An Improved Earliest-Delivery Routing Algorithm in Double-layered Satellite Delay Tolerant Networks

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Abstract—**Since presented by K.Fall, the new-type network Delay and Disruption Tolerant Network (DTN) came to become a hot area of research. In recent years, many kinds of DTN routing algorithms have been proposed. With the characteristics of long time delay, high packet loss rate and intermittent connectivity. Satellite networks also belong to a kind of DTN. But meanwhile, they have their unique characteristics of satellite nodes regular running in orbits and predictable inter-satellite links on and off, for which deterministic routing algorithm is more suited in Satellite DTN networks. This paper focuses on studying the theoretical knowledge of a kind of deterministic DTN routing algorithm, Earliest-Delivery(ED) algorithm. And combining with the characteristics of the satellite network above, we propose an improved ED algorithm from three aspects of distributed routing, routing update strategy and tag - based dynamic storage scheme. Ultimately, we simulate the LEO/MEO two-layer satellite delay tolerant network in OPNET, and analyze the performance of two algorithms upon packet delivery ratio, average end-to-end delay and the number of packets destroyed in the storage queue. The result shows the improved algorithm performs better in satellite DTN network.**

Keywords—satellite Delay and Disruption Tolerant Network; Earliest-Delivery algorithm; Distributed algorithm; optimized routing updates time slots

I. INTRODUCTION

With a large range of communication, reasonable cost and high construction speed, the superiority that satellite communication presents is obvious. Nevertheless, as a kind of DTN(Delay and Disruption Tolerant Network), their characteristics of long time delay, high packet loss rate and lack of end-to-end path cause that the traditional TCP/IP protocols can't be applied in satellite scenario.

To solve this communication problem, researchers began to study the key technologies of bundle protocol, information storage, custody transfer, bundle fragment, late binding, routing and so on[1]. The DTN implements store-and-forward message exchanges and defines a bundle layer. The bundle layer is an end-to-end message-oriented overlay layer. The bundle layer is associated with the bottom layer of a specific area so that applications can communicate in multiple areas. A single bundle layer protocol is applied to the entire network to form a DTN.Especially in routing technology, researchers have proposed many classic DTN network routing algorithms.

Summarizing the existing routing algorithms, we can roughly sort them into three categories, including algorithms based on redundancy, based on predicted knowledge or historical knowledge, and based on communication assistance node. Algorithms based on redundancy duplicate abundant packet copies to improve the transmission success rate, meanwhile causing link congestion and high storage capacity requirement; Algorithms based on predicted knowledge or historical knowledge determine next hop according to known knowledge, more suitable for scenes with certain or predictable node location, communication link condition. Algorithms based on communication assistance node, namely ferry node utilize some a forwarding node with guaranteed communication quality to provide communication opportunities for two nodes. Specific routing algorithms are as follows.

Direct Transmission is one of the simplest single copy routing algorithms that each source node will only forward a message to its destination node directly [2]. It resulted in minimal total transmission time but low delivery rate and long delivery delay. Probabilistic Routing Protocol using History of Encounters and Transitivity (PROPHET) selects the path by utilizing the history encounter probability between two nodes to calculate a predicted delivery probability [3]. When two nodes meet, they exchange summary vectors (record the predicted probability) then copy the message to another if the value of probability is higher. Literature [4] presented the spray and forwarding routing algorithm (SFR) based on Markov position prediction model. The DTN routing algorithm for quasi-deterministic networks (DQN)[5] combined the prediction knowledge with the redundancy strategy, it limits the number of copies according to the topology prediction compromising the redundancy and transmission performance. Contact Graph Routing (CGR)[6], achieve offline routing according to connectivity knowledge of network topology. CGR with earliest transmission opportunity (CGR-ETO) algorithm[7] considered the queuing delay and data priority based on CGR . Literature [8] referred to the positive routing algorithm based on the network prior knowledge and proposed the routing evaluation framework. In the paper, algorithms based on predicted knowledge are sorted into three classes of zero knowledge, partial knowledge and complete knowledge, according to the knowledge oracle algorithms considered. MED, ED, EDLQ, EDAQ are analyzed and compared to each other. Among all these algorithms, Earliest Delivery (ED) can maximize the use of link predictability of satellite networks and

