eq. (1), the file delivery time of LTP with $N_{\text{bundle}} = N_{\text{block}}$ in CDSNs can be calculated.

If $N_{\text{bundle}} > N_{\text{block}}$, a block consists of multiple bundles. The data transmission of LTP is a case of bundle aggregation. Aggregation takes time; thus, $T_{\text{file\_multihop}}$ contains T_{former}, $T_{\text{block}\_q\_\text{final}}$, and T_{latter}, as well as the aggregation time T_{aggre} that is mainly affected by the rate at which each communication node processes aggregation operations. The T_{aggre} formula is derived as follows:

$$\omega_i = \begin{cases} \frac{L_{\text{block}}}{\lambda_i}, \lambda_i \geqslant \frac{L_{\text{block}}}{t_{\text{lim}}} \\ t_{\text{lim}}, \lambda_i < \frac{L_{\text{block}}}{t_{\text{lim}}} \end{cases} \tag{11}$$

$$T_{\text{aggre}} = \sum_{a=1}^{n}\omega_a = \begin{cases} \sum_{a=1}^{n}\frac{L_{\text{block}}}{\lambda_a}, \lambda_a \geqslant \frac{L_{\text{block}}}{t_{\text{lim}}} \\ nt_{\text{lim}}, \lambda_a < \frac{L_{\text{block}}}{t_{\text{lim}}} \end{cases} \tag{12}$$

Thus, the calculation formula of file delivery time for LTP in complex scenarios, $T_{\text{file\_multihop}}$, can be summarized as follows:

$$T_{\text{file\_multihop}} = \begin{cases} T_1, & N_{\text{bundle}} = N_{\text{block}} \\ T_1 + T_{\text{aggre}}, & N_{\text{bundle}} > N_{\text{block}} \end{cases} \tag{13}$$

where T_{former}, $T_{\text{block}\_q\_\text{final}}$, and T_{latter} can be calculated by Eqs. (8)-(10), respectively.

In the deep space communication environment, the link delay is at the minute level, t_{lim} is in the second level, and t_{lim} is usually not set for a long time due to protocol efficiency; thus, $T_1 \gg T_{\text{aggre}}$. Accordingly, Eq. (13) can be simplified as

$$T_{\text{file\_multihop}} = T_{\text{former}} + T_{\text{block}\_q\_\text{final}} + T_{\text{latter}} \tag{14}$$

Furthermore, the file delivery goodput for LTP in the CDSNs with multihop transmission is

$$G_{\text{goodput}} = L_{\text{file}}/T_{\text{file\_multihop}} \tag{15}$$

5. Parameter optimization design

We measure the performance of file delivery for LTP in CDSNs with multihop transmission based on goodput. The higher the goodput, the better the protocol performance. Furthermore, according to Eq. (13), the shorter the total file delivery time for LTP, the better the protocol performance. For LTP, the parameters that have the greatest influence on its performance include the size of the block, the size of the segment, and the number of sessions.[6,13] Therefore, we choose the block, segment, and session that have the most significant influence on the performance of LTP for optimization to improve the LTP transmission performance.

5.1. Block and segment optimization

When LTP transmits data, one block corresponds to one RS. To cope with the asymmetric characteristics of the link in the deep space communication environment and avoid the delay of the RS of the block on the forward link, the transmission time of the block shall be greater than that of the RS, that is,

$L_{block\_frame}/R_{data} \geq L_{RS\_frame}/R_{ACK}$, where L_{block_frame} is the frame size of a block. Let L_{seg_header} be the header length of a segment. Accordingly, $L_{block\_frame} = L_{block} + (L_{block}/L_{seg\_payload}) \times L_{seg\_header}$, $L_{seg\_header} = L_{seg\_frame} - L_{seg\_payload}$. In addition, the LTP stipulates that a block is divided into several segments before subsequent transmission. Therefore, a block size should be at least greater than a segment size; thus the following formula can be listed for the block size:

$$L_{block} \geqslant \max\left(\frac{L_{RS\_frame} \times R_{data} \times L_{seg\_payload}}{R_{ACK} \times L_{seg\_frame}}, L_{seg\_payload}\right) \tag{16}$$

Analysis of Eq. (15) in MATLAB shows that when the segment size is fixed, the smaller the block size, the better the performance of LTP. Therefore, the optimal solution for the block size can be determined according to Eq. (16).

According to numerical analysis, $T_{former\_a}(L_{seg\_payload\_a})$, $T_{block\_q\_final}(L_{seg\_payload\_q})$, $T_{latter\_a}(L_{seg\_payload\_a})$ (where a represents the ath hop), and $T_{file\_multihop}(L_{seg\_payload})$ are convex functions. Thus, the segment optimization problem can be regarded as a convex optimization problem for determining the optimal solution of $T_{former\_a}(L_{seg\_payload\_a})$, $T_{block\_q\_final}(L_{seg\_payload\_q})$, or $T_{latter\_a}(L_{seg\_payload\_a})$ on each hop. The optimization problem can be expressed as follows:

min $T_m(L_{seg\_payload\_a})$,
s.t. $0 \leq L_{seg\_payload\_a} \leq \min(L_{MTU} - L_{seg\_header})$.
where T_m represents T_{former_a}, $T_{block\_q\_final}$, or T_{latter_a}, and L_{MTU} represents the MTU size of the link layer, $L_{MTU} = 1500$ B.

