Energy saving scheme of delay/disruption tolerant network in deep space communications

Yang Wang, Hong Yang, Xiaoguang Chen, Jiali Zheng, Song Chen, and Kai Ding
Institute of Manned Space System Engineering, China Academy of Space Technology
Beijing, 100094, P. R. China
E-mail: happyangw@yahoo.com

Abstract—**Delay/Disruption Tolerant Network (DTN) is playing an important role in the future space communications, especially the deep space communications. The available energy resources on the spacecraft are very limited and sometimes may become very scarce. In such conditions, the extra transmission effort is required as small as possible, to achieve the goal of saving energy resources. Current studies indicate that the packet sizes of DTN protocol layers such as bundle size, LTP block size, and Licklider Transmission Protocol (LTP) segment size have an impact on the extra transmission effort, but the studies are lack of theoretical model and analysis. Therefore, a theoretical model of extra transmission effort is proposed in terms of BP/LTP protocol stack, which can be applied to DTNs using other convergence layer protocol besides LTP. What's more, an analysis is made to the theoretical model and a scheme of saving the energy resources by optimizing the packet sizes of DTN protocol layers is presented. The numerical evaluation results show that this scheme can effectively conserve the energy consumption of the spacecraft, which can be a good solution to the scarcity of energy resources in space missions.**

Keywords—Delay/Disruption Tolerant Network; theoretical model; energy resources; packet sizes

I. Introduction

Delay/Disruption Tolerant Network (DTN) [1] is designed for the data transmission in the "challenged networks", which has the characteristics of long delay, link frequent interruptions, and high BER, such as Interplanetary Internet (IPN) and military ad hoc networks. The main concept of DTN proposed by Kevin Fall lies in "bundling", a mechanism used by space network node to store data when the next hop is unreachable. To store and forward the message, DTN architecture employs a new protocol called Bundle Protocol (BP) [2] to cover on the lower-layer protocols of the original network architecture. Also BP can support the point-to-point retransmission by custody transfer (CT), which can be optional, not mandatory. Besides, the protocol which runs under BP and implements the exchanges of bundles is named convergence layer protocol. Licklider Transmission Protocol (LTP) [3], specially designed for long delay and intermittent link, is believed to be the most appropriate convergence layer protocol in deep space communications.

Recently, the research of DTN mainly focuses on the performance of DTN protocols in space communications especially the deep space communications. Some researches concern about the effective throughput performance of DTN, both through the experimental and theoretical approaches [4][5][6][7]. Meanwhile, the node storage performance of DTN in space communications was analyzed in [8][9][10]. Energy resources consumption is an import performance metric in space DTN, as the energy resources is limited in spacecrafts especially in deep space missions. Therefore, it is necessary to study the extra transmission effort, in order to minimize the energy resources consumption needed when transmitting a certain file. In [11], the impact of bundle size/LTP block and LTP segment size on the extra transmission effort, effective throughput, and node storage was studied. Also in [12], the impact of bundle size and DTTP segment size on the extra transmission effort, effective throughput, and node storage was under consideration and a heuristic search was put forward. These studies [11-12] are carried out through experiments and lack of analytical models, which cannot be applied to other scenarios, and moreover, the study in [12] does not involve LTP. Accordingly, [13] proposed an analytical model focused on the impact of bundle size and LTP segment size on effective throughput, and a scheme to find the optimal packet sizes that maximize the effective throughput and also minimize the extra transmission effort was suggested. Unfortunately, the model did not consider the bundle-aggregation function of LTP and the effect of bundle size on extra transmission effort. Besides, the propagation delay was only 18 s and the bandwidth was 36 Kbps, which cannot reflect the characteristics of deep space communications. Hence, the analytical analysis of the effect of bundle size, LTP block size, and LTP segment size on extra transmission effort, as well as the scheme to save energy by using optimal packet sizes has not been considered.