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is brief to implement. So this paper focuses on studying ED and proposing the modified algorithm

The rest of this paper is organized as follows: In section II, we research the ED algorithm and present its disadvantages in satellite networks. In section III, we propose the modified ED algorithm from three aspects. In section IV, we construct a LEO/MEO two-layer satellite constellation as the simulation platform and simulate the ED algorithm and modified ED algorithm. In section V we draw the conclusion of this paper.

II. ED ALGORITHM OVERVIEW

ED algorithm is a kind of generalized Dijkstra algorithm. Dijkstra algorithm calculates the shortest path as the routing path, namely the cost function only considers the distance of paths. However, generalized Dijkstra algorithm sets one or many other parameters as the weight of edge between two nodes, including communication cost, mean length of queue, delay, and so on. Essentially, ED algorithm is the Dijkstra algorithm, which cost is the instantaneous delay of each link.

In satellite DTN networks, we study three kind of delay: Transmission delay is the time of satellites processing packets; Propagation delay is the time of transmitting a packet along an edge; Queuing delay means the time packets waiting in the queue to obtain an available routing path. And for ED algorithm, the delay we consider is the sum of transmission delay and propagation delay.

Nevertheless, differing from Dijkstra algorithm, the cost of ED algorithm is time-varying. We define the cost function of ED algorithm as $w(e,t,m,s)$. It means the value of the cost function depend on the edge e, calculating time t, the size of a packet m, and the node s where we calculate the cost. So when we calculate the cost of paths for one packet, the accuracy of t is of great importance.

In satellite networks, calculating the cost at a precise t for any packet at any time will waste a lot satellite memory and is inefficient and inadvisable. We usually take the measures of virtual topology strategy, which means by slice time at a reasonable time interval, we regard the network topology is constant over the whole time slice. Therefore, to make sure the topology closer to the correct values and reduce the error, how to divide time slices and judge which time slice the computing routing time belongs to is the key of ED algorithm in satellite DTN. And aiming at this modification point, in the third part below we will propose the optimization method.

And from the analysis above, ED algorithm seems to be an optimal algorithm. However, it is can not to be ignored that in the process of the calculating time delay, we haven't take the queue delay into consideration. With frequent DTN link break, packets are very easy to find no routing and be stored in the node. So the queuing delay value influences the value of total delay to great extent.

III. MODIFIED ED ALGORITHM

From the theoretical analysis of ED algorithm above, it can be seen that the ED algorithm for satellite DTN networks is not an optimal algorithm. As a source routing algorithm, path information is endowed with the packet from the source node. Once the network topology changes before the packet are delivered to the destination node, packets loss will follow. On the other hand, when there is no path between this node and the next-hop node according to the fixed routing path, the packet is stored in this node, which can cause missing the opportunities of transmitting the packet by other available edges. And the process of store and forward will increase the time delay to great degree. This article will define the modified algorithm as a distributed routing algorithm to make the choice of the next-hop more flexible when dealing with the network topology changes. And considering the connection prediction of inter-satellite links, this paper will optimize the routing update time slot, in order to improve the accuracy of cost calculation and the selection of the optimal path.

A. Distributed ED algorithm

Distinct from other DTN networks, satellite nodes' motion regularity means the network topology changes, the connection of inter-satellite links, the distance between two satellites are all predictable. Utilizing these prediction knowledges, once the network topology changes, we can establish node routing tables for each satellite node, in which the current node is the source node and other nodes are the destination node. As shown in the *Table I* below is the component unit of a node routing table.

TABLE I. A COMPONENT UNIT OF A NODE ROUTING TABLE

Number of routing updates time slots	Destination node	Next-hop

When the node receives a packet, it will no longer follow the fixed path of source routing algorithm but to requery the next hop jump on each intermediate node. When the next routing update moment comes, namely the network topology changes, all nodes update their routing table respectively at the same time.

