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Routing in LEO Satellite Networks: An Implementation

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ABSTRACT

In this study, we investigated the routing problem in low earth orbit satellite communication systems with intersatellite links and using a greedy optimization, we tested the performance of a routing algorithm proposed in the literature. The routing problem is divided into two separate problems: UDL and ISL routing. For the ISL routing, the problem has been defined as a minimization problem with start and end satellites known, and minimizing the path handover to connect these end satellites. We used greedy optimization to solve the problem. In order to use the algorithm on traffic requiring guaranteed QoS, we added an end-to-end delay constraint into the optimization process.

Keywords: *Intersatellite links, LEO satellite networks, routing, path handover*

1. Introduction

Personal communications using nongeostationary satellite systems can offer valuable services ranging from low speed data to voice communications. Some of these nongeostationary systems are low earth orbiting (LEO) satellite based systems in which satellites are positioned at altitudes below 2000 km. The preliminary design of such systems raises many more problems than with geostationary satellite systems, as a result of time-varying geometry of the satellite constellation and its evolving coverage. A methodology for rapidly evaluating the performance of LEO satellite systems is given in [1].

For the design of LEO satellite systems many requirements have to be taken into account. For reasons of link quality, global coverage must be achieved with a sufficient high satellite elevation. Together with the choice of orbit height and inclination, this requirement leads to the necessary number of satellites and orbits. [2] gives detailed information about how we can calculate systems parameters such as the number of satellites and orbits for a Low Earth Orbit(LEO) and Medium Earth Orbit(MEO) system.

For a LEO system, other than the satellite constellation related requirements, several networking aspects have to be considered [9]. The demand for telephony and its global distribution, together with upper limits for blocking probability and speech delay, essentially determine the requirements for network capacity and connectivity. These characteristics depend on the number of links between mobile users, satellites, and gateways, including intersatellite links (ISLs). For a high degree of connectivity, various routing alternatives are possible and a good distribution of the traffic flow can be achieved. Moreover, the flexibility of the network to cope with link or node failures is enhanced. On the other hand, manufacturing and positioning of a large number of satellites and gateways means high fixed costs.

In the satellite world, the first LEO and MEO satellite systems will start commercial operation within the next years to provide global personal communication services. Compared to geostationary satellites, these constellations offer a significantly smaller round-trip delay between earth and space segment. Moving toward lower orbits, we face the large scale advent of real networks in the satellite communication world. Moreover, due to the permanent mobility of the whole satellite network itself, the operation of such systems entails many new challenges to be tackled, especially on the networking level. In particular, intersatellite subnetworks in space, which is one of the most important advantages of proposed Iridium [3] and Teledesic [4] systems for transport of long distance traffic, are subject to permanent topological changes. Consequently, the routing task requires highly sophisticated approaches to provide the predominant connection-oriented services with acceptable QoS for the end user and efficient use of network resources.

	ICO	Odyssey	Globalstar	Iridium	Teledesic
Orbit Classification	MEO	MEO	LEO	LEO	LEO
Orbit altitude	1354km.	1054km.	1414km.	780km.	1600km.
Orbit period	360min.	360min.	114min.	100min.	118min.
Number of satellites	10	12	48	66	288
Number of orbits	2	3	8	6	12
Inclination	45	50	52	86.4	98.2
Intraplane ISL's per sat.	no	no	no	2-perman.	0-4 dynam
Interplane ISL's per sat.	no	no	no	0-4 dynam	0-4 dynam
Primary service	voice	voice	voice	voice	multimedia

Table 1: Promising LEO/MEO Systems

The focus of this study is on traffic routing aspects. Using an already proposed routing algorithm [9], we optimized the number of handovers occurring during a connection between given start and end satellites. The routing algorithm deals with providing paths for exchange of information between two satellites in the space segment. This entails identifying a start and end satellite and connecting these via a time-variant ISL infrastructure. Due to the motion of the satellites, the ISL path may change. Therefore, our aim is to minimize the number of path handovers during a whole orbit period.

The remainder of this paper is organized as follows: in Section 2, we give a literature review about the routing algorithms used in nongeostationary satellite systems together with the general characteristics of nongeostationary satellite constellations. In Section 3, we explained Intersatellite topology dynamics. Section 4 is devoted to ISL routing problem and the necessary network model proposed in [10,9]. In Section 5, we made implementation specific explanations. We gave our results in Section 6. Section 7 concludes our paper.

2. Literature Review

2.1.Nongeostationary Satellite Systems

The most promising candidates for satellite personal communication networks are listed in Table 1. ICO and Odyssey as outstanding MEO proposals and Globalstar[8] and Iridium[6] as two LEO representatives form a group of systems that aim at near future narrowband personal communications with voice as the strong primary service. Compared to them the Teledesic[7] concept may be regarded as even more forward-looking, already envisaging broadband service and incorporating ATM-like operation.

