0254-6124/2015/35(1)-116–10 *Chin. J. Space Sci.* 空间科学学报

Zhu Laitao, Li Yong, Zhang Junxiang, Wu Jing, Tai Xiao, Zhou Jianguo. Application of contact graph routing in satellite delay tolerant networks (in Chinese). *Chin. J. Space Sci.*, 2015, **35**(1): 116-125, doi:10.11728/cjss2015.01.116

Application of Contact Graph Routing in Satellite Delay Tolerant Networks

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Abstract Satellite networks have many inherent advantages over terrestrial networks and have become an important part of the global network infrastructure. Routing aimed at satellite networks has become a hot and challenging research topic. Satellite networks, which are special kind of Delay Tolerant Networks (DTN), can also adopt the routing solutions of DTN. Among the many routing proposals, Contact Graph Routing (CGR) is an excellent candidate, since it is designed particularly for use in highly deterministic space networks. The applicability of CGR in satellite networks is evaluated by utilizing the space oriented DTN gateway model based on OPNET(Optimized Network Engineering Tool). Link failures are solved with neighbor discovery mechanism and route recomputation. Earth observation scenario is used in the simulations to investigate CGR's performance. The results show that the CGR performances are better in terms of effectively utilizing satellite networks resources to calculate continuous route path and alternative route can be successfully calculated under link failures by utilizing fault tolerance scheme.

Key words Satellite Delay Tolerant Networks (DTN), Space oriented DTN gateway, Contact Graph Routing (CGR), Link failures

Classified index V 527

0 Introduction

Satellite networks, characterized by their global coverage, broadcast capability, and bandwidth on demand flexibility, have become an important part of the global network infrastructure. Satellite networks have long propagation delay, asymmetrical forward and reverse link capacities, high bit error rate and intermittent link connectivity due to orbital motion and impact of extreme space environments. Thus satellite networks can be regarded as a typical Delay Tolerant Networks (DTN)[1], which originated from the research on Interplanetary network and has expanded its applications to Wireless Sensor Networks (WSNs),

∗ Supported by the open project of Communication network transmission and distribution technologies Key Laboratory (ITD-12005/K1260011), the National Natural Science Foundation of China (61371126) and the National Natural Science Foundation of China (60903195)

Received January 24, 2014. Revised July 03, 2014

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Mobile Ad hoc network, satellite networks, and other challenged networks.

In order to conduct studies of space environment oriented DTN networks, especially the satellite networks, we designed a gateway model for spatial delay tolerant networks[2], and made simulations in OPNET. With this component, we can implement various simulation experiments and research on DTN communications, including DTN routing discussed in this paper.

High mobility of nodes and time-varying topology in DTN make the research of efficient routing protocol become a hot and challenging area. Various routing algorithms for DTN have been proposed, but each has its own certain applicable environments and none is universally applicable. In satellite networks, where satellite orbits are stable, precise and predictable, we may use the knowledge-based routing algorithm which assumes that each node in the network has exact knowledge of node trajectories, or node meeting times and durations[3]. Among these knowledge-based routing algorithms, Contact Graph Routing (CGR)[4] is used in deep space communication where contacts are scheduled, and can be expanded to other deterministic DTN environments including satellite networks.

CGR has been implemented in the open-source Interplanetary Overlay Network (ION) package developed by Jet Propulsion Laboratory[5]. In Ref. [6], CGR was evaluated in LEO satellite DTN communications by using the ION software mentioned above, and results showed that CGR was effective in selecting correct route and met the challenges posed by the dynamic network topologies.

Seguí *et al.*[7] proposed two improvements to CGR: (i) using the earliest arrival time as the cost function instead of earliest forfeit time, (ii) using Dijkstra's shortest path algorithm for path selection. JPL's Multi-mission Advanced Communications Hybrid Environment for Test and Evaluation (MACHETE)[8] was used to evaluate CGR's suitability for space applications. Their Enhanced CGR (ECGR) algorithm improves performance in terms of path computation time, efficient use of bandwidth, end-to-end latency and delivery ratio. Birrane *et al.*[9] proposed an extension to CGR, CGR-EB, which encoded a computed path and the subset of the contact graph that is used to calculate that path with the message being routed in the network. CGR-EB reduces processing time and has better fault tolerance.

