TDRSS Scheduling Algorithm for Non-uniform Time-Space Distributed Missions

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***Abstract*—With the rapid increase of mission demands for the tracking and data relay satellite system (TDRSS), the technical issue of high-efficient scheduling has attracted more attention in recent years. Most of previous scheduling algorithms are designed based on the assumption of missions' uniform time-space distribution, which have showed unsatisfactory performance in real scenarios with non-uniform distribution of mission demands. In this paper, we first transform the TDRSS scheduling problem into the heterogeneous inter-satellite link antenna (ILA) pointing route problem. Then, a two-stage heuristic algorithm with hierarchical scheduling strategies is proposed with the consideration of non-uniform time-space distribution of missions. Finally, we employ the TDRSS dataset to verify our proposed algorithm by comparing with the improved Rojanasoonthon's greedy randomized adaptive search procedure (GRASP) algorithm. Experimental results show that our proposed two-stage heuristic algorithm can schedule 2.41%, 4.43% and 6.02% more missions and consume 11.84%, 10.38% and 9.54% less setup times of SA antennas than the improved GRASP algorithm for the mission scale of 200, 400 and 600, respectively. In addition, setup times of SA antennas in those instances with non-uniform distribution in space can be more efficiently compressed by our proposed two-stage heuristic algorithm.**

***Index Terms*—Space communication network, tracking and data relay satellite system (TDRSS), inter-satellite link antenna (ILA), scheduling, dynamic setup times, time-space distribution characteristics.**

I. Introduction

Tracking and data relay satellite systems (TDRSS) play an important role in space communication network [1] [2] [3] [4]. The tracking and data relay satellite (TDRS), as the central unit of TDRSS, is deployed in the geosynchronous orbit to serve as a relay platform [5] for communications between the LEO spacecraft and the ground station. Spacecrafts can communicate with the system only when they are within the line-of-sight range of any TDRS, called visibility window, which is associated with the relative orbits of the TDRS and the spacecraft. In TDRSS, relay missions are processed by inter-satellite link antennas (ILAs) [6] of each TDRS, including two single access (SA) antennas and one phased array Multiple Access (MA) [7] antenna. The SA antenna rotates in a mechanical manner, while the MA antenna can form an electronically steered beam by continuously commanding appropriate phase shifts [2].

Due to the more and more relay demands [8] [9] [10] [11] for TDRSS, high-efficient mission scheduling has attracted increasing attention during the recent years. In the earlier stage, Reddy *et al.* [12] originally studied this problem from a directed graph point of view, and developed a dynamic-programming heuristic algorithm to solve this network model. Later, Rojanasoonthon *et al.* [13] formulated the mission scheduling problem as a parallel machine scheduling problem with the constraint of visible time windows and proved this problem to be NP-hard. Then they proposed a greedy randomized adaptive search procedure (GRASP) algorithm that has been proved to be effective in many optimization problems [14] [15]. Scheduling results showed that their GRASP algorithm was able to outperform the dynamic-programming scheme in [12] in the number of completed missions. Recently, Zhao *et al.* [16] and Lin *et al.* [17] represented algorithms based on different evolutionary strategies to improve the scheduling performance.

However, the aforementioned representative TDRSS scheduling algorithms were designed based on the hypothesis that the distribution of the requested missions is uniform in the time and spatial domain. Meanwhile, the characteristics of the distribution in real operation environment are not fully utilized, which has enforced negative influence on the efficiency of these algorithms. Considering these problems, in this paper, the TDRSS scheduling algorithm is specifically designed with the consideration of time-space distribution characteristics of requested missions, as well as associated with other factors like the visible time window constraint, the high-speed moving spacecraft, the heterogeneous SA and MA antennas. We first transform the original scheduling problem into an heterogeneous ILA pointing route problem in the antenna coordinate system, as shown in Fig. 1, and present a mixed integer programming model for this problem. Then, we propose an efficient heuristic algorithm to construct and optimize each ILA pointing route. As the length of setup times are the main costs of the TDRSS's daily operation, they should be compressed from an optimization point of view. In other words, it is expected that we can utilize limited ILA resource to process as many missions as possible. Therefore, there are two-level objectives in our problem, namely to maximize the number of scheduled missions and to minimize the total length of setup times of ILAs.

The remainder of this paper is organized as follows. In Section II, we present the mathematical formulation for the TDRSS scheduling problem. Then, a two-stage scheduling algorithm is described in Section III, while the computational

978-1-5090-5019-2/17/$31.00 ©2017 IEEE

results are shown and discussed in Section IV. Finally, Section V draws the conclusions.

II. Model Formulation

As shown in Fig. 1, the TDRSS scheduling problem can be defined on a directed graph $G = (V, A)$ in the coordinate system of ILA, where V represents the node set and $A = \{(i, j) : i, j \in V, i \neq j\}$ represents an arc set. The directed graph has $|V| = n + 2$ nodes, in which node 0 and node $n + 1$ represent the start and the end node of the pointing route of ILA, while other nodes represent missions denoted by $N = V\backslash\{0, n + 1\}$. Meanwhile, the position of each node is represented by the azimuth and elevation in the coordinate system of ILA. For node 0 and node $n + 1$, both azimuth and elevation are zero. All feasible ILA pointing routes correspond to the source-to-sink elementary paths in G. In order to formulate our problem, the following variables and parameters are defined.

