A Novel DTN Routing Algorithm In The GEO-relaying Satellite Network

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***Abstract*—Disruption-Tolerant Networks provides store-and-forward enabled routing strategies for the satellite networks with frequently intermittent links. However, current dynamic route selection algorithm (DRSA), including Contact Graph Routing (CGR) algorithm, could not find an end-to-end route over a serial of link segments with time-disjointed contacts. In this paper, we proposed a novel routing algorithm as expanding range route selection (ERRS), which could find the EDT-optimal route by searching at each snapshot of time-varying topology. The proposed algorithm is compared with DRSA on the Linux-based experimental platform with built-in ION (Interplanetary Overlay Networks) software. The results show our algorithm has less delivery time and the obviously improved throughput of the network.**

Keywords—Satellite network; DTN; CGR; ERRS; ION

I. INTRODUCTION

The timely transmission between a remote sensor-integrated satellite and ground station can be obviously improved by a network constituted of several MEO and GEO satellites. The data delivery protocols in satellite network need to cope with dynamic topology and time-varying characteristics of Inter-Satellite Links (ISLs) and Earth-Satellite Links (ESLs)[1][2].

Recently, Disruption-Tolerant Network (DTN) is proved to perform well in dealing with intermittent satellite network, which uses store-carry and forward transmission strategy without the assuming of persistent connectivity [3][4].For DTN architecture, every node has a bundle protocol (BP) layer between application layer and convergence layer. BP layer encapsulates application data units (ADU) into bundles and provides data delivery scheme with dynamic route selection algorithm (**DRSA**). Typically, in space applications, the exclusive convergence layer under BP is licklider transmission protocol (LTP) which guarantees the point-to-point reliability by providing ARQ-based re-transmission mechanism. In LTP, bundles is packaged into blocks and then fragmented into the basic transmission units of segments [5][6]. For the routing scheme in BP, DRSA uses a hybrid strategy including contact graph routing (CGR) and direct delivery without storing and carrying the bundles [7]. In the current version for deep space missions, CGR uses Dijkstra algorithm to build the route table on a pre-scheduled contact graph of the network links, with typical format as (*start time*, *end time*, *transmission rate*, *one way light time* (OWLT))[8]. If the payload, denoting the whole transmission capacity during a period over a link, is more than the size of a bundle, a best-case route without considering the re-transmission and failures time is selected [9]. If no route to the destination endpoint is found, then current endpoint will directly deliver bundles to its neighbor nodes in order. However, unlike WSN and deep space environment, near-earth satellite network is highly organized and has fewer accidents. DRSA, especially CGR depending on static graph, is not global optimal. The way of distributed calculation requires a huge amount of computations and has low efficiency [10].

In this paper, we proposed a strategy to reduce the waste of route computation and optimize the calculation. The algorithm includes two parts: The first part is to calculate the satellite orbit information in the ground station. Then the satellites are informed of route tables which are built for future use. All the reachable routes in the next period is included in the table. In this way the route table is updated regularly in the satellites. When a transmission task is started on a node, the route will be decided by the second part of algorithm which selects paths by considering both route table and new metrics with link reliability.

The structure of paper is as follows. In Section II we establish the geometry of satellite network and analyze the theoretical model of links. We describe two parts of the route algorithm and provide it as pseudo-code form in Section III. Section IV shows the experimental results on ION built-in platform. Section V is the conclusion and future works.