DTN networks are prone to message losses due to link failures, limited storage space, error paths or other problems. Jain *et al.*[10] improved the probability of successful message delivery in DTNs with path failures by employing erasure coding integrated with replication. CGR also needs fault tolerance to address these failures and ensures reliability of data transmission. In this paper, we build a multilayer satellite delay tolerant and disruptive networks simulated environment which consists of GEO, MEO and LEO satellites and a ground station. CGR and matching fault tolerance scheme are implemented in our space environment oriented DTN gateway model to evaluate their performances in the multilayer satellite delay tolerant networks.

1 Space Oriented DTN Gateway Design

1.1 Specific Protocol Stack of Space Oriented DTN Gateway

Space oriented DTN gateway was previously developed in order to conduct studies of space environment oriented DTN networks, especially the satellite networks discussed in this paper. Our main research purpose was to evaluate real-time DTN network behavior under space environment conditions by using the OPNET. And in order to do that, a specific protocol stack of space oriented DTN gateway was implemented.

Since there exists no ready-made space environment oriented DTN stack in OPNET, we have to implement the Bundle Protocol[11], as well as the relevant transport layer protocol and link layer protocol. For network layer, IP technology has been widely adopted in the terrestrial network, thus it is a reasonable idea to expand the IP technology to the space network. IP over CCSDS (IPoC) is a mechanism proposed by CCSDS to make it possible for carrying IP packets across space and ground networks[12].

Long propagation delays, limited bandwidth, high bit error rate, asymmetric link capacities, and intermittent connectivity that exist in the space communication environment pose great challenges to end-to-end reliable data communication. The performance of current Transmission Control Protocol (TCP) is severely limited by the harsh conditions of space environments. A number of extensions have been made to TCP to improve its performance in the space environment. Space communications protocol standards—transport protocol (SCPS-TP) is among one of the TCP extensions developed by Consultative Committee for Space Data Systems (CCSDS) for space communications[13]. SCPS-TP addresses the challenges exiting in the space environments by inheriting the relevant features from TCP as well as modifying others according to the specific characteristics of space links.

Advanced Orbiting Systems (AOS) developed by CCSDS act as a data link protocol for use in transferring any data over ground-to-space, space-to-ground or space-to-space data communication links. The CCSDS AOS standard integrates video, image and audio transfer, and supports asynchronous and synchronous transfer mode. So far we have discussed the specific protocol stack for space environment oriented DTN networks and in Fig. 1 we present the specific protocol stack of space environment oriented DTN gateway used in the simulation. In the following part, bundle layer as the core component offering DTN service is presented in detail. For more details about space oriented DTN gateway design, please refer to Ref. [2].

bundle	
TCP/UDP	SCPS-TP
IP	IP
ethernet	AOS
LAN	RF

Fig. 1 Space oriented DTN gateway stack

1.2 Bundle Protocol Design

The design of Bundle Protocol is composed of seven modules: bundle protocol agent, storage, registration, bundle routing, link management, neighbor discovery, convergence layer adapters, as illustrated in Fig. 2.

In our implementation of the bundle protocol, the bundle route computation is accomplished in two

