Precomputed routing on a Store and Forward satellite system

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***Abstract*—Satellite constellations like Orbcomm provide store and forward message communication services. Inter-satellite links (ISL) are not considered in order to keep the system simple and the costs moderate ([1], [2]). Rather, gateways may act as relays between satellites. In this context, routing is important because it helps to control the end-to-end delay and resources utilization (e.g. on-board memory). However, routing must face frequent changes and partitioning of the network because of the satellite motion. Similar routing problems have been studied in the transportation field (e.g. subway and railways). In this contribution, the Shortest Path Problem with Time Windows (SPPTW) is applied to satellite constellations and a pre-computed routing algorithm is derived. Simulation results show how this algorithm reduces the end-to-end delay of the routes.**

***Index Terms*—Asynchronous messaging, pre-computed routing, store and forward routing, delay tolerant networks, shortest-path with time windows, satellite constellation networks.**

I. Introduction

Systems like mobile ad-hoc networks, mobile sensor networks, deep space networks, battlefield communications and Store and Forward (S&F) satellites face challenges induced by the environment (high and variable error rates, long delays, disruption events, etc.). The absence of instantaneous end-to-end paths or frequent interruptions compromise traditional networking techniques. The Delay Tolerant Network (DTN) architecture addresses these challenging environments and proposes a S&F message switching paradigm (see [3]–[5]).

In the context of satellites, digital payloads for S&F systems have been proposed since 1973 ([6]). The first one has been placed in orbit in 1984 within the SSTL's UoSAT-2. S&F satellites convey stored information messages along their orbits. In combining them with gateways (GW) acting as relays, information can hop from one satellite to another in order to reach destination faster than waiting for a single satellite to fly over the destination. To the extent of our knowledge, the combination of relaying gateways and S&F satellites has never been addressed in the routing literature.

This kind of system presents similarities with transport networks, in particular with deterministic and scheduled systems like subway, rail, or airplane transports.

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This work applies transport routing concepts to solve a *Shortest Path Problem with Time Windows* (SPPTW) ([7]) in a satellite communications system. Section II describes a satellite system designed to offer short-message services to geographical areas where terrestrial communication infrastructure is scarce. The scenario conditions and the routing problem to solve are described as well. Section III presents an algorithm to find optimal routes following a pre-computed approach. Section IV presents simulation results showing the algorithm performance and its analysis. Finally, conclusions and future research directions are addressed in Section V.

II. Scenario Description

A. The context

This Section describes a Low Earth Orbit (LEO) satellite constellation offering S&F services including messaging, tracking and monitoring. It has been designed for the purpose of this study.

1) Description of the satellite system: This system offers messaging services to areas where the density of communication infrastructure is low. The Internet access points, GSM availability, and telephone lines per habitant have been evaluated in different Earth regions. The identified area is located between $[-30^\circ, +30^\circ]$ latitude.

The space segment: The system is composed of 21 satellites divided into two constellations: the first one covers the geographical zone between $[-30^\circ, +30^\circ]$ latitude (Region A) and the second one has a higher inclination angle and spans over $[-67.5^\circ, +67.5^\circ]$ latitude (Region A and Region B). A visibility algorithm [8] has been used to assess the coverage with respect to the targeted areas. See Table I for the detailed characteristics of these constellations.

The terrestrial segment: The system coverage area has been homogeneously divided into 15° sections. Each region with landmass has been associated to a GW station. The geographical distribution of GWs is shown in Fig. 1. There are 109 GWs distributed into two groups according to the region where they are located. It is assumed that each GW plays both the role of terminal and relay among satellites.

Table I
SPACE SEGMENT PARAMETERS

	Constellation	
Parameter	**1**	**2**
Number of satellites	12	9
Number of planes	3	3
Number of satellites by plane	4	3
Inclination Angle	$10°$	$45°$
Altitude	1000 km	1350 km
Minimum elevation angle	$10°$	$10°$
Covered Region (latitude)	Region A $[-30°, +30°]$	Region A+B $[-67.5°, +67.5°]$

B. The problem

Messages are transported by satellites from one GW to another. Intermediate GWs interconnect satellites by relaying messages. This way, messages can pass from one region to another without the use of wired links or ISL. Three types of routes are identified depending on the region of origin and destination: Type I from A to A, Type II from A to B and Type III from B to A (Fig. 1).
Since the number of satellites does not guarantee full instantaneous coverage for all GWs, permanent end-to-end connectivity cannot be expected. Communications among satellites and GWs are frequently interrupted as a consequence of the satellite motion. Under these conditions, the use of Internet-like routing schemes is not feasible. The deterministic characteristics of the system and the use of S&F devices make possible the use of specific precomputed routing techniques.
Similar problems have been addressed in the transportation field. With this respect, satellites are similar to means of transportation with a deterministic journey. In considering the dynamics of the topology induced by satellites motion, the problem of computing optimal paths in S&F satellite system can be formulated as follows.
There is a set of nodes containing GWs and satellites. Satellite nodes move along a deterministic trajectory and set up links with GWs within their footprint, making the topology network highly dynamic. The problem to solve consists in finding routes from one GW to all other GWs.
The metrics considered in route computation are: the end to end delay and the number of hops.

