Markov Decision Based Optimization on Bundle Size for Halo Orbit-Relay Earth-Lunar DTNs

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Abstract. Earth-Lunar communications are important for lunar exploration. Among them, Halo orbit relay satellite communications networks are extremely valuable. However, due to the highly dynamic and long-distance transmission characteristics, Halo Orbit-relay Earth-Lunar Disruption-Tolerant Networks (DTNs) have to endure severe latency. In order to deal with this problem, we propose a new solution that overcomes the impact of transmission characteristics by adjusting bundle size, thereby effectively reducing the latency of the Earth-Lunar relay communication networks. Considering the transmission characteristics and the deep space environment, we derive the delay formula of the Halo Orbit-relay Earth-Lunar DTNs and establish the distance model. In particular, in order to solve this model, we propose a Markov decision method. Finally, the simulation results verify the effectiveness of the Markov decision method.

Keywords: Earth-Lunar communications · Halo orbit · DTN · Markov decision

1 Introduction

With the proposal of the lunar exploration program in various countries, the Earth-Lunar communications have become one of the research hot spots. At present, the use of relay satellites of the Earth-Lunar system (L2) has attracted the interest of numerous countries [1]. Specially, China has carried out flight verification.

Special motion characteristics of the lunar cause an interruption in the communications between the back of the lunar and the earth. Therefore, the deployment of relay satellites has become an effective mean of establishing real-time communications between the earth and the back of the lunar. At this stage, the

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proposed lunar relay satellites are mainly lunar orbits, including elliptical orbit constellations, polar circular orbit constellations, inclined circular orbit constellations, etc. However, the above methods cannot enable real-time communications between the back of the lunar and the earth. Through recent studies, it is found that L2 point of the earth and lunar has unique geographical and dynamic characteristics. Specially, Halo orbit is completely unaffected by the lunar occlusion under certain conditions. Therefore, it is an ideal location to establish a relay satellite for the earth and the lunar. In summary, we use L2 point Halo orbit as a relay satellite orbit.

In Halo Orbit-relay Earth-Lunar DTNs [2], the relative distances among the earth, satellite and the lunar change instantly with satellites orbital motions, which will cause correspondingly time-varying properties of channel parameters. The authors in [3] use the DTN network to introduce the bundle layer protocol layer, which is located between the application layer and the protocol layer. In general, bundles stored for a long time can be used to overcome frequent link interruptions, long transmission distances, and high bit error rates. Recently, lots of works have studied on the optimization of bundle size in quasi-static scenarios [4], such as wireless sensor networks and social multimedia networks, which almost consider the channel parameters as constant values in the design of bundle delivery [5]. As a result, fixed optimal size of the bundle also leads to inefficiency of link usage and long latency of delivery, due to incapability of filling up different contacts during orbital motions of intermediate nodes. Therefore, we use Markov decision method to optimize the bundle size of Halo Orbit-relay Earth-Lunar DTNs [6]. The general process is shown in Fig. 1.

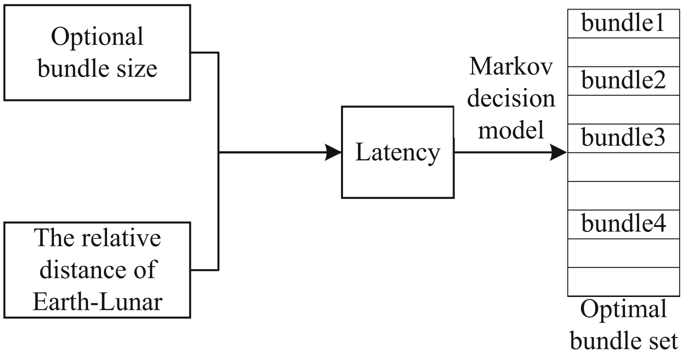


Fig. 1. Acquisition process of optimal bundle set.

The main contributions of this work is to reduce the communications latency of the Earth-Lunar relay communication networks by adjusting bundle size. (a) First, based on the particularity of the earth and the lunar environment, we derive a delay formula that is only related to the bundle size and the distance. (b) Then, we use Halo orbit to establish the distance model of the Earth-Lunar relay communication networks. (c) Finally, the model is solved based on Markov decision to obtain the optimal bundle size.

The rest of the paper is structured as follows: The second part establishes the system model. The third part describes the bundle transmission model and the delay metric, followed by Markov decision model in the fourth part. The simulation results are placed in the fifth part. Finally, the conclusions are given.