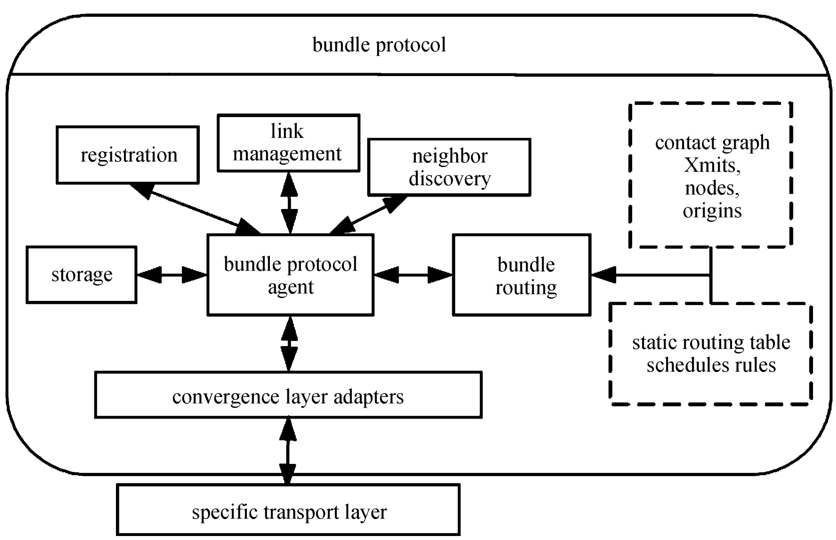

Fig. 2 Bundle protocol design

ways, *i.e.*, contact graph routing and static routing. Static routing is necessary in case bundles are destined for a given node to which no contact plan information is known (*e.g.* the destination node do not participate in contact graph routing at all). When there are bundles needed forwarding, Bundle Protocol Agent (BPA) consults static routing table to determine the packet's next hop or runs the contact graph routing to determine all plausible proximate nodes and then appends bundles to the transmission queue for the best plausible proximate node.

The implementation of bundle routing should also corporate with link manager and neighbor discovery to obtain a good performance. Neighbor discovery module maintains a neighbor list by periodically sending hello message. Link manager utilizes neighbor information gathered by neighbor discovery module and regularly exchanges link information between a pair of nodes to verify the connectivity of the links. Furthermore, link manager can manage failures by rapidly notification of the status of a link and thus make it easier to rapidly isolate data link failures.

Bundle protocol agent is the core component that executes the procedures of the bundle protocol. The key features of the bundle protocol are custody transfer mechanism, fragmentation and reassembly, possible deletion and final delivery, and these features are elaborated in Ref. [2]. A simplified description of the implementation of bundle processing is given in Fig. 3.

2 Contact Graph Routing

2.1 CGR Overview

CGR utilizes a set of pre-configured contact plan information regarding the changes of the network topology over time to compute possible routes through the network. Complete contact plan messages contain two parts: contact message and associated range message. Contact message can be represented as a 5-tuple as follows:

$$contact ::= \{fromTime, toTime, fromNode, toNode, rate\}.$$

The *fromTime* and *toTime* represent the time interval of the contact at the transmitting node, *fromNode* and *toNode* are numeric values identifying the transmitting node and receiving node of this contact, and the last element of the contact tuple represents the planned transmission rate between the transmitting node and the receiving node measured in bytes per second. The range message can be formed by repla-

