

On the Trade-off Analysis of Centralized and Distributed Routing in Delay Tolerant Satellite Networks

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Abstract

Given that satellite networks cannot assume continuous connectivity among nodes, an architecture known as Delay Tolerant Networking (DTN) has been proposed as an appealing communication paradigm. However, as space networks continue to grow in both number and size, the process of routing and forwarding traffic is rapidly becoming computationally expensive and challenging. Since these networks usually exhibit predictable trajectories and communication opportunities, the research community has proposed to provide nodes with scheduled contact plans in advance in order to make distributed routing decisions as they generate or receive traffic. On the other hand, a more attractive solution for the conservative space industry seems to be a centralized scheme. Based on a Software-Defined Network (SDN) approach, a route table can be computed on ground and then provisioned to nodes in space, which would no longer run any routing intelligence on board, only forwarding. In this work we analyze the dichotomy between distributed and centralized routing schemes in the context of DTN and provide insights regarding important aspects to take into account when designing and managing satellite networks.

1 Introduction

Large-scale satellite networks are becoming increasingly popular as a means to provide high quality imagery, video and communication services around the globe [1]. Efficient space-terrestrial communication technologies, capable of successfully moving large volumes of data between space and ground networks, are a key element in these networks. In this context, Delay Tolerant Networking (DTN) has been identified as a novel approach which can meet this goal in a cost-effective way by relaxing communication requirements and network infrastructure usually assumed in traditional protocols. The DTN architecture, originated from deep-space and interplanetary networking, embraces the concept of occasionally-connected networks that may suffer from frequent partitions, high delay, and that may be comprised of more than one divergent set of protocols [2]. To this end, a *bundle layer* that exists at a layer above the transport (or other) layers of the network, employs a persistent storage on each DTN node to store-carry-and-forward data packets called *bundles* as transmission opportunities become available.

In the case of space-based networks, the forthcoming episodes of communications and their properties can be determined in advance based on orbital dynamics. These types of deterministic DTNs are known as scheduled DTNs, and can take advantage of a *contact plan* comprising the future network connectivity in order to optimize data forwarding. Indeed, as showed in previous works [3, 4, 5, 6, 7, 8], contact plans can be properly designed in order to optimize data delivery and/or reduce energy consumption. Furthermore, the use of distributed routing solutions such as Contact Graph Routing (CGR) [9, 10] allows each DTN node to make efficient routing decisions based on the beforehand provisioned contact plan as they generate or receive traffic.

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On the other hand, a more attractive and controllable solution for the conservative space industry seems to be a centralized Software Defined Networking (SDN) approach [11]. In this case, each route table can be computed with a CGR or other routing algorithms on ground, and then provisioned to nodes in space, which would no longer run any routing intelligence on-board, only forwarding.

In this context, the present work aims to provide an analysis on the trade-off between a distributed and a centralized utilization of CGR algorithms. In Section 2 we provide some background on how routing is carried out in space DTNs. Then, in Section 3 we describe the specific routing schemes which will be analyzed by means of simulations. Afterwards, in Section 4 we evaluate the schemes through simulations of two realistic satellite constellations. Finally, we discuss the relevance of the results and summarize them in Section 5.

2 Background

2.1 Store-Carry-and-Forward

In DTN, Bundle Protocol data units (called *bundles*) are forwarded in a store-carry-and-forward fashion without assuming the next-hop node will instantly be available to respond. Figure 1 illustrates a typical delayed and disrupted space-terrestrial network where a rover in another planet (node 1) needs to send bundles to a ground station (node 3). Since there is no direct communication between the source and destination nodes, data needs to go through an intermediate satellite (node 2). However, because of signal propagation, the transmission opportunity window (a.k.a. *contact*) between node 1 and 2 is highly delayed, forbidding node 1 to assume node 2 can instantaneously confirm reception of bundles. Also, the communication between nodes 2 and 3 is temporarily disrupted and will not be available until a time specified in the future. Thus, once bundles are received in node 2, it decides to retain and carry in-transit data in its local storage until reaching the ground station communication range, allowing the final data transmission to start. In this type of scenarios, the lack of a stable end-to-end path restricts the utilization of end-to-end feedback messages and encourage error detection and correction, security, and other network features to be implemented on a hop-by-hop basis.