2 System Model

2.1 Reference Scenario

We consider the information transmission scenario of the earth to the lunar, in which a relay satellite is configured up to provide communications between the earth and the lunar. In such a scenario, the source node of information is referred to as a source node (SN), such as an earth base station, and a relay node (RN) capable of implementing information forwarding, such as a lunar relay satellite. On the other hand, the recipient of the target file is called a destination node (DN), such as a probe car or base on the back of the lunar. In particular, Earth-Lunar L2 point Halo orbit is periodic, and the relay satellite can be used to achieve full coverage of lunar back, providing real-time uninterrupted communications with the earth.

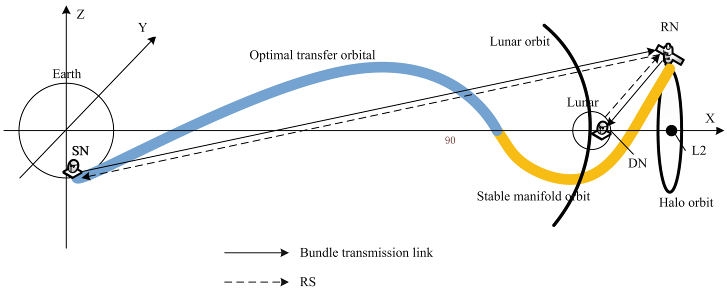


Fig. 2. Earth-lunar Halo orbit relay communication model.

Figure 2 describes the use of L2 point Halo orbit as a relay satellite orbit in communications between the earth and the lunar. The earth base station generates a transmission file as the source node SN, and the file is transmitted to the relay node RN in blocks. After receiving, the relay node RN transmits an acknowledgement signal RS to the source node SN for determining whether the file is successfully transmitted. The relay node RN sends the successfully received file block to the lunar back destination node DN, and at the same time obtains the returned acknowledgement signal RS.

Figure 3 describes the DTN network bundle forwarding flow for Earth-Lunar communications.

In summary, Earth-Lunar two-hop link is highly dynamic, and there is a very large distance difference, which will cause a great delay and reduce the link throughput. Aiming at such problems, we will propose a DTN network bundle size optimization method based on Markov decision.

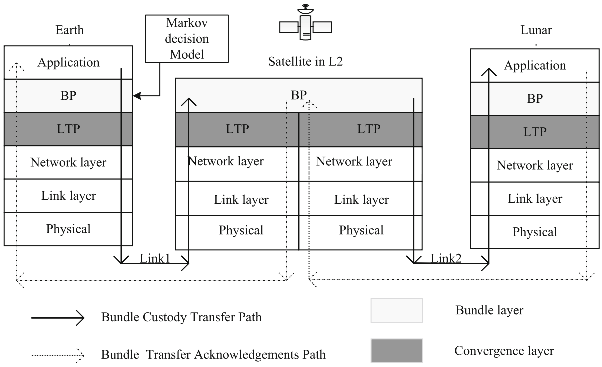


Fig. 3. Bundle forwarding mode.

2.2 Halo Orbit Relay Distance Model

Firstly, it is necessary to establish a distance model of Earth-Lunar communication networks. The direction of the earth and the lunar is the x-axis, the normal direction of the white plane is the y-axis, and the right-handed spiral determines the z-axis. L_{se} indicates the distances between the earth and the relay satellite, and L_{sm} indicates the distances between the lunar and the relay satellite. The specific model diagram is as follows.

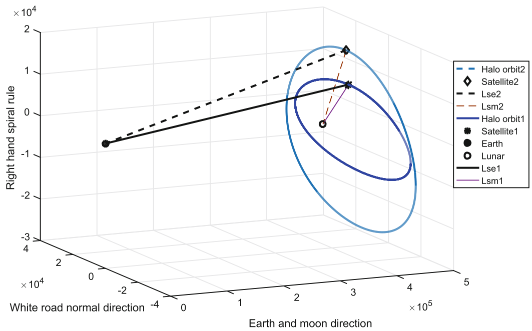


Fig. 4. Earth-Lunar distance model.