When the number of sessions can meet the one-time transmission of all data to be transmitted and $L_{block} = 1$ bundle, the sizes of block and segment jointly affect the transmission performance of LTP. This study adopts an iterative method to optimize the block and segment parameters. The optimal solutions should satisfy the Karush–Kuhn–Tucker (KKT) first-order necessary condition. The global optimal solution is found in four steps, as follows:

(1) Let $L_{seg\_frame\_a} = 1500$ B on each link and substitute it into Eq. (16) to obtain the minimum block size that is recorded as L_{b_min}.
(2) Substitute L_{b_min} into Eqs. (8)-(10), and determine the local optimal $L^*_{seg\_payload\_a}$ and KKT multipliers μ_1^*, μ_2^* that satisfy the KKT first-order necessary condition of $T_m(L_{seg\_payload\_a})$ as follows:

$$\begin{cases} \frac{\partial T_m}{\partial L^*_{seg\_payload\_a}} - \mu_1^* + \mu_2^* = 0 \\ \mu_1^* L^*_{seg\_payload\_a} = 0 \\ \mu_2^*\left(L^*_{seg\_payload\_a} - 1500 + L_{seg\_header}\right) = 0 \\ \mu_1^*, \mu_2^* \geqslant 0 \end{cases} \tag{17}$$

(3) Substitute $L^*_{seg\_payload\_a}$ obtained from Eq. (17) into Eq. (16) to obtain the minimum block size on each link, $L_{b\_min\_a}$. Then assign the maximum value of $L_{b\_min\_1}$, $L_{b\_min\_2}, \ldots, L_{b\_min\_n}$ to L_{b_min}, $L_{b\_min} = \max(L_{b\_min\_1}, L_{b\_min\_2}, \ldots, L_{b\_min\_n})$, $a = 1, 2, \ldots, n$, where n represents the total number of hops passed during data transmission.
(4) Repeat the second and third steps of iteration until the optimal solution that minimizes $T_{file\_multihop}$ is determined, in order to obtain the global optimal solution that optimizes the LTP performance, that is, maximizes $G_{goodput}$ that are L_{seg_opt} and L_{b_opt}.

5.2. Session optimization

According to the analysis of the session setting in the study of Yang et al.[27], a common choice for the number of sessions is

$$N_{sess} = 1.2(L_{file}/L_{block}) \tag{18}$$

For $L_{block} > 1$ bundle, the setting of bundle aggregation time limit may cause the actual aggregated block size, L_{block_act}, to be less than the preset block value, L_{block}. Therefore, the number of sessions set with (L_{file}/L_{block}) may not be enough to send all data of a file at once. Even setting the session value with $1.2(L_{file}/L_{block})$ does not guarantee that the channel resource can be fully utilized. In this case, if Eq. (18) is still used to set the number of sessions, the actual number of blocks may exceed the configured value of the number of sessions. According to the LTP data sending principle that a session contains a block, the additional blocks can be sent only after the first batch of sessions is released. However, only when a block is fully received by the receiving node will the session that hosts the block be released. Thus, the above situation will increase the overall delivery time significantly. Based on the above analysis, we improved Eq. (18). L_{block} in Eq. (18) is changed to L_{block_act}. L_{block_act} is determined according to whether the bundle is aggregated, as well as its aggregation time limit and aggregation rate. In addition, BDP, the product of 2 times bandwidth and delay, determines the maximum number of unconfirmed data in the link. Therefore, the configuration of session shall meet the condition that it does not exceed (BDP/L_{block_act}). Hence, the calculation formula for session optimization is as follows:

$$L_{block\_act} = \begin{cases} L_{block}, & L_{block} = 1 \text{ bundle} \\ L_{block}, & L_{block} > 1 \text{ bundle}, \ \lambda \geqslant L_{block}/t_{lim} \\ \lambda \times t_{lim}, & L_{block} > 1 \text{ bundle}, \ \lambda < L_{block}/t_{lim} \end{cases} \tag{19}$$

$$N_{sess\_opt} = \min\left(BDP/L_{block\_act}, \quad L_{file}/L_{block\_act}\right) \tag{20}$$

where λ indicates the bundle aggregation rate of the local node, t_{lim} indicates the setting bundle aggregation time limit, and N_{sess_opt} is the optimal design plan of a session. For the CDSNs with multihop transmission, the number of sessions on each hop can be calculated according to Eqs. (19)-(20).

5.3. LTP-PODA

Based on the above optimization design analysis of block size, segment size, and session number, we propose an LTP-PODA for block, segment, and session, as shown in Algorithm 1. Firstly, the algorithm obtains the global optimal solution of block and segment, L_{seg_opt} and L_{b_opt}, according to the four steps described in the block and segment optimization. Accordingly, L_{block_act} is calculated using Eq. (19) and L_{block_act} is compared with L_{b_opt}. If $L_{block\_act} = L_{b\_opt}$, the optimal design plans of block and segment remain unchanged. If $L_{block\_act} < L_{b\_opt}$, the optimal design plan of block remains unchanged. For the optimal design plan of segment, the actual block size, L_{block_act}, is substituted into Eqs. (8)-(10). Accordingly, Eq. (17) is solved to obtain the optimal design plan of segment. Finally, the optimal design plan of session N_{sess_opt} can be obtained according to Eq. (20).