In this paper, we focus on the optimization design of bundle size, LTP block size, and LTP segment size, in order to minimize extra transmission effort and save energy resources in deep space DTN. Through analyzing the PDU encapsulations and segmentations in DTN protocol layers and the retransmission mechanism of LTP, a theoretical model of extra transmission effort in DTN is established. Based on this model, the impact of bundle size, LTP block size, and LTP segment size on extra transmission effort is analyzed and the packet sizes are optimized. Numerical simulation results indicate that the proposed scheme that optimizes the bundle size and LTP segment size can effectively conserve the energy resources.

The remainder of this paper is organized as follows. In Section Ⅱ, the theoretical model of extra transmission effort in deep space DTN is proposed. In view of this, the energy saving scheme is designed by optimizing the packet sizes of DTN protocol layers in Section Ⅲ. Section Ⅳ presents the numerical

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simulation results and the discussions. In Section Ⅴ, the conclusion is drawn.

II. THEORETICAL MODEL OF EXTRA TRANSMISSION EFFORT IN DEEP SPACE DTN

In this section, we formulate a theoretical model of extra transmission effort in deep space DTN.

A. PDU encapsulations and segmentations in DTN

The data transmission process in DTN is described as follows: the source file is divided into multiple bundles. Taking into account the bundle-aggregation function of LTP, M bundles are aggregated to form a LTP block. Then a LTP block is segmented into L LTP segments. Finally, the LTP segment is added by the data link layer header, and passed to the physical layer to be transmitted. Fig. 1 shows the PDU encapsulations and segmentations in DTN.

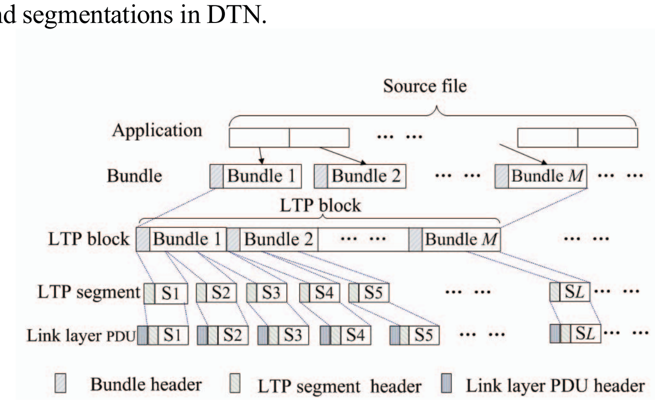

Fig.1. PDU encapsulations and segmentations in DTN.

B. Retransmission of data in DTN

The DTN architecture employed in this paper is BP/LTP/data link layer, with CT disabled.

Each LTP block is partitioned into two parts in view of the mission demands, i.e., the red part requires reliable transmission whereas the green part does not. Some LTP data segments are marked as checkpoints (CPs) to detect the receiving status of LTP block and the last segment of the red part must be marked as a CP. A CP is acknowledged by returning a report segment (RS) to the sender. The sender returns a report acknowledgment (RA) to the receiver to respond to a RS, meanwhile it retransmits the lost segments indicated by the RS. In addition, it needs retransmitting the RSs or CPs if not acknowledged before the corresponding timer expires.

C. Theoretical model of extra transmission effort in deep space DTN

Table I lists the notations to be used in the derivation.

TABLE I. NOTATIONS

Symbols	Definitions
p_{seg}/p_{CP}	Loss probability of a LTP data segment/ CP segment
L_{block}	Length of the client service data in a LTP block
L_{bundle}	Length of a bundle (not including the bundle header)
L_{seg}	Length of a LTP data segment at the data link layer
N_{bundle}	Number of bundles aggregated in a LTP block
N_{seg}	Number of LTP data segments contained in a LTP block
N_{block}	Number of LTP blocks generated from a file

