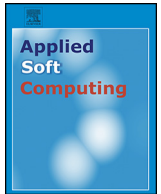




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An evolutionary approach towards contact plan design for disruption-tolerant satellite networks

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ABSTRACT

Delay and disruption tolerant networks (DTNs) are becoming an appealing solution for satellite networks where nodes can temporarily store and carry in-transit data until a link with a suitable next-hop becomes available. Since satellite trajectories and orientation can be predicted, on-board routing schemes can base these forwarding decisions on a contact plan comprising all forthcoming communication opportunities. In general, contact plans are previously calculated on ground where their design can be optimized to consider not only available spacecraft resources but also the expected traffic which is largely foreseeable in space applications. Despite optimal contact plan design procedures exist, their computation complexity might result prohibitive even for medium-sized satellite networks. In this work, we propose an evolutionary algorithm to provide sub-optimal yet efficient and implementable contact plans in bounded time. In particular, we depict specific strategies such as encoding and repairing techniques to later evaluate the algorithm performance in a typical scenario demonstrating its usefulness for planning future DTN-based satellite networks.

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1. Introduction

Today, optical and radar images are acquired continuously from orbit as they enable better understanding and improved management of the Earth and its environment. In particular, orbiting networks of distributed satellite sensors are emerging as a mean to extend Earth observation missions revisit time and ground coverage [1]. In order to optimize space-to-ground data delivery in satellite networks, nodes can cooperatively pass sensed data among them before establishing the final communication with the receiving ground station. To this end, satellites shall rely on efficient network protocols and algorithms properly designed to operate over inter-satellite links (ISLs) [2].

In the Internet, protocol operations are largely based on instant flow of information between sending and receiver nodes. However, in a space flight mission environment, the highly varying communication ranges on which mobile nodes have to operate, compels to face several disruptive situations [3]. For example, Fig. 1 illustrates a network of satellites with polar orbits where connectivity among them can only be guaranteed over the pole as ISL distances are minimal. Previous work has proposed to constrain ISL distances by applying strict flight-formations [4]; but later analysis showed that

disruptions could be handled by considering delay and disruption tolerant networking (DTN) architecture [5].

Originally proposed in [6], DTN protocols assumes no continuous connectivity throughout the network. In particular, lapses in wireless links may be routine, lengthy, and recurring and should not be interpreted as errors or unwanted changes in topology. Indeed, the interval of time during which data may be passed from one node to another over a link is defined as a *contact*. However, the impermanent nature of contacts compels the nodes to have local storage for temporary retention of data which cannot be forwarded immediately. As a result, information can flow between nodes through contacts in a *Store-and-Forward* fashion until reaching its final destination. This forwarding scheme is illustrated in Fig. 2, where node 1 sends data to node 3. Since there is no direct communication between the source and destination nodes, data needs to go through intermediate node 2. However, a sporadic link exists between nodes 2 and 3, which requires to store in-transit data on the local storage of node 2 until the contact with node 3 is available.

In general, episodes of communication between satellites and ground stations on Earth are typically scheduled weeks or months before they occur. Specifically, the beginning and end of each contact can be accurately computed from known orbital elements on ground [7]. As a result, all forthcoming network communication opportunities, including ISLs, can be imprinted in a *contact plan* (CP) which can be conveniently provisioned to DTN nodes in advance [8]. Then, as traffic flows in the network, on-board routing schemes

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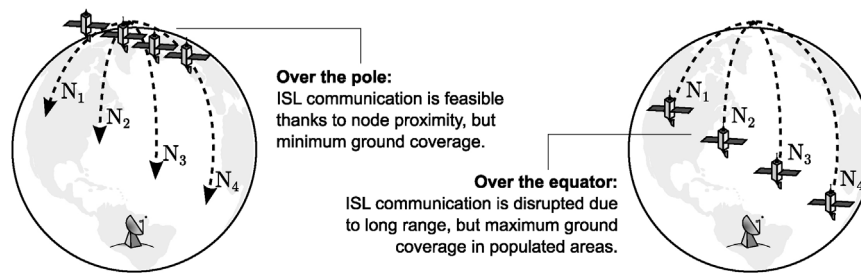


Fig. 1. Orbiting network of 4 polar orbit satellites.

can take advantage of this topological information to take efficient forwarding decisions.