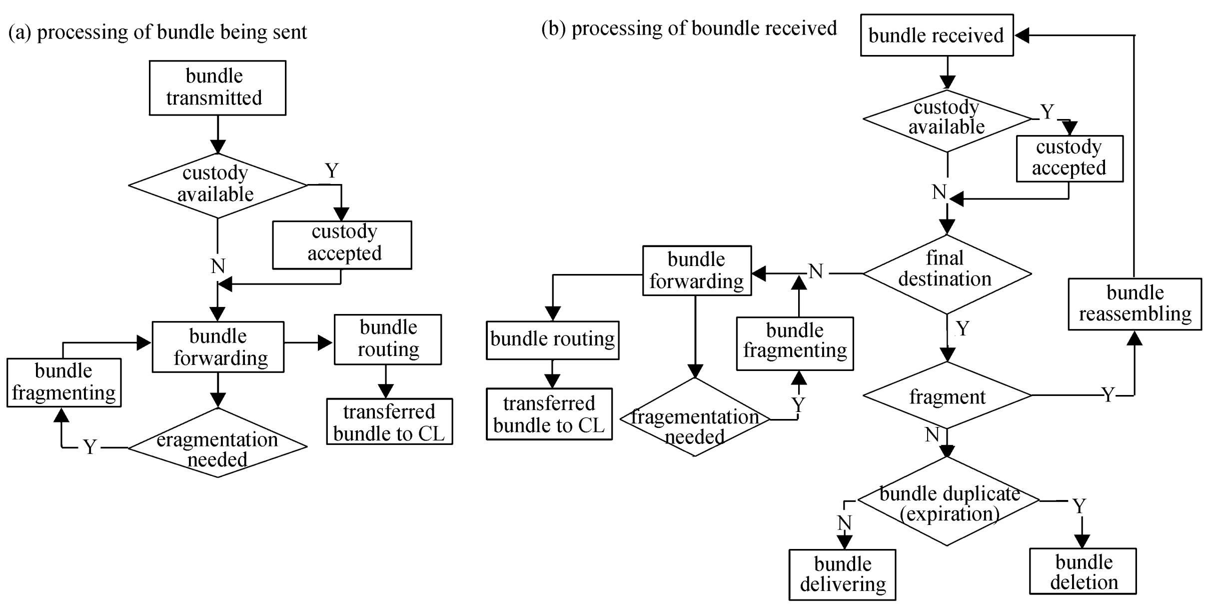

Fig. 3 Bundle processing flow chart

cing the last element of the contact tuple with distance measured in light-second representing the anticipated distance between the two participating nodes.

Given a complete contact plan, CGR can construct a contact graph (time-varying models of network connectivity) data structure for computing efficient routes in the later process. Here we give a time-varying satellite network topology as depicted in Fig. 4 to illustrate how the contact graph data is stored at a given node. This simple scenario contains four nodes: Node 1, Node 2, Node 3 and Node 4 as shown in the picture. Take Node 1 for example, the corresponding contact graph at Node 1 may look like Table 1.

After the contact graph has been constructed, CGR can analyze this contact graph and calculate a set of possible next-hop nodes (*i.e.* proximate nodes), then typically one of these is chosen according to some criteria acting as costs. Here we choose the earliest best-case delivery time as the criteria for selecting the "best" plausible route, and in case of ties (*i.e.* two proximate nodes associated with the same minimum delivery time), we select the best next-hop node with

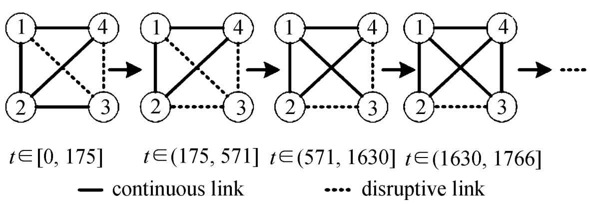

Fig. 4 The time-varying topology (in the particular case of 4 nodes)

the shortest hops from the destination node. One of the key rules for selecting the proximate node is that the link to the proximate node must have enough capacity to let the bundle go through, and this is done by comparing bundle's Estimated Capacity Consumption (ECC) with the associated contact's residual capacity.

Note that there exists no "routing tables" in CGR, *i.e.*, for a given destination node, one bundle destined for it may have a different route from another different bundle destined for the same node, due to the differences of bundle priority, bundle expiration time and transmission queues. The result computed for each bundle by the CGR algorithm is not an end-to-end path; it only consists of a set of adjacent nodes for bundles to be forwarded to. For more details about CGR, please refer to Ref. [4].

2.2 CGR Algorithm

Before jumping directly into the CGR algorithm, we need to firstly list the terminology used throughout the discussion.

ProximateList represents the list of neighbor nodes that offer plausible opportunities for transmitting the given bundle.

ExcludeList represents the list of excluded neighbors that should not be considered for a given bundle.

B represents the bundle being sent and $B_{\rm dest}$ is the destination of B. $B_{\rm ecc}$ represents the estimated capacity consumption of B. $B_{\rm expTime}$ represents the expiration time of B. LD stands for local node that will forward B.

