Computers and Operations Research 85 (2017) 12–21

Contents lists available at ScienceDirect

Computers and Operations Research

journal homepage: www.elsevier.com/locate/cor

High-performance technique for satellite range scheduling

Kaiping Luo[a,*], Haihong Wang[b,c], Yijun Li[c], Qiang Li[b]

[a] School of Economics and Management, Beihang University, Beijing 100191, PR China
[b] Beijing Institute of Tracking and Telecommunication Technology, Beijing, 100094, PR China
[c] School of Management, Harbin Institute of Technology, Harbin 150001, PR China

ARTICLE INFO

Article history:
Received 4 September 2015
Revised 2 March 2017
Accepted 27 March 2017
Available online 29 March 2017

Keywords:
Optimization
Satellite range scheduling
Conflict resolution
Bounding

ABSTRACT

As the number of daily satellite service requests increases, the satellite range scheduling problem becomes more intractable during the ground station operations management. The NP-complete problem involves scheduling satellite requests to ground station antennas within their time windows so that the profit from the scheduled requests is maximized. This paper analyzes various conflicts between satellite requests and then develops a conflict-resolution technique. The technique first builds an elite initial schedule using a prescheduling strategy and then improves the initial schedule using a rescheduling strategy in a subspace of feasible solutions. *The main highlight of the technique is its dual functions of quickly generating a high-quality solution and providing a good bound.* As shown in the experimental results from the actual data and more difficult random instances, the proposed technique is significantly better than the best-known heuristic.

1. Introduction

Satellite systems play an irreplaceable role in our daily lives and national defense because they provide various convenient services, such as pinpoint navigation, instant communication, more accurate weather predictions, clear Earth observation images, timely missile warning, etc. To support these services, satellites require frequent contact with remote tracking stations. The communication between a satellite and a remote tracking station is often called a *support*.

Satellite range scheduling is the process of scheduling communications between satellites and remote tracking stations to satisfy satellite support requests. More precisely, given a set of satellite requests, a set of ground remote-sensing antennas, and the visibility time window of each request-antenna pair, the total profit from a schedule is maximized, subject to the following constraints: (1) each request should be scheduled within its visibility window; (2) a request will be allocated to at most one antenna; (3) an antenna supports at most one request at a time; (4) an antenna requires enough turnaround time to support its successive request; and (5) a support cannot stop in general once it begins.

As mentioned in Marinelli et al. (2011), the profits may have different interpretations. In the case of mission planning, congestion at the ground station network often prevents all the required navigation services, and these requests must be ranked according to their relevance. Therefore, profit represents command priority. In the case of payload services, profits may represent prices negotiated by the ground station managers with external customers.

The number of daily communication requests becomes larger during the operations management of remote tracking stations. The ground remote-sensing antennas are oversubscribed. For example, over 500 requests in 2003 (Barbulescu et al., 2004) were received on a typical day by the scheduling center of the U.S. Air Force Satellite Control Network (AFSCN) composed of 16 antennas located at 9 ground stations. Similar situations occurred in the National Aeronautics and Space Administration (http://www.nasa.gov), the Indian Space Research Organization (http://www.isro.org), the European Space Agency (http://www.esa.int/), and the China National Space Administration (http://www.cnsa.gov.cn).

From a different viewpoint, remote tracking stations are expensive to build, operate, and maintain. The ground control networks are hardly expanding. As a consequence, an optimal schedule is becoming increasingly important. Unfortunately, this scheduling problem is quite difficult in practice. As mentioned in many papers, Gooley et al. (1996), Barbulescu et al. (2006b); 2004), and Marinelli et al. (2011), the common procedures based on experts and worksheets or other commercial off-the-shelf satellite scheduling packages often yield poor schedules or even infeasible solutions.

In effect, the satellite range scheduling problem is NP-complete (Barbulescu et al., 2004). Thus, some heuristics are proposed. These heuristics will be reviewed in the next section. Among these

---

[*] Corresponding author.
E-mail address: kaipingluo@gmail.com (K. Luo).

http://dx.doi.org/10.1016/j.cor.2017.03.012

heuristics, a meta-heuristic called *Genitor* has the best overall performance on actual AFSCN data and random test data according to the experimental reports of Barbulescu et al. (2006a); 2006b). However, as Wolfe and Sorensen (2000) have emphasized, the superior performance of the genetic algorithm in satellite scheduling is at the expense of a longer running time. This time-consuming aspect was also verified by our experimental results.

Barbulescu et al. (2006b) tried to conduct a few constructive heuristics and then announced that they had not found a good-enough problem-based heuristic for satellite range scheduling. Is there indeed no high-performance constructive heuristic for an NP-complete problem? No, our finding suggests otherwise.

Since the optimal solution of satellite range scheduling cannot be found in polynomial time, it becomes meaningful to explore the tight bounds of the objective function value. The Lagrangian relaxation technique is a good approach to obtaining the bounds for an integer or a mixed-integer programming model. Marinelli et al. (2011) formulated the satellite range scheduling problem as a time-indexed 0-1 programming model and then employed the common technique to calculate the bounds. Although this linear formulation can reduce our efforts of finding the bounds, it raises the difficulty in solving the problem. As those authors stated, the model with hundreds of thousands of Boolean variables and millions of constraints cannot be tackled by standard integer programming techniques.