Suppose each bundle has an equal length, and the length of the bundle header is L_{bundle_head}. Considering one block /multiple bundles, the length of a LTP block can be expressed as

$$L_{block} = N_{bundle} \times (L_{bundle} + L_{bundle\_head}). \tag{1}$$

The size of the file to be transmitted is L_{file}, so the number of LTP blocks originally transmitted is presented as

$$N_{block} = \frac{L_{file}}{N_{bundle} \times L_{bundle}}. \tag{2}$$

We assume that each LTP data segment is of the same length, denoted as L_{ltp_seg}. Define a LTP block can be divided into N_{seg} LTP data segments, i.e., $N_{seg}-1$ LTP non-CP data segments and the last CP segment. The number of LTP data segments in a LTP block can be formulated as follows:

$$N_{seg} = \frac{L_{block}}{L_{seg\_payload}},$$

$$L_{seg\_payload} = L_{ltp\_seg} - L_{ltp\_header} - L_{ltp\_metadata}, \tag{3}$$

where $L_{seg\_payload}$ is the length of the client service data in a LTP data segment; L_{ltp_header} and $L_{ltp\_metadata}$ are the length of the header of LTP data segment and the length of LTP segment metadata respectively.

We also assume that all bits are transmitted independently. Let p_e be the channel BER at the LTP layer, then the loss probability of per LTP data segment can be calculated as follows:

$$L_{seg} = L_{ltp\_seg} + L_{datalink\_header}, \tag{4}$$

$$p_{CP} = p_{seg} = 1-(1-p_e)^{8\times L_{seg}}. \tag{5}$$

Here, $L_{datalink\_header}$ is the header length of the data link layer.

In the data transmission of DTN, we define the extra transmission effort (*ETE*) [11][12][13] as the size of the total transmission data minus the application data, normalized by the application data size.

$$ETE = \frac{\text{Total transmission data- Application data}}{\text{Application data}}. \tag{6}$$

Here, *ETE* consists of two parts: extra transmission effort for overhead and extra transmission effort for retransmission, which can be expressed as follows:

$$ETE = ETE\_retransmitted + ETE\_overhead, \tag{7}$$

$$ETE\_overhead = \frac{\text{Total protocol header data}}{\text{Application data}}, \tag{8}$$

$$ETE\_retransmitted = \frac{\text{Total retransmitted data}}{\text{Application data}}. \tag{9}$$

Therefore, we can infer that the extra energy consumption can be reflected by extra transmission effort, and we will derive the analytical model of the extra transmission effort.

No matter which type the LTP data segment is, the sender will retransmit it if it is lost in the transmission. Thus, it has no necessary to consider the retransmission of the LTP non-CP data segments or the CP segments separately. The extra transmission effort for retransmission is formulated as

$$ETE\_retransmitted = (p_{seg} \times (L_{seg} \times N_{seg}) + {p_{seg}}^2 \times (L_{seg} \times N_{seg}) + \cdots + {p_{seg}}^k \times (L_{seg} \times N_{seg})) \times N_{block} / L_{file} = \frac{p_{seg}}{1-p_{seg}} \times \frac{(L_{seg} \times N_{seg} \times N_{block})}{L_{file}}. \quad (10)$$

Plugging (1)(2)(3)(4)(5) into (10), the extra transmission effort for retransmission can be written as

$$ETE\_retransmitted = \frac{1-(1-p_e)^{8\times(L_{ltp\_seg}+L_{datalink\_header})}}{(1-p_e)^{8\times(L_{ltp\_seg}+L_{datalink\_header})}} \times \frac{(L_{ltp\_seg}+L_{datalink\_header})}{L_{ltp\_seg}-L_{ltp\_header}-L_{ltp\_metadata}} \times (1+\frac{L_{bundle\_head}}{L_{bundle}}). \quad (11)$$

In terms of a data link frame, protocol overhead consists of the bundle header, LTP segment header and metadata, and the frame overhead. Hence, the extra transmission effort for overhead can be calculated as

$$ETE\_overhead = ((L_{datalink\_header} + L_{ltp\_header} + L_{ltp\_metadata}) \times N_{seg} + L_{bundle\_head} \times N_{bundle}) \times N_{block} / L_{file}. \quad (12)$$

Plugging (1)(2)(3)(4) into (12), the extra transmission effort for overhead is given as follows:

$$ETE\_overhead = \frac{L_{datalink\_header}+L_{ltp\_header}+L_{ltp\_metadata}}{L_{ltp\_seg}-L_{ltp\_header}-L_{ltp\_metadata}} + \frac{L_{bundle\_head}}{L_{bundle}} \times (\frac{L_{datalink\_header}+L_{ltp\_header}+L_{ltp\_metadata}}{L_{ltp\_seg}-L_{ltp\_header}-L_{ltp\_metadata}}+1). \quad (13)$$