Algorithm 1. LTP-PODA code

for all $a = \{a \mid 1 \le a \le n, a \in \mathbf{Z}^+\}$ **do**
$L_{seg\_payload\_a} \leftarrow (1500\ \mathrm{B} - L_{seg\_header})$; //initial segment size
end for
$\overrightarrow{L}_s \leftarrow (L_{seg\_payload\_1}, L_{seg\_payload\_2}, \ldots, L_{seg\_payload\_n})$;
$L_{b\_min} \leftarrow (\max((L_{RS\_frame} r_{CR} L_{seg\_payload})/ (L_{seg\_payload} + L_{seg\_header}), L_{seg\_payload}))$;
// initial block size, r_{CR} represents the channel rate ratio
$T_{file\_multihop\_min} \leftarrow T_{file\_multihop}(\overrightarrow{L}_s, L_{b\_min})$;
$\overrightarrow{L}_t \leftarrow \varnothing$;
while $L_{b\_min} \notin \overrightarrow{L}_t$ **do**
$\overrightarrow{L}_t \leftarrow \overrightarrow{L}_t \cup \{L_{b\_min}\}$;
for all $a = \{a \mid 1 \le a \le n, a \in \mathbf{Z}^+\}$ **do**
$L_{seg\_payload\_a} \leftarrow (\arg\min T_m (L_{seg\_payload\_a}))$;
$L_{b\_min\_a} \leftarrow (\max((L_{RS\_frame} r_{CR} L_{seg\_payload\_a})/ (L_{seg\_payload\_a} + L_{seg\_header}), L_{seg\_payload\_a}))$;
end for
$\overrightarrow{L}_s \leftarrow (L_{seg\_payload\_1}, L_{seg\_payload\_2}, \ldots, L_{seg\_payload\_n})$;
$L_{b\_min} \leftarrow \max(L_{b\_min\_1}, L_{b\_min\_2}, \ldots, L_{b\_min\_n})$;
if $T_{file\_multihop}(\overrightarrow{L}_s, L_{b\_min}) < T_{file\_multihop\_min}$ **then**
$T_{file\_multihop\_min} \leftarrow T_{file\_multihop}(L_s, L_{b\_min})$;
$\overrightarrow{L}_{seg\_opt} \leftarrow \overrightarrow{L}_s$;
$L_{b\_opt} \leftarrow L_{b\_min}$;
end if
end while
for all $a = \{a \mid 1 \le a \le n, a \in \mathbf{Z}^+\}$ **do**
if $L_{b\_opt} > L_{block\_act\_a}$ **then**
$L_{b\_min\_a\_new} \leftarrow L_{block\_act\_a}$;
$L_{seg\_payload\_a\_new} \leftarrow (\arg\min T_a (L_{seg\_payload\_a\_new}))$;
end if
$\overrightarrow{L}_{seg\_opt} \leftarrow (L_{seg\_payload\_1\_new}, L_{seg\_payload\_2\_new}, \ldots, L_{seg\_payload\_n\_new})$;
end for
$N_{sess\_opt} \leftarrow \lceil (1.2 \times (L_{file}/L_{block\_act})) \rceil$;

6. Experimental and performance evaluation

In this section, we present an experimental performance evaluation for the model and algorithm that are proposed in this paper. All simulation experiments are conducted without the custody mechanism of BP.

6.1. Experimental setup and configurations

The Mars exploration mission is considered as an example of the current international research hotspot. The UNICON-CDSN proposed in section 3 is selected as the simulation scenario of CDSNs. The implementation of the test bed of UNICON-CDSN for subsequent experiments is the same as that in Ref.[26] which includes communication scenarios of three hops, four hops, and five hops with one, two, and three relay UNICON satellites, respectively. The diagrams of the three paths are shown in the Fig. 2. N_U represents the number of relay satellites. The above three scenarios are represented by $N_U = 1$, $N_U = 2$, and $N_U = 3$. The testbed consists of nine communication nodes, including one Mars probe (Odyssey), six UNICON satellites, one GEO satellite, and one ground station (Kashi). Each communication node was simulated by Raspberry Pi. The nine Raspberry Pis are connected to a switch to realize data communication with each other. All communication nodes are installed with the Raspbian GNU/Linux 9 operating system. The protocol stack running on the testbed is BP/LTP/UDP/IP/Ethernet. Please refer to Ref.[26] for a physical diagram of the testbed.

Table 3 lists the major parameters of our experiments. Each experiment is conducted 10 times, and the results are taken as the mean.