II. BACKGROUND

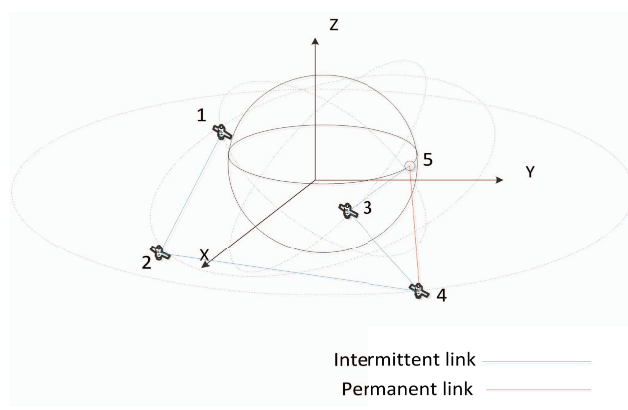

Fig.1 Geometry of GEO-Relaying satellite network

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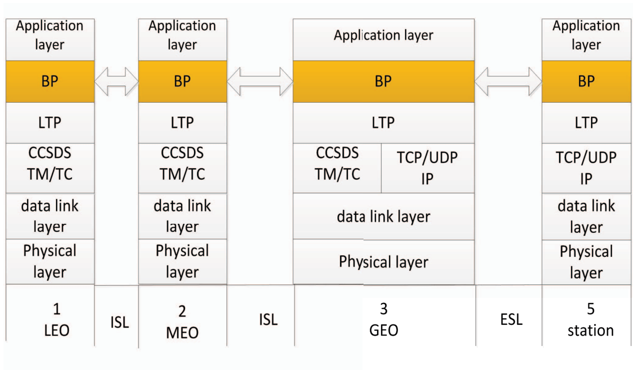

Fig.2 Protocol architecture

A. System Model

A DTN-based GEO-relaying satellite network model is shown in Fig.1. In the geocentric equatorial inertial frame (GEIF), four satellites are deployed in different orbits with a ground station as DTN nodes. In the network, **NODE 1** is a remote sensor-integrated LEO satellite typically for imaging missions, while **NODE 2** and **3** works as relay MEO satellites in the height between 10000km and 20000km. In particular, **NODE 4** is a GEO relay satellite with permanent link to **NODE 5** which is a ground station. There are few chances for **NODE** 1 to communicate with **NODE 5** directly. During a communication window, we make transmission at Round-Trip Time (RTT), which is assumed twice of OWLT. Communication windows of ISLs between **NODE 1** and other endpoints vary in minutes and in link ranges from 8000km to 45000km. The only permanent link is the earth-satellite link (ESL) between **NODE 4** and **NODE 5**.

The DTN architecture add a new layer between Transport and Application layers, called "bundle layer". Real end-to-end data reliability across a hybrid network is provided by the bundle layer. Though different protocols exist underneath, the component gives a uniform view of the network. The end-to-end connection is provided by "custody transfer" mechanism: Bundles are kept in the database of DTN nodes until the next hop is reachable, and is stored until the acknowledgment is received. Fig.2 shows the data delivery protocol stacks for the proposed network, where constant images fetched by LEO are firstly packaged into bundles and then changed into blocks and segments in LTP.

Preliminary definitions are shown as follows.

We assume that the initial state of model is t_0 in Universal Time Coordinated (UTC). In particular, l_i denotes the link i between two adjacent satellites v_β and v_μ, which exists from t_k to t_l with data rate $b_{forward}$ from v_β to v_μ, and b_{back} backward. Denote p_{l1}, p_{l2} as different bit error rate (BER) in the duplex channel, respectively. The complete $\boldsymbol{l_i}$ is formulated as $l_i\,(t_k, t_l, v_\beta, v_\mu, p_{l1}, p_{l2}, b_{forward}, b_{back})$. Let r_i<l_1, l_2, l_3, ... l_n> denote the route constituted of serial links. Besides, a node can be described as v<c, l_i, l_j, l_k......> with all the links to its neighbor and the residual storage c.

B. Link Analysis

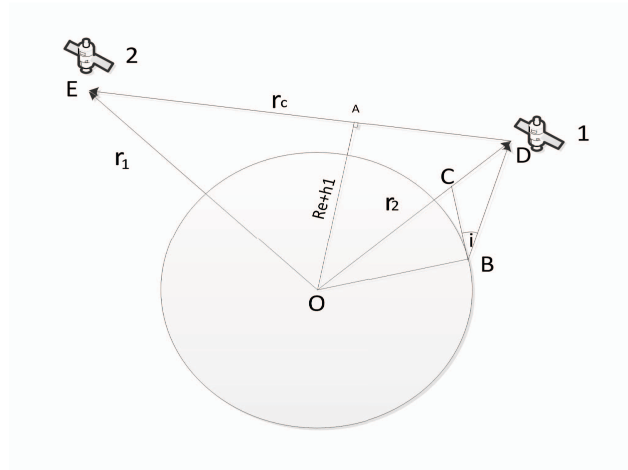

Fig.3 Links between satellites and station

Fig.3 shows the geometric constrains to create ISLs and ESLs. We describe the relative distance between **NODE 1** and **NODE 2** by vectors in GEIF as $r_c=r_1-r_2$. Since the height of avoiding ground clutter interference is h_1, the ISL minimum communication distance in sight is

