Performance Study of Routing Algorithms for LEO Satellite Constellations

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ABSTRACT

A comparative study of routing techniques is carried out on complicated LEO constellations interconnecting high speed terrestrial networks. Shortest path routing as well as optimal routing (flow deviation) methods are applied for balanced and unbalanced traffic load and for uniform and non uniform distribution of the earth stations. The performance of flow deviation method is proved to be very successful even for these big networks after a modification of the algorithm regarding the selection of the number of paths we work with. It is proved that a *k-paths flow deviation* method is always easy to obtain and gives robust results at a very affordable algorithmic complexity.

I. INTRODUCTION

The main function of a routing algorithm is the appropriate selection of a path (route) for any origin - destination pair on a network. Routing techniques for telecommunications networks have been studied extensively from early 60’s in terms of the main performance measures, throughput (quantity of service) and delay of messages (quality of service). For low or moderate traffic flow, throughput is equal to the offered traffic so delay is the only essential measure, and this is exactly the situation of current satellite constellations which are far from being congested [1].

There are a number of ways to classify routing algorithms. Centralized (all route choices are made at a central node) versus distributed (routing decisions made locally), static (fixed routes regardless traffic conditions) versus adaptive/dynamic (routes responding to traffic conditions), shortest paths versus optimal routing. On this last category we shall focus our research investigating their influence on network performance [2].

Most of the practical algorithms are based on the concept of a shortest path between two nodes. Here, each communication link is assigned a positive number called its length and between any pair of nodes we try to define the route of the shortest length. If the links are of unit length the shortest path is simply a minimum hop path. Shortest path routing has two drawbacks. First, it uses only one path per origin destination pair and second its capability to adapt to changing traffic conditions is limited by its susceptibility to oscillations. An improvement to this approach is the selection of *k*-shortest paths for any pair to use anyone depending on the network load.

Optimal routing, [2,3] is based on the optimization of an average delay-like measure of performance, splitting any origin-destination pair traffic to many links and shifting traffic gradually between alternate paths, thus resulting in a more balanced distribution of the load on the network. Its application gives always a better performance than shortest path simple topology networks. But if the network to be studied is of considerable complexity a thorough evaluation of the time / memory demands of the algorithms must be done.

In the following sections a comparative study of Shortest Paths (SP) and optimal routing algorithms for complicated LEO constellations will be presented. In section II the description and modeling of the system will be illustrated, in section III numerical results of extended algorithmic applications will be given and in section IV conclusions of the research and points of further investigation will be indicated.

II. SYSTEM MODELING

A. System description

A system of N=63 satellites in 7 circular orbits at a height of 1400 km is examined. The system is very close to systems proposed in the literature [1]. An extended study on the topology of the system based on the azimuth and elevation angles of the constellation resulted in the selection of six InterSatellite Links (ISLs) at every node (satellite) on the network [4]. The network topology is changing continuously through the movement of satellites but its connectivity remains constant, the only changing feature being the length of the links.

The constellation is used for the interconnection of terrestrial high speed networks so the traffic is bursty and of considerable intensity and the time constraints for some services are quite strict. In Table 1 are given some values of the selected system.

We examined two models for the terrestrial traffic distribution:

a) Earth stations are uniformly distributed on the earth surface, which is a very general assumption. The destination of each node generating traffic is chosen randomly through a uniform distribution. This assumption results in a very balanced load of the network.

b) Earth stations are gathered at some places on the earth surface [5] leading so to non uniform distribution of origin-destination pairs.

The load offered to the network is taken out of a normal distribution with mean value μ and variance σ. If the variance is taken equal to zero then all earth stations offer equal throughput which results in a balanced network load. The reason that we have used a distribution in order to determine the average throughput of each station, is that even for non-zero variance σ the mean network load remains constant, so different load situations can be compared.

B. Algorithms selected

Three standard SP algorithms are referred in the literature [6,7]: *Belman-Ford, Dijkstra* and *Floyd-Warshall*. The first two find the SP from all nodes to a given destination, while the third one finds the SP from all nodes to any other node. The worst case computational requirements of *Dijkstra* are considerably lower than the two others, (it works only with positive link lengths but this is the case in communications networks) so it has been applied extensively in routing studies.