III. AN ALGORITHM TO COMPUTE OPTIMAL PATHS

A. Background in transportation field

In the literature, various theoretical approaches exist addressing shortest path computation in dynamic networks. In Table II, these contributions are classified depending on the link dynamics. For a general survey in algorithms addressing

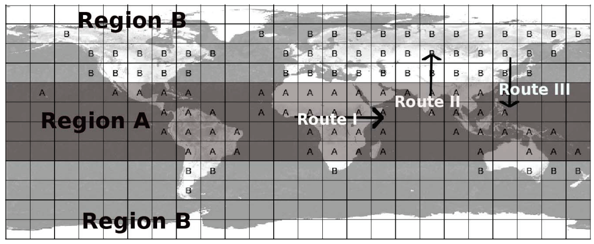

Figure 1. Identified regions (A, B), geographical distribution of GWs and the types of routes (I, II, III).

the shortest path problem in the transportation field see [9]. Among the problems identified in transportation optimization, the Shortest Path Problem with Time Windows (SPPTW) presents similarities to routing in a S&F satellite system. In the SPPTW, the links composing the paths can be used only during certain specified time intervals. SPPTW algorithms are described in [7], [10]–[12].

B. System model

The network which represents the system is modeled as a Space Time Network (STN) [9]:
Let G be a graph representing the STN, composed by a set of nodes and a set of edges.

$$G = \langle V, E \rangle \tag{1}$$

Let GW be the set of nodes representing GWs:

$$GW = \{1, 2, 3, \ldots, m\} \tag{2}$$

Let S be the set of nodes representing satellites:

$$S = \{1, 2, 3, \ldots, n\} \tag{3}$$

The set of nodes V in Equation (1) is:

$$V = GW \cup S \tag{4}$$

The edges are associated to links established between nodes in GW and nodes in S:

$$L = \{(i, j) : i \in GW, j \in S\} \tag{5}$$

Each link (i, j) is associated to a set of time windows which represents the time periods where it is established (visibility periods between satellite and GW):

$$W_{ij} = \left\{[a_1, b_1]_{ij}, [a_2, b_2]_{ij} \ldots [a_k, b_k]_{ij} : i \in GW, j \in S\right\} \tag{6}$$

a and b are the time boundaries defining the time windows. The set of edges existing at an instant t is defined as:

$$E_t = \left\{(i, j) : i \in GW, j \in S, \exists\, [a_k, b_k] \in W_{i,j}, a_k \leq t \leq b_k\right\} \tag{7}$$

which is also a representation of links in the discrete time domain.
The algorithm implemented to compute the fastest paths from one GW to all GWs is described in the next section.

Table II
MAPPING BETWEEN LINK DYNAMICS AND RELATED CONTRIBUTIONS

Link dynamics	**References**
No variable (static)	[13]–[15]
Time dependent	[15]–[19]
Random dependent	[20]–[24]
Random and time dependent	[25]–[28]

C. Algorithm description

We describe below the algorithm used to compute the fastest (end to end delay) route from a source GW to all the other GWs. The algorithm takes as input the graph G and the time windows W_{ij} associated to each link.

The core of the algorithm consists in building a tree of depth d. The root node is the starting GW. The leaf nodes are destination GWs that can be reached in d hops. The intermediate nodes are the hops from the source to the destination, that is, satellites and GWs. Each node of the tree is associated with a time of passage. As a result, by browsing the tree from a leaf up to the root, one is able to reconstruct the corresponding route.

The tree construction is a greedy algorithm where starting from a node, all valid next hops are added to tree and processed recursively. A next hop is considered valid according to three conditions:

1) a link is established (now or later) between the father node and the next hop,
2) the next hop does not create a loop in the route being computed and
3) the next hop fulfills a heuristic described later whose purpose is to limit the exponential growth of the tree.

Once the tree is fully computed and by considering all existing routes from the starting gateway to a given gateway, it is possible to identify the fastest (minimum end to end delay) one.

As noted previously, the tree grows exponentially with the number of GWs and satellites. A consequence of evaluating all possibilities of hoping from one satellite or one GW is the excessive use of computing power and memory. In order to alleviate it, heuristics are used to prune branches of the tree. The heuristic works as follows: since the end to end delay is expected to decrease with the number of hops (tree depth), the maximum of the minimum end to end delay for depth $2n$ is used as a boundary for depth $2(n+1)$. Branches of the tree displaying a larger delay are not developed.

