A Method for Performance Evaluation of the Low Earth Orbit Satellite Networks

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Abstract. Low Earth Orbit satellite communication system has the characteristics of low latency and wide coverage, and is widely used in the non-terrestrial communication systems. But at the same time, the characteristic of its fast-changing topology also brings the complex problem of network performance evaluation. In this paper, we propose a Minimum Delay Maximum Capacity algorithm based on Minimum Cost Maximum Flow algorithm to evaluate the performance of the LEO satellite networks. We analyze the performance of several different constellation configurations based on the proposed algorithm.

Keywords: Low earth orbit satellite network · Delay and capacity · Minimum delay maximum capacity

1 Introduction

Low Earth Orbit (LEO) satellite communication system has the advantages of low latency and wide coverage which is widely used [1]. There are several LEO satellite communication systems such as Iridium system and Globalstar system in the early stage, and many newly proposed systems like SpaceX, Telesat, and OneWeb. However, due to the dynamic topological structure and expensive simulation computation cost, it is complex to evaluate the performance of these networks. The performance metrics of a network include bandwidth, delay, delay jitter and the packet loss rate. However, the common methods for performance evaluation of satellite networks, which need to run complex routing algorithms with specialized satellite network simulation platforms such as OPNET, NS-2, NS-3 and STK. When the number of satellite nodes is large, time consumption has increased dramatically. Therefore, this paper proposes an efficient method to calculate the capacity and delay by the Minimum Delay Maximum Throughput (MDMC) algorithm, which can reflect the performance of the network.

At present, many researchers have analyzed the satellite network performance. In [2], a dynamic routing scheme for time-variant topology environments is proposed, which transforms the dynamic topology into a series of static virtual topology. Then a satellite network topology based on virtual nodes is proposed. In the satellite network with virtual nodes, topology is stable and can be regarded as static [3]. Someone sets

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up a series of “snapshots” for the network changes over time. Within each snapshot, the satellite network topology is considered unchanged [4]. In [5], the Quality of Services (QoS) model of space system is established. Previous study uses a finite state automaton (FSA) to solve the difficulty arising from dynamic topology [6]. Since network with less delay has better performance. An asymmetric Discrete Time based Routing Algorithm (A-DTRA) is proposed to find the shortest path with least delay in a snapshot [7]. But A-DTRA ignores the effect of bandwidth. In literature [8], the capacity of the satellite network is expressed by time varying graph and established by “all-to-all” model which is simulated by STK. However, all the above studies depend on sophisticated routing algorithms, and the computation task is heavy. The Maximum Flow (MF) algorithm is a simple and effective method to evaluate network performance. The paper [9] proposes a Location-Based Multi-Service routing algorithm, and uses the MF algorithm to calculate throughput. In [10], capacity and throughput are optimized with an improved push-pull flow algorithm and MF algorithm is used to analyze the throughput. However, the MF algorithm can only evaluate the capacity performance of a satellite network without considering the effect of delay on the network simultaneously.

In this paper, to evaluate the performance of the satellite network, we propose a MDMC method based on Minimum Cost Maximum Flow (MCMF) to calculate the capacity and delay. First, we provide a short overview about LEO satellite networks and ISL topology characteristics. Then we construct the capacity and delay model. Finally we analyze several different satellite network constructions, and compare the difference of their performance by using MDMC.

2 LEO Satellite Network Model

2.1 Satellite Constellation

There are several common configurations of satellite network constellation, such as Walker Delta and Walker Star. This paper focuses on Walker Star Constellation. It consists N orbit planes, M satellites are evenly distributed in each plane with angular distance of $2\pi/M$. The orbits are all circular orbit with the same altitude. And the inclination of each plane is near 90°. The ascending nodes of the orbit planes are arranged at equal intervals along the equator in the range of π. The fixed offset angle between adjacent orbits is π/N. The nearest satellites in adjacent orbits differ in phase by Δw_f degrees from each other (phase offset is given by formula (1)) [11].

$$\Delta w_f = \frac{2\pi}{N \cdot M} \cdot F \tag{1}$$

F is the phase factor ranging from 0 to $N - 1$.

2.2 Satellite Network Model

Each satellite serves as a node in the network topology. The link between the satellites is inter satellite link (ISL), and between the satellite and the user is user data link (UDL) [1]. Finally, we build a satellite network topology.