There are two types of ILAs, namely, SA and MA denoted by K_1 and K_2, respectively. Let K be the set of two heterogeneous ILAs, $K = K_1 \cup K_2$. Let us use v_k to denote the angular velocity of ILA k rotation during the setup times. In addition, the mission node related parameters and variables are defined as follows. Let p_i^k be the processing time of mission node i processed by ILA k and set $p_0^k = p_{n+1}^k = 0$ for the start and end nodes. Mission i has $|M_i|$ visibility windows and its m_{th} visibility window is denoted by $[w_{i,m}^s, w_{i,m}^e]$. Note that mission i should be processed within at most one window. At any time within window $[w_{i,m}^s, w_{i,m}^e]$, the position of mission node i is identified by the azimuth and elevation of ILA k, i.e., $(\alpha_{i,t}^k, \beta_{i,t}^k)$. Moreover, let us define the outdegree of mission i as $\delta^+(i) = \{j : (i, j) \in A\}$ and the indegree of mission j as $\delta^-(j) = \{i : (i, j) \in A\}$.

Furthermore, the formulation also requires three groups of decision variables. The first group models the node processing sequence on ILA k, defined by a binary variable $x_{i,j}^k$. If mission node i precedes j on ILA k, we have $x_{i,j}^k = 1$; otherwise, $x_{i,j}^k = 0$. The second group contains the start time t_i^s and the end time t_i^e of mission node i. This group also includes the setup times $s_{i,j,t}^k$ that represent the time length from the end time of mission node i to the start time of mission node j at instant t for ILA k. The third group contains binary parameter y_i^m that specifies the visibility window for processing node i. If mission node i is processed within its m_{th} visibility window in the set M_i, we have $y_i^m = 1$; otherwise, $y_i^m = 0$.

Based on all the aforementioned variables and parameters, the TDRSS scheduling problem can be formulated as follows:

$$\max \sum_{k \in K} \sum_{(i,j) \in A} x_{i,j}^k \tag{1}$$

$$\min \sum_{k \in K} \sum_{(i,j) \in A} x_{i,j}^k s_{i,j,t_j^s}^k \tag{2}$$

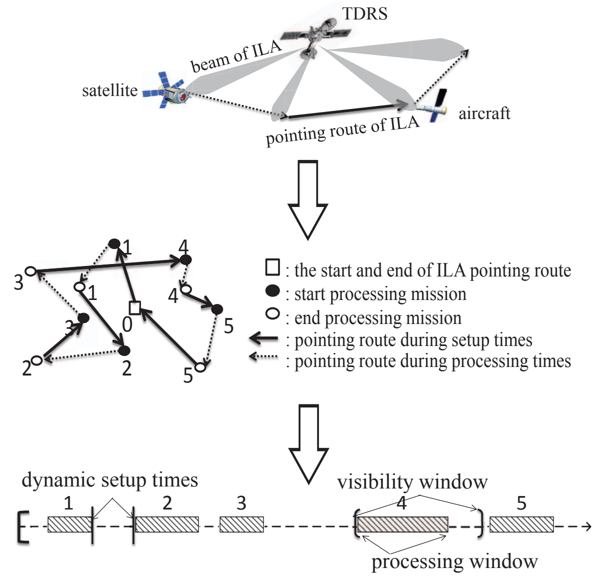

Fig. 1. The principle of our method in the TDRSS scheduling problem

subject to:

$$\sum_{k \in K} \sum_{j \in \delta^+(i)} x_{i,j}^k \leq 1, \quad i \in N \tag{3}$$

$$\sum_{j \in \delta^+(0)} x_{0,j}^k = 1, \quad k \in K \tag{4}$$

$$\sum_{i \in \delta^-(j)} x_{i,j}^k - \sum_{i \in \delta^+(j)} x_{j,i}^k = 0, \quad k \in K, j \in N \tag{5}$$

$$\sum_{i \in \delta^-(n+1)} x_{i,n+1}^k = 1, \quad k \in K \tag{6}$$

$$s_{i,j,t_j^s} = \frac{\max(|\alpha_{j,t_j^s}^k - \alpha_{i,t_i^e}^k|, |\beta_{j,t_j^s}^k - \beta_{i,t_i^e}^k|)}{v_k}, \quad k \in K_1, (i,j) \in A \tag{7}$$

$$x_{i,j}^k(t_i^s + p_i^k + s_{i,j,t_j^s}^k - t_j^s) \leq 0, \quad k \in K, (i,j) \in A \tag{8}$$

$$w_{i,m}^s \leq t_i^s \leq w_{i,m}^e - p_i^k, \quad k \in K, i \in V, m \in M_i \tag{9}$$

$$\sum_{m \in M_i} y_i^m - \sum_{k \in K} \sum_{j \in \delta^+(i)} x_{i,j}^k = 0, \quad i \in N \tag{10}$$

$$x_{i,j}^k \in 0, 1, \quad k \in K, (i,j) \in A \tag{11}$$

The two-level objectives shown in (1) and (2) include maximizing the number of scheduled missions and minimizing the sum of setup times of ILA, respectively. The first one is more important for the users of the TDRSS, compared with the second objective. Therefore, when the scheduled number of two solutions are identical, the solution with less ILA resource consumption is better. The constraints have following physical meannings:

- Constraint (3) states that each mission is processed no more than once by an ILA.
- Constraint (4) guarantees that each ILA is available for scheduling and departs from the start of its pointing route.