B. The optimization of routing updates time slot

With the delay cost formula above, we know that the value of the cost of ED algorithm is time-varied. So the time we select to calculate cost function can seriously affect the calculation precision of time delay cost, and then affects the accuracy of the optimal path selection. This paper proposes the modified routing update time strategy to reduce the calculation error of time delay cost.

In the virtual topology strategy, according to the characteristics of the time slice length, satellite system operation cycle can be classified as equal and unequal slice. In the equal time slice, the whole time is divided into isometric time slice so the method is simple and flexible. However, the problems of equal time slice method in satellite DTN network exist and are as follows: the time interval of ISL switching are unequal, so equal slice method may neglect some network topology changes and then lead to routing errors, which will increase the packet loss probability in the process of data transmission.

Optimization method is showed in *Fig. 1*. The specific steps are as follows:

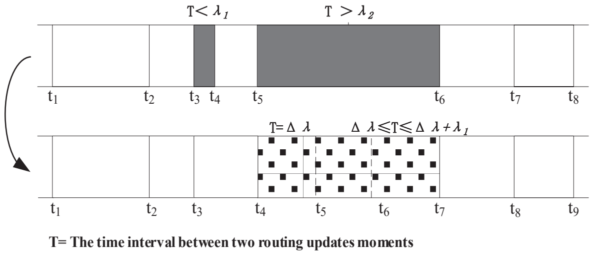


Fig. 1. Time slot optimization diagram

1) Because the link on and off between any two nodes will affect the state of the entire network topology, so the modified strategy select all of the on-off change moments as routing updates time node.

2) Set a time threshold value λ_1, and T is the time interval between two routing update moments, when $T < \lambda_1$, merge the two routing update moments to reduce the amount of time slices and solve the issue of low satellite calculating efficiency caused by too short time slices.

3) In a time slice, the topological structure don't change, but the distance between the nodes change over time, which affects the calculate result of time delay and the selection of optimal path. So in the modified routing updates time slot strategy, we set a second time threshold value λ_2, when $T > \lambda_2$, slice the time interval T for the second time at a shorter time interval of $\Delta\lambda$, here we set $\Delta\lambda = \lambda_2 / 2$.

C. Tag - based dynamic storage scheme

As the traditional storage and forwarding mechanism of DTN, sequential storage is applied universally. When rerouting for the data packets in a satellite's storage queue, we start from the queue header packet. If rerouting successfully, we remove the package from the queue, send it to the next satellite node and reroute for the new header packet. Otherwise, the queue will wait for the next rerouting opportunity, resulting in follow-up packets with communication opportunities can't be forwarded either. This paper presents a tag-based efficient storage and forwarding scheme as shown in figure 2.

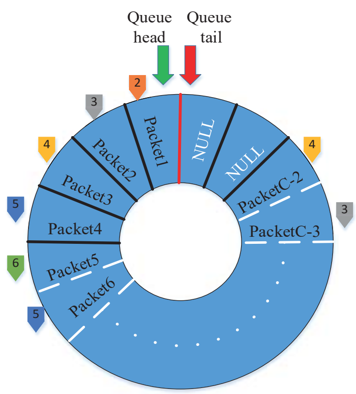


Fig. 2. Tag - based dynamic storage and forwarding

First, in view of the predictability of satellite topology, instead of the fixed reroute cycle, the aforementioned routing table update cycle is performed when rerouting the storage queue. Under this scheme, packets are forwarded at the first opportunity of communication, making full use of the valuable communication resource of DTN.

In addition, if packets stored by one satellite with the same destination node, they have the same next hop. That means after the routing table updating, they will all have the communication opportunities or all won't. So in the tag-based queue dynamic storage scheme, while storing the packet to the queue, we store the destination node of a packet as its tag number. And when the routing table is updated, the satellite node stores all the other satellite serial number that can communicate as a tag list after routing table traversal. Afterwards, when rerouting for the queue, instead of routing table traversal for all packets, we forward the packets corresponding to the tag number in the communication tag list. Ultimately, the packets that are not in the communicable list are pre-stored in the queue fill the blank storage area of the previously forwarded packet. As shown in the figure is the storage queue of satellite node 1, as routing table is dated, if there are communication links between the satellite node 4 and 5. So satellite node 1 forwarding all the packets with tag4 and tag5, regardless of the storage location of the packets.