2.2 Temporal Routes

It should be noted that, in this kind of networks, routing involves not only determining the next-hop node, but also considering time variables such as when the next-hop will be available or when is the latest time a

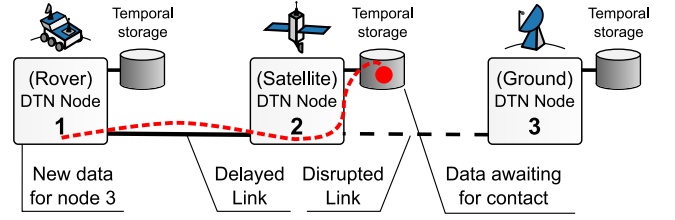


Figure 1: Store-carry-and-forward flow in space DTNs

bundle can be transmitted. Therefore each temporal route is conformed by a sequence of contacts, which, as we describe in the next section, result predictable in space DTNs and can be exploited with different schemes in order to achieve a good network performance.

2.3 Workflow in Space DTNs

As shown in Figure 2, the workflow in space DTNs goes through four stages: (i) planning, (ii) routing, (iii) enqueueing and (iv) forwarding.

In the planning stage (i), contact plans are determined by a central entity (a ground station or a Mission Operation Center (MOC)) based on the estimation of future episodes of communication. This task involves taking into account the physical disposition and orientation of nodes through time as well as their communication system configuration (antenna, modulation, transmission power, etc.). As a result, orbital propagators and communication models are combined to determine the contact plan which can be further tuned to reduce energy consumption or remove conflicting contacts [6, 7, 8]. Furthermore, unlike the In-

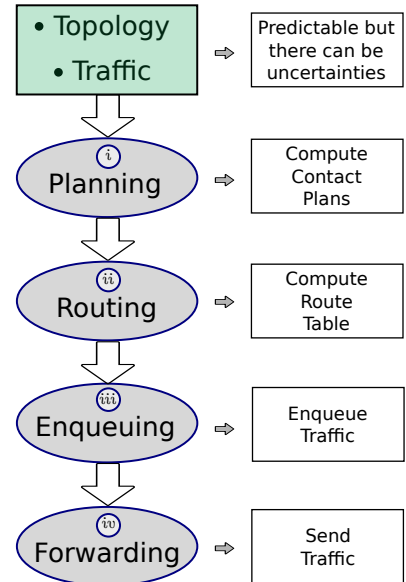


Figure 2: Workflow in space DTNs

ternet, network traffic can be predicted in some types of satellite networks such as Earth observation missions where data acquisitions are generated by operator commands. In general, although there can be uncertainties regarding the topology or the traffic in the future, both have a predictable nature and can be used as a valuable input in the planning stage. Afterwards, a routing procedure **(ii)** takes the contact plan as input to compute a route table, which can then be used by satellites to send bundles to destination. Currently, the most investigated routing scheme for predictable DTNs is Contact Graph Routing (CGR) [9] and is therefore considered in this work. This stage can be accomplished in two different ways. In a centralized approach, both the contact plan and the route table are computed by a central entity, after which it is distributed to all satellites. In a distributed approach, only the contact plan is provided to satellites, after which it can be used to compute routes when necessary and by demand. Then, either in the centralized or distributed scheme, when a local or in-transit data bundle needs to be sent, satellites carry out an enqueueing process **(iii)**, which consists in traversing the route table, selecting the best valid route to destination, and enqueueing the bundle to the neighbor node corresponding to the first contact of the selected route. Finally, when a contact with a neighbor node occurs, satellites perform the forwarding process **(iv)** by dispatching all the bundles enqueued to that neighbor.

2.4 Schemes Comparison

A conceptual comparison of the distributed and centralized use of CGR routing is summarized in Table 1. The main advantage of the centralized scheme is given by the reduction of the computation effort that will be performed on constrained on-board satellite comput-

ers. However, this advantage comes at the expense of having to provide additional routes to cover the uncertainties with respect to the topology and/or the traffic generated. On the other hand, the distributed approach provides a greater routing intelligence and computation effort to satellites, which allows to tolerate faults and uncertainties without incurring in the routes information overhead. In this work we will analyze this trade-off by means of satellite constellation simulations. Particularly, we will put the focus on the schemes described in the next section.

3 System Model

Regarding the distributed CGR strategy, we will consider two different possibilities. On the one hand, we will call *Distributed CGR Full Route Table* to the state-of-the-art algorithm as it is implemented in the ION 3.5.0 flight software. In this case, each node computes a complete route table to a given destination whenever it receives a bundle for that destination. In other words, the route table has as many entries as routes is able to discover the CGR algorithm. The interested reader is referred to [12] for a detailed implementation of this routing protocol. On the other hand, we will call *Distributed CGR Limited Route Table* to a modified version of CGR where the route table to a destination is limited to one route per neighbor. That means that there can be only one route to a given destination through a certain next neighbor node. This strategy was proposed, described in detail, and compared with others in the work presented in [10].

