A Space-Time Graph Based Unpredictable Interruptions-Resilient Routing Algorithm in Satellite Disruption-Tolerant Networks

Nan He(✉), Peng Yuan, Zhihua Yang, and Qing Guo

Communications Engineering Research Center, Shenzhen Graduate School,
Harbin Institute of Technology, Shenzhen, China
henan930906@163.com, yuanpl990@163.com,
{yangzhihua, qguo}@hit.edu.cn

Abstract. In a satellite Disruption-Tolerant Network (DTN), unpredictable interruptions from node malfunction and link disruption will lead to severe postponements and even failure of bundles delivery mission due to incapability of originally planned paths. In this paper, we propose a space-time graph based multicast routing algorithm for coping with an unpredictable interruption in the network. In particular, the proposed algorithm could find a group of new paths with minimal cost by re-planning the two-dimensional global topology in the updated space-time graph. As a result, the residual volume of target data could be successfully delivered in time even if there is an unexpected interruption in the network. The simulation results show that the proposed interruptions resilient routing algorithm can achieve as short as possible, given a defined data volume to be delivery in a certain time latency.

Keywords: Satellite Disruption-Tolerant Network · Space-time graph
Interruption · Routing

1 Introduction

Recently, satellite network has played an important role in the next generation network, due to its advantages of global coverage and realistic-time communication with their inter-satellite links (ISL). Compared with terrestrial networks, a satellite network confronts with a serial of unique challenges, i.e., intermittent links, limited resources and highly dynamic platforms, which probably cause no-existence of end-to-end paths for a delivery mission. Currently, Disruption Tolerant Network (DTN) is developing into a promisingly candidate solution for architecture of space information network especially satellite network, with its well-known store-carry-forward mechanism [1]. With the ever-increasing space scientific missions, massive amounts of various types of data require to be downloaded from orbits [2]. As a result, in a satellite DTN network, it is necessary to find reliable and efficient routes to deliver those bundled data for specific mission, considering full utilizations of transfer capability of network. Research on space DTN network routing algorithm has always been an important problem in space information network communication research. In recent years, most

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of the research optimize the space information network routing algorithm, so as to improve the satellite network link utilization, shorten the end to end delay, balance the amount of data and other purposes. In [3], with regarding to the unbalanced load and the multimedia service of multimedia QoS requirements in GEO/LEO double layer satellite networks, a GEO/LEO double layer satellite networks multi-service routing algorithm is proposed. An optimized layered routing algorithm based on TORA and Dijkstra's algorithms is customized for the hybrid GEO/LEO satellite networks and aimed at balancing between data traffic and end-to-end delay in [4]. [5] proposes a Light Weight Security algorithm that forwards messages only to the trusted nodes, thus prevents the malicious or selfish nodes from affecting the entire DTN communication. However, in these routing algorithms, there is no solution to the problem of data transmission when a link is interrupted suddenly in a space information network.

However, in a found end-to-end path of delivery, unexpected interruptions, such as node malfunctions or link disruptions, will produce potentially catastrophic even fatal challenges for the bundles delivery mission, since they will destroy originally planned routes on the network topology and possibly incur complete failures of bundles forwarding mission in extreme case. For example, if a DTN endpoint encounter a malfunction leading to a reject for incoming bundles in the satellite network, the to-be-forwarded bundles at those previous endpoints on the associated routes will be carried for waiting recovery of the local endpoint. In extreme case, if it is a permanent damage event, the pre-configured routing table is disabled for all related routes without any prior sign. If we do not employ specific routing strategy for distributing these bundles into other feasible routes, prolonged waiting time will lead to a total failure of certain mission with a rigid latency requirements. Moreover, a prolonged sojourn time possibly inflicts loss of bundles since a Time-To-Live criterion constrains a life time for a bundle on the way. More important, a certain portion of forwarded data are on the way at many intermediate nodes, while another part of original data are still waiting to start at the source node. Therefore, preplanning them with specific routing strategies is quite indispensable for the success of target delivery mission. Unluckily, we do not find effective approaches among current routing strategies in the satellite networks. Recently, a two-dimensional directed graph, called as space-time graph, is developed for describing the satellite network with time-varying topology, which could discretize a time-evolving topology into a serial of snapshots in time by assuming quasi-static in discrete time intervals. With an excellent capability of capturing the connectivity and disconnection of each node in a time-varying network, therefore, a space-time graph can be conveniently used for modelling a sequence of time and space-related unexpected interrupting events in the satellite network, especially for a specific design of routing strategy. In this paper, we present a space-time graph based unpredictable interruptions-resilient routing policy in Space Disruption-Tolerant Networks, which could efficiently achieve a successfully completion of a given delivery mission of bundled message even though an unexpected interrupt occurs in the network. In particular, a group of optimization algorithms, involved with source node, interrupted node and other related nodes, are respectively proposed for re-planning those residual bundles un-arrived to the destination node with respect to the minimal cost of energy.

