Computers & Operations Research 57 (2015) 1–16

Contents lists available at ScienceDirect

Computers & Operations Research

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

Optimization-based scheduling for the single-satellite, multi-ground station communication problem

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ARTICLE INFO

Available online 9 December 2014

Keywords:
Scheduling
Resource allocation
Integer programming
Satellite operations

ABSTRACT

In this paper, we develop models and algorithms for solving the *single-satellite, multi-ground station communication scheduling problem*, with the objective of maximizing the total amount of data downloaded from space. With the growing number of small satellites gathering large quantities of data in space and seeking to download this data to a capacity-constrained ground station network, effective scheduling is critical to mission success. Our goal in this research is to develop tools that yield high-quality schedules in a timely fashion while accurately modeling on-board satellite energy and data dynamics as well as realistic constraints of the space environment and ground network. We formulate an under-constrained mixed integer program (MIP) to model the problem. We then introduce an iterative algorithm that progressively tightens the constraints of this model to obtain a feasible and thus optimal solution. Computational experiments are conducted on diverse real-world data sets to demonstrate tractability and solution quality. Additional experiments on a broad test bed of contrived problem instances are used to test the boundaries of tractability for applying this approach to other problem domains. Our computational results suggest that our approach is viable for real-world instances, as well as providing a strong foundation for more complex problems with multiple satellites and stochastic conditions.

1. Introduction

The potential for small satellites to perform novel science, observation, and technology missions is being realized worldwide across academic, government, and industry settings. Satellites gather and store data as they orbit the Earth, and require a supporting network of ground stations to receive and distribute this data [1–7]. The existing ground station infrastructure for these missions has largely been monolithic, designed and used by independent organizations for a handful of satellite missions to date. However, federated ground station networks, consisting of autonomous, globally distributed ground stations, are now beginning to form [8]. The need to efficiently download data from the growing number of satellites to the existing and future ground station network gives rise to scheduling problems that are particularly challenging due to the exchange of limited resources between space and ground entities.

The goal of the research presented in this paper is to develop models and algorithms for building communication schedules for a single satellite and a heterogeneous network of globally distributed ground stations, so as to maximize the amount of data downloaded to Earth; we call this the *Single-Satellite Multiple-Ground Station Scheduling Problem* (*SMSP*).

The contributions of our research are three-fold. *First*, we develop models and algorithms that enable us to solve real-world instances of *SMSP* in acceptable run times. *Second*, our research lays the foundation for solving more complex satellite scheduling problems, such as those in which there is stochasticity in the system (e.g. uncertainty as to the availability of the ground stations) as well as problems in which there are multiple satellites competing for the same ground station resources. *Third*, the theoretical insights gained in this research have relevance for many other applications in which tasks must be scheduled subject to resource acquisition, storage, and utilization constraints.

The remainder of the paper is outlined as follows. Section 2 places our research problem in the context of the related existing literature. In Section 3, we formally state the problem and present a continuous-time model to demonstrate the physical dynamics of the system. In general, the associated non-linear optimization problem is not tractable except for limited special cases. We therefore develop a discretized *mixed-integer programming (MIP)*

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http://dx.doi.org/10.1016/j.cor.2014.11.004
0305-0548/

formulation in Section 4, which under-constrains the problem. A special case in which this model is guaranteed to yield optimal solutions to the original problem is discussed in Section 5, with corresponding computational results provided. For the more general case, we present an iterative algorithm in Section 6 that progressively tightens the constraints to converge to a feasible and thus optimal solution. Note that this approach differs from conventional cutting-plane algorithms in that it introduces new variables and constraints and solves a newly defined (and larger) problem at each iteration. Computational experiments are presented in this section as well, to demonstrate tractability and investigate problem structure. We conclude in Section 7 with a summary and suggestions for future research.

2. Literature review

There is a large body of related research on spacecraft operations and scheduling; however we have not encountered any other research explicitly studying *SMSP* as it is formulated in this paper. First, we review the well-studied problem of scheduling imaging spacecraft due to its extensive literature and similarities to the spacecraft communication scheduling problem. Next, we discuss approaches to solving spacecraft downlinking optimization problems. Finally, we describe limitations of the existing work and how our approach fits within the context of the existing literature.

