An Auction-Gaming Based Routing Model for LEO Satellite Networks

Ligang Cong(✉), Huamin Yang, Yanghui Wang, and Xiaoqiang Di

School of Computer Science and Technology,
Changchun University of Science and Technology, Changchun 130022, China
clg_cust@126.com, dixiaoqiang@126.com,
{yhm,wyh}@cust.edu.cn

Abstract. Characteristics of LEO satellite networks, like dynamically changed topological structures, limited on-board resources, and longer communication delay, have brought new challenges to the construction of satellite networks. By analyzing existing routing models for satellite networks, this paper proposes an auction-gaming-based routing model for LEO satellite networks, based on the DTN protocol and against such characteristics. By making use of an auction model, it takes space propagation loss, residual storage space of a node, and routing hop counts as important bases for routing selection. Analysis shows that besides the routing function, this model also plays an active role in avoiding "selfish" satellite nodes, as well as in relieving network congestion.

Keywords: Auction gaming · LEO satellite networks · Routing model

1 Introduction

LEO satellite networks have been taken seriously due to their unique advantages. However, their existing characteristics, such as dynamically changed topological structures, limited node resources, and longer communication delay, have brought about many problems to be solved during construction of such networks, and routing is just a highlighted one of these problems.

The routing technology is critical to the network construction. Some proposals were given to solve the problem. Chang et al. [1] advanced a routing algorithm based on the finite-state automation (FSA), which shielded the dynamic nature of topological structures to simplify the computation, but resulted in poor adaptation to emergent situations of networks, as well as in bigger demand for on-board storage resources. Ercetin et al. [2] put forward a probabilistic routing protocol (PRP), which reduced the number of times of call interruption and routing redefinition due to routing switching, but increased the call blocking rate and the probability of network congestion. Lee and Kang [3] proposed a hierarchical QoS routing protocol (HQRP), which reduced call

---

Supported by the National High-tech R&D Program of China (2015AA015701); Supported by Foundation of Jilin Educational Committee (JJKH20170628KJ); Supported by Science and Technology Development Project of Jilin Province (20150312030ZX).

X. Gu et al. (Eds.): MLICOM 2017, Part II, LNICST 227, pp. 498–508, 2018.
https://doi.org/10.1007/978-3-319-73447-7_54

interruption through optimization of the switching process and considered optimization of channel resources, but increased network overhead and lowered the whole network efficiency. Taleb [4] proposed an explicit load balancing routing algorithm (ELB), with which routing was selected under the condition that the load of the next link was known, and when links were congested, other satellites would be informed to lower the sending speed to reduce network congestion. However, this algorithm would fail in the case of severe congestion. Besides above methods, typical satellite routing algorithms also include ALBR [5], DRA [6], CEAARS [7], etc.

It is hard to tell which one of the above algorithms is more advantageous, because each has a different emphasis, as well as its own characteristics in different application environment. This paper proposes an auction-gaming-based routing model for LEO satellite networks, based on the DTN protocol. By fully using periodicity of topological structures of LEO satellite networks, this model divides dynamically changed topological structures into relatively static time slots and then introduces auction gaming into such time slots to solve routing problems of LEO satellite networks. Meanwhile, it avoids selfish nodes in networks to the greatest extent, and also prevents network congestion due to excessive resource consumption of individual nodes.

2 Definition of the System Model

2.1 Topological Structures of LEO Networks

Different from computer networks on the ground, LEO satellite networks have movable nodes, resulting in changeable topological structures. However, satellites move strictly along defined orbits, producing periodical and predictable changes in relevant topological structures. Therefore, during the research on routing of satellite networks, relevant strategies are generally adopted to shield the dynamic nature of such topological structures, and abstract static models are used instead for research. At present, relevant strategies mainly include the virtual topology strategy [8], virtual node strategy [6] and division of coverage domains [9]. This paper adopts the virtual topology strategy, which discretizes the dynamic topological relationship of satellite network nodes, and divides a complete running cycle of a satellite network into several time slots $[t_0,t_1]$, $[t_1,t_2]$, $[t_2,t_3]$, $[t_3,t_4]$, ……, $[t_n,t_{n-1}]$. The topology of a satellite network is considered to be fixed in each time slot, and it only changes at time nodes of t_1, t_2, t_3 … t_n.