The rest of this article is organized as follows. Section 2 describes the space-time graph model and the problem formulation. Bundled data transmission and interrupt routing algorithm is given in Sect. 3. Numerical results and discussions are seen in Sect. 4. Finally, Sect. 5 concludes.

2 System Model

2.1 Space-Time Graph

In this section, we use a space-time graph to describe the time-varying topology of satellite network. In the space-time graph [6–9], a time span of interest is discretized with a sequence of sufficiently small time intervals. In each time interval, a static graph *G (V, E)* can be used to describe the current topological relationship of network, in which V and E is the node and edge set respectively. We call this series of static images as snapshots of satellite network. Given a satellite network with n nodes $V = \{v_1, v_2, \ldots, v_n\}$, the time span of a transmission mission is divided into K equal time intervals. In order to represent the interconnection of K topological snapshots, the space-time graph (denoted as $\mathcal{G}$) is constructed with a hierarchical graph of $K + 1$ layers, each with a copy of all nodes. The node set of the l-th layer ($l \in [0, K]$) is $V^l = \{v_1^l, v_2^l, \ldots, v_n^l\}$. For a t-th snapshot of $G^t(V, E)$, if the node pair of $v_i, v_j (i,j \in [1, n])$ has a connection $v_i \leftrightarrow v_j$ ("$\leftrightarrow$" on behalf of a two-way link), we add two directional edges in the $\mathcal{G}$: $v_i^t \rightarrow v_j^{t+1}$ and $v_j^t \rightarrow v_i^{t+1}$, respectively. Neighbors of two adjacent nodes v_i^l and v_i^{l+1} can be connected by directed edges $v_i^l \rightarrow v_i^{l+1}$.

For a given task (φ, t_0, γ) of single source and multiple destination node, φ and t_0 represent the total amount of task data and required temporal duration of delivery respectively, while γ is the delay tolerance. We assumed that the sequential number of network node is defined by an integer from 1 to N. In particular, the first node with number "1" represents the source node, while those nodes from $N - NG + 1$ to N represents a group of NG ground stations. In addition, those remaining numbers represent a series of NS relay satellites. To construct a space-time graph of the target network, we will firstly determine an appropriately sampling interval τ to separate the time line into multiple time slots. Then, we will divide all the nodes in the network into different layers, in which N nodes of the i-th layer are sequentially numbered from integer $i \cdot N + 1$ to $i \cdot N + N$. With the start and end time t_{start} and t_{end}, it is possible to infer that $\mathcal{G}$ spans a group of discretized snapshots of $(t_{end} - t_{start})/\tau$ from the t_{start}/τ layer to the t_{end}/τ layer. Note that the node $\{i \cdot N + j | i = 0, \ldots, \gamma/\tau\}$ in the space-time graph exactly denotes the j-th node in the realistic network. Then, we add a serial of time and space links into the space-time graph, thus construct a complete graph.

2.2 Problem Formulation

Firstly, we will make analysis on the optimization problem without unexpected interruptions in the network. For a given task (φ, t_0, γ), we attempt to find a series of feasible paths $\mathrm{P} = \{p_1, \ldots, p_n\}$ in the space-time graph $\mathcal{G}$ for the complete delivery of task data. Through these paths, a global minimal cost of delivery (i.e. energy) $\mathcal{C}$ for the task is achieved. In particular, p_m is defined as the planning path in the network, f_{p_m} indicates the amount of data that passes through p_m, and w_{mn} is the energy cost required for the unit data transmitted by the link, respectively. Then, the problem could be formulated as a minimum-cost constrained routing problem

$$\begin{gathered}\textbf{Min } C = \sum_{(v_m,v_n)\in p_m, p_m\in P} w_{mn} \cdot f_{p_m};\ \text{s.t.} \sum_{p_m\in P} f_{p_m} = \varphi; \\ 0 \leq f_{mn} \leq c_{mn},\ \text{for } \forall(v_m, v_n) \in E;\ \sum_{(v_m,v_n)\in E} f_{mn} = \sum_{(v_n,v_k)} f_{nk},\ \text{ for } \forall v_n \in V\backslash\{s, d\},\end{gathered} \tag{1}$$

where s and d represent the source and destination nodes, respectively. In (1), first constraint makes sure that the amount of data from the source node s is equal to φ. The second constrain is the capacity constraint, which means the amount of data flowing through a certain edge is not greater than the capacity of that edge. The third constraint is a traffic-constrained condition, meaning that the amount of data flowing out a node, other than the source node and destination node, is equal to the amount of data flowing into it. In the space-time graph, the cost will be exploited for an objective function to find the shortest path, then update the network capacity in turn until finishing the residual amount of data.

