COMPLEX SYSTEM MODELING AND SIMULATION
ISSN 2096-9929 05/06 pp 232−241
Volume 1, Number 3, September 2021
DOI: 10.23919/CSMS.2021.0019

Multicommodity Flow Modeling for the Data Transmission Scheduling Problem in Navigation Satellite Systems

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Abstract: Introducing InterSatellite Links (ISLs) is a major trend in new-generation Global Navigation Satellite Systems (GNSSs). Data transmission scheduling is a crucial problem in the study of ISL management. The existing research on intersatellite data transmission has not considered the capacities of ISL bandwidth. Thus, the current study is the first to describe the intersatellite data transmission scheduling problem with capacity restrictions in GNSSs. A model conversion strategy is designed to model the aforementioned problem as a length-bounded single-path multicommodity flow problem. An integer programming model is constructed to minimize the maximal sum of flows on each intersatellite edge; this minimization is equivalent to minimizing the maximal occupied ISL bandwidth. An iterated tree search algorithm is proposed to resolve the problem, and two ranking rules are designed to guide the search. Experiments based on the BeiDou satellite constellation are designed, and results demonstrate the effectiveness of the proposed model and algorithm.

Key words: intersatellite link; navigation satellite system; data transmission; multicommodity flow; tree search

1 Introduction

As a key technology of Global Navigation Satellite Systems (GNSSs), InterSatellite Links (ISLs) from the main GNSSs of the world, including GPS, GLONASS, Galileo, and BeiDou, have received significant attention[1]. ISLs were first implanted in GPS Block IIR satellites[2] and operated in the ultrahigh frequency band with a radio frequency wide-beam antenna. Relative to wide-beam antennas, narrow-beam antennas have several advantages, such as pointing flexibility, strong antijamming capability, high ranging accuracy, and communication security[3–6]. The ISLs of GPS are set to be upgraded to narrow beams in the Ka or V bands[4]. For Galileo, narrow-beam antennas have been considered[7], and attention has been paid to laser link experiments. Through the introduction of ISLs, the BeiDou Navigation Satellite System (BDS-3) has achieved global navigation under the restricted distribution of ground facilities.

In BDS-3, Ka-band narrow-beam ISL is equipped on each satellite. ISLs can achieve intersatellite range measurements to determine satellite orbits, realize clock synchronization, and provide communication links for data transmission. However, because of satellite platform restrictions, the number of ISL antennas equipped on satellites is less than the number of visible satellites. The connectivity of satellite networks is not continuous because of satellite movement, and ISLs switch and reconstruct with time flexibly, thereby resulting in a time-evolving satellite network. Hence, the scheduling of data transmission between satellites to meet communication requirements and constraints is a challenging problem.

In recent years, several studies have explored data transmission (communication) scheduling in navigation ISL management. Xu et al.[8] used geosynchronous orbit satellites as the core transfer node and proposed a link assignment algorithm for a hybrid navigation

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Manuscript received: 2021-05-23; revised: 2021-08-03; accepted: 2021-08-29

constellation; however, their topology handling mode, which separates ranging and communication, is unsuitable for the latest systems. Hou et al.[9] described a type of data transmission problem, investigated its computational complexity, and proposed a linear programming model to solve it. Chu and Chen[10] proposed a mathematical model and presented a deterministic constructive algorithm to minimize the time required to transmit systematic data. However, they did not consider the periodicity of data generation. Some researchers have considered intersatellite ranging and communication requirements. Yan et al.[11] formulated the problem as a constrained optimization problem while considering intersatellite ranging as a constraint; they then set the intersatellite communication time delay as the optimization objective. Yang et al.[3] proposed a new grouping method to reduce communication time delays and a link scheduling method to meet intersatellite ranging requests. Hou et al.[12] presented a trade-off method for contact plans on the basis of maximum matching to improve intersatellite ranging and communication performance. Sun et al.[13] set a minimal number of ranging links and proposed a link scheduling method consisting of three steps. Yan et al.[1] discussed the requirements for distributed contact plan design and proposed a suitable scheduling algorithm. Liu et al.[14] conducted a preliminary exploration of hybrid network management, assuming that some satellites are equipped with a few laser transceivers and analyzed ranging and communication performance. These studies have simplified existing constraints and assumed that the bandwidth of ISLs is large enough.