The *Dijkstra* algorithm has been applied in our study in two versions: a) considering the link length equal to the distance (propagation delay $p_{i,j}$) between the two nodes it connects and b) taking the link length equal to a metric that depends on the link flow (*Dijkstra* with link flow).

From the class of optimal routing the Flow Deviation (FD) was selected for application [8]. The FD algorithm splits the load to different paths according to the path length given by a flow dependent metric. It continuously adapts this load deviation trying to minimize the cost function given below.

C. Cost function

A cost function adaptive to the transmission delay is chosen using the well known formula [2]

$$D = \frac{1}{\gamma}\left(\sum_{(i,j)} \frac{f_{ij}}{C_{ij} - f_{ij}} + p_{ij} f_{ij}\right)$$

Where $p_{i,j}$ is the transmission delay on link (i,j), $f_{i,j}$ is the flow on link (i,j), C_{ij} the capacity of link (i,j) and γ the total traffic offered to the network. The length of the link is taken equal to the derivative:

$$\frac{\partial D}{\partial f_{ij}}$$

The application of these equations assumes that the arrival pattern is Poisson, which is a very poor assumption for high speed networks. Recent studies and measurements of traffic on several networks have proved that self-similar modeling is more reliable and reasonable for traffic characterization [9].

So an interesting comparison is expected using self-similar and Poisson input for a real time simulation of the network performance.

The handoff delay at every node is also a measure of interest for further investigations.

III. NUMERICAL RESULTS

Any earth station is connected to a satellite node, which is continuously changing (handoff). Also, the six inter-satellite links are changing. These changes happen in a completely predictable way, so we can suggest to examine different *static* topologies of the system. We also assume that the handoff is perfect, the flows are transferred from one satellite to another with no bandwidth problems.

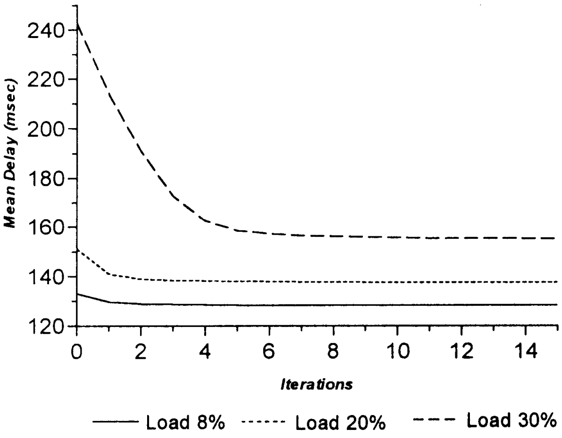

Figure 1. FD convergence for symmetric network load.

The comparison of the three algorithms proposed above leads to some very interesting results: In Fig. 1, the flow deviation algorithm is studied, in terms of delay versus convergence with parameter the mean load of the system, for a symmetric load (variance zero) and for symmetric distribution of the earth stations. Convergence is found to be slow for heavy load but successful in any case. Since the possible paths for any source destination pair are numerous we chose some paths to work with them. We denote N_p the number of alternative paths for each origin-destination pair. In Fig. 2 we give the influence of the selection of limited paths on the performance of the algorithm, again studying the mean delay versus convergence.

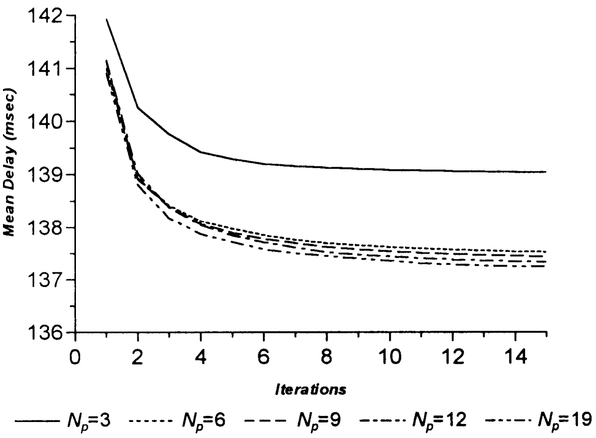

Figure 2. FD convergence and different number of paths N_p for symmetric network load.