Now, we will discuss about the above problem with interruptions in the network. We assume that an unexpected interrupt happens in the i-th node at time t, which is exactly on the end-to-end path for the task. For the source node, those to-be-sent data at the source node will lose a feasible path to the destination, if those data has been planned to go exactly through the interrupt node i at time t. Besides, a certain portion of ongoing data will make sojourn at those preceding nodes connected directly with the interrupted node, due to no feasible ways for forwarding. For the convenience of analysis, here we do consider those lost data due to hardware damages during the interruption. As a result, we assume that there is no data at the interrupt node i after time t since the previous hop nodes linked directly with i are rejected by node i. Therefore, for a given $\mathcal{G}$ we attempt to find a series of feasible paths $\mathrm{P} = \{p_1, \ldots, p_n\}$ after node i is interrupted, in order to efficiently finish the task data of size with the originally planned requirements. The optimization model with the interruption is divided into two parts. In particular, one is the optimization for the data φ_s that the source node has not transmitted at the time of the interruption, while another is a certain portion of ongoing data φ_i to make sojourn at those preceding nodes connected directly with the interrupted node. In addition, we define the data that has been ongoing in the network with the planned path not passing through the interrupt node after the interrupt occurs as φ_d. Here, φ_s, φ_i and φ_d satisfy the following relationship:

$$\varphi = \varphi_s + \varphi_i + \varphi_d \tag{2}$$

First, we analyze the data that has not yet been sent at the source node optimization problem.When the interrupt occurs, update the network space-time graph. $\mathcal{C}s$ indicates the energy cost of the data that the source node does not transmit after the space-time graph is updated. p_s indicates the path to which the data is not transferred at the source node from the time of the interruption. f_{p_s} indicates the amount of data that passes through the p_s.

$$\begin{gathered}\text{Minimize}\quad \mathcal{C}s = \sum_{(v_m, v_n) \in p_s, p_s \in P_s, m \neq i, n \neq i} w_{mn} \cdot f_{p_s}\,;\ \textbf{s.t.}\quad \sum_{p_s \in P_s} f_{p_s} = \varphi_s \\ 0 \leq f_{mn} \leq c_{mn},\ \text{for}\ \forall (v_m, v_n) \in E_s,\ \ m \neq i, n \neq i;\ \sum_{(v_m, v_n) \in E_s} f_{mn} = \sum_{(v_n, v_k)} f_{nk},\ \text{for}\ \forall v_n \in V_s \setminus \{s, d, i\},\end{gathered} \tag{3}$$

Next, we analyze the data that is ongoing to make sojourn at a group of preceding nodes connected with the interrupted node. p_i is defined as the replanning path the data of passing through the interrupt node after the time of the interruption. Where path p_i is the last hop of the interrupt node as the source node, and the bottleneck capacity of the path f_{p_i} is used as the flow. Because at this time the data has been transmitted in the network, only the last hop node of interrupt node as a new source node re-plan the path. $\mathcal{C}i$ indicates the energy cost of the data that last hop nodes of the interrupt node transmit after the space-time graph is updated. l indicates the set of last-hop nodes for the original scheduled path through the interrupt node. $f_{l_m n}$ indicates the flow that has flowed out of a last hop node of the interrupt node.

$$\begin{gathered}\text{Minimize}\quad \mathcal{C}i = \sum_{(v_m, v_n) \in p_i, p_i \in P_i, m \neq i, n \neq i} w_{mn} \cdot f_{p_i}\,;\ \textbf{s.t.}\quad \sum_{p_i \in P_i} f_{p_i} = \varphi_i \\ 0 \leq f_{mn} \leq c_{mn},\ \text{for}\ \forall (v_m, v_n) \in E_s,\ \ m \neq i, n \neq i\,;\ \sum_{(v_m, v_n) \in E_s} f_{mn} = \sum_{(v_n, v_k)} f_{nk},\ \text{for}\ \forall v_n \in V_s \setminus \{s, d, i, l\},\end{gathered} \tag{4}$$

