A Markov Decision Based Optimization on Bundle Size over Two-Hop Inter-satellite Links

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Abstract. In a satellite Disruption-Tolerant Network (DTN), bundle delivery is obviously affected by time-varying parameters, i.e. bit error ratio and propagation latency, due to constantly changing distance and connectivity between consecutive orbital nodes. In this paper, we proposed a Markov decision based optimization approach for bundle size, which could efficiently improve the expected time of delivery over a dynamic two-hop Inter-Satellite Link (ISL). In particular, a sequence of optimal bundle sizes are adaptively selected according to distance-dependent current channel parameters, which could make full utilization on intermediate node's memory. The simulation results verified the proposed method with different conditions with comparison.

Keywords: DTN · Markov decision · Bundles · Memory

1 Introduction

Due to high error ratio and frequent interruption, typical TCP/IP protocol cluster are not suitable for a satellite network with inter-satellite links (ISL), since scarcely continuous end-to-end paths exist for reliable delivery in the network. In these years, Disruption-Tolerant Network (DTN) architecture is proposed for an attractive candidate solution on those above challenges in satellite networks. In a DTN, as a main protocol of stack, bundle protocol (BP) exploits a custody transfer mechanism which could store bundling data temporarily in local endpoint's storage until forwarding them to next hop successfully. Typically, bundle is employed for a basic unit of delivery by BP agent, thus its size has an obvious impact on the transfer performance with respect to the latency and throughput over hop-by-hop links.

At present, a bulk of works focus on the optimization of bundle size in various scenarios of DTN. In [1, 2], one realistic application in DTN scenario is proposed for a so-called Ring Road networks with the improvements of delivery time. In [3, 4], a file delivery model in a single-hop link is proposed with a method to calculate round-trip time. An expedited scheme for bundle transfer is designed in [5] for coping with sudden link failures, which enables partially received segments to be forwarded towards the next node within a new bundle during previous-hop transfer cessation. Jiang and Lu in [6] establish a multi-hop transmission model in static link and propose an optimization method for bundle and segment size. In [7], a bundle distribution mechanism is

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constructed by a birth-death Markov process, in which the probability of successful delivery for a bundle is theoretically derived. Currently, these above works on bundle size optimization discuss mainly on static environments with a couple of fixed link parameters. In a DTN based satellite network, however, relative distance between satellite nodes changes instantly with node's orbital motions, which will cause correspondingly time-varying properties of channel parameters. In addition, periodically intermittent connectivity between satellite nodes also make obvious impacts on the bundles delivery. As a result, a fixed size of bundle possibly leads to inefficiency of link usage and long latency of delivery, due to incapability of filling up dynamic contacts, especially over a two-hop link with an intermediate node. Extremely, there could be no forwarding of a bundle due to unsuitable size compared with a short duration of contact. In this paper, therefore, we propose a Markov decision based optimization method for bundle size over a two-hop ISL, which could find a series of optimal sizes of bundle by adjusting the decisions accordingly with various channel parameters, given a constrained storage memory at the intermediate node. The simulation results verified that the proposed algorithm significantly improve the performance of bundle delivery with respect to the transfer latency.

The remainder of the paper is organized as follow: Sect. 2 describes bundle delivery model and delay metric. In Sect. 3, Markov decision model is presented and numerical results are discussed in Sect. 4. Finally the conclusion is drawn in Sect. 5. In this paper, the used abbreviation are specified in Table 1.

Table 1. Abbreviation

Abbr	Definition	Abbr	Definition
ISL	Inter-satellite links	*ACK*	Acknowledgement signal
BP	Bundle protocol	LEO	Low earth orbit satellite
LTP	Licklider Transmission Protocol	MEO	Medium earth orbit satellite Medium Earth Orbit
CAi	the *i*-th reverse link	GEO	Geosynchronous

2 System Model

2.1 DTN over Two-Hop ISL

In a DTN in-built satellite network, a flow of application messages, i.e. image files, will be transferred with a bulk of bundles encapsulated by BP (Bundle Protocol) and LTP (Licklider Transmission Protocol) agents. Initially, a target file is sent from application layer to BP layer, which will be divided into a series of bundles according to the optimal bundle size obtained by the proposed algorithm in this paper. Then, LTP agent receives bundles from BP layer and encapsulates them into blocks, which are subsequently sliced into segments as basic transmission units. Due to a custody transfer mechanism, these bundles are stored in the endpoint's permanent storage before transferred successfully to the next endpoint. Normally, local endpoint will delete one bundle if its next-hop node receives the entire bundle successfully.