$$l_{ED}=\sqrt{r_1^2-(R_e+h_1)^2}+\sqrt{r_2^{\,2}-(R_e+h_1)^2} \tag{1}$$

Assuming minimum received elevation of station is i, minimum ESL distance should be

$$l_{BD}=\sqrt{(R_e\sin i)^2+2R_e+h}-R_e\sin i \tag{2}$$

According to the two-body motion equation, we get

$$\frac{d^2\vec{r}_t}{dt^2}=-\mu\frac{\vec{r}_t}{r_t^3},\quad \frac{d^2\vec{r}_c}{dt^2}=\frac{d^2\vec{r}_1}{dt^2}-\frac{d^2\vec{r}_2}{dt^2} \tag{3}$$

$$r_t=\frac{a_t\left(1-e_t^2\right)}{\left(1+e_t\cos\theta_t\right)} \tag{4}$$

By transforming it from GEIF to spacecraft local orbital frame, we get the Hill equation

$$\begin{cases}\ddot{x}=2n\dot{z}\\ \ddot{y}=-n^2y\\ \ddot{z}=3n^2z-2n\dot{x}\end{cases},\quad n=\sqrt{\mu/r_t^3} \tag{5}$$

Set $X=[x,y,z,x',y',z']$ and initial state t_0, then we get

$$X(t)=\Phi(t-t_0)X(t_0) \tag{6}$$

Accordingly, the relative distance to a link of $\boldsymbol{l_i}$ is

$$l_i(t)=r_c(t)=\sqrt{x^2(t)+y^2(t)+z^2(t)} \tag{7}$$

C. Network Capacity

We discuss the network capacity in the following part. Route capacity is limited by its bottleneck. For example, considering a transmission from **NODE 1** to **NODE 3** in Fig.4 through the links <l_1,l_2,l_3>.

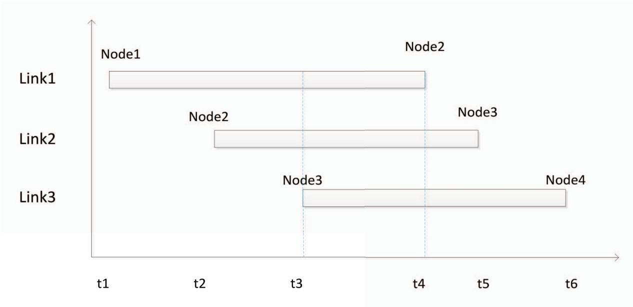

Fig.4 Intermittent route

We found that the end-to-end route only exists during (t_3, t_4) with the payload, defined as

$$payload(t_3,t_4) = (t_4 - t_3) \times \min[b_{12}, b_{23}, b_{34}] \quad (8)$$

On the other side, the total transmission capacity during the period from t_1 to t_6:

$$capacity(t_1,t_6) = \min\{b_{12} \times (t_4 - t_1), b_{23} \times (t_5 - t_2), b_{34} \times (t_6 - t_3)\} \quad (9)$$

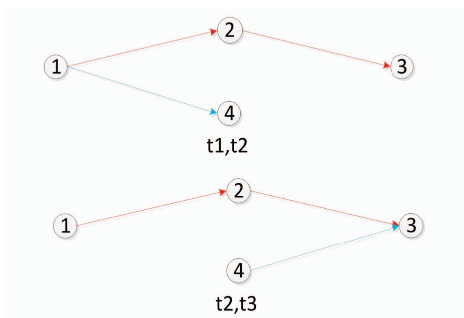

Fig.5 Payload compared in two routes

For the bottom example in Fig.5, we compared the payload between a direct transmission route <1,2,3> and a store-forward transmission route<1,4,3> in the period t_1 to t_2 and t_2 to t_3, as follows.

$$payload <1,2,3>= (t_3 - t_1) \times \min\{b_{12}, b_{23}\} \quad (10)$$

$$payload <1,4,3>= \min\{b_{12}(t_2 - t_1), b_{23}(t_3 - t_2)\} \quad (11)$$

D. Metrics for Bundle Delivery

We assume that a bundle is delivered over a contact with BERs of p_{l1} and p_{l2}. With one bundle loaded into one block, each block is divided into m segments with the size of α bytes. During the block's session, if all segments are received correctly, a θ bytes size ACK will be returned. The failure of any segment delivery will cause a whole block re-transmission.