Overall, the research into intersatellite data transmission (communication) scheduling is still limited. To the best of our knowledge, the capacity restrictions of ISL bandwidth have not been considered in the existing literature, whereas ISL bandwidth is an important and limited space resource in practical applications. Therefore, suitable mathematical models and algorithms should be designed to describe bandwidth capacity restrictions and optimize data transmission (communication) performance.

In this work, we focus on the intersatellite data transmission scheduling problem with capacity restrictions. On the basis of the periodic and dynamic characteristics of intersatellite networks, the data transmission scheduling problem is converted to a variant of the single-path multicommodity flow problem. A mathematical optimization model is built to minimize the maximal cost of ISL bandwidth. To resolve this problem, we propose an Iterated Tree Search (ITS) algorithm. A series of experiment instances based on simulation satellite constellations are generated. Comparison results demonstrate the effectiveness of the proposed model and algorithm.

The rest of the paper is organized as follows. Section 2 describes the problem. Section 3 presents the model conversion strategy and builds a mathematical model. Section 4 presents a detailed description of the ITS algorithm. Section 5 describes the experiment design and the result analysis. Finally, Section 6 draws the conclusions and describes future works.

2 Problem Description

2.1 Dynamic network scheme

As a result of the dynamic visibility between satellites and the pointing flexibility of narrow-beam antennas, time-evolving navigation intersatellite networks can be modeled as a Finite-State Automaton (FSA)[15].

- The system period is divided into several equal-length time intervals, each of which corresponds to an FSA state. The visibility of the satellite network is fixed during each FSA state, and two satellites are defined to be visible if and only if they are visible throughout the FSA state.
- Each FSA state contains several equal-length time intervals, which are defined as superframes. All superframes in a state have the same contact plan.
- Each superframe consists of several equal-length time slots, and an ISL between two satellites is established at each slot. The ISL is a bidirectional link, and the ranging and communication between linked satellites can be implemented at each slot simultaneously. Each satellite has only one onboard Ka-band antenna so that each satellite holds a maximum of one link at a slot. ISLs switch between adjacent slots according to a predesigned contact plan.
- The protection band at the beginning and end of each slot is designed to guarantee the quality of linking and integrity of data transmission between linked satellites.

The intersatellite network handling scheme of navigation satellite systems is shown in Fig. 1.

2.2 Intersatellite data transmission

A contact plan defines how one satellite connects sequentially with other satellites as the slot switches. It

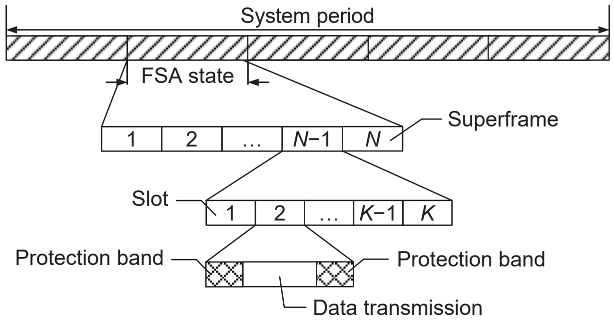
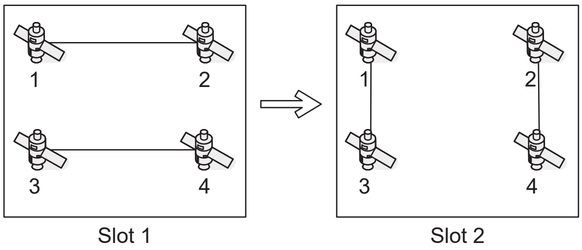


Fig. 1 Intersatellite network handling scheme.

is predesigned by the ground management center, uploaded by ground satellite antennas, and then stored on the satellite as a series of tables. When the contact plan is available, each satellite establishes different ISLs at different slots, thereby making a dynamic network topology structure. Figure 2 shows a simple illustration of the dynamic topology of a four-satellite constellation. In two slots, Satellite 1 establishes different ISLs with Satellites 2 and 3. The latest study on contact plan design considers the requirements of intersatellite ranging and intersatellite communication. Contact plans are the prerequisites and input conditions of the intersatellite data transmission scheduling problem.