In a scenario with two consecutive links, delivery of bundles from sender node to receiver node will experience two individual contacts with differently dynamic channel parameters, i.e., bit error ratio (BER) and propagation delay. As a result, the performance of delivery will present an obvious inefficiency if with a fixed set of bundle size in two links. In this section, therefore, we propose a Markov decision model in BP layer to calculate a couple of optimal bundle sizes for two-hop delivery, by making analysis on the dynamic of memory at intermediate node during the whole delivery. In particular, the optimal size of bundle will be adaptively selected from a limited candidate set according to current status of channels.

2.2 Bundle Delivery Time

Typically, bundle is a basic protocol data unit in BP layer. In a delivery, a round-trip time (RTT) consists of propagation delay, bundle and ACKs transmission delay and random delay, respectively.

Figure 1 shows a temporal sequence of one bundle delivery in a dynamic space channel, which is developing worse with time. In the figure, transmission delay $T_b(i)$ and propagation delay $T_p(i)$ progress larger respectively. Generally, a successful delivery of bundle in a single-hop link means that the entire bundle has been received reliably by destination node with a transferred custody. At the same time, source node removes the bundle copy from memory. As a result, a RTT of bundle at time t is expressed as follow

$$RTT(t) = 2 \cdot T_p(t) + T_{ca} + T_b(t) + T_{random}, \tag{1}$$

in which the used notations are specified in Table 2.

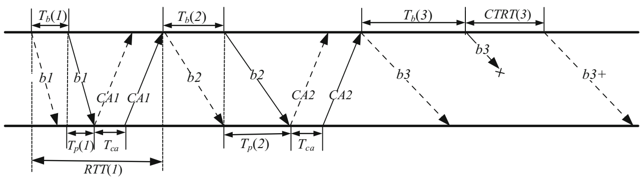


Fig. 1. Bundle delivery procedure

In Fig. 1, bundle *b3* is lost during a spurt due to bad link conditions, which will start a re-transmission immediately after a corresponding timer *CTRT* is timeout. Hence, if a bundle is transferred with one spurt successfully, the delivery time of this bundle is same as a RTT. Otherwise, it is equal to the value of custody-confirm timer (*CTRT*). As a result, the delivery time of one bundle can be represented by an expectation of RTT as follows

$$RTT_{ev}(t) = (1 - P_{ef}(t)) \cdot RTT(t) + P_{ef}(t) \cdot CTRT(t), \tag{2}$$

in which

$$CTRT(t) = 2 \cdot T_p(t) + T_{ca}. \tag{3}$$

Table 2. Notations

T_p	Propagation delay	L_{space}	Free space path loss
T_b	Transmission time of bundle	E_0	Sum of constant variables about *SNR*
T_{ca}	Transmission time of ACK signal	f	Frequency
CTRT	Timeout length	D	Distance
RTT	Round-trip time	RTT_{ev}	Expect of round_trip time
P_{ef}	Bundle lost probability	T_{random}	Random noise
P_e	Error bit rate	N_0	Unilateral noise power spectral density
Lbundle	Bundle size	B	Bandwidth
SNR	Signal to noise ratio	E_b	Energy per bit
L_{ca}	The size of ACK signal	R_{ca}	The rate of ACK signal