6.2. Evaluation of the proposed model

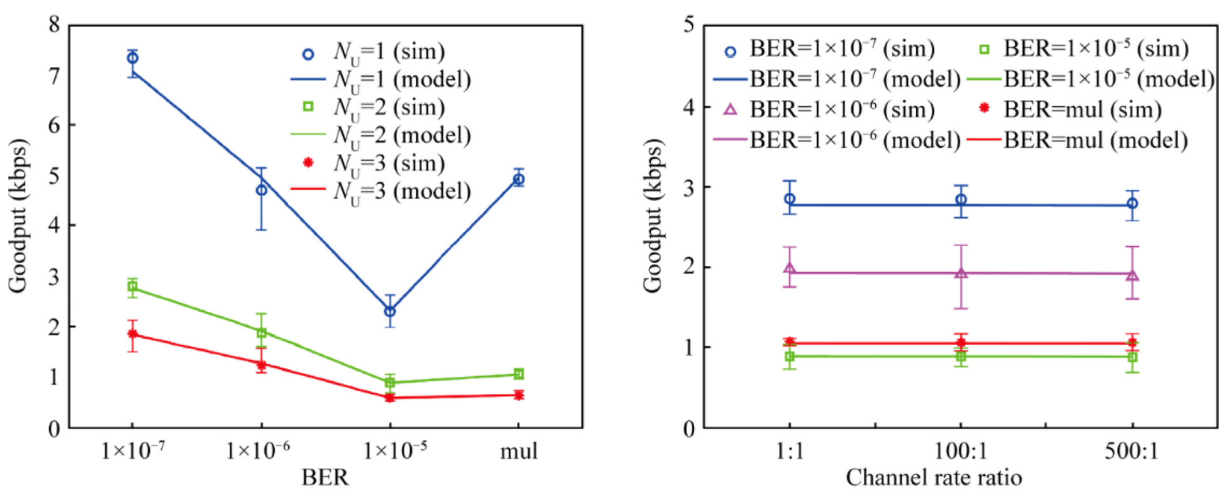
6.2.1. Model correctness

To verify the correctness of the LTP file delivery time model of complex deep space communication networks proposed in this paper, the following simulation experiments are designed in this study. Unless otherwise specified, the environment of each link is the same. Moreover, the LTP parameter configuration for each link is also the same. Let $L_{bundle} = 1$ KB that is close to the telemetry engineering parameter value of the spacecraft, or $L_{bundle} = L_{block\_payload}$, where $L_{block\_payload}$ is the payload size of a block. Bundles are sent in the form of data stream and can reach the ground data system alone. The number of LTP sessions is set to $N_{sess} = \max(\lceil 1.2(L_{file} + L_{bundle\_head} N_{bundle})/L_{block} \rceil, \lceil 1.2(L_{file} + L_{bundle\_head} N_{bundle})/(\lambda\omega) \rceil)$. The parameters of the experiment are shown in Table 3. In the table, the parameters of the bundle aggregation rate of the communication nodes are presented in the form of arrays, and the data in the array are the bundle aggregation rates of the communication nodes passing from the source node to the destination node (including the source node and excluding the destination node) from left to right according to the order of the data transmission passing through the communication nodes. 'mul' represents the mixed BER, that is, the BER of each link in the entire network is different. The specific settings are presented in the form of an array, and the BER settings of the passing links from the source node to the destination node are in turn from left to right in the array of Table 3. Experiments are conducted with different link environments or different protocol parameter configurations to evaluate the correctness of the model of file delivery time for LTP in CDSNs.

Fig. 4 shows the comparison of simulation results and model calculation results with different link environments. Fig. 4(a) represents the comparison results between the simulation experiments and model calculations when the channel rate ratio is 500:1, and the BERs are 1×10^{-7}, 1×10^{-6}, 1×10^{-5}, and mul with three transmission paths ($N_U = 3$, $N_U = 2$, and $N_U = 1$). Fig. 4(b) represents the comparison results between simulation experiments and model calculations when the channel rate ratios are 1:1, 100:1, and 500:1 with four BERs on the transmission path with $N_U = 2$. For transmission paths with $N_U = 3$ and $N_U = 1$, the comparison results

Table 3 Experimental factors and settings.

Experimental factor	Setting	Value
Implementation of DTN protocol stack		ion-3.7.0
Data rate of data channel (kbps)	Odyssey-UNICON	60
	UNICON-UNICON	20
	UNICON-GEO	60
	GEO-Kashi	1×10^4
BP custody transfer option		Disabled
Aggregation time limit (s)		1
File size (MB)		1, 5
MTU (B)		$L_{seg\_payload\_i} + 100$
Bundle aggregation rate of communication nodes, λ (kbps)	$N_U = 3$	[37.143, 30.588, 38.519, 37.143, 49.524]
	$N_U = 2$	[37.143, 30.588, 38.519, 49.524]
	$N_U = 1$	[37.143, 30.588, 49.524]
Bundle size (KB)		500
		1
One-way link delay (s)	$N_U = 3$	$358 + 725 \times 2 + 285 + 0.125 = 2093.125$
	$N_U = 2$	$296 + 725 + 273 + 0.125 = 1294.125$
	$N_U = 1$	$245 + 241 + 0.125 = 486.125$
BER		1×10^{-7}, 1×10^{-6}, mul, mul_1, mul_2,mul_3, 1×10^{-5}
(mul, mul_1, mul_2, and mul_3 are mixed BERs)	mul $N_U = 3$	[1×10^{-6}, 1×10^{-5}, 1×10^{-5}, 1×10^{-6}, 1×10^{-7}]
	mul $N_U = 2$	[1×10^{-6}, 1×10^{-5}, 1×10^{-6}, 1×10^{-7}]
	mul $N_U = 1$	[1×10^{-6}, 1×10^{-6}, 1×10^{-7}]
	mul_1 $N_U = 2$	[1×10^{-6}, 1×10^{-5}, 1×10^{-6}, 1×10^{-7}]
	mul_2 $N_U = 2$	[1×10^{-5}, 1×10^{-5}, 1×10^{-6}, 1×10^{-7}]
	mul_3 $N_U = 2$	[1×10^{-5}, 1×10^{-5}, 1×10^{-6}, 1×10^{-5}]
Channel rate ratio (data rate/ACK rate)		1:1, 50:1, 500:1
Experimental repetitions		10



(a) Channel rate ratio=500:1 (b) N_U=2

Fig. 4 Comparison of simulation results and model calculation results with different link environments.

between simulation experiments and model calculations with four BERs are similar to Fig. 4(a) when the channel rate ratios are 100:1 and 1:1; thus, they are not listed here. It can be seen from Fig. 4 that the calculation results of the model are in good agreement with the simulation results, which proves the correctness of the model of file delivery time for LTP with different link environments in the CDSNs. When the BER is low, the error of the calculation results of the model increases compared with the real situation. This is because the lower the BER of the link, the closer the number of transmission rounds experienced when completing the data delivery will be to 1, and the greater the deviation between the number of transmission rounds calculated by the mean idea of the model and the actual value will be. The delays generated by the transmission rounds are the most important parts of the delivery time of LTP files in deep space communications. Therefore, the deviation between the model and the experimental results increases when the BER is low.