The probability of successful delivery:

$$p = (1 - m\alpha p_{l1})(1 - \theta p_{l2}) \quad (12)$$

The re-transmission count k obeys the following distribution:

$$f(k) = (1-p)^{k-1} p \quad (13)$$

Accordingly, the total expectation transmission quantity of one bundle B_{cost}:

$$B_{cost} = \frac{m\alpha}{p} byte \quad (14)$$

We denote t_b as the total data delivery time, t_A as ACK delivery time, then the delivery time T_{cost} of the bundle delivered is:

$$T_{cost} = \frac{(RTT + t_b + t_A)}{(1 - m\alpha p_{l1})(1 - \theta p_{l2})} \quad (15)$$

Many routing algorithms evaluate the performance of route by its hop count and transmission delivery time [11][12]. However it does not consider the link reliability. A route may spend more time in delivery than a route with less BER of all its links.

We take re-transmission into consideration and value route by valuing transmission performance with expected delivery time (**EDT**) and expected transmission cost (**ETC**).

ETC is defined as total bandwidth cost of a bundle transmitted on a route of k links:

$$ETC = \sum_{z=1}^{k} \frac{m\alpha}{p_z} byte \quad (16)$$

EDT is the sum of waiting time and the expectation delivery:

$$EDT = \sum_{z=1}^{k} \frac{(RTT + t_b + t_A)}{(1 - m\alpha p_{l_z 1})(1 - \theta p_{l_z 2})} + \sum_{z=1}^{k} (t_z - t_{z-1}) \quad (17)$$

III. EXPANDING RANGE ROUTE SELECTION

The proposed algorithm named as expanding range route selection (**ERRS**) includes two parts. The first part which is done on the ground station uses time shots to describe the dynamic topology of the GEO-relaying satellite network and records all the reachable routes. A serial of listed graphs in discretized timeline is exploited to record the detailed changes of network topology, as shown in Fig.6.

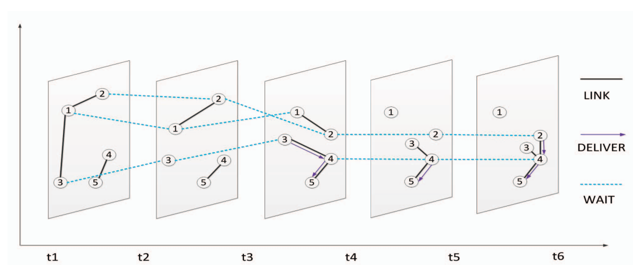

Fig.6 The snap shots of network topology

In Fig.6, dynamic network is described by a series of graphs step by step, in which the first graph lasting from t_1 to t_2 differs only in one link with the second graph, considering no link changes within one graph. In the whole period, **NODE 1** delivers packets to **NODE 5** in different routes. The routes marked in the Fig.6 shows the delivery in one graph, and consequently their storage states between different graphs.

Since none end-to-end path exist in one graph, the proposed **EDT**-optimal algorithm needs to find all the routes among the serial graphs. Given a link-leg of route incorporating storage time of waiting for next contact in the local intermediate node, it is hard to find the optimal solution with CGR and the built-in Dijkstra algorithm which can only work on a static graph. Therefore, we introduce the proposed routing algorithm in the following part.