Each satellite has a maximum of four point-to-point duplex ISLs, two of them are intra plane ISLs, and the others are inter plane ISLs. Because the relative velocity of the satellite over the polar region and the satellite on both sides of the reverse seam is too high, ISLs over polar regions and inter ISLs across reverse seam are closed [12] (the connection states of ISLs between satellites are presented in Fig. 1).

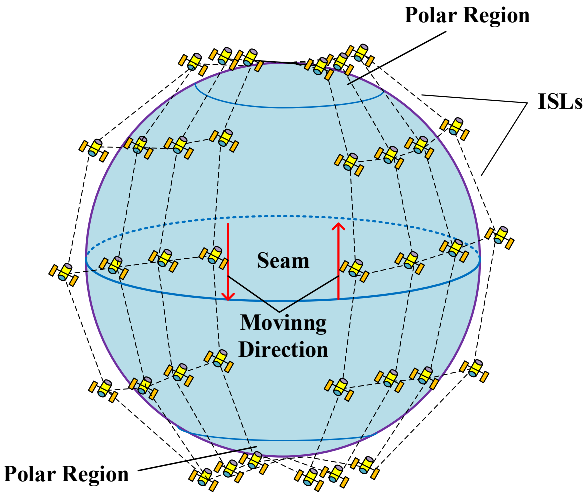

Fig. 1. Satellite network topology and ISLs.

The MDMC algorithm can analyze the network with single source and single terminal, while the LEO satellite network is the network with multi-source and multi-terminal. Thus, we need to introduce a virtual source and destination to solve this problem. The users on the ground dynamically connect with virtual source and destination under the full coverage.

2.3 Graph Model

The position of the satellites in the constellation changes over time, as a result, the topological structure of satellite network changes dynamically. We can use the temporal graph which is also called Time-Evolving Graph (TEG) [13] to show the dynamic changes of the LEO satellites networks. In Fig. 2, within a constellation period, period can be equally divided into K time intervals and the satellite network topology can be also divided into K different snapshots with the same time. A TEG can be expressed as $G(T_i, P_i)$, in which i is from 1 to K. We donate a snapshot as $P(S_j, E_j)$, where S means the Node Set of satellites and E means the Edge Set of ISLs, and j is from 1 to the number of total satellites.

Each snapshot is created dynamically, and the topology structure within the snapshot can be regarded as static. It can be found that, because of the symmetry of the constellation, the topology graph within the K snapshots is isomorphic. Therefore, we only need to select any snapshot for analysis to obtain the network topology of the entire

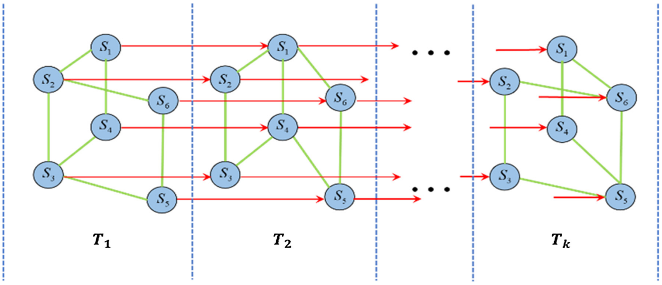

Fig. 2. Time-evolving graph.

constellation. When considering seam and polar regions, an example of satellite network topology in a snapshot is shown in Fig. 3. In Fig. 3, we build a Walker Star Constellation with three orbital planes and four satellites of per plane. And we number the satellites from 1 to 12 in order of their orbital planes. At the same time, we add two ground users numbered 13 and 14 as the source and destination to connect to the satellite randomly. Now we get a satellite network graph.

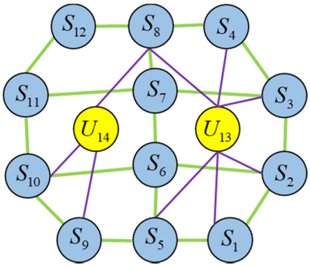

Fig. 3. Satellite network graph.

2.4 Delay and Capacity Evaluation Model

Delay Model. For the entire network, the total transmission path delay T_{total} includes the processing delay $T_{process}$, the propagation delay $T_{propagation}$, and the queuing delay T_{queue} [7]. The total delay between two adjacent nodes is given by

$$T_{total(i,j)} = T_{process(i)} + T_{propagation(i,j)} + T_{queue(i)} \tag{2}$$

The processing delay $T_{process(i)}$ between any two nodes is determined by specific hardware platform. When the hardware platform is determined, its value can be assumed fixed [14].