Satellite nodes in a network store not only their own status information, but also status information of adjacent satellite nodes related to the routing. Such status information includes communication distances, residual node storage space, node hop counts to the destination, etc., which is stored in satellite nodes as tables. These tables will change periodically as the topological structure of the satellite network changes. By taking the satellite node of v_1 as an example, Table 1 shows some status information of its adjacent satellite nodes, within the time slot of t.

Table 1. Information table of a satellite node

Adjacent satellite nodes	Communication distance (Unit: km)	Hop counts through this neighbor node to the target	Satellite storage space (Unit: MB)
v2	d2	h2	m2
v3	d3	h3	m3
v4	d4	h4	m4

2.2 Definition of the Routing Problem

The key part of this research is to set up a reliable and highly efficient spatial routing path by designing an incentive mechanism to boost cooperation between nodes. The LEO satellite network studied by this paper is based on DTN, and the basic store-and forward routing mode is adopted. Therefore, the routing problem can be converted into a problem to find the proper store-and-forward nodes.

As shown in Fig. 1, in a LEO satellite network, multiple paths are available for selection when a node generates data and needs to send them to the destination. The first step for path selection is to select the suitable node for data forwarding among multiple neighbor nodes, with a process similar to the item auction in real life. Therefore, it is possible to abstract the selection of a forwarding node as an auction gaming process [12, 13], in which the data source node is considered as a buyer of forwarding services, while its neighbor nodes are considered as sellers of such services. As shown in Fig. 2, in general cases, multiple forwarding nodes will be used before data can be sent to the destination, and therefore auctions will be repeated for many times. Every time an auction is finished, except the data-forwarding node, other nodes will not participate in the next auction, and this data-forwarding node will turn from the seller into a buyer in the new auction, which will repeat until the destination node is reached.

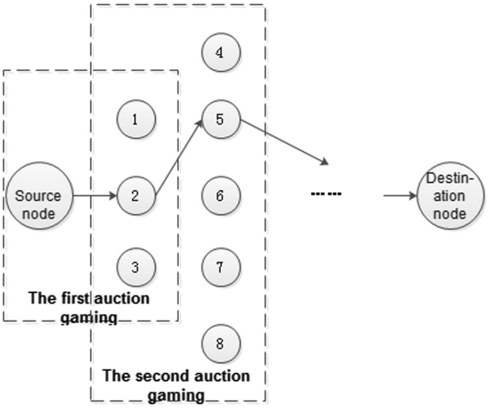


Fig. 1. Schematic drawing of data auction

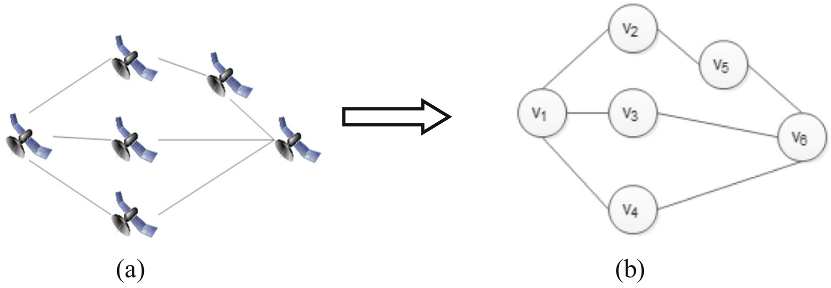


Fig. 2. Sketch of local satellite network connection

3 Definition of the Routing Auction-Gaming Model

As mentioned above, the routing problem is abstracted as a data auction process. In this section, gain rules related to such auctions are defined, and gain models of both the source and the forwarding nodes are described.