3 Routing Algorithm

3.1 Bundle Transport Mechanism

In a space network implemented with a DTN architecture, a bundle protocol layer will incorporated between application layer and transport layer, with a Custody Transfer mechanism. In particular, bundle, as BP Protocol Data Unit (PDU), is a basic message storage and forwarding unit. In the proposed stack, a flow of Application Data Unit (ADU) will be encapsulated into a serial of bundles as payloads, with corresponding bundle headers. By calling the proposed algorithmic procedure, a group of address, as a calculated end-to-end route by the algorithm, will be appended and encapsulated together with the payload. Then, these bundles will be delivered down to the lower layer for delivery, i.e., LTP protocol proposed by DTNRG. The LTP protocol takes the bundle as an LTP block and divides it into multiple sub-blocks, which are encapsulated into the segments. In the receiver nodes, after receiving the segments over the space channel, LTP protocol will check them with an interaction mechanism of checkpoints and acknowledgments for reliable delivery. In particular, if the segments data are lost, receiver sends the report to the sender (RS) for feedback.

As an edge's weight in the space-time graph, we define a capacity of one space (time) link as the maximum number of DTN bundles n that can be transmitted (stored) within the duration of each edge in $\mathcal{CC}$ quantized by discrete time intervals. Besides, one unit transmission (storage) cost of space (time) link is defined as the amount of energy consumed to transmit (store) a DTN bundle within those discrete time intervals. In the following, we provide mathematical analysis on the spatial link capacity and unit transmission cost. The variables used are shown in Table 1.

Table 1. Declarations of variables

Variable symbol	Definition
PER (PERRS)	Segment (RS) packet loss rate
cj	The number of the j-th segment transmissions
M	The maximum number of transmissions for all segments
N	The total segments in bundle

Here, we only consider those energy costs for transmitter side sending packets and receiver feed-backing RS. In specific, the energy costs of sending a segment and a RS is respectively defined as e_s and e_{rs}, then the unit transmission cost of space link $i \rightarrow j$ is recorded as

$$w_{ij} = \mathrm{E}[\sum\nolimits_{j=1}^{N} c_j \cdot e_s + \sum\nolimits_{k=1}^{M} i \cdot e_{rs}] = \frac{N \cdot e_s}{1 - PER} + \frac{M \cdot e_{rs}}{1 - PER_{RS}}. \tag{5}$$

3.2 Interruption Resilient Routing

In a space network, nodes confronts frequently with abrupt events, such as platform failure, link outage and resource exhausted, leading to expected disruptions in the delivery mission. For example, in Fig. 1, i-th node is exactly interrupted at time t with a duration of len time slots, as

$$k = (t \text{ - } t_{start})/\tau \tag{6}$$

Here, we assume that a discrete time interval τ can totally capture the connection and interruption of the link. And γ can be divisible by τ. If the space link contact time can not be captured by τ in the network, the time of the space link is rounded off. The τ mentioned in the following section satisfies the above requirements. In the graph, firstly, we delete the time link.

$$\{j \cdot N + i \rightarrow (j + i) \cdot N + i | j = k, \ldots, k + len\} \tag{7}$$

and define $\{j \cdot N + i | j = k, \ldots, k + len\}$ as the start point and $\{j \cdot N + i | j = k, \ldots, k + len\}$ as the end point of the space link, respectively. The new space-time graph is shown in Fig. 2. The new source node in the figure indicates that the previous hop node before the interrupt node will reallocate the data.

To solve the above problem, we propose a multicast routing algorithm to deal with the interruption in the constructed space-time graph. In particular, the main idea is to