In particular, P_{ef} (t) is a bundle loss probability obtained by a specific function coupling bundle size with bit error rate of P_e, which is determined by both modulation technique and signal-to-noise ratio together. With a BPSK modulation, the bundle loss probability is expressed as follow

$$P_{ef}(t) = 1 - (1 - P_e(t))^{8 \cdot Lbundle}, \tag{4}$$

in which

$$P_e(t) = 0.5 \cdot erfc(\sqrt{SNR(t)}). \tag{5}$$

In (5), $SNR(t)$ is calculated by channel parameters in a ISL. Defining a main variable of $L_{space}(t)$ with other constant variables, we express $SNR(t)$ as

$$SNR(t) = E_0 - 10 \lg L_{space}(t). \tag{6}$$

Due to relative motion of two satellites, the range of $D(t)$ changes over time t, which determines the free space path loss $L_{space}(t)$ and $T_p(t)$ as

$$\lg(L_{space}(t)) = 92.45 + 20 \lg D(t) + 20 \lg f. \tag{7}$$

With (6) and (7), $P_e(t)$ can be express:

$$P_e(t) = 0.5 \cdot erfc(\sqrt{E_0 - (92.45 + 20 \lg D(t) + 20 \lg f)}). \tag{8}$$

In addition,

$$T_p(t) = D(t)/C. \tag{9}$$

For T_b, it is related with bundle size and a transmission rate, as

$$T_b(t) = L_{bundle}(t)/R_{data}(t) \tag{10}$$

in which

$$R_{data}(t) = \frac{SNR(t) \times N_0 \times B}{E_b}. \tag{11}$$

In conclusion, one RTT can be rewrote as

$$\begin{aligned} RTT_{ev}(t) = {} & (1 - 0.5 \cdot erfc(\sqrt{C_0 - 20\lg D(t)}))^{Lbundle} \times (2 \cdot T_p(t) + T_{ca} + T_b(t) + T_{random}) \\ & + (1 - (1 - 0.5 \times erfc(\sqrt{C_0 - 20\lg D(t)}))^{Lbundle}) \times CTRT(t) \end{aligned}, \tag{12}$$

where

$$C_0 = E_0 - (92.45 + 20\lg f). \tag{13}$$

3 Markov Decision Model

In a two-hop ISL, we could make an optimization of bundle size in order to get a shorter latency of file delivery. In a general optimization method, a bundle size is uniquely determined according to current link state, until the entire file is transferred. In a satellite network, especially with two-hop ISL, however, link state changes dynamically, leading to an inefficiency of fixed size in the transmission process. Therefore, in this paper, we propose a Markov decision based optimization model for finding a couple of suitable bundle sizes, by making different decisions in a set of candidate actions with a constrain of intermediate node memory.

3.1 Problem Formulation

Firstly, source node delivers a series of bundles to intermediate node in a two-hop ISL. If one entire bundle is received by intermediate node successfully, it will be stored in the memory of intermediate node. With convenience of analysis, in this paper, we assume that the memory of intermediate node has exactly a volume of one bundle. As a result, the intermediate node could receive another bundle from the sender, only after it has forwarded successfully that store-in-memory bundle to the next-hop destination node. It is means that, the intermediate node could accept new bundles only when memory becomes empty. Hence, the dynamic of memory in intermediate node can reflect the delivery performance of one bundle over the two-hop ISL. Comprehensively, a small size leads to a faster transfer of bundle, which could pass the intermediate node quickly and be delivered to the destination node. However, a smaller bundle size will cause more bundles need to be sent for a target file, which will enlarge the total delivery time. Therefore, an adaptive bundle size is necessary for improving delivery efficiency and shortening the file end-to-end delivery time.

In this section, we consider a Markov decision model to select a bundle size, by which a rate of memory utilization at the intermediate node is improved as largely as possible. The progress of Markov decision model is shown as Fig. 2. In the proposed algorithm, when the time t is updated, a new bundle size according to a related decision is outputted at time t. Finally, we can obtain a set of bundle sizes based on different link states at each moment. In Fig. 4, *RTT* (State of Link I) and *RTT* (State of Link II) can be calculated by a reward function expressed in (17), respectively.

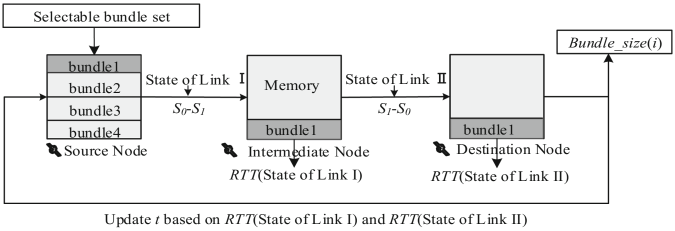


Fig. 2. Markov decision model based file delivery in a two-hop link

3.2 Markov Decision Strategy

Typically, the proposed Markov decision model consists of five associated parts as follows.