Navigation satellites constantly generate telemetry data, which need to be transmitted to the ground station throughout their life cycle. Given the restricted distribution of ground facilities, ground antennas are unable to track all satellites along their entire arc. Therefore, in each FSA state, the satellites are divided into domestic satellites and overseas satellites. The former is visible to the ground while the latter is not. The telemetry data of domestic satellites can be directly transmitted to the ground. By contrast, the telemetry data of overseas satellites must first be sent to domestic satellites through ISLs and then be downloaded to ground facilities through ground satellite links (GSLs). The main work of data transmission scheduling is to assign suitable transmission paths for each overseas satellite at each slot. To obtain telemetry data timely and reduce the packet loss probability during data transmission so as to reduce the data transmission time delay are one of the main requirements of intersatellite data transmission scheduling.



Slot 1 Slot 2

Fig. 2 Dynamic network topology.

The data transmission time of GSLs is very short (several hundred milliseconds) and can be ignored relative to the slot switching time (several seconds). Thus, the data transmission time delay of a navigation satellite network refers to the slot switching time of ISLs. In this work, the time unit is denoted as a time slot.

Figure 3 depicts a simple illustration of the data transmission paths of a four-satellite constellation comprising three slots; here, Satellite 2 is a domestic satellite while the others are overseas satellites. At the start and end of a slot, the status of each satellite is different, especially the amount of data stored in the satellite. The dotted arrow in Fig. 3 represents the data transmission line between the adjacent status of one satellite, while the solid arrow denotes the data transmission line between two linked satellites at one slot. For the data stored in Satellite 1 at Status 0, Fig. 3 shows two paths to domestic Satellite 2. In Path 1, the data are still stored in Satellite 1 at Slot 1, and then sent to Satellite 4 at Slot 2 before finally being sent to Satellite 2 at Slot 3. In Path 2, the data are sent to Satellite 2 at Slot 1. The data transmission time delay of Path 1 is equal to 3 time slots, while that of Path 2 is equal to 1 time slot. Hence, Path 2 is preferable to Path 1.

As shown in Fig. 3, the path with the shortest data transmission time delay is equivalent to the shortest path in the satellite network. Without any capacity restriction, the shortest path can be obtained by

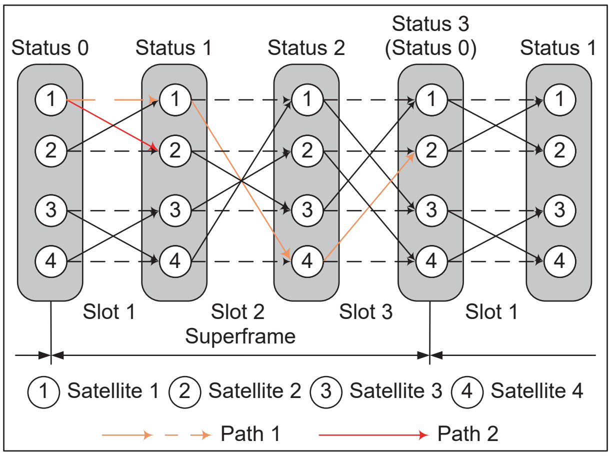


Fig. 3 Data transmission paths of the satellite network.

common search algorithms, such as the Dijkstra algorithm[16, 17]. However, the ISL bandwidth (data transmission rate), which is an important space resource, is usually limited. In addition to reducing communication time delay, data transmission scheduling requires reduced ISL bandwidth consumption. To the best of our knowledge, the scheduling models in the existing literature cannot describe bandwidth restrictions. Hence, we design a model conversion strategy to build a corresponding new flow model.

3 Problem Model

3.1 Model conversion strategy

Considering that contact plans for all superframes in an FSA state are the same and that satellite telemetry data are generated constantly, we regard the last status in one superframe to be the same as the first status in the next superframe, e.g., Status 3 is equivalent to Status 0 in Fig. 4 . Let us consider each data transmission demand as a flow demand from one overseas satellite to domestic satellites. The data transmission process of all sequential superframes in one FSA state can then be described by a network flow model on the basis of one superframe. In this section, the intersatellite data transmission scheduling problem is modeled as a variant of the MultiCommodity Flow Problem (MCFP) by employing model conversion.

First, we introduce the basic MCFP model. Consider a directed graph with a number of nodes and capacitated edges. A set of commodities comprises a source, sink, and demand[18]. The main constraints include link (edge) capacity and flow conservation. The scheduling process involves finding the transmission path for each commodity from the source to the sink through the capacitated network.