With respect to the centralized strategy, we will call *Centralized CGR Full Route Table* to the scheme in which a central MOC node, analogous to a SDN controller, is in charge of computing and providing the complete route table for each other node in the net-

Table 1: Comparison of distributed and centralized use of CGR

Distributed CGR	Centralized CGR
Each node has the intelligence to calculate route tables in orbit and by-demand based on a previously distributed contact plan.	A central node (i.e., mission control on ground) calculates and distributes route tables in advance.
Will calculate those routes that are strictly necessary to forward traffic (scales better).	Will calculate several routes that probably will not be finally used (high provisioning and memory overhead).
Better adapt and react to unexpected events (unexpected traffic sources, contact failures, etc).	Reaction to unexpected events will require alternatives routes distributed in the route table (high provisioning and memory overhead).
Difficult to optimize and control what each node calculates in the end, thus how the traffic will flow.	Allow for more controlled calculation and optimization of the whole network.
In-orbit nodes need to use its local processor to calculate route tables (high in-orbit processing overhead).	Free in-orbit nodes resource-constrained processors from calculating complex paths.

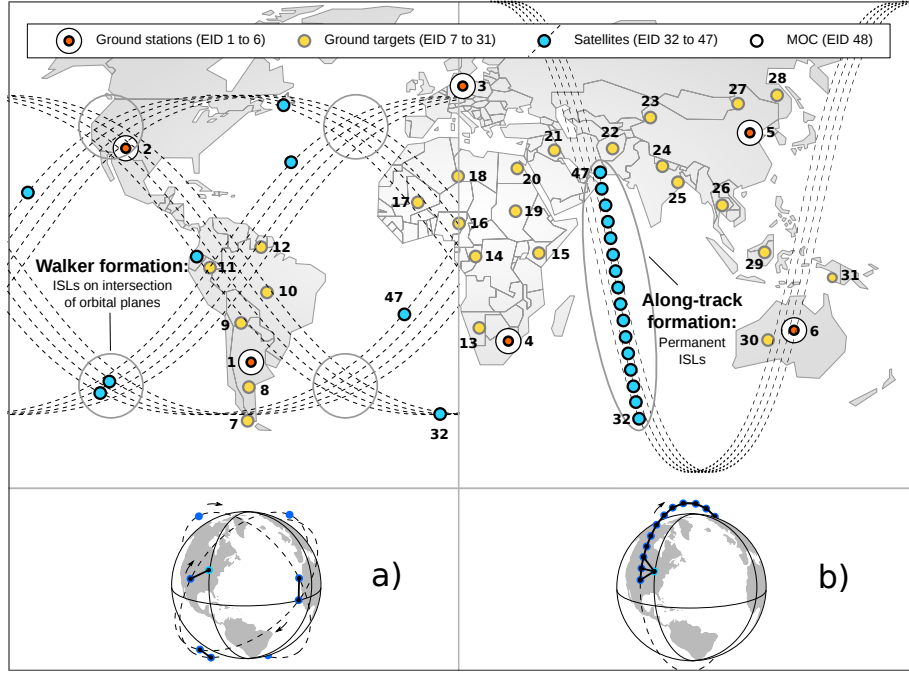


Figure 3: Simulation case studies: a) Walker formation, b) Along-track formation

work. To this end, the same CGR used in distributed approaches was executed on the topology on a centralized node and resulting paths were recorded and provisioned to nodes in advance. Once nodes receive their respective route tables, they only need to make enqueueing and forwarding decisions. Unlike the distributed case, if the full route table were limited in this case, nodes would not be able to compute new routes on demand in the case of uncertainties or unexpected events. Given that this would provoke a considerable performance reduction in terms of bundles delivered, we will not consider a Centralized CGR Limited Route Table strategy in the present analysis.

4 Simulation Analysis

In order to analyze the proposed schemes, we have adapted and extended a discrete event-driven simulator publicly available called DtnSim [13]. We run simulations of the two realistic satellite constellations depicted in Figure 3. A walker-delta formation (a) and a sun-synchronous along-track constellation (b), both composed of 16 cross-linked LEO satellites (max. link range of 1000 Km at 500 Km height) with ids 32-47, 25 ground target points (e.g., user terminals) with ids 7-31, and 6 ground stations with ids 1-6 connected through Internet to a central MOC node with id 48. These scenarios have been previously presented in [10] and are reconsidered in this analysis under a time horizon of 6 hours.