Part One: a state set S is defined as S: $\{S_0, S_1\}$.

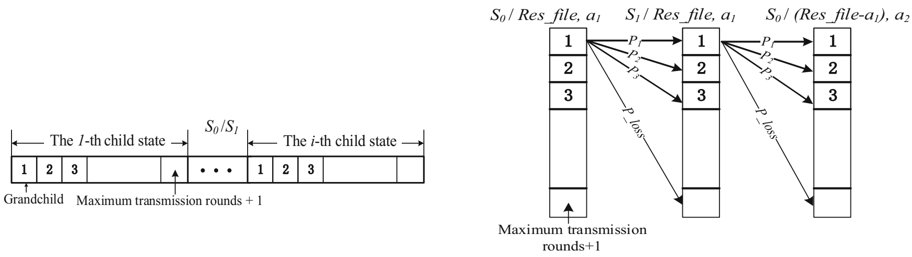
In the set, S_0 represents that the memory of intermediate node is empty without bundle. On the other side, S_1 represents that there is exactly an entire bundle in the memory. That is, S_0 and S_1 also express two transport processes of first hop and second hop, respectively. Here, the state of S_0/S_1 is determined by two following rules.

(a) Once the entire file is transferred completely, we need an absorbing state to stop the procedure. Therefore, we divide S_0 and S_1 individually into i child states, which is calculated according to file size and minimum bundle size. As a result, the i-th child state means that the remained file size is $Lfile - i \cdot Lb_{\min 1}$. If the remained file size is zero, a corresponding state is an absorbing state;

(b) Due to two bad channels, bundles are successfully delivered with differently uncertain latency. Therefore, time span of transition is accordingly different from one state to another state. Hence, we need further divide i-th child state in (a) into a certain number of grandchild states, which is exactly equal to the maximum transmission rounds of one bundle plus 1. In particular, the additional "1" means the transmission failed. The number of child state of S_0/S_1 shown in Fig. 3(a) is calculated by

$$NUM = Lfile/Lb_{\min 1} \times (max\_trans\_round + 1). \tag{14}$$

Part Two: an action set A includes all alternative bundle sizes. Defining a minimum bundle size of $Lb_{\min}$ as a basic unit, we determine a selectable set of bundle size with an adaptive step of $Lb_{\min}$ by A:$\{Lb_{\min 1}, Lb_{\min 2}, Lb_{\min 3}, \ldots\}$ and $Lb_{\min i} = \mathrm{i} \times Lb_{\min 1}$.



(a) S0 /S1 child state (b) State transition diagram.

Fig. 3. S0/S1 child state and state transition diagram.

Part Three: a Markov strategy set π is the set of all selected bundle sizes at each state outputted by the proposed decision model.

Part Four: a transition probability P_i is calculated collectively by transmission rounds, bundle loss probability and bundle size in current link state.

By the transmission rounds, we can find the next state *s_next* and consequently calculate the transition probability from *s_current* to *s_next*, based on bundle loss probability. Figure 3(b) provides a state transition diagram. If the residual file size is *Res_file* within the current state of a child state S_0, then the next state must be the child state of S_1 and the residual file size is same as S_0 when we take action a_1. That is, next state and probability of transition are collaboratively determined by action and bundle loss rate P_{ef} in current link state.

In particular, the transition probability can be calculated as (15). In addition, *P_loss* represents a probability that one bundle is abandoned once transmission rounds exceeds the maximum rounds, as (16).

$$P_i = (1 - P_{ef}) \cdot P_{ef}^{i-1} \tag{15}$$

and

$$P\_loss = P_{ef}^{i}. \tag{16}$$

Part Five: a reward function r is the RTT of bundle under action a and transmission round i, as

$$r = RTT(s\_current, a) + (i - 1) \times CTRT(s\_current, a) \tag{17}$$

where *RTT* and *CTRT* are calculated respectively by (2) and (3), and *s_current* shows the current link state.