Let v_k denote the node number of an endpoint. $l_j(t)$ denotes the OWLT value of a link j. In the period from t_1 to t_2, we use its mean value as weight:

$$l_{mean} = \frac{l_i(t_1) + l_i(t_2)}{2} \tag{18}$$

We take $G_i(V, E_i, W)$ as a direct graph describing the ith snapshot of topology during t_i to t_{i+1}, where V is a set of all nodes, E_i is the set of all links, and W is the set of $\bar{l}$, respectively. $R_{vkm}(V,r)$ is a set of nodes linked to the node v_k including the paths. $S_{m+h}(V(R_{vk(m+h)}, R_{vj(m+h)}, R_{vi(m+h)}))$ is a table of all the paths found in period of $m+h$. **SVR** is a chain table of S_{m+h}. Set $r_{whole}<r_1(l_1, l_2...), r_2().....r_{m+p}()>$ as a store-and-forward route from source to destination endpoints in route set $R\{r_{whole1}, r_{whole2}, r_{whole3}...\}$. $LR<l_{r1}, l_{r2}, l_{r3}....>$ is the left capacity of bandwidth.

A. Building the route table

We explain the expand range searching algorithm with Algorithm 1 in details. Considering that the initial endpoint O is the center of a circle, then every endpoint in the first circle becomes a new center of a circle including the endpoints they can reach in the second graph. Repeating the above procedure until a particular time we set. By this way, we can form a chained table **SVR** to record the route information. Especially, during each graph, we use l_{mean} as a rough estimate of $l(t)$.

Algorithm 1. Build the route table

```
Put vj into the S list.  //Use Dijkstra algorithm to search the reachable
point list with all the shortest routes Rvxj(V,r)from vx in G{G0,G1,G2....}
j=0;
While Gj!=NULL
   While  Sj!=NULL
    Take vx from Sj;
       Rvxj(V,r)= Dijkstra (Gj,  vx );
       Sj+1(V;
    End while
   j++;
End while
Rank the set SVR with EDT;
Output: SVR
```

Fig.7 Building route table

B. Route selection

Algorithm 2 is used at the beginning of transmission. The procedure starts to traverse the composite list from $S_m(V(R_{vkm}))$. If v_d is found in R_{vlm+p}, we will make a reverse traversal to find its route to initial node v_k. The route can be described as $r_{whole}<r_1(l_1,l_2...),r_2(...)...r_{m+p}(...)>$.

All the routes found form a set $R\{r_{whole1},r_{whole2},r_{whole3}....\}$ in the order of **ETC** value. Above all, every node has a list of the record LR of left capacity of bandwidth of its all links to the neighbor. If the **ETC>**l_{ri} is true, the route is not chosen.

Algorithm 2. Route selection of fastest delivery

```
Input: SVR,bundle information <vd,Stime, Etime>
Search the time sequence T{t0,t1,t2...} until find the sequence ta<Stime>tb,
tc<Etime<td.;
 vertex=vd;
  α=1;
While i!=d  //d denote the destination node
  While vs!=vd
   Search vertex in SVR;
       If vertex is included in Si(V)
            find the routing r in Si-1(V(R));
             vertex =vs;
              rα(r;  //take r into set rα
             ++α;
         End while;
          R(r;
         Select the r in set R(r1,r2,r3.....) with ETC;
   i++;
End while;
Output: r
```

Fig.8 Route selection

C. Dealing With the Exception

We consider two kinds of exception in the network. One is caused by uncertain effects of external radiation on the satellite-carried hardware, in which a single event-upset phenomenon can be modeled of a Poisson distribution with a fault parameter λ [13]. Another is the link delay jitter. For the exception events, we use an experience of transmission to modify the expected delivery time as $T_{correct}=max\{EDT,T_{e1}\}$. Here, T_{e1} denotes the delivery time of the bundle transmitted over the link just before.

After the route selection, the procedure will check both the hardware and link situation of next point. If any of them is in "*fault*", a recalculation of the routing will be made.

IV. Performance Evaluation

We built a Linux-based experimental platform which could simulate a more realistic data flow in a DTN-based dynamic satellite network scene. In the experiments, we constructed the network model as shown in Table.1 with the software of Satellite Tool Kits (STK), and simulated it during a period from 1 Jul 2015 04:00:00.000 to 2 Jul 2015 04:00:00.000. With the outputted report of link access duration and link range, the required configuration files are fixed for Interplanetary overlay network software (ION) accordingly. As higher orbit satellite has a better coverage of the low satellite, a higher transmission rate of the down-link is regulated more than the up-link, and BER is a monotone function of the link distance. We simulated Transmission on several random time points and compared our algorithm **ERRS** with **DRSA** in ION.