Hence, we have a motivation for developing a high-performance technique for satellite range scheduling. We note that antennas are oversubscribed and the conflicts between support requests are the root of the intractable problem. Therefore, we analyze various conflicts in satellite range scheduling and then develop a conflict-resolution technique with two phases. In the first phase, a good initial schedule is quickly generated using a prescheduling strategy. In the second phase, the initial schedule is improved using a rescheduling strategy in a search subspace composed of feasible solutions rather than all permutations of support requests.

The idea of the prescheduling strategy is that an inflexible request with a higher profit is preferentially scheduled during an available time window with a minimal impact on untreated requests. In the strategy, the crucial efforts are how to measure the flexible degree of a request and how to seek its available time window with a minimal impact on other untreated requests.

The idea of the rescheduling strategy is to resolve reconcilable conflicts between unscheduled requests and scheduled requests according to an insertion rule, a tabu rule, and a self-adaptive mechanism. In the strategy, the main difficulties are how to identify irreconcilable conflicts and how to find the optimal insertion slots for interchange operations.

The new idea of the proposed technique is to discriminate between reconcilable conflicts and irreconcilable conflicts, and to prohibit ineffective interchanges between unscheduled requests and scheduled requests.

The main highlight of the technique is that it provides two benefits: rapidly generating a high-quality schedule for satellite range scheduling and providing a tight bound.

The remainder of this paper is organized as follows. In Section 2, we review the related literature. Section 3 presents an improved mathematical programming formulation of the satellite range scheduling problem. A new de-conflicting and bounding technique for the problem is proposed in Section 4. Experimental results from old benchmarks and new test instances are reported in Sections 5 and 6, respectively. In Section 7, we illustrate the reason for the high performance of the proposed technique. Finally, Section 8 concludes the paper.

2. Related literature review

We first review the previous works in three aspects: (1) problem complexity, (2) problem solving, and (3) solution quality evaluation.

The satellite range scheduling problem, similar to the vast majority of job scheduling problems, is NP-complete. Barbulescu et al. (2004) proved that satellite range scheduling on a single antenna is equivalent to the problem of minimizing the number of late jobs on a single machine in the traditional scheduling domain and then extended this conclusion to the general satellite range scheduling problem. Arkali et al. (2008) addressed the computational complexities of the low-orbit satellite range scheduling problem in four cases combined by support policy (preemptive or non-preemptive) and reconfiguration time (existent or nonexistent). The low-orbit satellite range scheduling problem is NP-hard, except that it is still open in the preemptible and reconfiguration-free case. In effect, the communication between a low-orbit satellite and a ground station is hardly preempted once the processing is initiated owing to the extremely short visible window. In general, remote-sensing antennas at the ground stations are reoriented to support each passing satellite, and operational parameters are reset to accommodate each allocated request because any satellite support must go through four phases: preparation, acquisition, tracking, and release. In practice, a feasible schedule must take into account the turnaround time of each allocated request on each antenna.

To automate satellite range scheduling, some authors have presented some heuristics. Gooley et al. (1996) developed a two-phase approach based on mixed-integer programming and insertion and interchange heuristics. In the first phase, low-orbit satellite supports are considered; an initial schedule is generated by a mixed-integer programming procedure and then improved by a two-satellite interchange procedure. In the second phase, medium- and high-orbit satellite supports are inserted into this schedule in descending order of their difficulties, and then a three-satellite interchange procedure is implemented to further raise the quality of this schedule. The testing results from actual AFSCN data circa 1992 showed that the heuristic of splitting tasks into low- and high-orbit requests can obtain a good schedule. As illustrated by Barbulescu et al. (2004), however, a greedy heuristic cannot yield an optimal solution and it is no longer a good strategy for larger problem instances.

In view of the fact that genetic algorithms have been successfully applied to job scheduling, Parish (1994) formulated this scheduling problem as a sequencing problem and then employed an order-based genetic algorithm called *Genitor* to solve it. In the meta-heuristic, solutions are encoded as permutations of support requests. A feasible schedule is easily built from the sequence of supports using a simple “first available” rule, namely, assigning the first available antenna from the list of alternatives and at the earliest possible start time. Unlike the orthodox genetic algorithm, in each iteration, Genitor (i) selects two parents according to the rank of individuals’ fitness instead of the fitness itself, (ii) reproduces new genotypes on an individual basis, (iii) performs Syswerda’s order crossover, and (iv) replaces the worst individual in the population without the usual operation of mutation so that parents and offspring can co-exist. As shown in the experimental reports of Barbulescu et al. (2006a); 2006b); 2004), Genitor outperforms stochastic hill-climbing, squeaky wheel optimization, heuristic-biased stochastic sampling, Gooley’s splitting heuristic, and other constructive heuristics (Bar-Noy et al., 2001). However, the better performance of the genetic algorithm in satellite range scheduling is at the expense of more time consumption because it must perform an extra operation of building a feasible schedule to obtain a valid fitness evaluation for a new offspring at each iteration. Moreover, Barbulescu et al. (2006b) indicated that