The propagation delay between node i and node j is formulated as

$$T_{propagation(i,j)} = \frac{d_{i,j}}{c} \tag{3}$$

$d_{i,j}$ is the distance between two adjacent nodes, and c represents the light speed.

The queuing delay $T_{queue(i)}$ depends on the specific traffic demand and node processing capability and is not considered in this paper. Therefore the total delay between two adjacent nodes is corrected to

$$T_{total(i,j)} = T_{process(i)} + T_{propagation(i,j)} \tag{4}$$

Capacity Model. Capacity is defined as bandwidth or throughput between any two nodes. And the capacity is divided into two categories. One is generated by the all ISLs. The capacity of ISL is identified as identical. The other one is from all the satellite-ground links (SGLs) which is from satellite to source or sink node. The link relationship between the satellite and the source or sink node is determined by the current coverage of satellite. The capacity of SGLs is regarded as infinite.

3 The Algorithm

3.1 Constructing the Topology Within a Satellite Snapshot

Using the virtual topology method, we divide the satellite period into K static snapshots. The performance evaluation algorithm is applicable for each snapshot. In each snapshot, we use the properties of LEO satellite to build network topology with capacity and cost. Besides, we add two virtual nodes as source and destination. Then, we calculate the visibility and distance between any two satellites, obtain the adjacency matrix and delay matrix, and combine them into capacity and delay expansion graph $G = \{V, E, Cap, Cost\}$, where V is vertex set, E is edge set, Cap is the capacity set of all edges in E, and $Cost$ is the delay set of all edges in E. Next, we describe the algorithm that generates the graph.

Algorithm 1. MDMC Graph Construction

```
Input: Satellite snapshot parameter $S = <N, M, h, inc, F, LatPLR>$
Output: Network topology with capacity and cost $G = \{V, E, Cap, Cost\}$
Construct the adjacency matrix $ISL(u, v)$ and delay matrix $PLinkDelay(e)$
repeat
  Initialize $i = 1$
  repeat
    Initialize $j = 1$
    if $(i, j)$ are not in polar region and not in seam
      $ISL(u, v) = 1$
    end
  until $j = M$
until $i = N$
repeat
  Initialize $i = 1$
    Calculate the inter ISLs $PLinkDelay(i)$
until $i = M$
Calculate the intra ISLs $VLinkDelay$
repeat
  Initialize $i = 1$
  repeat
    Initialize $j = i$
    if $ISL(i, j) = 1$
      Set $G(V_u) = i$, $G(V_v) = j$, calculate the capacity $G(Cap_{(u,v)})$
      if $i = j-1$
        $G(Cap_{(u,v)}) = VLinkDelay$
      else
        $G(Cost_{(u,v)}) = PLinkDelay(i)$
      end
    end
  until $j = M$
until $i = N$
Add virtual source node $v_{N \times M+1}$ and sink node $v_{N \times M+2}$
Extend $G = \{V, E, Cap, Cost\}$ to a digraph
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3.2 MDMC Algorithm

The MDMC based on MCMF aims to calculate the minimum delay and the maximum capacity from source node to sink node. In a flow digraph, each edge has two attributes, the maximum capacity and the cost of per unit flow. The goal of the algorithm is to find a path from the origin to the destination, which minimize the cost under the condition of maximum flow. For example, in Fig. 4, the path with the minimum cost and maximum flow can be found by using MCMF.

The total minimum cost *minC* is formulated as

$$minC = min\sum\nolimits_{(u,v)\in E}\left[c(u,v) \times f(u,v)\right] \quad (5)$$

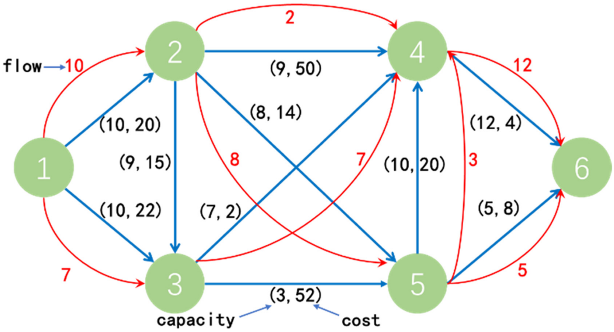

Fig. 4. An example of the flow network graph. The source is node 1 and the destination is node 6. The solution of the MCMF problem is highlighted by red arcs.

$c(u, v)$ is the cost of per unit of flow between two adjacent nodes, $f(u, v)$ represents the actual flow between two nodes, it must be less than the capacity, and *minC* is the minimum total cost from source to destination. In MDMC, $c(u, v)$ is the delay between two adjacent satellites, $f(u, v)$ represents the throughput between two satellites, it must be less than or equal to the bandwidth, and *minC* is the minimum Bandwidth-Delay Product (BDP) which is the minimum number of bits with maximum throughput from source to destination. Then the minimum delay *minD* is given by

$$minD = \frac{BDP}{maximum\ Capacity} \tag{6}$$

maximum Capacity is the maximum throughput from source node to sink node in MDMC.

There are two main methods to solve MCMF. The one finds the path of minimum cost firstly, and then increases to maximum flow on the path. The other one finds the path of maximum flow firstly, then uses the negative circuit to cut the cost to minimum. In this paper, we use the first method.

For a given digraph with delay and capacity. Firstly, we construct a residual network by adding one inverted edge to every edge (see Algorithm 2). Next we use the Improved Dijkstra Algorithm (IDA) to find the minimum delay paths from source node to sink node in the residual network [15]. Then we calculate the flow in this path, we add flow to positive edge and subtract flow from inverted edge. Continuing operating the above steps until there is no path from source node to sink node. After that, we get maximum throughput and the minimum BDP. Finally, we use formula (6) to get the minimum delay. Certainly, the more capacity and the less delay means better performance for a given satellite network.

Algorithm 2. MDMC Based on MCMF