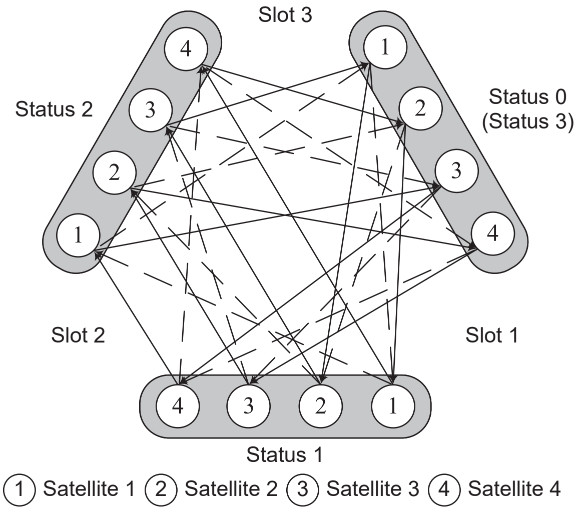


Fig. 4 Status loop of a four-satellite constellation.

The model conversion strategy is presented as follows:

(1) Node conversion

Each satellite at each status is regarded as a node. Overseas and domestic satellites correspond to overseas and domestic nodes, respectively.

(2) Commodity conversion

Each data generated in an overseas satellite during one slot are regarded as a commodity, in which the demand is the data amount, the source is the overseas node, and the sink can be any domestic node.

As the MCFP requires the sink of a commodity to be known, we create a unified sink node for all commodities that corresponds to the ground station.

The transmission line from each domestic node to the unified sink node is then established.

(3) Edge conversion

Each transmission line is converted as an edge. The transmission line includes three types: the transmission line between a domestic node and a sink node is converted into a ground satellite edge; that between the same satellite at different statuses corresponds to an intrasatellite edge; the transmission line between two linked satellites at one slot is an intersatellite edge that is equivalent to the ISL such that the flow amount of the intersatellite edge reflects the consumption of ISL bandwidth.

Figure 5 shows an illustration of the model conversion from Fig. 4, where Node 0 represents the unified sink node and four satellites in three slots are converted into 12 nodes. Three domestic Nodes 2, 8, and 10 build the transmission line with Node 0. Each overseas node generates a commodity, and all transmission lines are converted into edges. In this way, a four-satellite network with three slots is converted into a multicommodity flow model with 13 nodes, 27 edges, and 9 commodities.

In the navigation satellite network, each data generated during a slot cannot be split. Hence, only a single path is allowed for the flow of each commodity. This problem is known as the unsplittable MCFP or the Single-Path MCFP (SPMCFP). The SPMCFP is an NP-hard problem that was first introduced by Kleinberg[19]. To meet the time delay requirement, we introduce the path length constraint representing the data

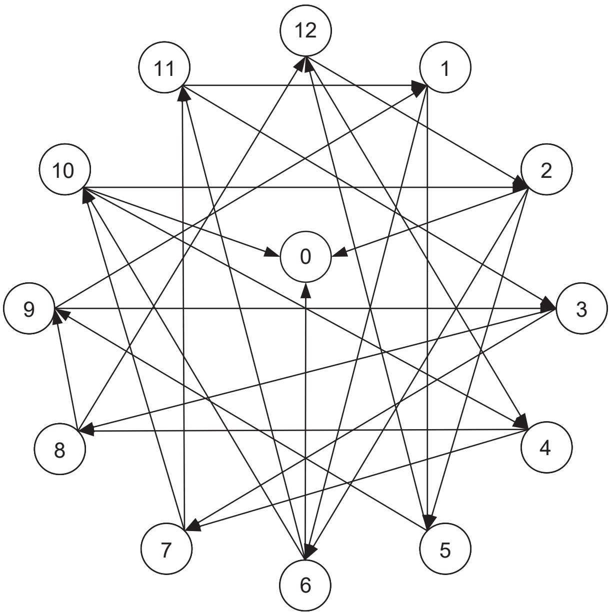


Fig. 5 Flow model converted from a four-satellite constellation.

transmission time delay into the SPMCFP and extend it as a Length-Bounded Single-Path MultiCommodity Flow Problem (LBSPMCFP). Hence, the intersatellite data transmission scheduling problem is equivalent to the LBSPMCFP. The optimization objective of the LBSPMCFP is to minimize the maximal sum of flows on each intersatellite edge, which is equivalent to the maximal occupied ISL bandwidth. The length of data transmission flow is the main constraint that corresponds to the communication time delay.