Table 1 Contact Graph stored at Node 1 for a given time

fromNode	*toNode*	*fromTime*/s	*toTime*/s	*Rate*/(kByte·s^{-1})	*Range*/light-second
1	2	0	1766	125	0.1157
3	2	0	175	130	0.0133
1	3	571	1766	125	0.1202
2	3	0	175	130	0.0133
1	4	0	1766	125	0.1892
2	4	0	1766	130	0.1012
3	4	1630	1766	150	0.1031

D is the destination variable and M represents the contact item in node D's list of contact messages.

X is the deadline variable and has the initial value the same as B_{expTime}. T represents the last moment for sending a bundle during contact M. L stands for estimated forwarding latency for the given bundle.

$HopCnt$ represents the anticipative number of hops and EDT represents the earliest predicted delivery time for the given bundle. P_{HopOut} represents the minimum hop for which B can reach the final destination D. P_{EDT} is the earliest time at which B can reach D.

$M_{\text{startTime}}$ and M_{stopTime} represent the start time and end time of contact message M, respectively. M_{fromNode} and M_{stopTime} stand for the transmitting node and receiving node of M, respectively. M_{resCop} is the residual capacity of contact M.

In Fig. 5 we illustrate the contact review procedure of CGR.

2.3 Link Failures Handling

CGR computes route is based on a set of scheduled contact plan information which is assumed to be unchanged. However, the contact plan may change due to harsh communication environments of DTN. CGR must calculate a new path when some scheduled contacts become unavailable.

In our implementations, link failures are addressed by neighbor discovery mechanism and route recomputation. DTN node employs neighbor disco-