TABLE.1 ORBIT PARAMETERS OF SATELLITE

Node number	Apogee Radius	Perigee Radius	Inclination	Argument of Perigee	Lon. Ascn. Node	True anomaly
1	7178.14km	7178.14km	45deg	0deg	21.1033deg	0deg
2	15000 km	15000 km	120 deg	30deg	120 deg	0deg
3	20000 km	20000 km	28.5 deg	0deg	21.3024deg	0deg
4	42166.3km	42166.3km	0deg	0deg	100 deg	0deg

In particular, **Node 5** is located with Latitude of 32.9022deg and Longitude of 101.707deg, as a ground station.

The links data rates are

$$l_{41}, l_{42,} l_{43}, l_{31}, l_{35}, l_{21}, l_{25}, l_{15} = 100kb/\sec$$
$$l_{12}, l_{13}, l_{14}, l_{24}, l_{34}, l_{51}, l_{52}, l_{53}, l_{54} = 50kb/\sec \cdot$$
$$l_{45}, l_{23}, l_{32} = 300kb/\sec$$

We use package loss rate (PER) to represent the influence of BER and consider the PER as a simple step function:

$$\begin{cases} PER = 5\% & [0,1000km] \\ PER = 10\% & (1000km,2000km] \\ PER = 20\% & (2000km,5000km] \end{cases}$$

We set the Bundle size 200kb, Block size 200kb and Segment size 10kb, respectively.

During the experiments, it is observed that **DRSA** strategy in ION is more likely to meet a transmission failure by over-estimating a route capacity, for it ignores the intermittent properties of links. We simulated transmission at 10 time points during one complete system period, and compared delivery times between **ERRS** and **DRSA** in Fig.9. **ERRS** spent more time on delivery in the cases of 1,4 and **7**. Due to high PER of links in case 6, it failed to deliver bundles on a link and thus took a recalculation for another novel route.

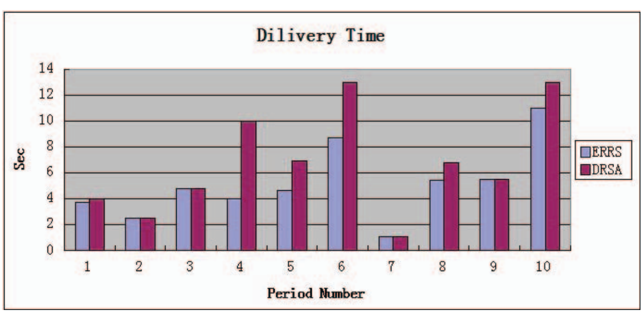

Fig.9 Delivery Time

We tested the system throughput during Period of 1, 2 and 3 and compared the mean value between the proposed **ERRS** and DRSA algorithm. Here, the system payload is calculated as time-averaged value of its bottleneck bandwidth from **NODE 1** to **NODE 5**. In particular, the algorithm's throughput is calculated by summing up the resulted throughput of all the routes from route table by function (7), (8) and (9) in Section II. The results indicate that **ERRS** is more likely to reach the system payload than the **DRSA**.

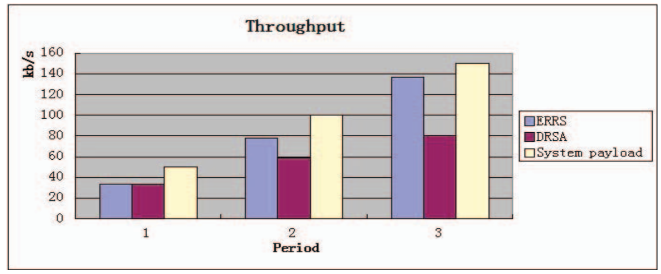

Fig.10 Throughput

V. CONCLUSION

In this work, we proposed a CGR-enhanced routing strategy to cope with the intermittent connection in the GEO-relaying satellite networks. The proposed algorithm could find the best route by calculating at each snapshot of time-varying topology, while the dynamic route selection algorithm using CGR could not guarantee the successful delivery rate and minimal delivery time. We put forward two new metrics for route selection. The simulation performance shows that the proposed algorithm could achieve more efficient utilization of the system capacity.

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