Fig. 5 shows the comparison of simulation results and model calculation results with different protocol parameter configurations when the link environmental condition is $N_U = 2$, 1×10^{-5} of the BER and 500:1 of the channel rate ratio. The protocol parameters of Figs. 5 (a), (b), and (c) are configured as follows: (A) $L_{block} = 1$ bundle, $L_{seg\_payload} = 1400$ B; (B) $L_{block} > 1$ bundle, $L_{seg\_payload} = 1400$ B; (C) $L_{block} = 1$ bundle, $L_{bundle} = 50$ KB. It can be seen from Fig. 5 that the model calculation results are in good agreement with the simulation results when sending the files of various sizes with different settings of bundle, block, segment, and session. Therefore, it can be proved that in the CDSNs, the model of file delivery time for LTP can accurately predict the total file delivery delay with different protocol parameter configurations.

6.2.2. Model advantages

Considering the Mean Absolute Percentage Error (MAPE) as the evaluation standard, we compare the accuracy of the model proposed in this paper with two classical single hop link transmission models that are referred to model 1[11] and model 2,[10] respectively, to evaluate the advantages and necessity of this model. The selection of experiment parameters and corresponding experiment numbers are shown in Table 4.

Figs. 6 (a) and (b) shows the comparison results of MAPEs of three theoretical models with different link environments and different protocol parameter configurations, respectively. It can be seen from the MAPE comparison results in Fig. 6 that the LTP file delivery time (or goodput) predicted by the theoretical model proposed in this paper is closer to the simulation results than that predicted by model 1 and model 2 with different link environments and various protocol parameter configurations in the CDSNs. Combining Figs. 6 (a) and (b), the average MAPE of the theoretical model proposed in this paper is 7.27%, while that of model 1 and model 2 are 18.92% and 13.74%, respectively. Therefore, the theoretical model in this paper has 6.47% higher prediction accuracy than model 1 and model 2. In addition, the theoretical model in this paper can also predict the LTP data transmission when the link environments in a CDSN are different (the BER of each link passing through the data transmission path is different). However, model 1 and model 2 do not provide the prediction and calculation method of LTP file delivery time (or goodput) in this scenario. To summarize, model 1 and model 2 are not applicable to the prediction and calculation of file delivery time (or goodput) for LTP in the CDSNs. Therefore, the proposal of the theoretical model in this paper is necessary in the more common complex deep space communication scenarios than the simplified scenarios.

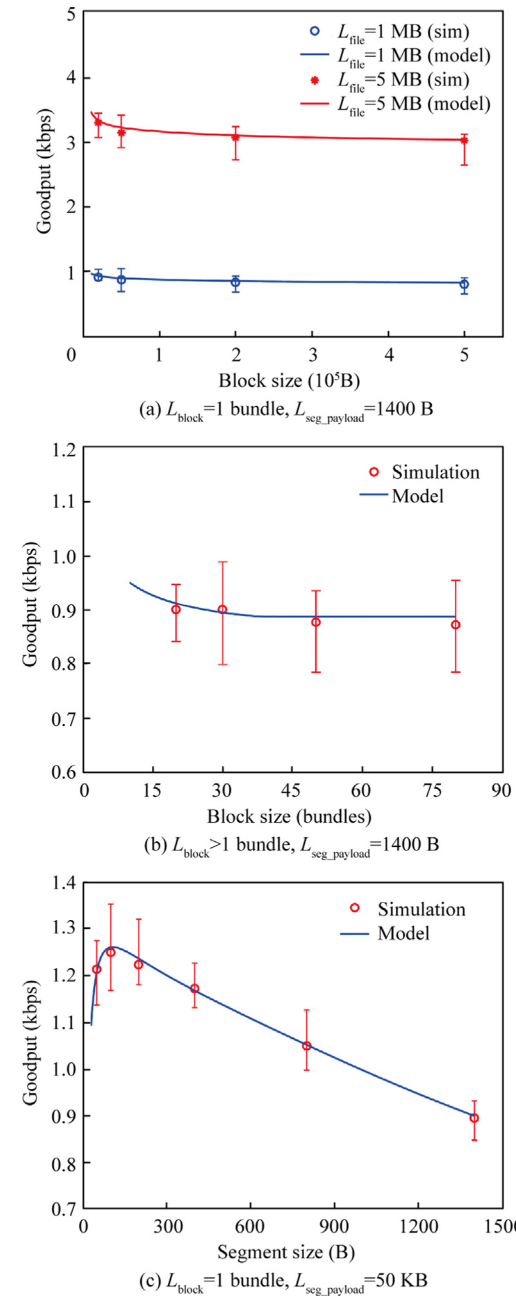


Fig. 5 Comparison of simulation results and model calculation results with different protocol parameter configurations.

6.3. Evaluation of proposed algorithm

In this section, according to different link environments, the LTP-PODA algorithm proposed in this paper is used to optimize the LTP parameter configuration in the UNICON-CDSN, and the parameter configuration optimization plan in the corresponding scenario is proposed. With different communication environments, the performance of the optimized parameter configuration plan is compared with other parameter configuration plans, to verify the effectiveness of LTP-PODA algorithm in improving the transmission performance of LTP. The specific number of each plan and corresponding description are shown in Table 5. Plan 1 is a configuration plan in which all three parameters, block, segment, and session, are optimized. Plan 2, plan 3, and plan 4 represent the plans in which the block, segment, and session, respectively, are not optimized. Plan 5, plan 6, and plan 7 represent the plans in which only the block, segment, and session, respectively, are optimized. Plan 8 is a plan in which none of the three parameters are optimized. The selection of parameter values in each plan is as follows. $L_{block} = 500$ KB and $L_{seg\_payload} = 1400$ B are selected as the block size and segment size, respectively,

Table 4 Parameter settings of experiments for calculating MAPE.