As showed in the Fig. 4, the model selects two Halo orbits of different magnitude in the Halo orbital family. At the same time, it is guaranteed that the communications between the relay satellites and the earth in the two Halo orbits are not affected by the lunar mask. In particular, the same set of distance calculation formulas can be used for these two orbits. The coordinates of the relay satellite are represented by $(X(t), Y(t), Z(t))$, and the distance between the earth and the lunar is 384400 km, which can respectively obtain the distance formula of the distance between the lunar and the relay satellite at different times.

$$L_{se}(t) = \sqrt{X(t)^2 + Y(t)^2 + Z(t)^2} \tag{1}$$

and

$$L_{sm}(t) = \sqrt{X(t - 384400)^2 + Y(t)^2 + Z(t)^2} \tag{2}$$

It can be seen from the Fig. 4 that the Halo orbit is the key to the whole model, and the establishment of the Halo orbit needs to be converted from the Earth-Lunar coordinate system to the rotating coordinate system centered on the L2 point. Such a rotating coordinate system can be expressed as $L_2 - \varepsilon\eta\zeta$, and the L2 point is the origin. The direction of the earth pointing to the lunar is the ε axis, the direction of the normal of the white plane is the ζ axis, and the η axis is determined by the right-handed spiral law, and the equation of motion of the satellite is obtained. In particular, we can determine the satellite coordinates by the orbit equation.

$$\begin{cases} \ddot{\varepsilon} - 2\dot{\eta} - (1 + 2c_2)\varepsilon = \frac{\partial}{\partial\varepsilon} \sum\limits_{n\geq 3} c_n \rho^n P_n(\frac{\varepsilon}{\rho}) \\ \ddot{\eta} + 2\dot{\varepsilon} - (1 - c_2)\eta = \frac{\partial}{\partial\eta} \sum\limits_{n\geq 3} c_n \rho^n P_n(\frac{\varepsilon}{\rho}) \\ \ddot{\zeta} + c_2 = \frac{\partial}{\partial\zeta} \sum\limits_{n\geq 3} c_n \rho^n P_n(\frac{\varepsilon}{\rho}) \end{cases} \tag{3}$$

For the L2 point, the c_n in the equation is expressed as follows.

$$\begin{cases} c_2 = \frac{\mu}{\gamma^3} + \frac{(1-\mu)}{(1+\gamma^3)} \\ c_n = \frac{1}{\gamma}[(-1)^n \mu + (-1)^n (1 - \mu)(\frac{\gamma}{1+\gamma^{n+1}})], (n \geq 3) \end{cases} \tag{4}$$

The Richardson third-order approximate solution of the motion equation in this coordinate system is derived by the Lindstedt-Poincare method.

$$\begin{cases} \dot{\varepsilon} = \alpha\omega cos\tau - 2(a_{23}\alpha^2 - a_{24}\beta^2)\omega sin2\tau - 3(a_{31}\alpha^3 - a_{32}\alpha\beta^2)\omega sin3\tau \\ \dot{\eta} = k\alpha\omega cos\tau + 2(b_{21}\alpha^2 - b_{22}\beta^2)\omega cos2\tau + 3(b_{31}\alpha^3 - b_{32}\alpha\beta^2)\omega cos3\tau \\ \dot{\zeta} = -\beta\omega sin\tau - 2d_{21}\alpha\beta\omega sin2\tau - 3(d_{32}\beta\alpha^2 - d_{31}\beta^3)\omega sin3\tau \end{cases} \tag{5}$$

The coefficients in the formula are as follows.

$$\begin{cases} \tau = \omega t + \varphi \\ \omega = \omega_0 + \omega_1 + \omega_2 \\ \omega_0 = \sqrt{(\sqrt{9c_2^2 - 8c_2} - c_2 + 2)/2} \\ \omega_1 = 0 \\ \omega_2 = s_1\alpha^2 + s_2\beta^2 \end{cases} \tag{6}$$

The amplitude satisfies the relationship.

$$\begin{cases} l_1\alpha^2 + l_2\beta^2 + (\omega_0^2 - v_0^2) = 0 \\ l_1 = -\frac{3}{2}c_3(2a_{21} + a_{23} + 5d_{21}) - \frac{3}{8}(12 - k^2) + 2\omega_0^2 s_1 \\ l_2 = \frac{3}{2}c_3(a_{24} - 2a_{22}) + \frac{9}{8}c_4 + 2\omega_0^2 s_2 \\ v_0 = \sqrt{c_2} \end{cases} \tag{7}$$

These coefficients constitute a complete third-order analytical solution equation, and the final Halo orbit is obtained by Matlab. The variables are defined as shown in the following table (Table 1).