The chosen constellations are suitable for Earth

observation missions, data-collection or high-latency communication systems. If used for Earth observation, the ground target locations would represent points of interest from which on-board instrumentation can acquire optical or radar images, or other remote sensing data. If used for data-collection or high-latency communication systems, ground targets would stand for ground-based equipment relaying either science or local user data. In both cases, data sent from ground targets are addressed via orbiting satellites to the centralized MOC. We consider a bi-directional publish/subscribe traffic pattern from all ground targets to the MOC and reversal. In particular, each ground target generates an increasing number of bundles of 125 KBytes to be delivered to the MOC. In turn, the MOC sends an increasing number of bundles to each ground target. Besides, the transmission data-rates for both inter-satellite and Earth-to-satellite links are set to 100 Kbps.

We quantify the routes information overhead of the schemes proposed in Section 3 through the number of route table entries created in each case. Figures 4 a) and 4 b) show the results for the walker-formation and along-track scenarios respectively. The *Centralized CGR, Full Route Table* strategy provides the same quantity of route table entries independently of the increasing traffic, given that this scheme is proactive in terms of routes computation and does not take into account the traffic generation. As we previously discussed, this overhead information is necessary in order to face uncertainties both in the predicted topol-

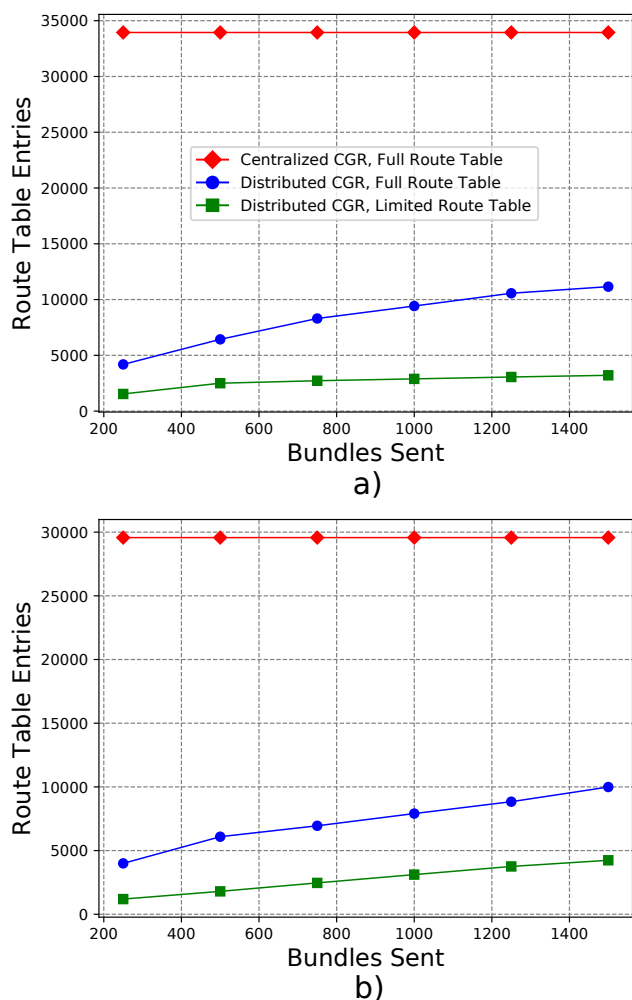


Figure 4: Results for the a) Walker-formation scenario and the b) Along-track formation scenario

ogy or the traffic generated. On the other hand, the distributed approaches compute route tables as traffic is generated and routed through intermediate nodes. Therefore, these schemes compute a much smaller number of routes. Besides, as expected, the *Distributed CGR, Limited Route Table* scheme generates fewer route table entries than *Distributed CGR, Full Route Table*.

5 Conclusions

In this work, we have described and analyzed aspects concerning distributed and centralized routing solutions for satellite-based Delay Tolerant Networks (DTNs). The centralized approach was evaluated as a means to implement a Software Defined Networking (SDN) paradigm into DTN space networking.

We have evaluated the route table entries metric in two realistic satellite constellations and the results provided evidences on the quantity of routes which were

computed but not used by the centralized scheme as compared to distributed schemes. Although this study suggests that distributed approaches are appealing regarding the use of computed information, other relevant aspects like the cost of processing in space nodes and the required controllability of the network need to be taken into account when deciding the most appropriate scheme. Future work will explore other comparison metrics between distributed and centralized routing in order to derive a complete evaluation framework that facilitates future space DTN designers to make an informed decision on the optimal routing strategy.

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