IV. THE SIMULATION AND RESULT ANALYSIS

This paper constructs a two-layer satellite constellation scenario, selects the significant parameter in DTN networks of node store capacity as the variable, and selects the average end-to-end delay, packet delivery ratio and the number of packets destroyed in the storage queue as the main parameters of simulation and analysis to contrast the performance difference between the modified ED algorithm and ED algorithm.

A. Simulation environment introduction

OPNET (Optimized Network Engineering) is a network simulation software. In this paper, we utilize OPNET to complete the whole work of network simulation and use STK to construct the satellite constellation that composed by six LEO satellites in walker constellation and one MEO satellite.

B. LEO/MEO construction in STK

TABLE II. SATELLITE CONSTELLATION PARAMETERS

parameters of the constellation	LEO	MEO
Altitude (km)	1680.8	20000
The number of orbits	3	1
The number of satellites in an orbit	2	1
The orbital Inclination (°)	60	55
Orbit period/min	120	710
Constellation type	Walker	Walker

STK (Satellite Tool Kit) is an analysis and visualization tool. STK supports the entire process of space missions, including design, test, launch, operation and mission applications. We structure the simulation DTN double-layer satellite constellation in STK, as shown in figure3 is the 3D schematic. The specific parameters of LEO/MEO two-layer satellite constellation are as shown in *Table II*. In addition, we set the LEO satellites as the source nodes and destination nodes, MEO satellite only as the relay node of packet transmitting.

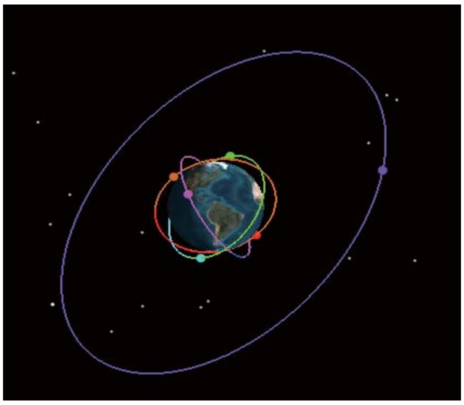


Fig. 3. The 3D schematic of MEO/LEO double-layer constellation

In STK, we name the six LEO satellites as LEO_{ij}, i is the orbit number and j is the satellite number in the orbit. We complete the visibility analysis, which can show us the on and off changes of any two satellites. *Fig.4* is the link on-off performance between LEO11 and other satellites (the end-to-end paths between LEO11 and LEO12, LEO21, LEO32 do not exist, so there is no display in the figure). The result completely conforms to the link characteristics of DTN.

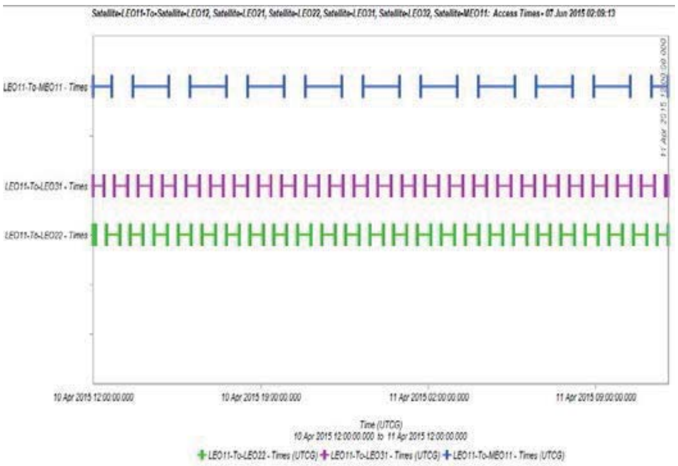


Fig. 4. Link on-off performance between LEO11 and other satellites

C. *OPNET Simulation design*

1) *Network model*

Fig.5 is the double-layer satellite network model. Each satellite has its corresponding custom satellite node model. And the topo node model is set as the central control node, used to read the satellite network routing update intervals and static topology matrix calculated by MATLAB. At each routing update moment, topo node obtains the satellites' positions for current time, calculates the link delay between any two satellites, and adopts the modified ED algorithm to calculate the optimal path with minimum delay. And then topo node sends the routing table to each satellite in turn, with the satellite as source node and all other satellites as the destination node.