Recent research has suggested to further adapt and optimize CPs in accordance with available on-board transceivers on each node [9]. This process became known as *contact plan design* (CPD) and has received increasing attention from the community as different criteria can significantly impact the final network performance [10–15]. Among existing schemes, the Traffic-Aware Contact Plan (TACP) [15] was proposed in 2016 as a suitable scheme for satellite networks as it considers all possible parameters including the expected amount of traffic and its generation time. Indeed, data acquisitions from on-board instruments are also centrally scheduled by a mission control center on ground [16].

Nonetheless, TACP operating performance relies on a mixed integer linear programming (MILP) formulation whose computation complexity becomes intractable even for medium-sized networks. The latter becomes a critical issue in DTN satellite networks where CPs have to be timely provisioned to orbiting nodes. In order to guarantee bounded duration in the CPD cycle, this article contributes with an heuristic alternative to TACP based on evolutionary algorithms (TACP-EA). Even though a similar algorithm based on simulated annealing have recently been proposed for the CPD problem [14], it assumes as optimization criteria tailored for navigation constellations with unpredictable traffic. To the best of authors knowledge, this is the first time an heuristic approach is proposed for the CPD of Earth observation satellite networks with scheduled traffic.

This work is an archival quality version of the article [17] with a more detailed explanation on the algorithm and an extended and improved performance analysis. The article is structured as follows. In Section 2 we provide a general overview of the CPD problem and the design constraints to later describe TACP and discuss its computational limitations. In order to overcome the latter, we describe TACP-EA as an alternative approach in Section 3. Next, in Section 4 we evaluate the performance of TACP-EA in a Low Earth Orbit (LEO) satellite network example to finally draw the conclusions in Section 5.

2. Contact plan design overview

Colloquially, a contact can be defined as a communication opportunity between DTN nodes. In practice, the information encoded in a contact include source and destination node, start and end time, and expected data rate. Indeed, these parameters

can be calculated on ground by means of precise orbital mechanics comprising position, range, and attitude (orientation of the spacecraft in the inertial system) [7]. Also, the resulting values such as transmission power, modulation, bit-error-rate, etc. can be further adjusted based on wireless communication models. Finally, the set of all feasible contacts within a given time *interval* are imprinted in the CP and provisioned to the orbiting DTN nodes. Protocols for distributing CP information has been studied in [18], but they are beyond the scope of this article.

Once on-board, the CP is used by existing distributed routing schemes such as contact graph routing (CGR) [19] to determine the optimal next-hop for a given packet flow. In particular, CGR runs in each DTN node, and creates a *contact graph* based on the CP where a modified Dijkstra's search can be executed. Furthermore, CGR considers the data rate encoded in the contacts in order to avoid overbooking of future links (i.e., congestion) [20]. The interested reader can refer to [19] for an extended analysis on how distributed routing exploits the data encoded in CPs.

Unfortunately, due to limited resources in satellite platforms, e.g., limited available transceivers, not all calculated contacts in a CP can be implemented. For example, a node may have potential contacts with more than one node at a given time but only one of these opportunities can be utilized taking into account one transceiver on-board. As a consequence, only a subset of the feasible contacts can be activated simultaneously in the final CP [9]. The latter selection process is known as CPD, and should be carefully addressed in order to schedule those contacts that resolve possible resource conflicts as described below.

2.1. Design constraints and procedures

Among the resource limitations of traditional satellite architectures, authors have classified and analyzed those concerning wireless communications [9]. For instance, the simplest yet more frequent constraint is evidenced when a spacecraft antenna radiation pattern allows to reach two or more neighbors as shown in Fig. 3(a). However, multiple channel access schemes is generally discouraged in satellite networks due to the impact of the negotiation overhead over long distances [21]. As a result, even though two simultaneous contacts are feasible, only one can be included in the final CP. Next, Fig. 3(b) and (c) illustrates a similar situation where two antennas and two transceivers are available on-board, but only one of them can be enabled at a given time. Also, when considering electronically or mechanically steerable antenna techniques

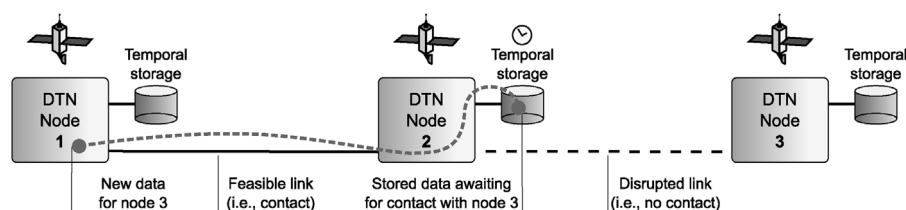


Fig. 2. Store-and-Forward scheme in DTN.

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