III. ENERGY SAVING SCHEME IN DEEP SPACE DTN

In the common earth-orbit satellite communications, the data retransmission scarcely exists because of good channel conditions. Accordingly, *ETE* comprises only the protocol overhead, and we expect the protocol overhead as small as possible. However, in the deep space communications, the channel conditions may be harsh, which leads to more frequent data retransmission. Here, both parts of *ETE* should be considered, and we should minimize *ETE* to save energy resources.

As shown in (11) and (13), with the given overheads and at a constant BER, $ETE\_retransmitted$ and $ETE\_overhead$ are merely related to the LTP segment size and the bundle size, whereas the LTP block size has no impact on the *ETE*. Hence, the effects of LTP segment size and bundle size on $ETE\_retransmitted$, $ETE\_overhead$, and *ETE* are analyzed respectively, to optimize the protocol packet size in terms of energy consumption. The objective function are selected as $ETE\_retransmitted$, $ETE\_overhead$, and *ETE*, which can be denoted as $f_1(L_{ltp\_seg}, L_{bundle})$, $f_2(L_{ltp\_seg}, L_{bundle})$, and $f(L_{ltp\_seg}, L_{bundle})$ respectively.

A. Optimization design of bundle size

This paper concerns about the bundle aggregation function of LTP, so the bundle size cannot exceed the LTP block size, i.e., $0 \le L_{bundle} \le L_{block}$.

The first order partial derivative of f_1 with respect to L_{bundle} is as follows:

$$\frac{\partial f_1}{\partial L_{bundle}} = \frac{1-(1-p_e)^{8\times(L_{ltp\_seg}+L_{datalink\_header})}}{(1-p_e)^{8\times(L_{ltp\_seg}+L_{datalink\_header})}} \times \frac{L_{ltp\_seg}+L_{datalink\_header}}{L_{ltp\_seg}-L_{ltp\_header}-L_{ltp\_metadata}} \times (-\frac{L_{bundle\_head}}{{L_{bundle}}^2}). \quad (14)$$

Based on (14), we can determine that the first order partial derivative of f_1 with respect to L_{bundle} is constantly negative, regardless of the LTP segment size and the channel BER, i.e., f_1 is a monotonous decrease function of L_{bundle} . But when L_{bundle} is increased to a certain large value, the term $L_{bundle\_head} / L_{bundle}$ tends to be 0. Thus, f_1 will be reaching the minimum value at a given LTP segment size

$$\frac{1-(1-p_e)^{8\times(L_{ltp\_seg}+L_{datalink\_header})}}{(1-p_e)^{8\times(L_{ltp\_seg}+L_{datalink\_header})}} \times \frac{(L_{ltp\_seg}+L_{datalink\_header})}{L_{ltp\_seg}-L_{ltp\_header}-L_{ltp\_metadata}}, \quad (15)$$

and then the increase of L_{bundle} has no effect on f_1 .

The impact of L_{bundle} on f_2 or f is similar to the effect of L_{bundle} on f_1 . f_2 or f is a monotonous decrease function of L_{bundle} and when L_{bundle} is increased to be large enough, the increase of L_{bundle} has no influence on f_2 or f . Thus, f_2 or f will approach its minimum value at the given LTP segment size.

Consequently, if L_{bundle} is selected large enough that the term $L_{bundle\_head} / L_{bundle}$ tends to 0, then the extra transmission effort will be the minimum at a given LTP segment size.