3.1 Definition of Gain Rules

In a routing auction model, a data-sending node is considered as a buyer, while its neighboring nodes that have participated in an auction before are considered as sellers. Such sellers provide the buyer with data forwarding services, and the buyer determines the forwarding node by selecting the best among various service prices offered by these sellers. The destination node will provide expense compensation for nodes involved in data transmission. During data forwarding, the forwarding success rate is introduced to avoid selfish nodes. The higher the success rate, the higher the gains. On the contrary, the lower the success rate, the lower the gains. Detailed gain rules of relevant nodes are listed as follows:

(1) During the whole routing process in a LEO satellite network, involved nodes can be classified into three types: data source nodes, forwarding nodes and destination nodes;
(2) If a satellite node doesn't belong to any one of three types mentioned in (1), its gain is 0;
(3) For a source node, its gain comes from the compensation provided by a destination node;
(4) For a forwarding node, its gain can be divided into two parts, which are gains obtained during two gaming processes of data reception and transmission respectively;
(5) For a destination node, it has no gain, and it only pays for services of other nodes;
(6) Deduction of relevant costs is needed to get final gains of a source and a forwarding node.

3.2 Definition of an Auction Bid

Price is the fundamental factor to determine a data-forwarding node. The auction model in this paper defines the price of data forwarding services based on link quality and node status, and a source node selects the lowest bid to determine the forwarding node. A bid includes the satellite link quality and the data-forwarding rate of a node, which are two critical points influencing the routing auction model. Relevant definitions are shown below:

Definition 1: link quality of a LEO satellite network is represented as:

$$r_{ij}(t) = \frac{L_{ij}(t)}{100} + h_j(t) + \frac{m_{ip}}{m_j(t)} \tag{1}$$

where $L_{ij}(t) = 32.44 + 20\log d_{ij}(t) + 20\log f_i$ means the spatial propagation loss produced during data transmission from the satellite node of v_i to satellite node of v_j at the time oft; $d_{ij}(t)$ refers to the distance between nodes of v_i and v_j at the time of t $h_j(t)$ means the hop counts that the node of v_i needs at the time of t to reach the destination node while through the node of v_j, and its value depends on the scale of the LEO satellite network; $m_j(t)$ means the residual storage space of v_j at the time of t; m_{ip} means volume of data that needs to be transmitted. The bigger the value of $r_{ij}(t)$ is, the poorer the link quality is. On the contrary, the smaller this value is, the better the link quality is.

Definition 2: the data forwarding rate is defined as:

$$s_i(t) = \frac{p_{is}(t)}{p_{ir}(t)}, \tag{2}$$

where $p_{is}(t)$ means the sum total of data packages sent by the satellite node of v_i up to the time of t; $p_{ir}(t)$ means the sum total of data packages received or generated by the satellite node of v_i up to the time of t.

According to above definitions, a bid for forwarding services, which is composed of the satellite link quality and the data-forwarding rate, can be represented as:

$$c_{ij}(t) = \frac{r_{ij}(t)}{s_j(t)}, \tag{3}$$

which means the routing service price provided by the node j, at the time of t, for the node i. The price is in direct proportion to the link quality, while it is in inverse proportion to the data forwarding rate.

The network studied in this paper is based on the DTN protocol, with basic routing mode of “store – carry – forward”. If node storage space is 0 or smaller than data to be received, routing can’t be done. Therefore, neighboring nodes that don’t have enough storage space to meet requirements of data reception will not participate in bidding.

After all neighboring nodes place their bids, the data source node will select the node with the lowest price for data forwarding, and at this time, the expense that the data sending node needs to pay is:

$$o_{ik}(t) = \min c_{ik}(t) \quad k \in N_i, \tag{4}$$

where N_i is the set of neighboring nodes of the node i. The selected node will trade with the price of $o_i(t)$.

3.3 Gain Model for Source Nodes

A source node generates data, and then completes data transmission once. It plays as a routing buyer in the auction model. Suppose that every time the source node sends units data, the destination node will give corresponding compensation. Then, the sending node uses such compensation to pay for forwarding expenses and meanwhile obtains certain gains. The compensation is represented by g. For simplicity, suppose that the cost of data generation and transmission of a source node is 0, and therefore the gain function of the source node, i, is:

$$u_i(t) = g \bullet m_{ip} - o_i(t)\, k \in N_i, \tag{5}$$

where m_{ip} means the data volume sent by the source node; $g \bullet m_{ip}$ means the total compensation obtained from the destination node. If $g \bullet m_{ip} < \, = o_i(t)$, the source node has a negative gain, and at this moment it will refuse to send data as there is no incentive. Therefore, a destination node must provide suitable compensation: higher prices for key source nodes and lower prices for subordinate source nodes. In addition, as the data forwarding rate is introduced, the source node will improve the success rate as much as possible in order to obtain more gains. It can be said that this mechanism not only improves network routing efficiency, reduces network loads and relieves network congestion, but also avoids selfishness of satellite nodes.