With two-hop dynamic ISL, we will obtain a group of link state at each time in the experiments by sampling the distance between two related nodes with an interval of Δt. In specific, we record a sequence of delivery times of each bundle during the file transfer. By accumulating the recording results until the sum of accumulation is more than Δt, we consider that the link state changes exactly at that time. Then, we input a set of new parameters of link state I and link state II. Based on the new states, we can get a series of optimized bundle sizes by solving the proposed Markov decision model.

3.3 Value Iteration Algorithm

Generally, an optimal policy of Markov decision is solved by value iterative equation. In this paper, we design a corresponding Value Iterative Equation for the proposed decision model.

(1) If the current state is S_0,

$$v0(s) = \min_a \sum_n P(s\_next|s)\{r(s|\pi(s)) + v1(s\_next)\}, \tag{18}$$

in which $a \in A$ and $s\_current$ is rewritten as s in (18) and (19).

(2) If the current state is S_1,

$$v1(s) = \sum_n P(s\_next|s)\{r(s|\pi(s)) + v0(s\_next)\}. \tag{19}$$

The detailed Value Iterative Algorithm is shown in Table 3.

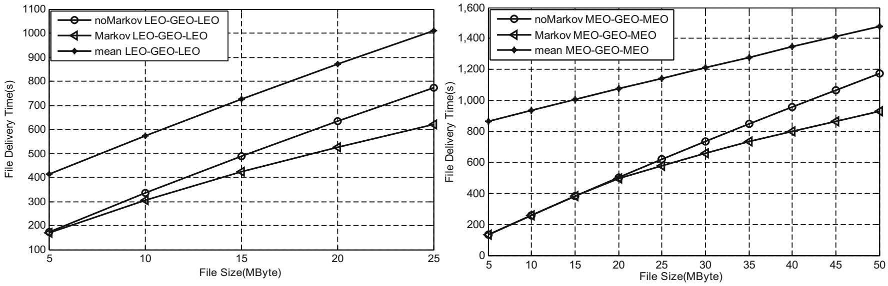
Table 3. Value iterative algorithm

Input matrix *S0,S1,A* $v0(num) \leftarrow 0$; $v1(num) \leftarrow 0$; $p(num) \leftarrow 0$; // p is the action set
$loop \leftarrow num + max \;\; trans \;\; round + 1$;
While(*loop*){
  For each $s \in num$ {
  $(p \;\; trans1, trans \;\; round1) \leftarrow link \;\; state(s \;\; current \;\; link1,\ a)$;
  $(p\_trans2, trans\_round2) \leftarrow link\_state(s\_current\_link2,\ a)$;
   If $(trans\_round1 \le max\_trans\_round) \cup (trans\_round2 \le max\_trans\_round)$
    $v0(s) \leftarrow \min_a \sum_{n\_next} p\_trans1 \times (r(trans\_round1,\ a) + v1(s\_next))$; //calculate $v0$
    $p(s) \leftarrow a$;
    $(p\_trans2, trans\_round2) \leftarrow link\_state(s\_current\_link2)$; //calculate $v1$
    $v1(s) \leftarrow \sum_{n\_next} p\_trans2 \times (r(trans\_round2,\ a) + v0(s\_next))$;
   End If
    $Refresh\_state(s\_current\_link1,\ s\_current\_link2)$; }
  End For
 $loop \leftarrow loop - 1$; }
End While

4 Numerical Results

In this section, we make performance comparison with respect to bundle end-to-end delivery time. In the simulations, we assume the rate of CA_i is constant, and we sample link distance at 60 s interval. Furthermore, the number of state S_0/S_1 is calculated by (14).