B. Optimization design of LTP segment size

The bundle size is selected as the optimal bundle size analyzed above. The minimum value of LTP segment size is the length of LTP segment header plus the length of LTP segment metadata. In contrast, the maximum value of LTP segment size can achieve the size of the MTU in the data link layer. That is, the constraint of L_{ltp_seg} is

$$L_{ltp\_min} \le L_{ltp\_seg} \le L_{ltp\_max}, \quad (16)$$

$$\text{where } L_{ltp\_min} = L_{ltp\_header} + L_{ltp\_metadata}, \quad (17)$$

$$L_{ltp\_max} = L_{datalink\_mtu}. \quad (18)$$

The first order partial derivative of f_2 with respect to L_{ltp_seg} is calculated as

$$\frac{\partial f_2}{\partial L_{ltp\_seg}} = -(1+\frac{L_{bundle\_head}}{L_{bundle}}) \times \frac{(L_{datalink\_header}+L_{ltp\_header}+L_{ltp\_metadata})}{(L_{ltp\_seg}-L_{ltp\_header}-L_{ltp\_metadata})^2}. \quad (19)$$

Similarly to the analysis in the above subsection, the first order partial derivative of f_2 with respect to L_{ltp_seg} is constantly negative. It means that f_2 will achieve the minimum value when L_{ltp_seg} is to be L_{ltp_max} .

The computation of the first order partial derivative of f_1 with respect to L_{ltp_seg} is very complex, and it is difficult to obtain the analytical expression. Also the first order partial derivative of f with respect to L_{ltp_seg} . As a result, the impact of LTP segment size on extra transmission effort can be concluded to a nonlinear optimization problem with constraints.

The objective function and constraint are determined, and the mathematical expression for the optimization problem is given as follows:

$$\begin{aligned} &\min \quad ETE \\ &\text{s.t.} \quad L_{\text{ltp\_min}} \le L_{\text{ltp\_seg}} \le L_{\text{ltp\_max}} \end{aligned} \tag{20}$$

The optimal LTP segment size can be obtained by solving the above optimization problem with optimization algorithm. As the bundle size has already been optimized, so the value of the objective function with optimal LTP segment size is the minimum value of the extra transmission effort at a certain BER.

IV. Numerical evaluation and discussion

In this section, the proposed energy saving scheme is evaluated through MATLAB. This work concentrates on the deep-space scenario where the Mars relay satellite communicates with the earth station. The length of the bundle header, the LTP segment header, the LTP segment metadata, and the frame header is 40 Bytes, 4 Bytes, 6 Bytes, and 6 Bytes respectively. The MTU size at the data link layer is set to 1400 Bytes. The simulation parameters are as shown in Table Ⅱ.

TABLE II. Simulation parameters and values

Simulation parameters	**Values**
Data rate of the downlink	250 KBytes/s
One-way propagation delay	600 s
BER	10^{-5}, 10^{-6}, 5×10^{-6}, and 10^{-7}
File size	0.8 MBytes
LTP block size	250 KBytes
Bundle size	1 KBytes to 250 KBytes
LTP segment size	200 Bytes, 600 Bytes, 1000 Bytes, and 1400 Bytes

A. Impact of bundle size on ETE

The extra transmission effort for retransmission when the bundle size varies from 1 KBytes to 250 KBytes is numerically presented in Fig. 2, with different LTP segment size in each subgraph. As is shown, the extra transmission effort for retransmission is slight larger when the bundle size is small than 10 KBytes. Also the extra transmission effort for retransmission will tend towards a minimum value once the bundle size is larger than 10 KBytes in Fig. 2, at a given LTP segment size. The minimum value of $ETE\_retransmitted$ at a given LTP segment size and a given BER can be calculated from (15). For example, the minimum value of $ETE\_retransmitted$ under the conditions of LTP segment size 1400 Bytes is 12%，5.9%，1.1%, and 0.1%, when the BER is 10^{-5}, 10^{-6}, 5×10^{-6}, and 10^{-7} respectively. This result is consistent with the result in Fig. 2(a). Besides, when the BER is high, such as 10^{-5}, the extra transmission effort for retransmission is very large due to more lost LTP segments, which can occupy about 12% as can be observed in Fig. 2(a). However, with a lower BER at 10^{-7}, the extra transmission effort for retransmission only occupies about 0.1%.