3.2 Model conversion strategy

After model conversion, the intersatellite data transmission scheduling problem can be formulated as follows:

Consider a directed graph $G(V,E)$, where V is a set of nodes and E is a set of edges. k commodities $l_1,l_2,\dots,l_k$ are defined as $l_i=(s_i,t,d_i)$, where s_i is the source, t is the sink, and d_i is the demand. As a commodity can only have a single flow, the commodity is also called flow in the following discussion. All flows have the same sink t. We define m as the maximal length of all flows. The variable $f_i(u,v)$ defines the fraction of flow l_i along the edge (u,v), and $d_i f_i(u,v)$ denotes the amount of flow l_i along the edge (u,v). E_S is the set of intersatellite edges, while the variable c denotes the maximal sum of flows on each intersatellite edge.

The optimization objective of the data transmission scheduling problem is to minimize the maximal occupied ISL bandwidth, which is equivalent to the maximal sum of flows on each intersatellite edge. The mathematical optimization model is formulated as

$$\mathit{Minimize}\ c \tag{1}$$

subject to

$$\sum_{i=1}^{k} d_i f_i(u,v) \leqslant c, \quad \forall (u,v)\in E_S \tag{2}$$

$$\sum_{(u,v)\in E} f_i(u,v) \leqslant m, \quad 1\leqslant i\leqslant k \tag{3}$$

$$\sum_{w\in V} f_i(u,w) - \sum_{w\in V} f_i(w,u) = 0, \\ \forall u\in V\backslash\{s_i,t\}, 1\leqslant i\leqslant k \tag{4}$$

$$\sum_{w\in V} f_i(s_i,w) - \sum_{w\in V} f_i(w,s_i) = 1, \quad 1\leqslant i\leqslant k \tag{5}$$

$$\sum_{w\in V} f_i(t,w) - \sum_{w\in V} f_i(w,t) = -1, \quad 1\leqslant i\leqslant k \tag{6}$$

$$f_i(u,v)\in\{0,1\}, \quad \forall (u,v)\in E \tag{7}$$

$$c\in \mathbf{Z}^{+} \tag{8}$$

Constraint (2) indicates that c is the maximal sum of flows routed over an intersatellite edge. Constraint (3) ensures that the length of all flows does not exceed the maximal length. Constraint (4) shows that for a node u that is not a source or sink node, the amount of flow entering it is the same as the amount of flow exiting it. Constraint (5) indicates that a flow must exit its source completely. Constraint (6) means that a flow must enter the unified sink completely. Constraints (7) and (8) define the variable ranges.

4 Scheduling Algorithm

As heuristic algorithms can reasonably find a feasible solution within an acceptable time frame, they have been widely used to solve complex optimization problems[20, 21]. In this section, we design a novel heuristic algorithm called the ITS algorithm to resolve the intersatellite data transmission scheduling problem.

4.1 Two ranking rules

On the basis of the optimization objective and data transmission time delay constraint, two heuristic ranking rules are proposed to guide the search directions.

4.1.1 Occupied bandwidth ascending rule

As the optimization objective is to minimize the maximal occupied ISL bandwidth, we set an upper bound (UB) for the occupied bandwidth while searching for available paths for commodities. UB is initialized to a small value and then increased gradually until every commodity has an available transmission path so as to find a feasible solution and reduce the ISL bandwidth consumption as much as possible.

4.1.2 Path length ascending rule

The data transmission time delay is the main constraint of this problem that limits the maximal length of transmission paths. The shortest path length should be assigned to meet this constraint. After assigning a path to a commodity, the maximal occupied bandwidth is updated; if it exceeds the current UB, then it is reassigned with a longer path.

4.2 Breadth-first tree search

According to the source and sink of a commodity, a tree search algorithm can be used to search all transmission paths for it. The breadth-first search and depth-first search algorithms are two common tree search algorithms. Considering the path length ascending rule, we adopt the breadth-first search algorithm to search paths in ascending order of path length.