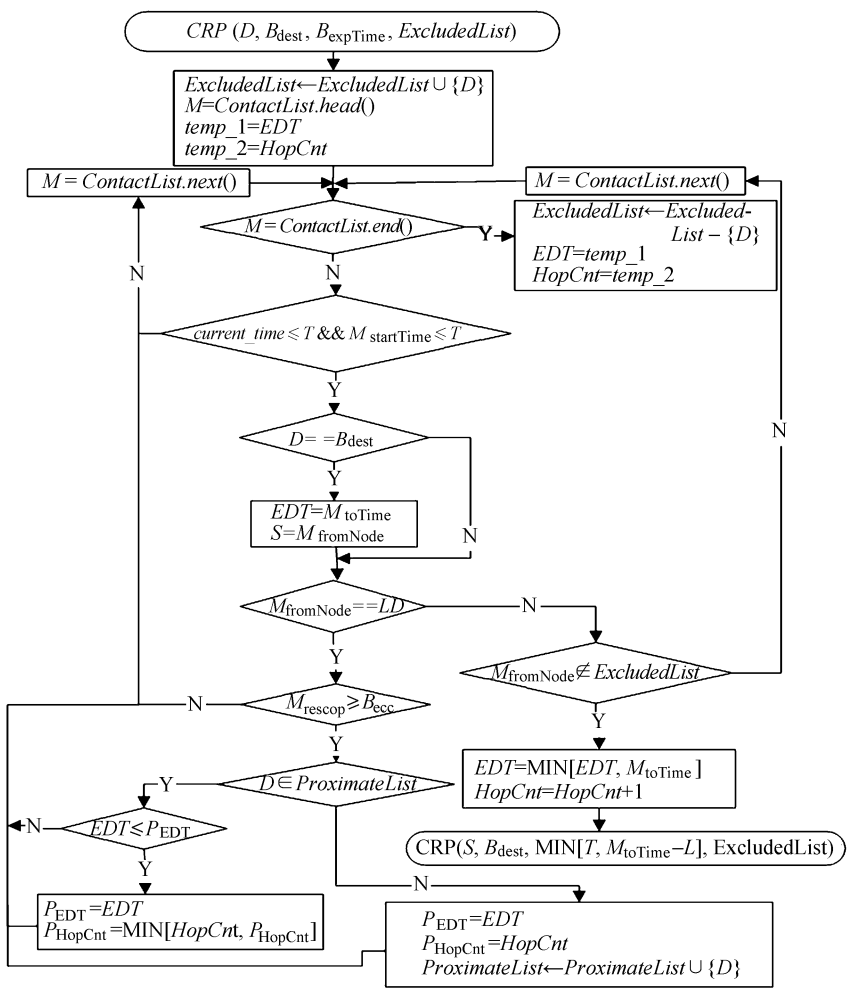

Fig. 5 Contact review procedure of CGR

very module to determine its location and neighbors by periodically sending neighbor discovery message to special multicast address each DTN node will listen to and respond with node announcement message which contains node ID when hearing that message. Thus, each DTN node keeps a neighbor list which is periodically refreshed.

Next hop selected by CGR must be part of the neighbor list maintained by neighbor discovery module. If the selected next hop is not in the neighbor list, conveyance of the bundle from source to destination can inevitably fail due to the unprepared link between current node and the selected next hop. Thus, custodial retransmission mechanism will be invoked since the next hop node is unreachable. When such error is encountered, the unavailable selected next hop is added to the excluded list and alternative routes are recalculated by CGR. The failed link will be regarded as unavailable until it is detected by the neighbor discovery module again. But such problems should been detected earlier when more candidate nodes are available.

3 Simulation and Results

3.1 Simulation Scenario

In order to investigate the applicability of CGR to satellite networks, we consider a simulated satellite networks scenario where DTN technology and CGR routing algorithm are implemented with the support of OPNET. The simulated satellite networks scenario (see Fig. 6) comprises three kinds of satellites, namely LEO, MEO, and GEO satellites and one ground station located in Xichang (latitude 27.98°N, longitude 102.18°E), further details about the satellite orbits are shown in Table 2. Satellite Tool Kit (STK) which allows engineers and scientists to perform complex analysis of ground and space assets, is used to generate satellite orbit files and contact information for use in OPNET simulation.

We choose Earth observation application for the test and the resolution of image for transmitting is 128×120. S4 and ground station (*i.e.* G1) are configured as source and destination respectively. Image data is transmitted between source and destination with the help of space oriented DTN gateways which are located at the border of this heterogeneous space information networks. Other satellite nodes acting as DTN routers forward bundles within one single DTN region. Note that there is no ready-made image transmission application in OPNET and we do this by modifying the frame interval time of Video Conference application to one frame per second, thus forming a continuous image data traffic. The simulation duration time is set to 2 hours during which there is no continuous connectivity between the source and

Table 2 Satellite orbit information

satellite ID	perigee/km	apogee/km	Inclination/(°)	period/min	semi major axis/km
S1	35 789.4	35 798.6	0.0	1 436.1	42 465
S2	35 789.6	35 798.0	0.0	1 436.1	42 164
S3	35 777.0	35 811.6	0.0	1 436.1	42 165
S4	1 521.7	1 522.5	52.0	116.3	7 893
S5	1 864.9	1 865.9	52.0	124.0	8 236
S6	1 629.8	1 639.8	52.0	118.8	8 005
S7	20 001.8	20 378.4	56.5	718.0	26 560
S8	19 635.4	20 742.0	53.4	717.9	26 559
S9	20 005.7	20 372.6	53.0	718.0	26 560

destination. Indeed, the direct connectivity between the source and destination is available from 0 s to 1420 s.

Single link failure scenario is simulated to investigate the performance of fault tolerance scheme. The network is set to be disrupted by the single link failure between S4 and S1 after simulation has been started for 2000 s. We also implement the static routing for contrast: image data traffic flows from S4 through S1 to G1. Due to the mobility of satellites, the static route path is available during two time intervals (Table 3) in the whole simulation process.