The impact of bundle size on extra transmission effort for overhead is illustrated in Fig. 3. We can infer that the overhead will tend to a minimum value at a given LTP segment size when the bundle is large enough such as 50 KBytes, which is in accordance with the analysis in the above section. It can be simply analyzed: the length of the bundle header is constant, so

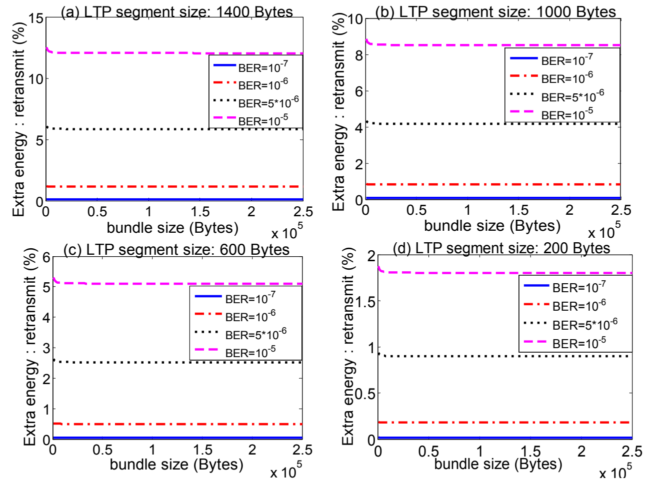

Fig.2. Extra transmission effort for retransmission versus bundle size at different BERs.

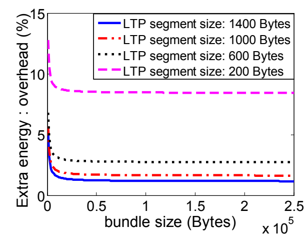

Fig.3. Extra transmission effort for overhead versus bundle size.

the larger the bundle size, the more the proportion of the payload in the total transmission data. Since the overhead in this paper means the protocol overhead in the first transmission round, channel BER has no impact on the overhead.

Fig. 4 presents the effect of bundle size on extra transmission effort. We can see that the curves in the Fig. 4 are all consistent with the analysis in the above section. Thus, to conserve the extra energy resources, the optimal bundle size is selected as a large value 80 KBytes.

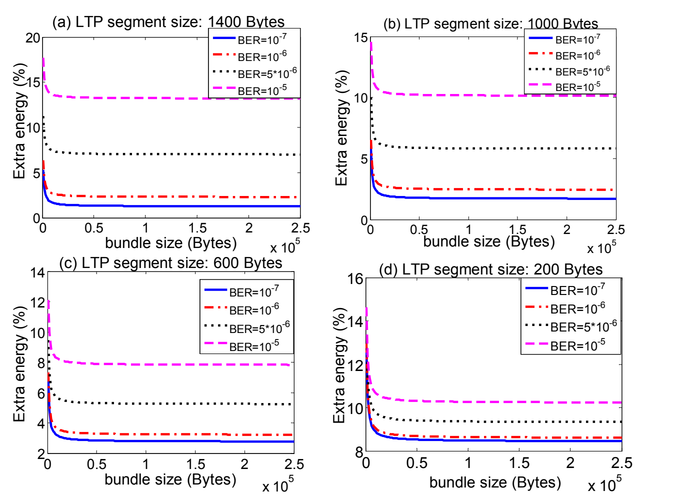

Fig.4. Extra transmission effort versus bundle size at different BERs.

TABLE III. COMPARISONS OF *ETE* BETWEEN THE SCHEME WITH THE OPTIMAL BUNDLE SIZE AND THE SCHEME WITH THE NORMAL BUNDLE SIZE.

BER	**Bundle size/ KBytes**	***ETE***
10^{-5}	Optimal size	0.1325
	1	0.1772
5×10^{-6}	Optimal size	0.0706
	1	0.1128
10^{-6}	Optimal size	0.0235
	1	0.0639
10^{-7}	Optimal size	0.0132
	1	0.0532

The extra transmission efforts with optimal bundle size and the normal bundle size (1 KBytes) at different channel conditions are presented in Table III. As shown in Table III, the scheme with optimal bundle size will save the extra transmission efforts by 4.5%, 4.2%, 4%, and 4%, in contrast to the scheme with the normal bundle size at BER of 10^{-5}, 10^{-6}, 5×10^{-6}, and 10^{-7}.