```
Input: Network digraph with capacity and cost $G=\{V,E,Cap,Cost\}$
Output: Total minimum delay $del$ and maximum capacity $cap$
Construct residual network graph $G=\{V,E,flow=Cap,cost=Cost\}$, add the
    new $edge=\langle v,u,flow=0,-delay\rangle$ between node $u$ and node $v$
repeat
    Use the IDA to find a minimum delay path from source node to sink node in
        residual network graph and calculate the $cost$ and $flow$
    $edge=\langle u,v,0,cost\rangle+flow$, and $edge=\langle v,u,0,-cost\rangle-flow$
until we can not find the path from source node to sink node
$cap=\sum flow$, $BDP=\sum(delay\times flow)$, which $flow>0$
Output $cap$, $del=BDP/cap$
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3.3 Time Complexity

When calculating the performance of giant constellations, algorithm with high time complexity will lead to a rapid increase in running time. Therefore, in this paper, a cost flow algorithm based on Dijkstra shortest path algorithm is modified to obtain an algorithm with low time complexity. The total time complexity of this algorithm mainly contains two parts. One is the construction of MDMC graph, the other one is MDMC. The first part is $O(M\cdot N)$. In a MDMC graph, the number of edges is a maximum of $2(N-1)M$ and the number of satellites is N. The most of the time for MDMC is spent finding shortest path by IDA. When we denote by C the maximum capacity of all edges, the number of executions of the IDA is $O(E\cdot log(C))$. And the complexity of IDA is $O(E\cdot log(E))$ by using Fibonacci Heap. Therefore, the total complexity is $O(E(E+NlogN)logC)$ [15].

4 Simulations and Discussion

In this section, we design three simulation cases. Each case studies one or multiple Walker Star Constellations. For anyone of these constellations, it consists N orbit planes, and each of plane is with M satellites. The orbit inclination (*inc*) of each plane is 90°. The range of the phase factor(F) is from 0 to 6. And the orbit altitude(h) is set from 800 km to 1500 km. The latitude of the polar region (*LatPLR*) is set as 70°. Finally, the capacity of each ISL is set as 100 Mbps and UDL is set as unlimited.

In the first scenario, we design and test two groups of constellation experiments. The first group of experiment contains 7 constellations, of which the number of orbit planes is set as 6, while the number of satellites of each plane is increased from 12 to 24 with 2 satellites of interval. The second group of experiment also compares 7 constellations, of which the number of satellites in each plane is set as 12, while the number of orbit planes is from 6 to 12. Other parameters are the same in both two groups.

