Algorithmic Solutions For Schedule-Aware Bundle Routing

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1 Motivation: Routing in Delay-Tolerant Space Networks

Interplanetary networks are challenged by extensive signal propagation *delays* and *disruptions* caused by planetary occlusion. These issues necessitate using multi-hop strategies to improve reliability and reduce delivery delays [7]. Likewise, utilizing a few Low-Earth Orbit (LEO) satellites in a Ring Road Network (RNN) offers an economical alternative to massive constellations, achieving widespread surface connectivity but facing challenges primarily from *disruptions* that render increased latency [5].

In such networks, nodes utilize the Delay- and Disruption-Tolerant Networking (DTN) architecture [2] and the Bundle Protocol [1]. This setup enables in-transit nodes to minimize message exchange and to store protocol transfer units, known as bundles, for extended periods until the next transmission opportunity arises. In space networking, the trajectories and orientations of satellites, landers, and probes can be forecasted and scheduled beforehand. This allows for creating a *contact plan* detailing future network connectivity, which routing routines can use to optimize data forwarding decisions.

In this context, the Consultative Committee for Space Data Systems (CCSDS) has introduced the Schedule-Aware Bundle Routing (SABR) standard as the preferred routing method for pre-planned space Delay-Tolerant Networks (DTNs). Furthermore, the Interagency Operations Advisory Group's *Future Mars Communications Architecture* final report identifies DTN and SABR as crucial components for the upcoming Mars network infrastructure.

2 Problem: Schedule-Aware Bundle Routing

SABR defines a route as a sequence of contacts from a source to a destination. The network topology is a multigraph (there can be multiple contacts between two nodes), with nodes as vertices and unidirectional contacts as arcs (an alternative description exists). Each contact has a specific start time, end time, data rate, and propagation delay.

Bundle arrival at a node is the sum of its transmission end time and the contact's delay. Transmission to a neighbor must start after the contact begins and end before it finishes. Transmission starts when the contact begins, or when the bundle arrives at the local node, whichever is later. The transmission end time is determined by the transmission start time, the bundle size, and the contact data rate.

The optimal route for a bundle is the one that ensures the earliest arrival time and the least hops from source to destination, using sequential contacts. If two routes have the exact arrival time, the one with fewer hops is chosen. Additional tie-breaking rules are detailed in the standard. SABR is an on-board approach and intends to efficiently solve the problem of route construction and reuse for spacecraft highly constrained in computational resources.

3 Solutions: CGR and SPSN

Contact Graph Routing (CGR) [6] is the standard implementation of SABR, involving route construction and selection processes. When scheduling a bundle, the selection process activates, comparing candidate routes based on SABR's tie-break rules to determine the best route for each destination's routing table. The candidate list is formed by pre-filtering to eliminate routes unsuitable for end-to-end transmission.

If no candidates exist, the procedure defaults to route construction. This involves an infinite loop using Yen's K-shortest path algorithm (treating K as infinite), which supplies new routes to the selection process one at a time. It pauses when a route successfully passes the selection's pre-filtering. Notably, route construction does not consider the size of the bundle.

CGR has been shown to have scalability issues, and recent studies have identified operational risks such as excessive memory usage and processing time for scheduling a single bundle, even in relatively small networks [4]. Additionally, the Dijkstra implementation in CGR sometimes fails to consistently identify the best existing route due to conflicts in predecessor assignments within Dijkstra's algorithm.

To address these issues, the shortest path tree routing for Space Networks (SPSN) was enhanced in [3]. Following the reuse principle, the algorithm generates shortest-path trees rather than paths for individual destinations, necessitating a redefinition of DTN concepts and graph structure as per section 2. Secondly, SABR's selection prefiltering is incorporated into the pathfinding algorithm, allowing for the creation of at most one tree per bundle alongside specific checks to identify potentially filtered and viable paths for future bundles with fewer constraints. Lastly, Dijkstra's algorithm iterations, termed RouteStages, are stored as follows: in Dijkstra's priority queue and node-specific lists ordered according to SABR's tie-break rules. A RouteStage is added to the priority queue only if it meets the criteria for insertion into the node-specific list, and insertion triggers pruning of the list if applicable.

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