This choice of a limited number of paths, can be considered a very serious modification in the application of the FD algorithm on complicated network topologies. Thus the adoption of a new category of *mixed flow-deviation and k-shortest paths algorithms* is found to be necessary for being able to apply realistically the FD technique. Of course the main result is that the more paths we use the less delay we obtain, so a complete flow deviation is always superior than any k-shortest path. But investigating the profit we have from a complete FD running we see that considerable improvement is noted between 3 and 6 paths selection. Above 6 paths the improvement in delay does not compensate the complexity of the algorithm. We note that the selection of the paths to be used can be done through various criteria. We have applied here a minimum hop algorithm for the selection of the six alternative paths.

A very interesting input is given in Fig. 3. The mean delay is studied in two cases: a) any origin-destination pair uses 6 alternative paths, the minimum hop paths selected as in Fig. 2 and b) any origin-destination pair uses 6 alternative paths, each one stemming from a different ISL. The performance is better in the first case leading to the conclusion that the intersatellite links may be not used any time.

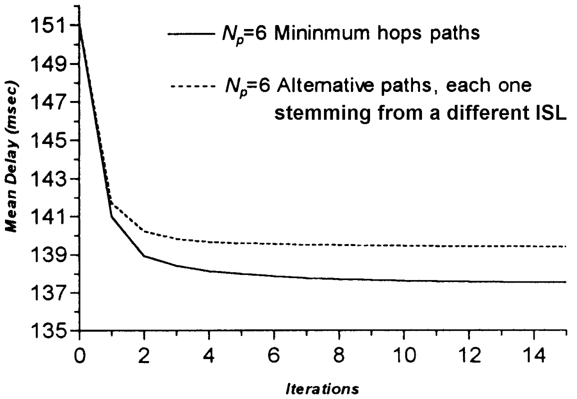

Figure 3. Mean delay vs convergence for different number of N_p.

In Fig. 4 we study the performance of FD for an unbalanced traffic load. We observe that despite an increase in the variation of load we obtain the same satisfactory performance of FD.

In Figs. 5 and 6 we compare the three algorithms referred in section II. Delay versus load for the balanced and unbalanced network cases.

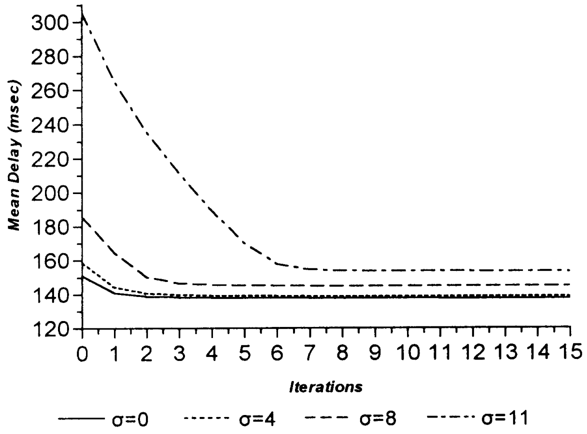

Figure 4. FD convergence for unbalanced network load value of 18% with different variation.

As we expected the performance of *Dijkstra* is failing for heavy load and what is important it fails in unbalanced situations which is the permanent status of satellite constellations. The modified *Dijkstra* (*Dijkstra* with link flow) having the possibility to adapt to traffic changes performs better but the FD with the limited number of paths (thus low complexity) is still superior.

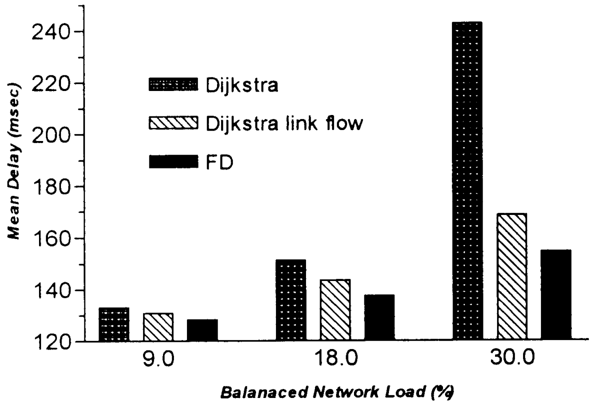

Figure 5. FD, *Dijkstra* and *Dijkstra* with link flow for different amounts of balanced network load.