Number	Transmission path	BER	Channel rate ratio	Bundle (KB)	Block (bundles)	Segment (B)
a	$N_U = 2$	1×10^{-7}	500:1	50	1	1400
b	$N_U = 2$	1×10^{-6}	500:1			
c	$N_U = 2$	1×10^{-5}	500:1			
d	$N_U = 2$	1×10^{-5}	100:1			
e	$N_U = 2$	1×10^{-5}	1:1			
f	$N_U = 3$	1×10^{-5}	500:1			
g	$N_U = 1$	1×10^{-5}	500:1			
h	$N_U = 2$	1×10^{-5}	500:1	50	1	1400
i				200	1	1400
j				50	1	800
k				50	1	100
l				1	20	1400
m				1	50	1400

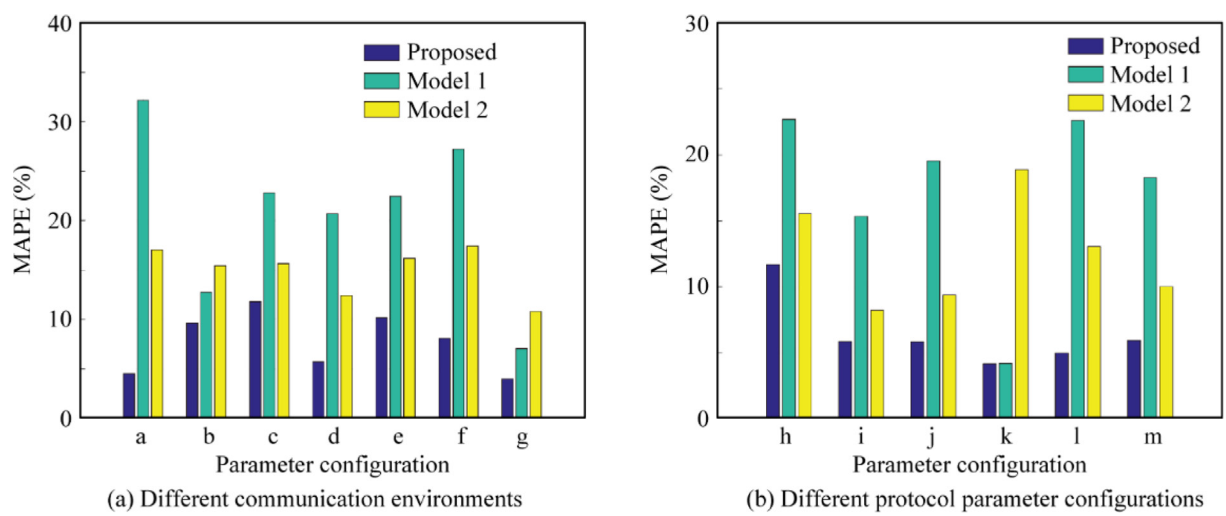


Fig. 6 MAPE comparison of three theoretical models with different communication environments and different protocol parameter configurations.

Table 5 Plan numbers and descriptions.

Number	Description of plans		
	Categories	Optimized parameters	Unoptimized parameters
1	Optimization plan	block, segment, session	
2	Two parameters are optimized	segment, session	block
3		block, session	segment
4		block, segment	session
5	One parameter is optimized	block	segment, session
6		segment	block, session
7		session	block, segment
8	No parameter is optimized		block, segment, session

without optimization. If $L_{block} = 1$ bundle, $N_{sess} = 1/2(L_{file}/L_{block})$ is used to calculate the session value without optimization, where L_{block} is equal to L_{block_act}. If $L_{block} > 1$ bundle, $N_{sess} = 1.2(L_{file}/L_{block})$ is used to calculate the session value without optimization, where L_{block} is not equal to L_{block_act}. A 1 MB file is sent for experiments to evaluate the effectiveness of LTP-PODA in optimizing the LTP performance in various environments.

The simulation experiment parameters are shown in Table 3. In the experiment, the environment of each link is the same unless otherwise specified. Accordingly, a file is sent with the size of 1 MB. With the experiment, the effectiveness of LTP-PODA algorithm for optimizing LTP transmission performance is verified. Moreover, the impacts of different link delays, BERs, channel rate ratios, and bundle aggregation on the optimization effect of LTP-PODA algorithm are analyzed.

Fig. 7 shows the impact of different BERs ($p_{\text{ber}} = 1 \times 10^{-7}$, 1×10^{-6}, mul_1, mul_2, mul_3, 1×10^{-5}) on the optimization effect of LTP-PODA algorithm when $N_U = 2$ and $r_{CR} = 500{:}1$, where r_{CR} represents the value of channel rate ratio. mul_1, mul_2, and mul_3 refer to mixed BERs, that is, the BER of each link in the entire network is different. The three mean that 1, 2, and 3 links in the network are set to high BERs, respectively, and the other links are set to low BERs. For the network with $N_U = 2$, the BER settings of the links from the source node to the destination node is shown in Table 3. From Fig. 7, we can draw the following conclusions:

(1) In the environment of low BER, for the three plans that optimize only one parameter, the plan that optimizes only segment reduces goodput the most, followed by the plan that optimizes only block, and subsequently the plan that optimizes only session. For the three plans with only two parameters optimized, the goodput reduction of the plan without optimized segment is the least, that of the plan without optimized block is the second, and that of the plan without optimized session is the largest. Therefore, in the low BER environment, the optimization of session has the greatest impact on the performance improvement of LTP, followed by block and then segment.

(2) For the network with the mixed BERs, that is, the data transmission link with both high BERs and low BERs, irrespective of the number of high BER links of 1, 2, or 3, the file delivery goodput for LTP of the eight plans from high to low is as follows: plan 1, plan 2, plan 3, plan 7, plan 4, plan 6, plan 5, and plan 8. Therefore, in the network with mixed BERs, the optimization of session has the most significant impact on the performance of LTP, followed by segment. The optimization of block has the least significant impact on the LTP performance.