3.4 Gain Model for Forwarding Nodes

Suppose the node of v_j is selected for data forwarding and v_j is not a destination node. Thus, its gains include two parts. The first part is the forwarding expenses paid by its prior node, when the node serves as a seller. The second part is the compensation obtained during a new auction, when the node serves as a source node, a buyer.

(1) Gains of a forwarding node as a seller

The forwarding node of v_j will be paid for data reception, with a price of $c_{i,j}(t)$. Besides, the received data will take up certain storage space of the node, which means the cost of the forwarding node. Therefore, the gain function can be represented as:

$$u_{j1}(t) = c_{ij}(t) - \frac{m_{jr}}{m_j(t)}, \tag{6}$$

where m_{jr} is the received data volume, and $m_j(t)$ is the residual storage space of the node before it receives the data packages.

(2) Gains of a forwarding node as a buyer

When the forwarding node, v_j, sends data, it becomes the buyer for forwarding services in a new auction. This new auction has the same process as the last one, except that the prior node v_i is not involved any more. Therefore, the gain function for node v_j as a buyer can be represented as:

$$u_{j2}(t) = g \bullet m_{jp} - o_j(t), \tag{7}$$

where $o_j(t)$ means the trade price between node v_j and its neighboring nodes during the second gaming process; m_{jp} is the volume of data packages to be sent. Therefore, the total gain of node v_j in routing is the sum of gains obtained during data receiving and forwarding processes, which can be expressed as:

$$u_j(t) = u_{j1}(t) + u_{j2}(t) \tag{8}$$

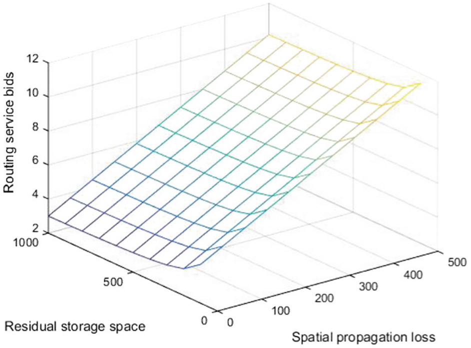
4 Analysis of the Routing Model

According to formulas defined in Sect. 3, major factors that influence satellite node gains during the routing process include free-space propagation loss of electromagnetic waves, node storage space, and path hop counts. Values of the three factors will directly influence gains of spatial nodes, and further influence selection of routing nodes. This section focuses on relationships between the three factors and node gains as well as routing selection.

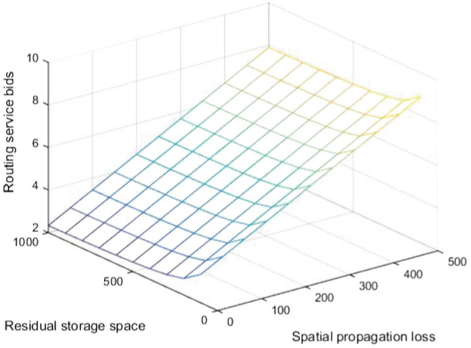
As shown in Fig. 2, a local part of a LEO satellite network in a time slot of t is taken for analysis, which is abstracted as an undirected graph shown in Fig. 2(b). In this graph, v_1, v_2, v_3, v_4, v_5 and v_6 are six satellite nodes, among which v_1 is a source node and v_6 is a destination node. The line between any two nodes means an available communication link between the two satellites, and two nodes without a line in between can't communicate with each other directly. When the node of v_1 generates data and needs to send such data to the destination node of v_6, its neighboring nodes will participate in auction gaming. Hop counts of v_1, through v_2, v_3 and v_4, to the destination are 2, 1 and 1 respectively. Suppose that the data volume of the source node is 100 MB, and the compensation that the destination node has to pay for transmission of 100 MB data is g. Then, influences of spatial propagation loss, hop counts and residual storage space on node gains and routing can be studied based on conditions mentioned above.