B. *Impact of LTP segment size on ETE*

Given the bundle size is selected as the optimal bundle size 80 KBytes, the extra transmission effort for overhead, the extra transmission effort for retransmission, and the extra transmission effort with varied LTP segment size are illustrated in Fig. 5, Fig. 6, and Fig. 7 respectively. As shown in Fig. 5, the extra transmission effort for overhead decreases along with the increase of the LTP segment size, as analyzed in Section III.B. This is reasonable as the larger the LTP segment size, the more the proportion of the payload in the total transmission data.

In Fig. 6, we can see that the curve is convex, especially at the high channel BER. And there exists an optimal value of LTP segment size, at which the extra transmission effort for retransmission achieves the minimum.

The impact of LTP segment size on extra transmission effort can be observed in Fig. 7, and it is obvious that the optimal LTP segment size exits and varies with BER. When BER is high, the optimal LTP segment size is small. However, the optimal LTP segment size will be larger at a lower BER.

By solving the optimization problem with simulated annealing algorithm, Fig. 8 shows the optimal LTP segment size at different BERs. At BER of 10^{-5}, the optimal value is about 445Bytes and it will increase to 1400Bytes as the BER decreases to 10^{-6} or much lower value.

The extra transmission efforts with optimal LTP segment size and the normal LTP segment size (1400Bytes) at different channel conditions are compared in Table IV. It indicates that the scheme with optimal LTP segment size will save the extra

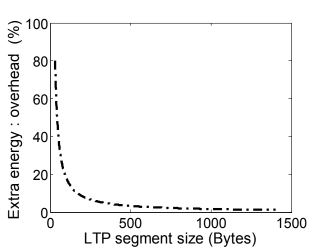

Fig.5. Extra transmission effort for overhead versus LTP segment size.

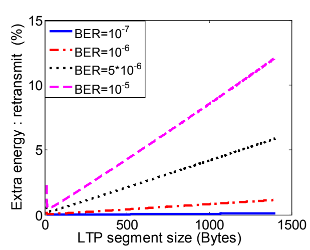

Fig.6. Extra transmission effort for retransmission versus LTP segment size at different BERs.

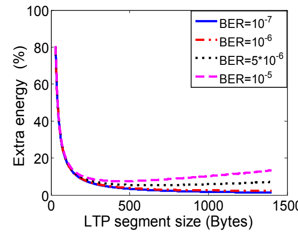

Fig.7. Extra transmission effort versus LTP segment size at different BERs.

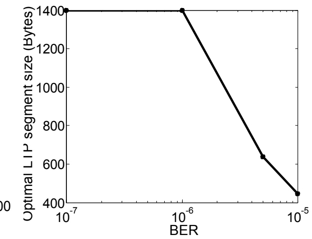

Fig.8. Optimal values of LTP segment size at different BERs.

TABLE IV. COMPARISONS OF *ETE* BETWEEN THE SCHEME WITH THE OPTIMAL LTP SEGMENT SIZE AND THE SCHEME WITH THE NORMAL LTP SEGMENT SIZE

BER	**LTP segment size/Bytes**	***ETE***
10^{-5}	Optimal size	0.0754
	1400	0.1327
5×10^{-6}	Optimal size	0.0528
	1400	0.0707
10^{-6}	Optimal size	0.0218
	1400	0.0218
10^{-7}	Optimal size	0.0122
	1400	0.0122

transmission efforts by 5.7% and 1.8% at channel BER of 10^{-5} and 5×10^{-6} respectively.

V. CONCLUSIONS

In this paper, we formulate a theoretical model of extra transmission effort in deep space DTN based on the characteristics of the DTN protocols. Then an energy saving scheme through optimizing the bundle size and the LTP segment size is proposed. Simulation results reveal that the optimal schemes with the optimal bundle size and the optimal LTP segment size will save the energy resources efficiently, compared with the scheme with the normal packet size. This can be of great importance when the energy resource in spacecraft becomes scarce, especially in deep space communications.

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