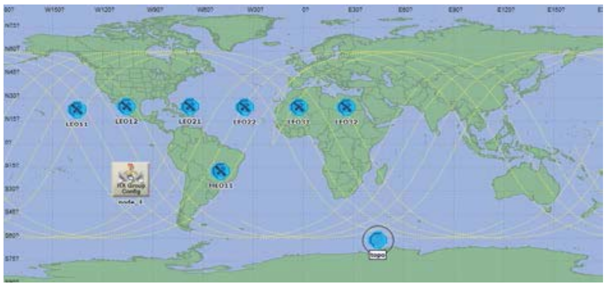


Fig. 5. Network model

2) *Node model*

In this scenario, satellite node models are basically the same. We set different frequencies for each satellite receivers and transmitters. And since the MEO satellite sends no packets, there is no packet generation module (source) and packet information writing module (src) in its node model. Taking the satellite LEO11 for example, its node model is as shown in the *Fig.6* below. In the node model, we set one satellite receiver and 6 transmitters.

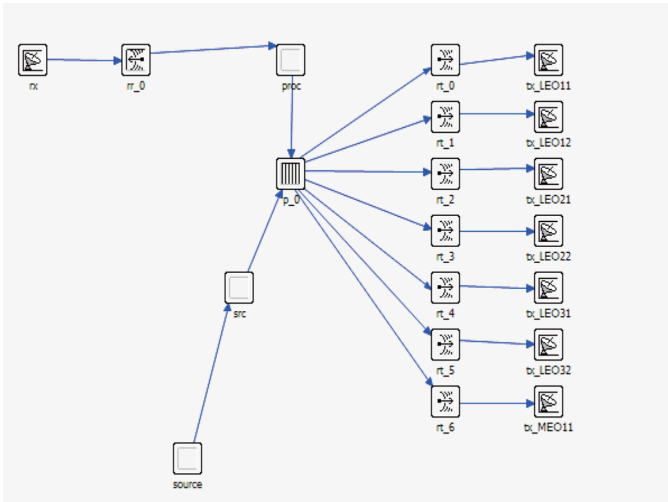
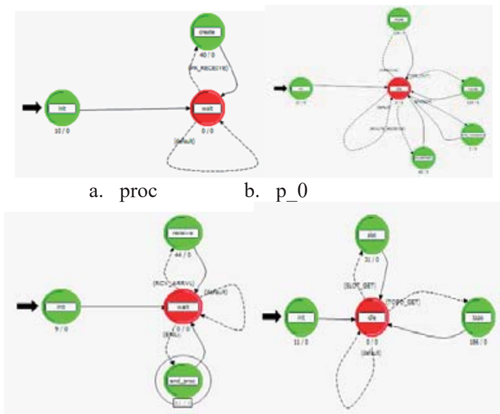


Fig. 6. Satellite Node model



a. proc b. p_0

b. src d. topo

Fig. 7. Process models

3) *Process model*

In Fig.7 are the process models including proc, p_0, src, topo. And endow every satellite nodes the basic functions of sending and receiving packets, obtaining and querying the routing table and storing and forwarding packets.

D. Simulation and result analysis

Table III is the slot 1 routing table that topo node calculate and send to satellite node LEO11. So once the network topology changes, the topo node calculate the routing for one time,and send the 7 routing table to 7 satellite nodes respectively.