4.3 Iterated tree search

Combined with two ranking rules and the breadth-first tree search algorithm, the ITS algorithm is proposed. The main steps are summarized as follows:

Step 1: Initialize UB as 1, put all k commodities in the wait sequence, and initialize the failure sequence as empty.

Step 2: Take out the first commodity from the wait sequence, and use the breadth-first tree search to search the shortest path for it.

Step 3: Compute the maximal occupied ISL bandwidth. If it does not exceed the UB, then record the path, delete the commodity from the wait sequence, and move to Step 5; otherwise, move to Step 4.

Step 4: Use the breadth-first tree search to find a long path for the commodity. If the path length exceeds the maximal length, then move the commodity from the wait sequence to the failure sequence and move to Step 5; otherwise, return to Step 3.

Step 5: Check the wait sequence. If it is not empty, then return to Step 2; otherwise, move to Step 6.

Step 6: Check the failure sequence. If it is not empty, $UB = UB + 1$, then move all commodities from the failure sequence to the wait sequence and return to Step 2; otherwise, terminate the algorithm, and output the result.

The flow chart of the ITS algorithm is shown in Fig. 6.

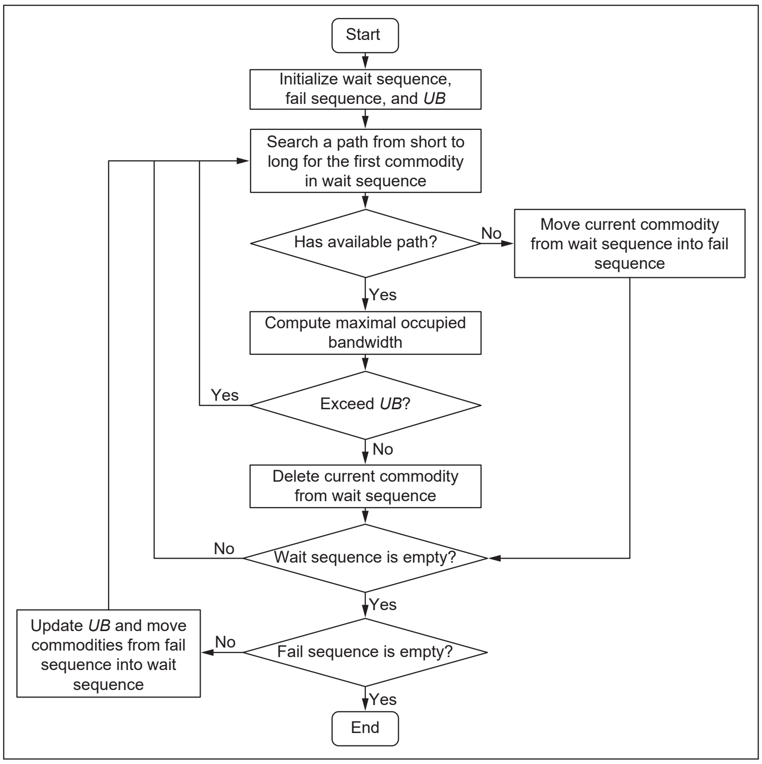


Fig. 6 Flow chart of ITS.

5 Experiment Design and Analysis

5.1 Experimental instances and parameter setup

The proposed algorithm is implemented in C++ on Microsoft Visual Studio 2015, and the experiments are tested on an Intel Core i7 computer with a 1.8 GHz processor and 8 GB RAM.

On the basis of BDS-3, a hybrid simulation satellite constellation is built. It consists of 24 Medium Earth Orbit (MEO) satellites, 3 Geosynchronous Earth Orbits (GEO) satellites, and 3 Inclined GeoSynchronous Orbit (IGSO) satellites. The main parameters of the satellite are shown in Table 1.

The contact plans determine the ISL topology structure and serve as the basis of intersatellite data transmission scheduling. We use the solution of contact plans from the research of Sun et al.[13] as the input data of our experiments. The entire system period is $168(24\times7)$ h according to the regression cycle of the satellite constellation. Each FSA state lasts 1 h and contains 60 superframes. Each superframe consists of 20 slots, and each slot lasts 3 s (1 time slot = 3 s). The range of the number of domestic satellites is 11–18. Sun et al.[13] generated the contact plan for each superframe, whereas we only select the contact plan in the first superframe as that for the entire FSA state. Thus, a system period includes 168 experimental instances.