4.1 Analysis of Node Bids

Suppose that the change interval of spatial propagation loss is [100, 500] that the change interval of residual node space is [1, 9], and that satellite nodes have two data forwarding rates of 70% and 90% respectively. Thus, changes in bids of v_2, v_3 and v_4 can be shown in Figs. 3 and 4.



(a) Forwarding rate of 70%



(b) Forwarding rate of 90%

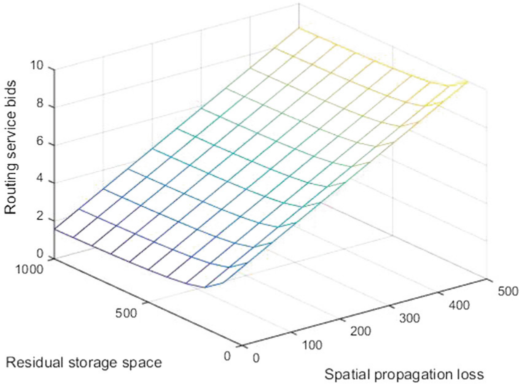
Fig. 3. Bid changes of v_2

From the Fig. 3, bids of the node v_2 increase as the spatial propagation loss increases, while decrease as the residual storage space increases. Under the same conditions, the higher the data forwarding rate is, the lower the bids are.

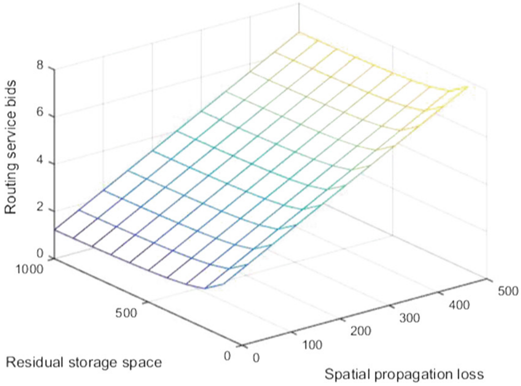
As nodes of v_3 and v_4 have the same hop counts, they will have consistent changes in bids for routing services. From the Fig. 4, under the condition of the same hop counts from a node to the destination, the bigger the residual space of a node is and the smaller the free-space propagation loss is, the lower the bid of a node is, and otherwise the higher the bid is. Compared with the Fig. 3, it can be seen that under the same conditions, the bigger the hop counts, the higher the bids.

4.2 Analysis of Node Gains and the Routing Process

Suppose that nodes of v_2, v_3, v_4 and v_5 in the network model have status parameters shown in Table 2, and that receiving data volume equals to sending data volume during the data transmission between nodes. Then, gains of nodes can be analyzed through a simple simulation of routing selection.



(a) Forwarding rate of 70%



(b) Forwarding rate of 90%

Fig. 4. Bid changes of v_3 and v_4

Table 2. Scene parameter table for data analysis

Node parameter	Free-space propagation loss	Residual storage space	Hop counts to the destination	Data forwarding rate
v_2	220	400	2	80%
v_3	270	500	1	80%
v_4	170	400	1	90%
v_5	170	300	1	80%

As mentioned above, there are three paths from the source node to the destination: $v_1 \rightarrow v_2 \rightarrow v_3 \rightarrow v_4 \rightarrow v_5 \rightarrow v_6$ and $v_1 \rightarrow v_4 \rightarrow v_6$. After comparison of node gains, obtained through above formulas, under the three conditions, the selected path is

$v_1 \rightarrow v_4 \rightarrow v_6$. See Table 3 for details. The selection of routing is converted into a game to find the cost-optimal forwarding services. By comparison, the node v_1 selects the node with the lowest bid for data forwarding. Lower bids mean better forwarding services, which refer to lower spatial propagation loss, more residual storage space, and few number of times of forwarding. It can be concluded that the source node can find a suitable data forwarding path after repeated gaming.