Table 1. Orbital equation coefficient

Coefficient	Definition
μ	Dimensional lunar mass
γ	L2 point to the lunar distance
ω_0	Linear frequency
α, β	Amplitude in all directions
k	Linear term amplitude ratio
$a_{21} \sim a_{32}$	Constant
$b_{21} \sim b_{35}$	Constant
$d_{21} \sim d_{32}$	Constant

2.3 Problem Definition

In the Earth-Lunar communication scenarios, the delay reduction problem of the two-hop link can be expressed as the bundle size adjustment problem of the DTN network [7]. Abstract formula is as follows.

$$S_l = \arg\min_b RTT_{all} \tag{8}$$

and

$$RTT_{all} = RTT_{se} + RTT_{sm} \tag{9}$$

According to the distance model of the previous part, the distance set L of the Earth-Lunar two-hop link is obtained, and B is a given optional bundle set. In which, $l \in L$ and $b \in B$. As can be seen from the formula, we give a two-hop link distances l, and then select the bundle size that minimizes RTT_{all} from b to form the optimal bundle set. In summary, after derivation, the latency of the two-hop links is only related to the distance and the size of the bundle. After the distance is fixed, the latency can be reduced by adjusting the size of the bundle. Among them, random factors such as an optional bundle set and distance can be characterized by a Markov model, so we model the adjustment of bundle size into a Markov decision process. The specific latency derivation process is explained in the next part.

3 Bundle Delivery Time over Halo Orbit-Relay Two-Hop Link

It can be observed in the figure that the DTN network is used in the Halo orbit two-hop delay system to transmit information through the bundle [8]. Due to the large distance differences between the Earth-Lunar two-hop link, it is necessary to select the optimal bundle size through the change of the distances, adapting to the entire end-to-end Earth-Lunar communication networks, and reducing the latency to improve the throughput [9].

According to the change in the distances between the two-hop link, the two-hop link latency is obtained by the delay calculation formula, and then the Markov decision is used to obtain the optimal bundle size for different distances.

Next, the calculation formula of the single-hop link delay is analyzed. Generally, the propagation delay, the transmission delay of the bundle and ACK, the queuing delay and the random delay are included in one RTT process [10]. The Fig. 5 shows the round trip transmission process of the single-hop bundle.

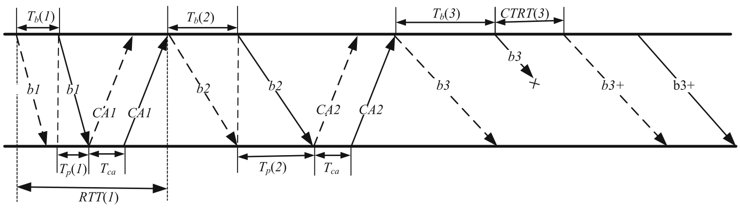


Fig. 5. Bundle delivery time.

In the most ideal communication situation, a bundle is successfully received by the next node after transmission, and no retransmission is required [11]. In this scenario, it can be seen from the above figure that the single-hop link delay is mainly composed of transmission delay $T_b(i)$ and propagation $T_p(i)$ delay. The RTT of a bundle at a certain time t can be expressed as follows.

$$RTT(t) = 2T_p(t) + T_{ca} + T_b(t) + T_{random} \tag{10}$$

However, the actual situation is not so ideal. Space communication often has a high bit error rate. It can also be seen from the figure that b3 has lost packets during transmission. Once a packet loss occurs, it needs to be retransmitted. The number of transmissions determines the different round-trip time. In this paper, for the sake of analysis, if the packet loss occurs, the round-trip delay of the bundle is equal to the value of the storage timer CTRT confirmed by the bundle set in advance, and the two cases are combined. You can get a general round-trip delays expectation expression [12].

$$RTT_{ev}(t) = (1 - P_{ef}(t)) \cdot RTT(t) + P_{ef}(t) \cdot CTRT(t) \tag{11}$$

in which

$$CTRT(t) = 2 \cdot T_p(t) + T_{ca} \tag{12}$$

The packet loss rate $P_{ef}(t)$ is determined by the size of the bundle and the bit error rate.

$$P_{ef}(t) = 1 - (1 - BER(t))^{b \cdot L_{bundle}} \tag{13}$$

Among them, $BER(t)$ is expressed as the bit error rate at time t, and the underlying bit error rate is determined by the modulation technique and the signal-to-noise ratio. In this paper, if BPSK modulation is selected, the bit error rate can be expressed follows.