As each experimental instance includes 30 satellites and 20 slots, it can be converted into a multicommodity flow graph with 601 nodes. The numbers of commodities and edges are different and depend on the visibility and contact plan of the superframe, i.e., Fig. 7 shows the number of commodities for 168 instances. Set each flow demand d_i to the same constant value 1, since the maximal sum of flows on each intersatellite edge is equivalent to the maximal occupied ISL bandwidth, for ease of understanding and presentation, we omit the specific unit of ISL bandwidth.

To test and verify the proposed algorithm, we adopt the ILOG CPLEX solver into experimental instances as a comparison algorithm. The ILOG CPLEX solver is a common mathematical programming solver that integrates a series of exact algorithms and strategies, and it has been widely applied to many scheduling and optimization problems[22, 23].

Table 1 Main parameters of the satellite constellation.

Type	Number	Orbit parameter
MEO	1 – 24	Walker 24/3/1; orbit height: 21 528 km; inclination: 55°
GEO	25 – 27	Orbit height: 35 786 km; longitude: 80°, 110.5°, and 140°
IGSO	28 – 30	Orbit height: 35 786 km; inclination: 55°

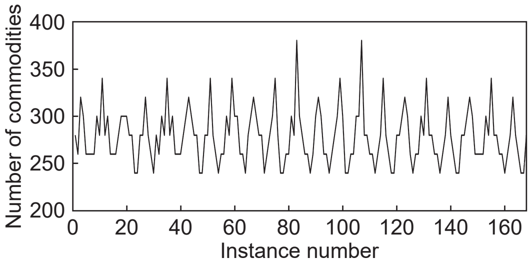


Fig. 7 Main parameters of the satellite constellation.

The maximal length of optional paths m denotes the maximal acceptable data transmission time delay. In the study of Sun et al.[13], the maximum of minimal time delay for all overseas satellites is 4 time slots without considering bandwidth costs. Hence, the value of m cannot be less than 4.

5.2 Result analysis

First, we compare the results of ITS and CPLEX for Instances 1 – 10. Tables 2 and 3 show the results with m being 4 and 5, respectively; here, Max-BW denotes the minimal occupied bandwidth that is also the optimization objective of this problem, and Ave-BW represents the average occupied bandwidth. From Tables 2 and 3, we can see that the computing time of ITS for each instance is much less than that of CPLEX. The time needed by CPLEX, for instance, is more than 20 min. Hence, the time for the entire system period (168 instances) will be more than 50 h, which is unacceptable for practical applications. Except for Instance 3 with $m=4$ in Table 2, the ITS algorithm obtains the same optimal solution for every instance as

Table 2 Results of ITS and CPLEX for 10 instances (m = 4).

Instance	ITS			CPLEX		
	Max-BW	Ave-BW	Time (s)	Max-BW	Ave-BW	Time (s)
1	**2**	**2.72**	**0.015**	2	2.96	3434.13
2	**2**	**2.91**	**0.016**	2	3.09	2590.87
3	3	**2.87**	**0.016**	**2**	3.17	2765.93
4	**2**	**2.81**	**0.016**	2	3.32	5887.35
5	**2**	**2.96**	**0.013**	2	3.49	1626.45
6	**2**	**2.68**	**0.007**	2	3.16	1987.01
7	**2**	**2.89**	**0.008**	2	3.13	1800.22
8	**2**	**2.94**	**0.009**	2	3.24	1562.26
9	**2**	**2.9**	**0.009**	2	3.38	2847.72
10	**2**	**2.82**	**0.008**	2	3.31	3918.96

Table 3 Results of ITS and CPLEX for 10 instances (m = 5).