The rounds of transmission can be calculated by bundle loss probability P_{ef}. In general, with the increasing of transmission rounds, the transmission failure probability decreases exponentially. When the failure probability is less than a threshold value, we consider that the bundle is sent successfully. Here, we set the threshold of 0.001, thus we can get the transmission rounds of one bundle. If the transmission round is more than a maximum value, however, we think the related bundle size is not accepted. In particular, L_{ca} is set by 100 Byte, R_{ca} is 8000 bps and C_0 is set with 104.22, respectively. The simulation results are presented in Figs. 4, 5 and 6.



a) LEO1-GEO-LEO2 b) MEO1-GEO-MEO2

Fig. 4. File delivery time in scenario LEO1-GEO-LEO2 and MEO1-GEO-MEO2

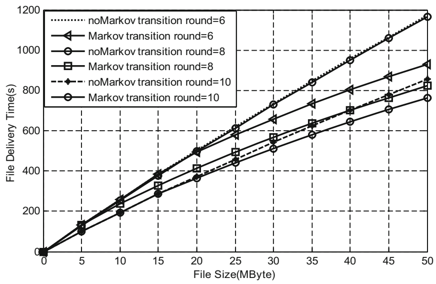


Fig. 5. Under different rounds.

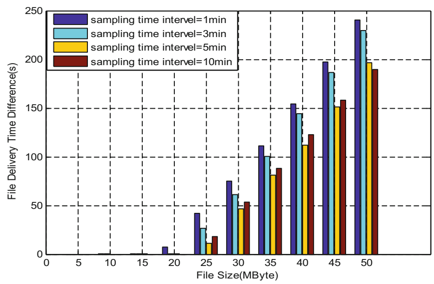


Fig. 6. Under different sampling intervals

The scenarios in Fig. 4(a) are defined by ISLs of LEO1-GEO-LEO2. Here, we set a maximum transmission rounds of six. In particular, we select a traditional optimal method and a mean value method separately as comparisons. The traditional optimal method is that we choose an optimum bundle size according to a set of constant link parameters. On the other side, the mean value method expresses the average value of all file delivery time under a group of fixed bundle sizes. If a bundle with chosen size is not able to be sent under the current link state due to its transmission round more than the allowed maximum round, the algorithm needs to wait for the arriving of next sampling time, which leads to an extra sampling time on file delivery time. Comparing the results from Fig. 4(a), we can observe that both traditional optimal method and Markov decision model have obvious optimization effects. It is noted that, with a file size less than 5 Mbyte, the delivery time under the two methods are equal. The reason is that, since the end-to-end delivery time is less Δt, those trivial changes of link state during the delivery do scarcely make realistic impacts on the transmission. However, with the file sizes more than 5Mbyte, Markov decision can obtain relatively less delivery time than traditional method. With file size increasing, the optimization effect is more obvious, which is quite suitable for those bulk-data return missions over space links, such as disaster surveillance and remote imaging.

In Fig. 4(b), the scenario is defined by a MEO1-GEO-MEO2 link with maximum rounds of six. In particular, we assume that the two consecutive links do not increase or decrease synchronously. From the results, with file sizes less than 20 Mbyte, the delivery time is very short, since the change of distance is not enough to make effects. That is, Markov decision choose only one optimal value of bundle size in the current state, which will keep unchanging until the entire file is transmitted. When the variation of distance is enough large, Markov decision will adaptively change the strategy to get more reward. Hence, larger file size will obtain better optimization than unchanging strategy for all the different states.

In Fig. 5, with one of MEO1-GEO-MEO2 links, the results show that, if the maximum round increases in a proper range, the delivery delay will decrease accordingly. Because more bundle sizes in set A can be chose, Markov decision model will choose the better one on different states. In Fig. 6, the sampling interval are 1 min, 3 min, 5 min and 10 min respectively. The result shows that, if the sampling time interval is much smaller, the optimal effect is more obvious. However, when the sampling interval is too much, traditional method and Markov decision model will are nearly same under different sampling time intervals.

5 Conclusion

In this paper, we proposed a Markov decision base optimization model to achieve optimal bundle size for bundle end-to-end delivery over a dynamic two-hop ISL. By comparing delivery time of files with different sizes, respectively by using Markov decision, fixed optimal parameter and the mean method in end-to-end transmission, the simulation results show that the Markov decision model can effectively reduce file end-to-end delivery delay than traditional optimization method as the increasing of file size. Moreover, a greater file size can obtain better effects of the proposed algorithm. Besides, increasing a maximum transmission rounds or decreasing the sampling time of link distance can improve the optimization effects in certain degree.

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