$$BER(t) = \frac{1}{2} \times erfc(\sqrt{SNR(t)}) \tag{14}$$

$BER(t)$ is the signal-to-noise ratio at link t, and the signal-to-noise ratio is determined by the parameters of the spatial channel. In order to facilitate the analysis, this paper will consider the factor that has less influence on the signal-to-noise ratio as a constant, and use spatial free loss as the main cause of the dynamic change of signal-to-noise ratio.

$$SNR(t) = E_0 - 10lgL_{space}(t) \tag{15}$$

The expected value of the bundle round-trip delay is expressed as follows.

$$\begin{aligned} RTT_{se}(t) = (1 - \frac{1}{2}erfc(\sqrt{C_0 - 20lgL_{se}(t)}))^{L_{bundle}} \cdot \\ (2 \cdot T_p(t) + T_b(t) + T_{ca} + T_{random}) + (1 - (1 - \\ \frac{1}{2}erfc(\sqrt{C_0 - 20lgL_{se}(t)}))^{L_{bundle}}) \cdot CTRT(t) \end{aligned} \tag{16}$$

and

$$\begin{aligned} RTT_{sm}(t) = (1 - \frac{1}{2}erfc(\sqrt{C_0 - 20lgL_{se}(t)}))^{L_{bundle}} \cdot \\ (2 \cdot T_p(t) + T_b(t) + T_{ca} + T_{random}) + (1 - (1 - \\ \frac{1}{2}erfc(\sqrt{C_0 - 20lgL_{sm}(t)}))^{L_{bundle}}) \cdot CTRT(t) \end{aligned} \tag{17}$$

The comprehensive delay of the two-hop link between the earth and the lunar is as follows.

$$RTT_{all}(t) = RTT_{se}(t) + RTT_{sm}(t) \tag{18}$$

In summary, the delay is only related to the distance of the two-hop link. The meaning of the parameters used in the formula is shown in the following table (Table 2).

Table 2. Bundle delay calculation parameter

Coefficient	Definitions
T_p	Propagation delay
T_b	Transmission time of bundle
T_{ca}	Transmission time of ACK signal
P_{ef}	Bundle lost probability
P_e	Bit error probability
L_{bundle}	Bundle size
SNR	Signal to noise ratio
E_0	Sum of constant variables
RTT_{all}	End-to-end delay
T_{random}	Random noise

4 Markov Decision

First of all, we have specified the number of retransmissions of the bundle of the Earth-Lunar communications, and found that the next retransmission probability is independent of the previous, satisfying the Markov property. By defining state sets and behavior sets, Markov decision can be used to derive optimal bundle size set from the cost function. The general process is shown in Fig. 6 (Table 3).

Table 3. Bundle delay calculation parameter

Notations	Definitions
M	State set
A	Action set
S_c, S_c'	Current states of the links
p, p'	Maximum number of retransmissions
$P_s, {P_s}'$	The probability of successful transmission
B_s	Optional bundle set
B_f	Optimal bundle set
a	Picked bundle size
p_{max}	Maximum number of retransmissions
v, v'	The latency of two links

We set a state set M, which contains two states M_0 and M_1. M_0 indicates that there is no bundle in the storage device of the relay satellite, and M_1 represents that a complete bundle is being stored in the storage device. According to S_c,

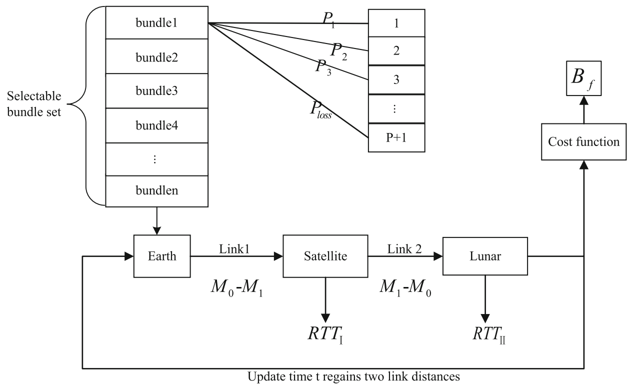


Fig. 6. Markov process.

we can choose different bundle sizes from A, which can minimize the $v + v'$. The probability of successful transmission and the cost function is as follows.

$$P_s = (1 - P_{ef}) \cdot P_{ef}^{p-1} \tag{19}$$

and

$$C = RTT(S_c, A) + (p - 1) \times CTRT(S_c, A) \tag{20}$$

The specific steps of Markov decision are as follows.