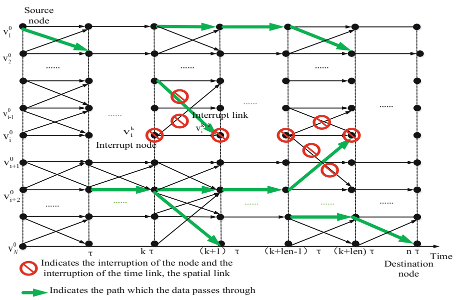

Fig. 1. Space-time graph with interruptions

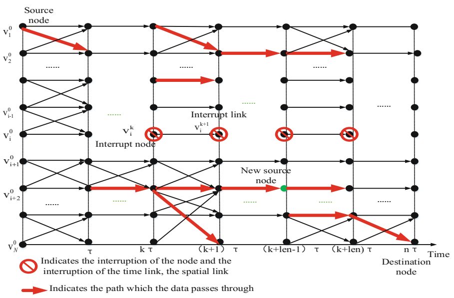

Fig. 2. New space-time graph after interruptions

Table 2. Interruptions resilient routing algorithm

The pseudo-code algorithm

```
INPUT: $\mathcal{G}(V,E,C,W)$ , $\mathcal{C}$, $\mathcal{T}$, P
OUTPUT: $\mathcal{C}$_NEW, $\mathcal{T}$_NEW, P_NEW
For each $j=N-NG+1,L\ ,N$ and $i=1,L\ ,\left\lfloor \frac{t_0}{\tau} \right\rfloor$
find（P==$i \cdot N+j$）=（i,j）//find the path associated with the interrupt node
P_DIS ⟵ P(i,:) ; // Extract the path
$\mathcal{G}$_NEW ⟵ SETUP_GRAPH ( $\mathcal{G}$, $p, c_p$ , $N_i$ ) //Update
$\varphi=\varphi-\sum c_p$ ,$\mathcal{C}$_NEW= $\mathcal{C}$- $\mathcal{C}$_DIS;// update the capacity
    $p \leftarrow$ FIND_PATH ( $\mathcal{G}$_NEW );    //The source node at the time of the interruption and the interrupt hop node as the source
while $f<\varphi$ and $p \neq \varnothing$ do // flow is less than data
        P_NEW $\leftarrow$ P-P_DIS $\cup$ p;
        $f \leftarrow f+c_p$ ;
        if $f>\varphi$ do //
    $c_p \leftarrow c_p-(f-\varphi)$ //The last path transmission data is less than$c_p$
            $f \leftarrow \varphi$;
          end if
          $\mathcal{C}$_NEW ⟵ $\mathcal{C}$_NEW+ $w_p \cdot c_p$ ;
        $\mathcal{G}$_NEW ⟵ UPDATE_GRAPH ( $\mathcal{G}$_NEW, $p, c_p$ )
      $p \leftarrow$ FIND_PATH ( $\mathcal{G}$_NEW) // Find $w_p$ the smallest path
end while
    if $f<\varphi$ do
Return –f;  // The return transmission task can't complete the flag
else do
    $\mathcal{T}$_NEW $\leftarrow$ CALCULATE_DELAY_DIS ( P_NEW) ;
    P_NEW $\leftarrow$ TRANSLATE_PATHS_DIS ( P_NEW );
    Return $\mathcal{C}$_NEW, $\mathcal{T}$_NEW, P_NEW;
end
```

update the space-time graph from the time t interruption happens, and reallocate the residual data in the network after the interruption occurs with a group of re-planned routes. In the algorithm, we define the capacity and cost as two weights of one edge and update these weights after the interrupt occurs. For source node s, those residual data waiting to transmit will be re-planned with a new group of end-to-end routes between the source and the final destination node from time of the interruption. For an intermediate node exactly at the original route, if it is at one preceding hop from the interrupted node with a connection, it will re-plan a new group of route from it to the destination for its sojourned data by the proposed algorithm in the following section. By the update of graph, all the data in the network is redistributed to find the optimal route after interruption, with a Bellman-Ford algorithm of finding the minimum cost path. Once the interruption happens, each node with sojourned data before the disrupt node would be considered as a new source node. As a result, the path re-planning problem for residual data of given task is transformed into a shortest path of multi-source and multi-destination routing problem with respect to energy cost. Table 2 provides a pseudo-code routing algorithm.

4 Numerical Results

In this section, we will compare the performances on several given data volumes with different interrupt lengths with respects to the energy costs and time delays in MATLAB. The simulation parameters are listed in Table 3. In the simulation, we assume that the interrupt time can be exactly captured by a serial of integral time intervals. In particular, the evaluation metrics are mainly the delay $\mathcal{T}$ and the transmission overhead $\mathcal{C}$. Typically, we study an experimental scenario of Earth observation satellite network as follows: an Earth remote sensing satellite of China remote sensing satellite with high resolution (GF-II), which operates at a height of 631 km in the sun synchronous orbit with an inclination of 97.908°; six relay satellites distributed in a constellations of Walker (6/6/4), where the seed satellites runs on a circular orbit with a height of 1414 km (using the global orbit height) and inclination of 52°; three ground stations are located in China's Miyun (40.3°N, 116.8°E), Kashi (39.5°N, 76°E) and Sanya (18.2°N, 109.5°E) respectively; the observation target in the experiment is