TABLE III. SLOT 1 ROUTING TABLE FOR LEO11

Number of routing updates time slots	Destination node	Next-hop
1	2	6
1	4	4
1	5	4
1	6	6

1) Packet delivery ratio

Fig.8 reflects the influence that different satellite node store capacity have on packet delivery ratio of the two algorithms. As the precious resource on satellites, storage capacity is limited, and it has great influence on the performance of algorithm. So this article set this parameter to multiple values. As is shown, with the node storage capacity increasing, the packet delivery ratio increase gradually, until the storage capacity is up to 500, packet delivery ratio come to the maximum and keep stable. This is because the packet is destroyed when the number of package storage reach the capacity limit, causing a high packet loss rate until the storage capacity can satisfy the demand of store and forward data in this scenario. Compared with ED routing algorithm, distributed routing strategy is more flexible when topology changes and then lose fewer transmitting packets. In conclusion, the packet delivery ratio increased about 3 percent.

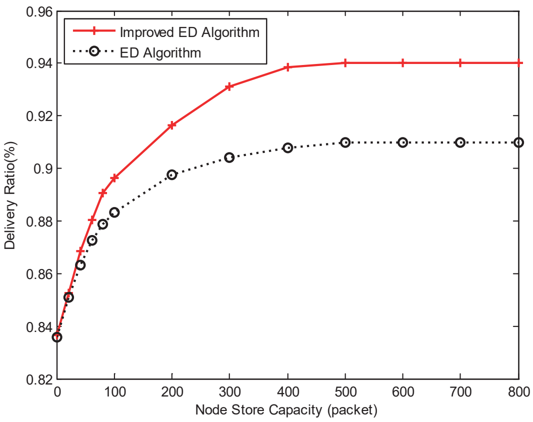


Fig. 8. Delivery Ratio

2) End-to-end delay

As shown in *Fig.9* is the discrete end-to-end (Ete) delay of the packets received by satellite LEO11, when we apply the improved ED algorithm. At different simulation time, the value of delay varies a lot. If a packet can directly find the next hop along the path, the end-to-end delay generally is only a few hundred milliseconds, but when the packet cannot find the next hop at some a node, it is stored in the store volume and waiting for forwarding, which cause high queuing delay, and the total end-to-end is up to 800s.

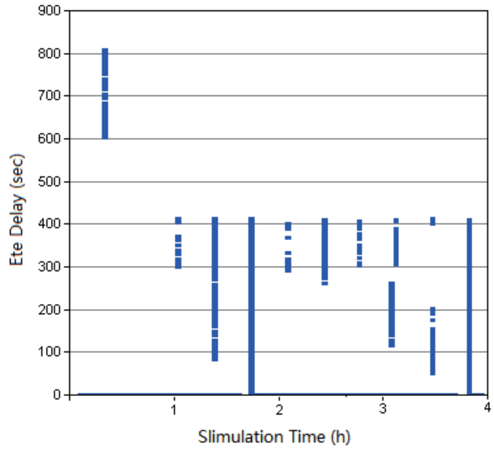


Fig. 9. Ete Delay of Packets Received by LEO11

Fig.10 reflects the influence that different satellite node store capacity has on average end-to-end delay of the two algorithms. With the increase of storage nodes, average end-to-end delay increase gradually. This is because when the node store capacity is insufficient, parts of the packets that can't find routing and need to be stored and forwarded have long end-to-end delay, then they are destroyed by the node. So the average end-to-end delay is low. When the storage capacity increases gradually, destroyed package volume decreases, and the delay increases until the storage capacity reaches requirement, after which the average end-to-end delay reaches its stable value. Compare the improved ED algorithm with ED algorithm, average end-to-end delay is reduced after optimization, which is because the new chosen routing path is closer to ED algorithm optimal path, which cause the average delay drop of about 2.5s.