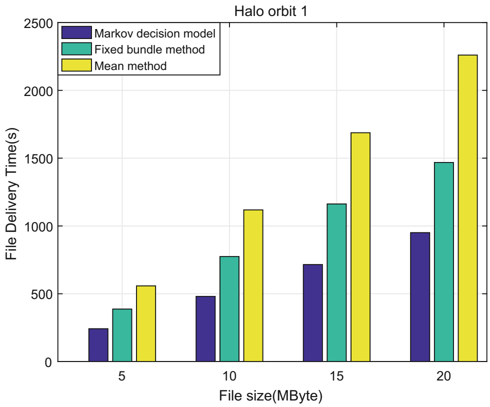
Algorithm 1. Markov Decision

Input: M_0, M_1
Output: the optimal bundle set B_f

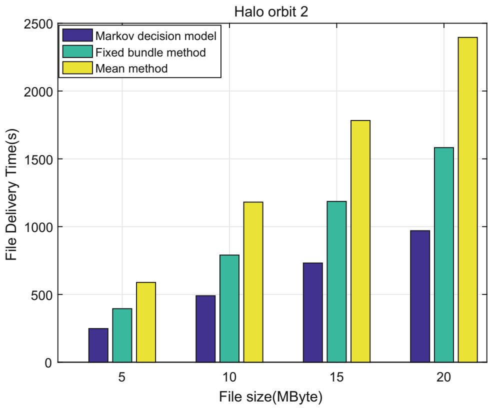
for $S_c, S_c' \in M$ **do**
  $(P_s, p) \leftarrow S_c$;
  $(P_s', p') \leftarrow S_c'$;
  if $(p \le p_{max}) \cup (p' \le p_{max})$ **then**
    for $a \in A$ **do**
      $C \leftarrow \sum_a P_s \times (r(p, a) + v'(S_n))$;
      $C' \leftarrow \sum_a P_s' \times (r(p', a) + v(S_n))$;
    end for
    $B_f \leftarrow \arg\min_a (v + v')$;
  end if
  $Refresh(S_c, S_c')$;
end for

5 Numerical Results

In this part, we compare the performance of the end-to-end latency of the bundle. Through the orbit equation, the satellite coordinates needed to calculate the



(a) Halo orbit 1

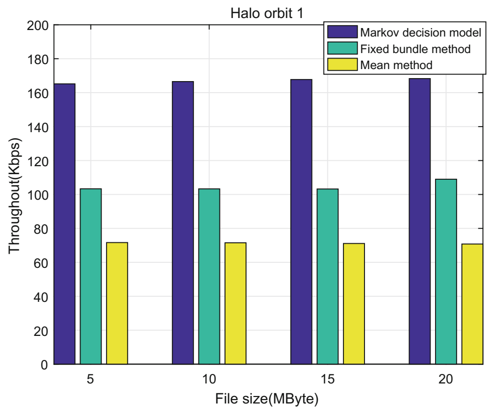


(b) Halo orbit 2

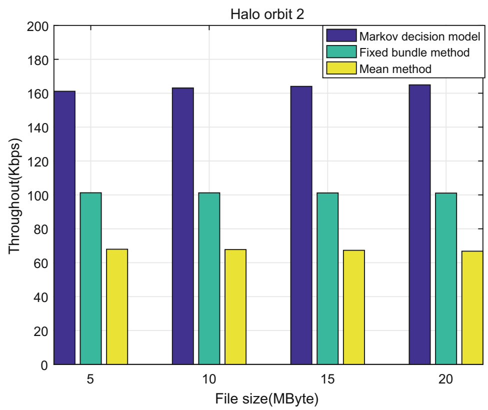
Fig. 7. File delivery time in Earth-Lunar communication.

distance are obtained. In the simulation, we assume that CA_j is a constant, and it takes 7.5 days for the satellite to fly around the Halo orbit. In addition, the number of transmission rounds can be calculated by the bundle loss probability P_{ef}. In general, as the number of transmission rounds increases, the probability of transmission failure decreases exponentially. When the probability of failure is lower than a limit, we believe that the bundle has been successfully transmitted. In this article, we define the threshold to 0.001. So, we can get the number of transmission rounds of a bundle. If the number of transmission rounds is greater than the maximum, we think that such a bundle size is not acceptable.