Table 3. Simulation parameters

Parameter	Value	Parameter	Value
Bundle size	100 kbytes	*Different types of links BER*	GF-*RS*: 10^{-6}; GF-*GS*: 10^{-7}; *RS*-*RS*: 10^{-6}; *RS*-*GS*: 10^{-7}
Segment size	1250 bytes	*Time and space link unit energy cost*	10^{-3} kJ; 10^{-4} kJ; 10^{-5} kJ
Data transmission rate	GF-II: 20 Mbps; *RS*: 50 Mbps; *GS*: ∞	e_s	2.5×10^{-5} kJ
RS feedback rate	*RS*: 10 Mbps; *GS*: 5 Mbps	T_{prop}	GF-*RS*: 30 ms; GF-*GS*: 10 ms; *RS*-*RS*: 30 ms; *RS*-*GS*: 10 ms
Storage	GF-II: ∞; *RS*: 10^5; *GS*: ∞		

located in Sahara (28°N, 11.5°E) corresponding to the transmission task $(\varphi, 12:00(\mathrm{UTC}), 2\mathrm{h})$. The start time of the task is selected based on the contact time between GF-II and the observed target. Given a mission of delivering remote sensing image data encapsulated in bundles, φ is determined as 10000, 12500, 15000 and 16000, respectively.

In particular, the time instant t_{start} and t_{end} of all links are rounded to the nearest integer minute, in which t_0 is the starting point of time as "0". The time span is $[0, \gamma]$ with discrete time interval τ of 1 min. As can be seen in Fig. 3, with the duration length of interruption increasing, the energy cost becomes larger, since it is possible to find a smaller energy cost path than the previous path after recovery of interruption. Give the interrupted node on the path of the minimum energy cost, when the interrupt stops, data flow can still be re-allocated. On the other side, given a small amount of missioned data, with time length of interruption changing, energy costs do not change obviously.

As can be seen from Fig. 4, when the amount of data is large, the interrupt length becomes larger, the time delay will be larger. Because the available path in the space network is reduced when the interrupt time of the interrupt node becomes longer. So that the transmission delay may be increased at the same amount of transmission data.

Table 4 shows the original and resulted routing paths in the network when the interrupt time is 20 min. According to the connections between nodes within the observation time range, 20 min can be regarded almost as a permanent interrupt. It can be seen that some of the data of the interrupt node is transmitted by other relay nodes, resulting in a longer time delay and a larger network energy cost Table 5 shows two comparative paths with an interruption time of 1 min (actually within one time interval). We can see that, once the interrupt stops, the energy cost and time delay becomes smaller due to a different path produced by the proposed routing strategy. Table 5 shows two comparative paths with an interruption time of 1 min (actually within one time interval). We can see that, once the interruption stops, the energy cost and time delay becomes smaller due to a different path produced by the proposed routing strategy.

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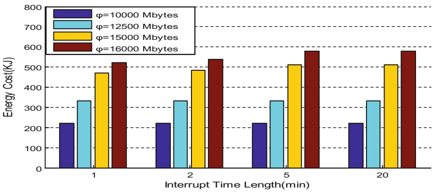

Fig. 3. Comparison of energy under different interrupts

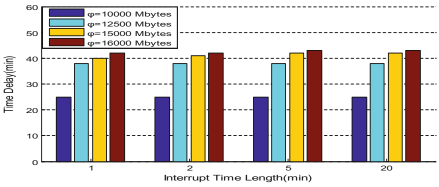

Fig. 4. Comparison of time delay under different interrupts

Table 4. Routing paths

	Start node	End node	Start time	End time	Data
Original routing path table	1	5	16min	24min	6887
	5	8	17min	25min	6887
	1	9	17min	23min	8113
Interruption –resilient routing path table	1	5	16min	18min	1656
	5	8	17min	19min	1656
	1	6	30min	40min	5231
	6	8	31min	41min	5231
	1	9	17min	23min	8113

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	6	8	31min	39min	4403
	1	9	17min	23min	8113
	1	5	21min	24min	2484
	5	8	22min	25min	2484

5 Conclusion

In this paper, we design a routing algorithm for dealing with unpredictable interruption in space DTN network. The algorithm uses the space-time graph as the network model, and find the minimum energy cost paths for the given data volume after the interruption occurs. The simulation results verified the proposed algorithm.

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