(3) When the BER is high, the goodput of plan 1 increases by 39.73%, 33.86%, 59.65%, and 93.64% compared with plans 3, 4, 6, and 7, respectively. Therefore, the optimizing segment improves the goodput more than the optimizing session. Compared with plan 2, the goodput of plan 1 increases by 17.46%, which is the least improved compared with other plans. Therefore, the optimizing block can at least improve the goodput compared with the other two parameters. Thus, in the high BER environments, the optimizing segment can improve the LTP performance the most, followed by the optimizing session and then the optimizing block.

(4) In any BER environment, compared with other parameter configuration plans, deploying the optimization plan for LTP can obtain the best transmission performance. Configuring the optimization plan for LTP helps improve the protocol transmission performance by at least 18.95% on average.

Fig. 8 shows the impacts of different link delays ($N_U = 3, 2, 1$, and Table 3 shows the specific link delays) on the optimization effect of LTP-PODA algorithm in the link environments with high channel rate ratio, $r_{CR} = 500{:}1$ and high BER, $p_{\text{ber}} = 1 \times 10^{-5}$. It can be seen from Fig. 8 that under three conditions of $N_U = 1$, $N_U = 2$, and $N_U = 3$, the LTP performance of the eight plans from excellent to poor is as follows: plan 1, plan 2, plan 4, plan 3, plan 6, plan 7, plan 5, and plan 8. The transmission performance of plan 1 is 24.75% higher than that of plan 2 on average. Thus, the link delay has no impact on the optimization effect of LTP-PODA. The number of hops through which data is transmitted in the network also has no impact on the optimization effect of LTP-PODA.

Fig. 9 shows the influence of different channel rate ratios ($r_{CR} = 500{:}1$, $50{:}1$) on the optimization effect of the LTP-PODA algorithm when $N_U = 1$ and $p_{\text{ber}} = 1 \times 10^{-5}$. It can be seen from Fig. 9 that for the low channel rate ratio with

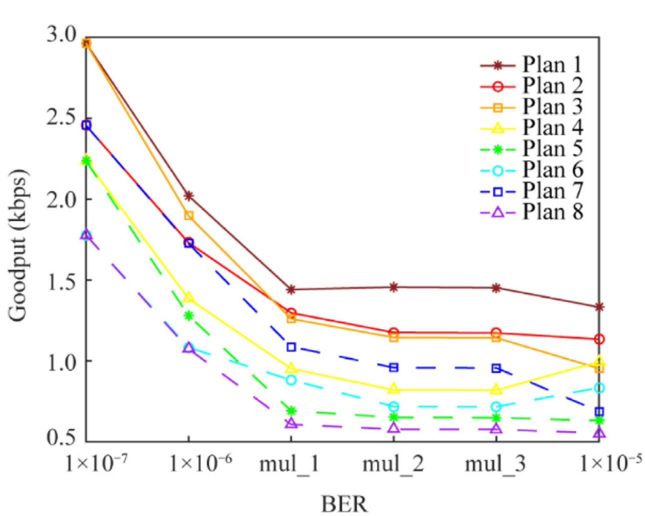


Fig. 7 LTP performance comparison of different parameter configuration plans with various BERs.

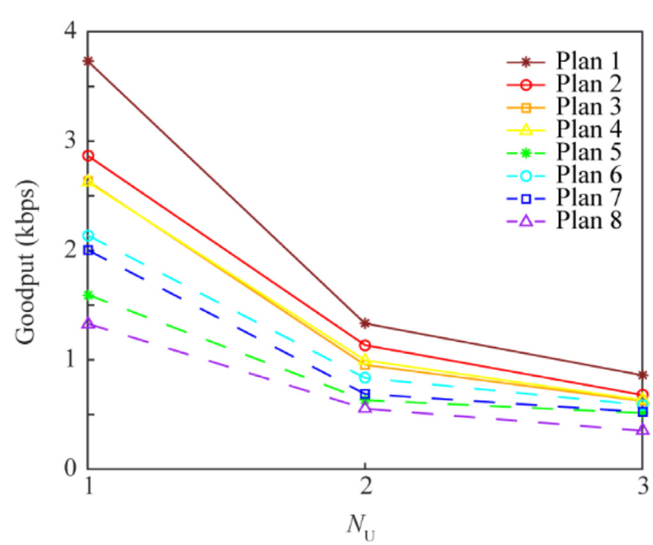


Fig. 8 LTP performance comparison of different parameter configuration plans with various one-way link delays.

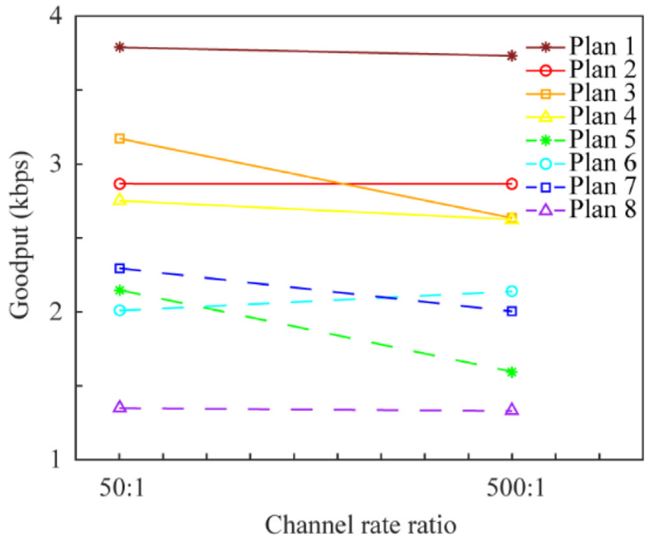


Fig. 9 LTP performance comparison of different parameter configuration plans with various channel rate ratios.