In Fig. 7, the scene is defined as the Halo orbit relay communication networks with a maximum number of retransmissions of 6. Among them, the amplitude of the Halo orbit selected by the Fig. 7(b) is larger than that of the Fig. 7(a). Then, for two different Halo orbit relay environments, we choose the fixed bundle method and the median method as comparisons respectively. The fixed bundle method is to select an optimal bundle value through a fixed set of link parameters. On the other hand, the media method is to average latency of all optional bundle sizes for the same file size. If the bundle size selected in the current link state cannot be transmitted because of exceeding the maximum number of retransmissions. Therefore, the proposed method is required to wait for the next sampling time to arrive, which results in an additional sampling time in the file transmission latency. Comparing the results of Fig. 7, we can find that facing different Halo orbits, Markov decision can obtain lower delay than the other two methods. At the same time, with the increase in file size, such optimization is more obvious, which is very suitable for Earth-Lunar communications in the future. In particular, we find that the median method has a higher latency growth rate than the fixed bundle method, because in the face of long-distance communication, the extra delay caused by the size of the bundle that cannot be transmitted at all is greatly affected.



(a) Halo orbit 1



(b) Halo orbit 2

Fig. 8. Throughput in Earth-Lunar communication.

In Fig. 8(a) and (b), we choose the throughput metric to measure the effects of different optimization methods under two scenarios. In Fig. 8(a), the parameters are same as Fig. 7(a), while the scenarios and channel parameters in Fig. 8(b) are same as Fig. 7(b). The results show that using a fixed bundle size or using the median method yields less throughput than using Markov decision. One reason is that the optimal bundle size in the fixed state may be not the optimal size after the changing of the link state. On the other hand, for the median method, the selected bundle size may not be able to transmit at all on this link. Therefore, the extra latency has a higher impact in the Earth-Lunar communication networks, resulting in low throughput.

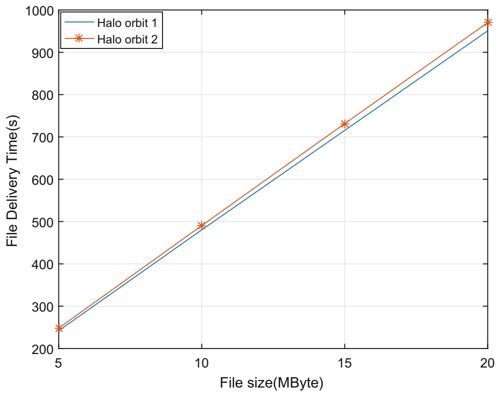


Fig. 9. The comparison of file delivery time between two different Halo orbits.

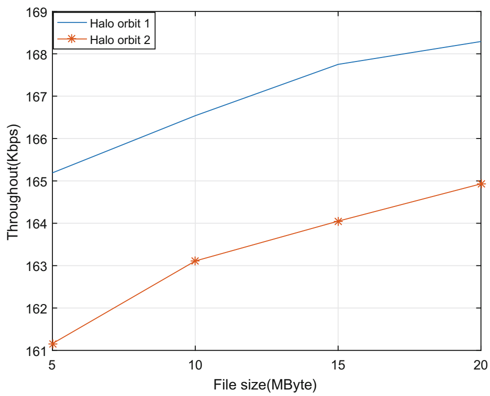


Fig. 10. The comparison of throughput between two different Halo orbits.

In Figs. 9 and 10, we compare the effects of two Halo orbits on latency and throughput. In Fig. 9, the results show that the delay gap increases with the increase in file size. In Fig. 10, the results show that Halo orbit 1 act as a relay orbit with a smooth increase in throughput compared to Halo orbit 2. The reason for the above results is that the distance among Halo orbit 1 and the earth and the lunar is relatively smaller than that of Halo orbit 2, resulting in a smaller transmission loss of the bundle. On the other hand, for files of the same size, low latency can achieve higher throughput.

6 Conclusion

In this paper, we proposed a Markov decision base optimization model to achieve optimal bundle size for bundle end-to-end delivery over the Halo Orbit-relay Earth-Lunar DTNs. For different Earth-Lunar distances, Markov decision will choose different size of the bundle for transmission. Moreover, by comparing Markov decision, fixed bundle method and the mean method respectively, the simulation results show that the disadvantages of other two methods are more and more obvious with the increasing of file size. However, the proposed Markov decision model can effectively reduce file end-to-end latency and increase throughput.

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