3.2 Results

In Table 4, we give the route path calculated by CGR. We observe that CGR algorithm succeeds in calculating right paths without interrupting the data traffic. Statistical curve of global traffic sent and received (see Fig. 7) also demonstrates that. It can be seen that global traffic sent is equivalent to global traffic received during the whole simulation process by utilizing CGR algorithm. Static routing fails to adapt to network outages when the route path is not available. Still, due to the custody transfer mechanism of the space oriented DTN gateway, image data that fail to get through the network are accepted custody by the intermediate node (*i.e.* S1) and transmitted to the destination as soon as the route path is recovered (see Fig. 8). Thus, data reliable transmission is guaranteed by custody transfer mechanism of the space oriented DTN gateway and no packet loss occurs when path is interrupted.

End-to-end delay refers to the time taken for a packet to be transmitted across the satellite network from the source to destination, which includes trans-

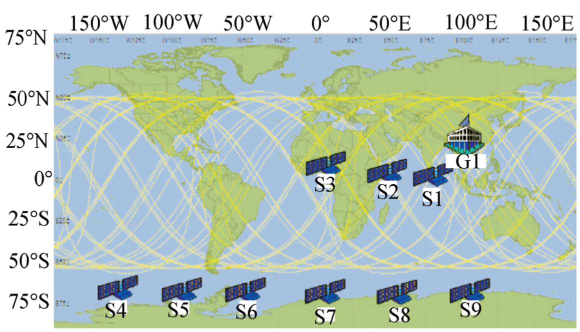

Fig. 6 Simulated satellite networks scenario

Table 3 Static route path state

time interval/s	route path state
0∼2387	connected
2387∼4267	unconnected
4267∼7200	connected

Table 4 Route path calculated by CGR

time interval/s	forward path	reverse path
0∼1420	S4-G1	G1-S4
1420∼2402	S4-S1-G1	G1-S1-S4
2402∼3321	S4-S2-G1	G1-S2-S4
3321∼4015	S4-S3-G1	G1-S3-S4
4015∼4349	S4-S8-S1-G1	G1-S9-S4
4349∼5068	S4-S8-S1-G1	G1-S1-S4
5068∼7200	S4-S1-G1	G1-S1-S4

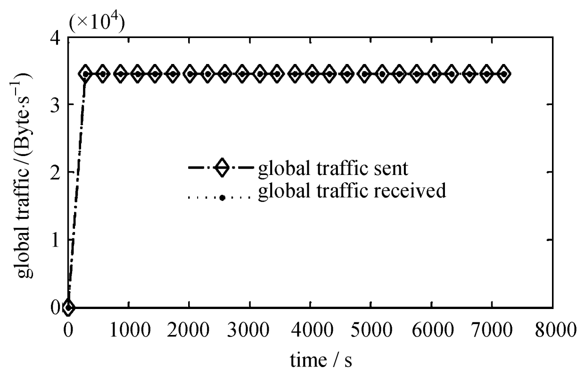

Fig. 7 Global traffic under CGR

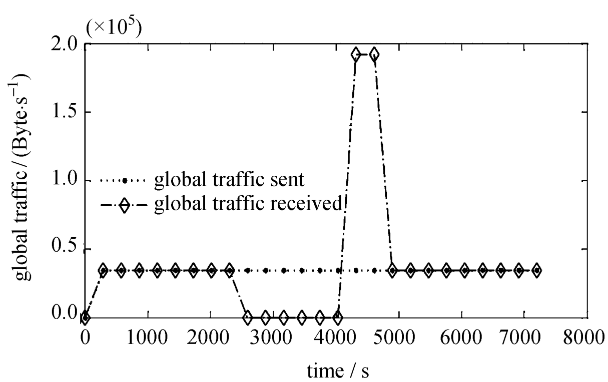

Fig. 8 Global traffic under static routing

mission delay, onboard processing delay and propagation delay. Among these delays, the propagation delay is the main factor that affects total end-to-end delay since the distance between the source and destination may vary from thousands to hundreds of thousands kilometers. Fig. 9 presents the global packet end-to-end delay. CGR shows a lower delay than static routing. Meanwhile, for the static routing, as there is no connected path from 2387 s to 4267 s, the end-to-end delay has no statistical results during that time and reaches a very high level after the route path is reestablished and the custody transfer starts. Similarly, static routing shows extremely high packet delay variation after connection breaks off (see Fig. 11).