Instance	ITS			CPLEX		
	Max-BW	Ave-BW	Time (s)	Max-BW	Ave-BW	Time (s)
1	**2**	**3.06**	**0.01**	2	3.1	1924.49
2	**2**	**3.27**	**0.009**	2	3.67	1772.44
3	**2**	3.29	**0.01**	2	**3.25**	3733.61
4	**2**	**3.17**	**0.009**	2	3.23	2581.23
5	**2**	**3.39**	**0.009**	2	3.43	1367.89
6	**2**	**2.93**	**0.009**	2	3.52	2010.96
7	**2**	**3.24**	**0.008**	2	3.29	2163.13
8	**2**	**3.25**	**0.008**	2	3.51	1861.21
9	**2**	**3.29**	**0.011**	2	3.4	2387.34
10	**2**	**3.11**	**0.009**	2	3.24	2701.28

CPLEX. Except for Instance 3 with $m = 5$ in Table 3, the ITS algorithm performs better than CPLEX for all instances in terms of the average occupied bandwidth.

As CPLEX takes too long to search for the optimal solution, we set the maximal computing time of CPLEX to 2 min for each instance. We run ITS and CPLEX for all 168 instances. Figures 8 and 9 show the results with m being 4 and 5, respectively, where INF means the infeasible solution. From Fig. 8, we can see that CPLEX cannot obtain a feasible solution in most of the 168 instances within 2 min. Meanwhile, the ITS algorithm can find good solutions for each instance in less time, with the maximal time delay being 4 time slots ($m = 4$). As shown in Fig. 9, with a longer time delay ($m = 5$), CPLEX obtains a feasible solution in most instances within 2 min, but the occupied bandwidth of ITS for each instance is still better than that of CPLEX. ITS can occupy minimal bandwidth with a relatively short data transmission time delay.

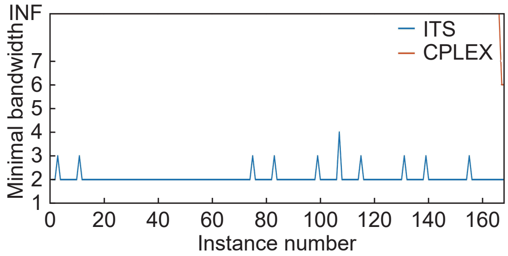


Fig. 8 Bandwidth comparison results of CPLEX and ITS solutions for 168 instances (m = 4).

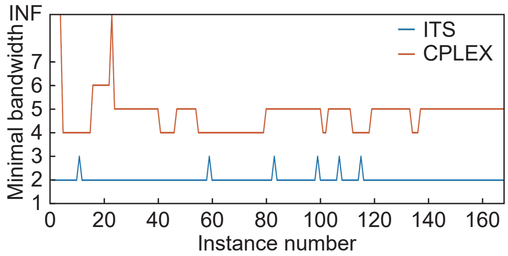


Fig. 9 Bandwidth comparison results of CPLEX and ITS solutions for 168 instances (m = 5).

In summary, although the CPLEX solver can determine the optimal solution, its time consumption cannot meet practical system requirements. Under a restricted running time, CPLEX cannot find a feasible solution for each instance with a short time delay, whereas the proposed ITS can obtain a better solution with less computing time. Thus, ITS is an efficient algorithm for the intersatellite data transmission scheduling problem.

6 Conclusion

In this work, we study the intersatellite data transmission scheduling problem in navigation satellite systems. Considering the capacity restrictions of the ISL bandwidth, we design a model conversion strategy and build a length-bounded single-path multicommodity flow model, in which the optimization objective is to minimize the maximal occupied ISL bandwidth. Then, we propose the ITS algorithm to resolve the model and design two ranking rules to improve the search efficiency. A series of experimental instances based on BDS-3 is designed to evaluate the proposed ITS. Relative to the CPLEX solver, ITS obtains the same optimal solutions for most instances. Moreover, it consumes less computing time than CPLEX. Under computing time restrictions, ITS can obtain better solutions for all instances and maintain a shorter data transmission time delay than CPLEX. The results demonstrate that the proposed multicommodity model and ITS algorithm are effective and efficient in solving the data transmission scheduling problem in navigation satellite systems.

In the future, we plan to consider other optimization directions, such as minimizing hops and balancing the load of different ISLs, and to utilize multiobjective algorithms to solve the problems. We will also consider the uncertainty and robustness of contact plans.

Acknowledgment

This work was supported by the National Natural Science Foundation of China (Nos. 61773120 and 71901213), and the Foundation for the Author of National Excellent Doctoral Dissertation of China (No. 2014-92).

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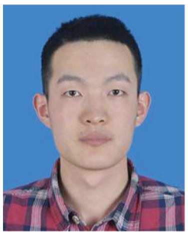

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