Table 3. Gains of nodes in different paths

Node gain path	v_1	v_2	v_3	v_4	v_5
$v_1 \rightarrow v_2 \rightarrow v_5 \rightarrow v_6$	g − 5.563	g + 1.521	0	0	g + 3.459
$v_1 \rightarrow v_3 \rightarrow v_6$	g − 4.875	0	g + 4.675	0	0
$v_1 \rightarrow v_4 \rightarrow v_6$	g − 3.278	0	0	g + 3.028	0

5 Conclusions

This paper solves the routing problem in a LEO satellite network by introducing an auction-gaming model, converts the routing selection into a process to find forwarding services with the lowest price, and introduces four important parameters related to network service quality, including spatial propagation loss, residual storage space of nodes, data forwarding hop counts, and data forwarding rate of satellite nodes, into the decision-making process for neighboring node bidding so as to determine relations between various parameters and forwarding service bids through model analysis. In addition, routing selection is done and gains of various nodes are analyzed through this model. Theoretically, this model can avoid selfish nodes in a network, and meanwhile it can also prevent nodes with inadequate space from forwarding data, effectively relieving congestion of the network.

In future work, comparative analysis between this model and other routing models for satellite networks will be conducted through network simulation tools. Moreover, this model will be further improved so as to fully exert its advantages in solving routing problems, reliving network congestion, and enhancing network efficiency.

References

1. Chang, H.S., Kim, B.W., Lee, C.G.: FSA-based link assignment and routing in low-earth orbit satellite networks. IEEE Trans. Veh. Technol. **47**(3), 1037–1048 (1998)
2. Ercetin, O., Krishnamurthy, S., Dao, S., Tassiulas, L.: Provision of guaranteed services in broadband LEO satellite networks. Comput. Netw. **39**(1), 61–77 (2002)
3. Lee, J., Kang, S.: Satellite over satellite (SOS) network: a novel architecture for satellite network. In: Proceedings of the IEEE INFOCOM. IEEE, Piscataway, pp. 315–321 (2000)
4. Tarik, T., Daisuke, M., Jamalipour, A.: Explicit load balancing technique for NGEO satellite IP networks with on-board processing capabilities. IEEE/ACM Trans. Netw. **17**(1), 281–293 (2009)

5. Rao, Y., Wang, R.C.: Agent-based load balancing routing for LEO satellite networks. Comput. Netw. **54**(17), 3187–3195 (2010)
6. Ekici, E., Akyildiz, I.F., Bender, M.D.: A distributed routing algorithm for datagram traffic in LEO satellite networks. IEEE/ACM Trans. Netw. **9**(2), 137–147 (2001)
7. Cao, J.H., Stefanovic, M.: Cross entropy accelerated ant routing in satellite networks. In: Proceedings of the American Control Conference (ACC). IEEE, Piscataway, pp. 5080–5087 (2010)
8. Werner, M.: A dynamic routing concept for ATM-based satellite personal communication networks. IEEE J. Sel. Areas Commun. **15**(8), 1636–1648 (1997)
9. Hashimoto, Y.: Design of IP-based routing in a LEO satellite network. In: Proceedings of the 3rd International Workshop on Satellite-Based Information Services. ACM, New York, pp. 81–88 (1998)
10. Lu, Y., Zhao, Y.J., Sun, F.C., Li, H.B., Ni, G.Q., Wang, D.J.: Routing techniques on satellite networks. J. Softw. **25**(5), 1085–1100 (2014)
11. Xi, Y., Yeh, E.M.: Pricing, competition, and routing for selfish and strategic nodes in multi-hop relay networks. In: Proceedings of IEEE INFOCOM 2008. IEEE, Phoenix, pp. 2137–2145 (2008)
12. Ng, S.-K., Seah, W.K.: Game-theoretic model for collaborative protocols in selfish, tariff-free, multihop wireless networks. In: Proceeding of IEEE INFOCOM 2008. IEEE, Phoenix, pp. 762–770 (2008)
13. Keränen, A., Ott, J., Kärkkäinen, T.: The ONE simulator for DTN protocol evaluation. In: 2nd International Conference on Simulation Tools and Techniques, SIMUTools 2009, Rome, March 2009
14. Vahdat, A., Becker, D.: Epidemic routing for partially connected ad hoc networks. Technical report CS-200006, Duke University (2000)