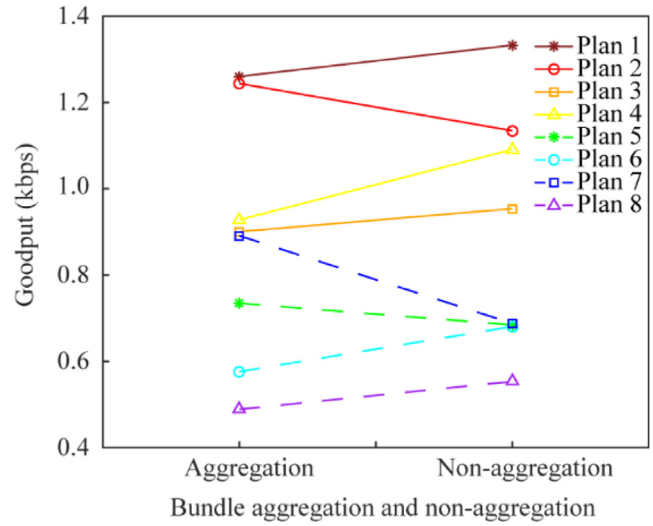


Fig. 10 LTP performance comparison of different parameter configuration plans with bundle aggregation and non-aggregation.

r_{CR} = 50:1, the data transmission goodput of plan 1 is increased by 32.15%, 19.43%, 76.35%, and 88.56% compared with plans 2, 3, 5, and 6, respectively. Therefore, the optimizing block can improve the transmission performance of LTP better than the optimizing segment. Compared with plans 2, 4, 5, and 7, the goodput of plan 1 is increased by 32.15%, 37.68%, 76.35%, and 65.11%, respectively. Therefore, the optimization of session improves the LTP performance more than that of block. Thus, in the environment of low channel rate ratio, the optimization of session can improve the LTP file transmission goodput the most, followed by the optimization of block and finally the optimization of segment. For the high channel rate ratio with r_{CR} = 500:1, the LTP file transmission goodput of the eight plans is as follows, from high to low: plan 1, plan 2, plan 4, plan 3, plan 6, plan 7, plan 5, and plan 8. The transmission performance of plan 1 is 31.17% higher than that of plan 2 on average. Thus, in the environment of high channel rate ratio, the optimizing segment can improve the LTP file transmission goodput the most, followed by the optimizing session, and finally, the optimizing block.

Fig. 10 shows the effectiveness of the LTP-PODA algorithm in the case of bundle aggregation and non-aggregation with the environment of N_U = 2, r_{CR} = 500:1, and p_{ber} = 1 × 10^{-5}. In the case of aggregation, L_{block} = 1 bundle, then $L_{bundle} = L_{block} - L_{bundle\_header}$, where L_{bundle_header} = 40 B. In the case of non-aggregation, L_{block} > 1 bundle, and the bundle size is L_{bundle} = 1 KB. It can be seen from Fig. 10 that the LTP performance of the eight plans in the case of bundle aggregation and non-aggregation is as follows, from excellent to poor: plan 1, plan 2, plan 4, plan 3, plan 7, plan 5, plan 6, and plan 8. Thus, irrespective of whether the bundles are aggregated, the optimization effect of LTP-PODA remains uninfluenced. The transmission performance of plan 1 is 18.77% higher than that of plan 2 on average.

Through the analysis of the above four images, the following conclusions are drawn by comparing the performances of LTP in various communication environments when LTP is configured with the eight parameter configuration plans:

(1) The parameter optimization plan that is based on LTP-PODA to configure LTP can improve the LTP performance. According to Figs. 5–8, the performance is improved by at least 18.77% on average.
(2) Communication hops (or one-way link delays) and bundle aggregation have no influence on the optimization performance of LTP-PODA. The differences of BERs and channel rate ratios have a certain impact on the optimization effect of LTP-PODA.
(3) When the link environment is characterized by low BERs or low channel rate ratios, session optimization can improve the transmission goodput of LTP the most, followed by block optimization and, finally, segment optimization.
(4) In the network that is composed of links with mixed BERs, the number of sessions has the largest influence on LTP performance, followed by the segment and block sizes.
(5) With high BERs and high channel rate ratios, if $N_{sess} \geq 1/2 \times (L_{file}/L_{block})$, the segment optimization improves the LTP performance more than session optimization does, and if $N_{sess} < 1/2 \times (L_{file}/L_{block})$, session optimization improves the LTP performance more than segment optimization does. In this communication environment, block optimization improves the LTP performance the least.

7. Conclusions

In this paper, first, we propose a theoretical model of file delivery time for LTP in CDSNs. Next, we choose block, segment, and session for optimization design. We propose the optimization basis of the three parameters through theoretical analysis based on the proposed model of file delivery time for LTP in CDSNs. Subsequently, we propose the LTP-PODA algorithm. Finally, the correctness of the proposed model and the effectiveness of LTP-PODA in improving the LTP transmission performance are experimentally demonstrated. We draw the following valuable conclusions:

(1) The calculation results of the proposed model are in agreement with the simulation results. The accuracy of the model is 6.47% higher than that of the latest and most accurate model based on simplified scenes. In addition, the model can be applied to communication scenarios with mixed BERs, and is more suitable for CDSNs.
(2) In any communication environment, the optimization plan in the corresponding environment can be obtained by using the LTP-PODA algorithm. Compared with plans without parameter optimization or incomplete parameter optimization, configuring the optimization plan acquired by LTP-PODA for LTP can result in higher protocol performance under any communication condition. The performance is improved by at least 18.77%.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This work was supported by the Strategic Leading Project of the Chinese Academy of Sciences (No. XDA15014603).

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