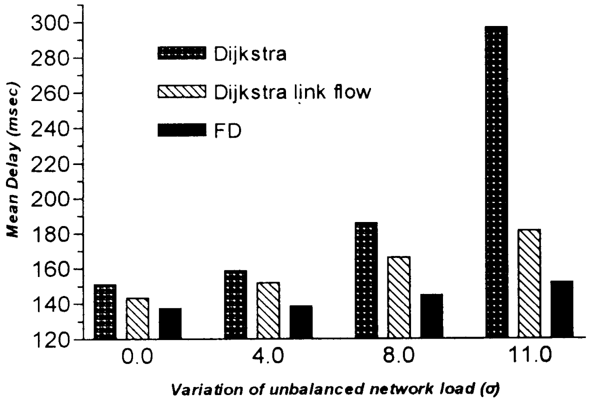

Figure 6. FD, *Dijkstra* and *Dijkstra* with link flow for unbalanced network load with variation σ, and mean network load 18%..

In Fig. 7 the case of non-uniform distribution of earth stations is examined. The load of the stations is assumed to be balanced. In the same figure the case of uniform distribution of earth stations is also displayed. The second bar of similar pairs corresponds to the non-uniform case of the corresponding algorithm. For light conditions of input load the three algorithms present no significant difference from the uniform case. But for heavy load conditions the simple *Dijkstra* algorithm fails to route the traffic. The other two algorithms present similar behavior in the case of uniform and non-uniform earth stations distribution, but they increase slightly the mean delay of the network. This was, anyway, their behavior on the case of unbalanced network load with uniform distribution of earth stations.

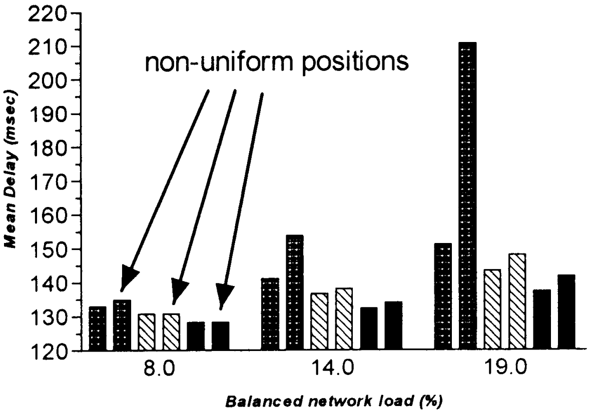

Figure 7. FD, *Dijkstra* and *Dijkstra* with link flow for balanced network load and non-uniform distribution of earth stations.

IV. CONCLUSIONS

A comparative study of different routing algorithms has been carried out on complicated satellite constellations. The well used approaches of shortest path algorithms were applied together with the flow deviation of optimal routing techniques. Balanced and unbalanced traffic load and uniform and non uniform distribution of earth stations has been considered and some trials with the link length function have been investigated.

In any case the performance of flow deviation techniques is always better. But due to the complicated topology of the system we proposed and applied successfully a modification of FD algorithm choosing only a limited number of paths to work with. A quantitative estimate of this number has been done through simulation and it was proved that we can find always a very low number of paths to work without loosing in quality of performance.

A further investigation of the topic is interesting, especially using a modified Cost Function to include any possible parameters which influence the performance of the system, like the Doppler effects, the on-board processing time, etc. as well as applying a more general class of optimal routing techniques, the gradient projection methods.

Table 1. Constant parameters of the selected system

ISLs Capacity	**Radius**	**Sat/Orbit**
4.5 GBps	6350+1400 Km	9
ISL Propagation Delay		**Uplink Delay**
10 msec		5 msec

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