A very common scheduling problem addressed in the literature is the *Earth Observing Satellites*scheduling problem (*EOS*). In *EOS*, the goal is to take the maximum number of high-priority observations with on-board spacecraft sensors during a given time period. This problem is similar to *SMSP* in that they both consist of scheduling a set of complex tasks involving the exchange of limited resources between an orbiting spacecraft and Earth-based targets. [Key differences between the problems are discussed in the following paragraph.] Additionally, data and energy are collected and consumed in both problems, providing restrictions on when and how the desired tasks can be performed. *EOS* is often generalized to a more common problem structure, such as a knapsack problem [9–12], a packing problem [13], a single-machine scheduling problem [14], or a network flow problem [15]. Constraint programming is used by others [11,12,16,17]. One of the most common approaches in solving *EOS* is a greedy algorithm based on spacecraft priorities [11,13,18–21]. Other common techniques include dynamic programming [11,15], heuristic approaches [19,22,23], and genetic [9,13,14,22,24]. Look-ahead methods are used by [13], look-behind pre-emption methods by [25], repair-based iterative schemes by [26] and [27], and particle swarm optimization by [16]. Other methods used to solve *EOS* include prune and search trees [28], branch and bound procedures [29], and tabu searches with intensification and diversification [10,30]. Finally, [24] provides a comparison of several strategies for solving *EOS*, including a genetic algorithm, hill climbing, simulated annealing, squeaky wheel optimization, and iterated sampling implemented as permutation-based methods.

Despite the similarities between *EOS* and *SMSP*, there are differences in the problem objectives, decisions, and constraints. For example, in addition to decisions on *when* to download, *SMSP* includes decisions on *how* to download (i.e. what data rate, energy utilization, and efficiency), which governs the relationship between the energy and data consumed during downloads. Thus *SMSP* must be modeled and solved in a new way. However, much of the *EOS* literature is informative in developing these models and algorithms.

Conventional approaches to satellite operations often use greedy scheduling, where the satellite performs mission operations and downloads data at every feasible opportunity. This approach may be sub-optimal since in some cases it may be preferable to store resources for a future time period with more beneficial download options.

Only a handful of researchers have studied the scheduling of spacecraft downlinks [22,23,31–33]. Ref. [31] considers multiple spacecraft downlinking. Polynomial time algorithms are used to solve several special cases, including a greedy algorithm and an approach based on exploiting a longest-path formulation in a directed acyclic graph. Ref. [32] focuses on minimizing the communication time required to meet the download constraints of a system with multiple spacecraft and ground stations. They formulate and solve a non-linear constrained optimization problem, showing results for small network examples with a simplified set of communication parameters and constraints. Ref. [23] studies a hierarchy of successively more complex spacecraft scheduling problems and propose a tight time-indexed formulation. A Lagrangian relaxation heuristic is implemented to solve the scheduling problem and results are shown for the GALILEO constellation; however spacecraft energy collection, storage, and consumption are not considered in the analysis.

In general, the formulations and approaches in the literature towards optimizing satellite downlink schedules ignore important logistical constraints (e.g. on-board energy and data buffers) necessary in *SMSP* and treat only small-scale problem instances. More sophisticated models relative to those presented in the literature are required to accurately represent the realistic constraints of *SMSP*, including representations of on-board data storage, communication systems, and energy management systems. Higher levels of modeling fidelity are also required, as is the ability to extend the model to incorporate the even greater challenges of multiple spacecraft and multiple ground stations concurrently, as well as to address system stochasticity. Developing such models, as well as the corresponding algorithms to find high-quality solutions in acceptable run times, is the goal of our research.

3. Problem description and system dynamics

The goal of *SMSP* is to maximize the amount of data downloaded to a network of ground stations from a single spacecraft orbiting the Earth. In this problem, we assume the following:

- A single satellite is orbiting Earth, collecting both data (via on-board instruments) and energy (via solar panels) along its orbit.
- The satellite's energy and data acquisition rates may vary over time. For example, the collection of data depends on whether the spacecraft is in view of a target of interest (e.g. a science or surveillance target) and the collection of energy depends on the line of sight of the solar panels relative to the sun.
- Energy is required to conduct basic operational functions of the spacecraft and download data.
- The satellite has finite limits on the amount of energy and data that can be stored at any given time.
- We assume that the spacecraft orbit is deterministic and known such that the access times to the globally distributed ground stations are known a priori.
- There are multiple ground stations to which the satellite can download, each of which periodically comes into view of the satellite. Note that the view periods have variable durations, which depends on the geometry of the orbit relative to the ground station.
- More than one ground station may be in view of the satellite simultaneously, but the satellite can only download to one ground station and at one data rate at a time.
- Ground stations may vary in their characteristics, both with respect to the rate with which they may receive data (bits-per-second) and the energy utilization from the satellite required to do so (Joules-per-bit). Ground stations also vary in the *efficiency* of the data download (i.e. the fraction of transmitted data that