IV. ALGORITHM PERFORMANCE

Scenario of simulation: The system described in Section II is represented through a STN. The W_{ij} sets (Equation 6) are precomputed using [8]. In order to evaluate the performance for different path lengths (tree depths), simulations were run

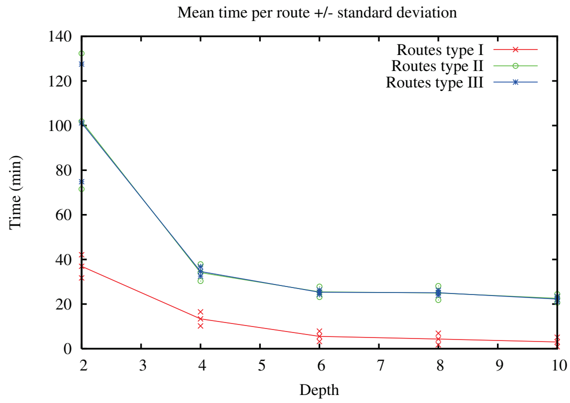

Figure 2. Mean end-to-end delay per type of route

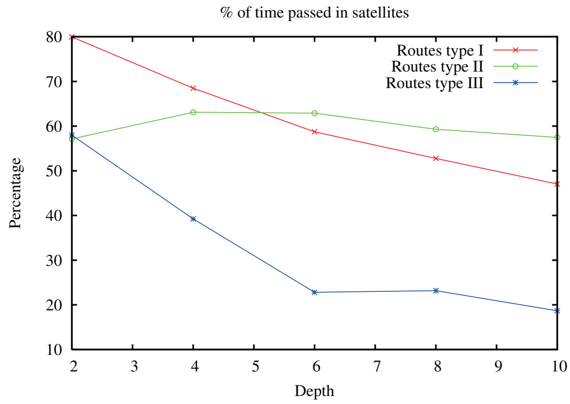

Figure 3. Storage time in satellites

to obtain the fastest routes from one GW to all GWs for path length values varying from 2 to 10.

In order to evaluate the algorithm performance, three metrics are considered: the end to end delay, the percentage of time of using satellites within the routes and the computation time.

Simulation results: In Fig. 2, a reduction of the end to end delay as a function of the path length is observed for the three types of routes. A higher number of hops in constructing the routes makes it possible to reach quickly the destination GW. An important reduction of the end to end delay is obtained when routes include more satellites (more trajectories). The most important reductions of the end to end delay are obtained in increasing the length of the routes from 2 to 4 and to 6.

The end to end delay of the routes includes the storage time in satellites and GWs. When the routes become longer, the percentage of time that the satellites are used within the route (see Table 3) is reduced as a consequence of a new distribution of the storage time among the nodes of the route. Routes with more hops offer new opportunities to exploit the many trajectories of the constellations and to display a lower end to end delay. The time spent in orbit is therefore reduced (more than 30 % from a 2 hop to a 6 hop type III route). The reduction rates depend on the constellation (1 or 2) involved in the routes.

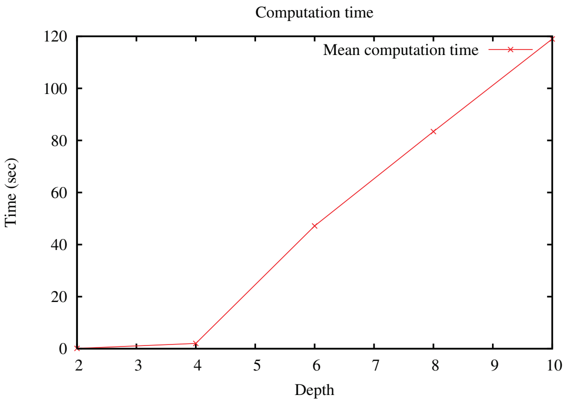

Figure 4. Mean computation time per route

Finally, Fig. 4 shows the impact of the tree depth on the computation time. Thanks to the heuristics used, the growth is linear rather than exponential for a depth longer than 4 hops.

V. Conclusion and outlook

Most routing studies applied to constellations found in the literature are based on satellites equipped with inter-satellite links. The routing problem must be revisited when applied to Store and Forward (S&F) satellites.

In this study, routing solutions developed for transportation systems are extended to the field of S&F satellites. A precomputed routing scheme has been evaluated for the proposed system. The performance study shows that increasing the number of hops allowed from a given source to a destination yields shorter routes in terms of end to end delay and a reduction of the satellite memory usage.

Future work includes the extension of the algorithm to traffic adaptive routing and congestion control.

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