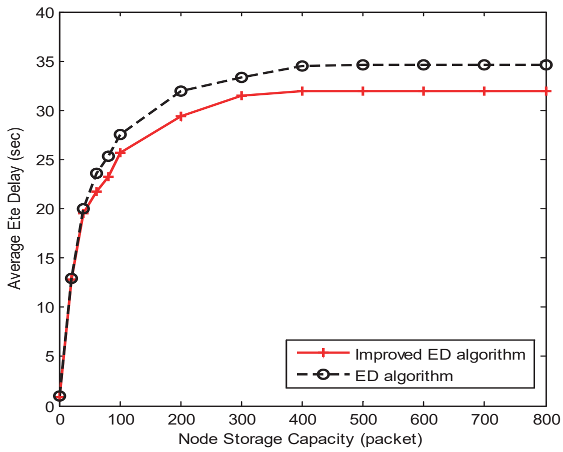


Fig. 10. Average Ete Delay

Since the ETE delay of direct transmission packets and the storage and forwarding rerouting packet have great difference, we hereby simulate the average delay of the rerouting data packets, as shown *Fig. 11* shows the average delay of the rerouting packets. With the store capacity C grows, the advantage of the improved algorithm is outstanding. Until C is up to 500, the delay performance of the two algorithms is stable, and the improved algorithm reduces the average delay of the rerouted data by 20s, about 8%. By contrasting the two algorithms, in ED algorithm, packets are forwarded after all packets in front of the queue are forwarded. Therefore, the larger the queue capacity is, the longer queuing delay packets suffer. Nevertheless, under the tag-based dynamic storage scheme, packets with available communication link are forwarded concurrently, effectively shortening the queue delay.

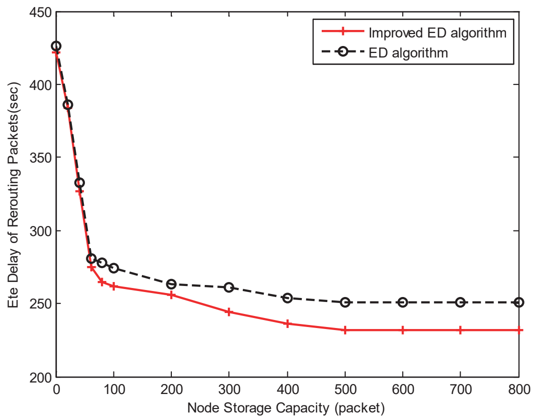


Fig. 11. ETE Delay of Rerouting Packets

3) *Number of packets destroyed in the storage queue*

Fig.12 shows that the number of packet destroyed in the queue decreases with storage capacity increase. This is because the distributed routing method can avoid packets into the queue. In addition, tag-based dynamic storage scheme can forward packets efficiently, saving the storage resources on satellites, avoiding packets destruction.

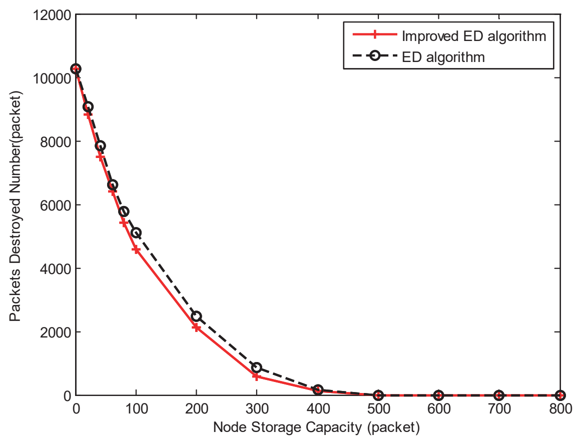


Fig. 12. Packets Destroyed number in the queue

V. CONCLUSION

This paper analyzed the basic theory of ED algorithm in the DTN network. And based on the predictability of satellite ISL, we proposed three modifications and construct a platform of LEO/MEO satellites when simulating the algorithms. By comparing the ED algorithm and modified ED algorithm, we draw the conclusion that the new algorithm has obvious advantages in packet delivery ratio and average end-to-end delay, and can avoid packets destruction to some degree. through improving the storage and forwarding scheme. In addition, in the process of calculating delay cost, queuing delay was not taken into account. And as long as the queuing delay is large, the choice of the optimal path is no longer accurate. So there is great need to do further research in this aspect.

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