Fig. 10 shows the end-to-end delay of single link failure scenario. The data transmission is not interrupted after the link between S4 and S1 begins to fail. Alternative node (*i.e.* S2) is early selected at 2000 s and will remain as the next hop from 2000 s to 3321 s.

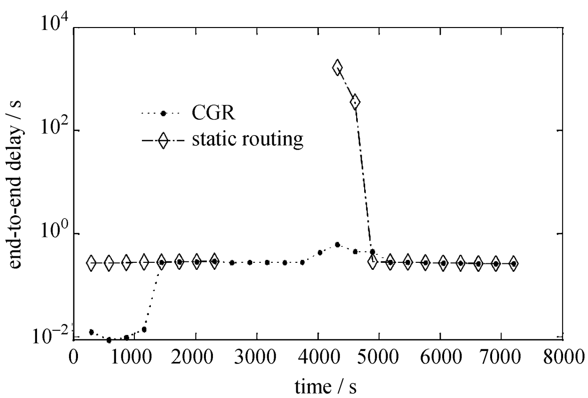

Fig. 9 End to end delay

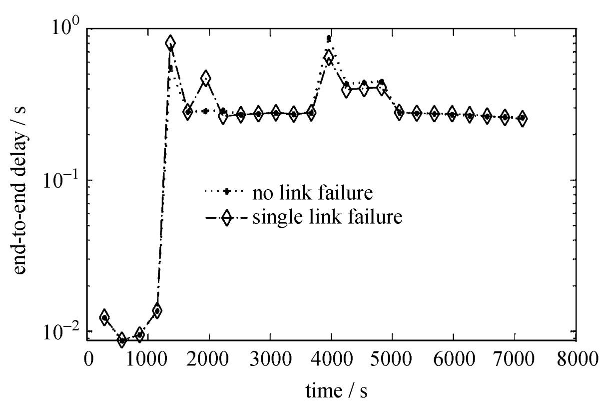

Fig. 10 End to end delay under link failure

From the results we can see that space oriented DTN gateway can reduce the packet loss due to frequent link disruptions, enhance data transmission reliability and make it easier to extend delay-tolerant applications to space missions. Moreover, CGR performs well in satellite delay tolerant network routing because CGR is a dynamic route computation algorithm and can be re-applied to the bundle so that an alternate continuous route can be computed when link failure happens.

4 Conclusion

This paper presents an investigation of the applicability of CGR in satellite delay tolerant networks. CGR routing in the presence of link failures is also discussed and matching fault tolerance scheme is proposed. A space oriented DTN gateway model, which shows superior performance in terms of conquering delay and disruption in satellite delay tolerant networks, is also presented. In an image data transmitting simulation scenario through OPNET, we show that CGR succeeds in effectively utilizing the network resources to calculate continuous route path in the space delay tolerant networks and can be an excellent candidate for satellite delay tolerant networks.

CGR utilizes a set of scheduled contact information to compute routes and lacks a dynamic understanding of the whole network topology and network resources. Thus, traffic congestion is easy to happen

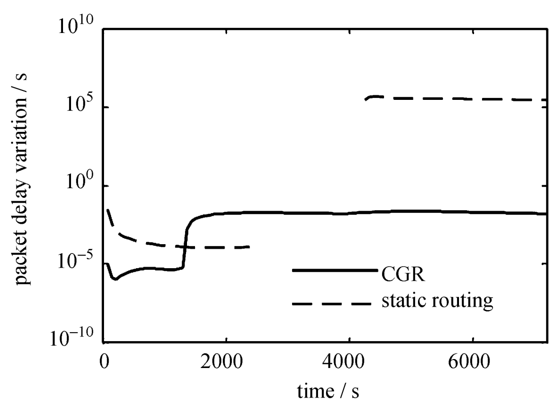

Fig. 11 Packet delay variation

and it is hard to predict potential link failure. Future research will be aimed at traffic congestion control mechanism and fault tolerance scheme based on predicting link failures.

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