In Fig. 5, we calculate the capacity and delay of each constellation by MDMC. From the two sets of results. As the total number of satellites increases, the capacity of both two groups of constellations also increase, but the delay of the most of constellation

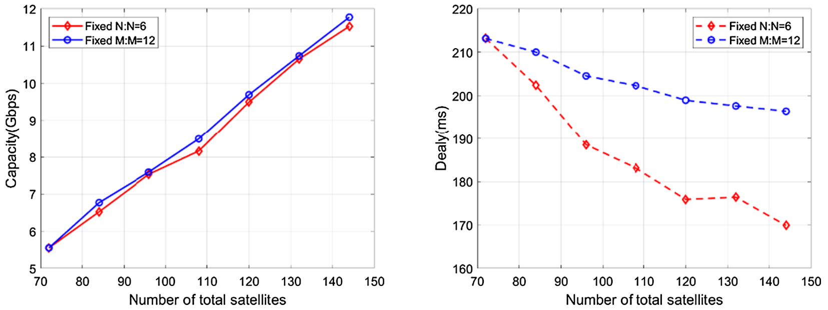

Fig. 5. The capacity and delay of the fixed number of orbit plane (FNOP) and the fixed number of satellites of each plane (FNSP).

decrease. Then we compare two sets of the results. When the total number of satellites is the same, the capacity of FNSP is higher than FNOP. However, the difference between delays is much greater than the difference between capacities. It can be explained as follows: As the total number of satellites increases, the number of ISLs is increasing, which lead to an increase in capacity and hop count. Especially the delay performance of FNOP is better than FNSP, because ISLs of FNOP is less affected by polar regions when the total satellites increase and can get better paths. In conclusion, as the total number of satellites increases, it is better to increase the number of satellites in the same orbit than to increase the number of orbits.

In the second scenario, we analyze the effect of orbit altitude on the performance of satellite network. The orbit altitude is divided into 8 groups from 800 km to 1500 km with 100 km interval. Other parameters are the same in each group. In Fig. 6, as the height increases, the capacity has little change, but the delay increases which results in degradation of the network performance. This result can be explained as follow: with the increase of orbit height, the topology of ISLs is unchanged, however the increase in distance of two adjacent satellites results in the increase of delay.

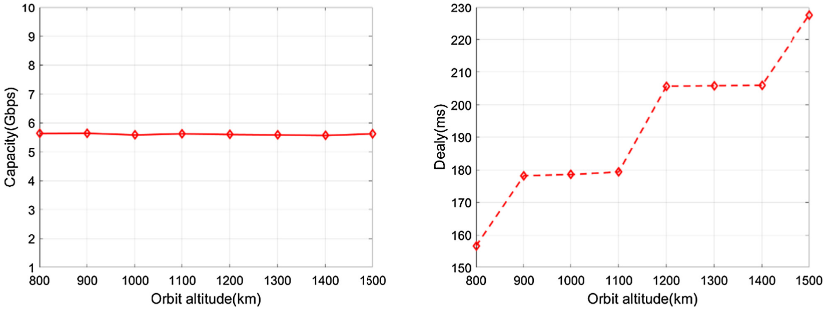

Fig. 6. The capacity and delay of constellations with the different orbit altitudes.

In the third scenario, we analyze the effect of phase factor on the performance of satellite network. According to formula (1), we set 6 groups of phase factor from 0 to

5. Other parameters are the same in each group. In Fig. 7, as the phase factor increases, the capacity decreases, but delay firstly decreases and then increases. With phase factor increasing some satellites are located in the polar region, thus available ISLs are less. However, when the phase factor is 1, the topology structure is the most optimal, which the delay is minimum. Then as the phase factor increases, the delay also increases.

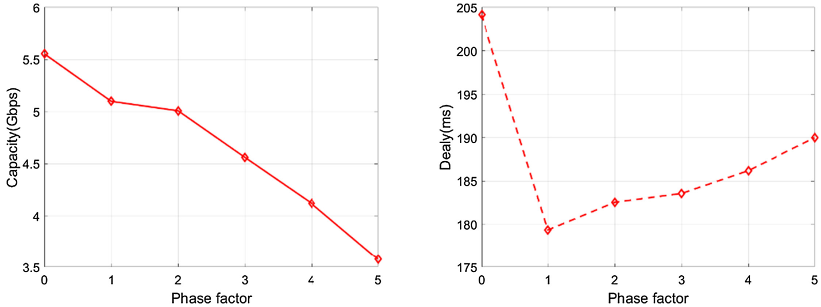

Fig. 7. The capacity and delay of constellations with the different phase factor.

5 Conclusion

This paper proposes an efficient algorithm MDMC for evaluating the performance of LEO satellite networks. Firstly, we build a fixed satellite topology. Then capacity and delay model are added into ISLs. Next, we use MDMC to evaluate network performance by calculating the minimum delay and maximum capacity. Finally, three different cases are set to study the difference of performance of constellation network. From the results, MCMD is appropriate to evaluate and compare the performance of LEO satellite networks.

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