All of these LEO and MEO systems are based on satellite constellations with several circular common-period orbits of low or medium altitude; all orbits in each constellation have the same inclination with respect to the equatorial plane. The same number of satellites circulate in each of the orbits, and so do the corresponding circular coverage areas (footprints) on earth, thus achieving continuous and worldwide coverage. More details on constellation geometry and system parameters can be found in [2] and [5].

The relative movement of satellites and user location areas on earth leads to a complex combined spatial and time-variant traffic pattern collected and delivered by every single satellite in its footprint [10]. In systems providing an intersatellite link infrastructure, the long-distance share of this traffic is routed through the space segment. Characteristics of source/destination traffic variance are then transferred into the ISL traffic mix in a smoothened form because every single intersatellite link also carries a lot of transit traffic. In this study, only systems employing ISL's are considered and Iridium system is taken as an example. In other words, the routing is done based on Iridium like dynamic ISL constellations even if it is possible to change the system dynamics by changing the databases used for ISL connectivity and constellation. Figure 1 shows the polar view of the 66-satellite Iridium constellation with six quasipolar orbits. The specific orbit pattern results in a longitude "seam" encountering between two neighboring orbits where satellites are moving in opposite directions. With respect to this seam, the constellation comprises two hemispherical areas of corotating orbits, each extending from the north to the south pole.

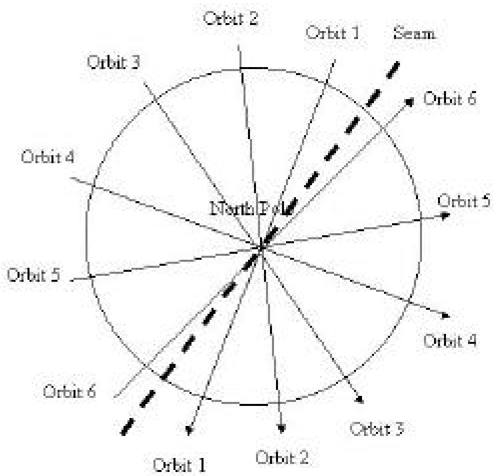

Figure 1: Iridium: Polar View of Orbits

2.2.Routing Algorithms

A number of authors have dealt with the very interesting problem of routing in a satellite system. In [9, 10], Werner *et al*., proposed a dynamic routing algorithm for ATM-based LEO and MEO satellite systems. Due to the fact that satellites move in orbits and orbits slowly rotate around the earth, the network topology can be seen as consisting of a series of topologies which continuously repeat themselves. For each topology, end-to-end routes are calculated. Subsequently, an optimization procedure is carried out over all the network topologies with a view to minimizing the occurrence of hand-offs between successive topologies. In [15], Mauger and Rosenberg proposed the *virtual node* routing algorithm for ATM traffic. Users are mapped onto virtual nodes, and each virtual node is served by a satellite. When the satellite passes, the next satellite takes its place and serves the virtual node. Routing is performed according to the topology of the virtual nodes.

Chang *et al*., proposed the finite state automaton (FSA) model in [13, 11] to solve the ISL link assignment problem in LEO satellite systems. The total time it takes the position of all the satellites over the earth to repeat itself, is divided into equal length intervals during which the visibility between satellites, that is the network topology of the satellites, does not change. Given a traffic matrix for each interval, a link assignment algorithm is run with a view to maximizing the residual capacity of the bottleneck links. The result is a table that shows connectivity between satellites for each interval. These tables can be stored in each satellite, and during the real-time operation of the system the inter-satellite links are established according to these tables. Further related research can be found in [14, 12].

Uzunalioglu *et al*., suggested in [17, 18] a connection hand-off protocol for LEO satellite systems. First, a minimum cost route for a connection between two points on the earth is obtained. This route is used for as long as possible. When a hand-off occurs at either end of the connection, the protocol simply adds the new link to the path. This continues for a predetermined amount of time, when the protocol computes a new end-to-end path for the connection. In [16], Uzunalioglu proposed a probabilistic routing protocol based on the above approach. Finally, a new traffic load balancing algorithm was proposed by Kim *et al*., in [19].

3. Intersatellite Links

The physical time-variant topology of the system consists of all instantaneously existing direct links between pairs of satellites. At that point, a distinction has to be made between intraplane ISL's connecting successive satellites in the same orbit plane and interplane ISL's connecting satellites in adjacent corotating orbits. Whereas, in the first case the distance and the antenna pointing are fixed, interplane ISL's are subject to continuous variations of both the distance and the antenna pointing, with specific consequences for the networking and routing. In the extreme case of counter rotating orbits where the satellite speeds relative to each other is twice more than the satellites at other neighboring orbits, which results in permanent switching of ISL's necessary, a fact that has led to avoiding links across the seam in general. Besides the continuous distance changes on corotating interplane ISL's, there is also a discrete-time contribution to the ISL topology dynamics: the effectively implemented interplane ISL's (one per satellite and per neighboring corotating orbital plane) are deactivated in polar regions; this means on/off switching of certain links in the topology. As a result, the number of simultaneously operational ISL's varies between two and four in the quasipolar Iridium constellation. This twofold variance of the ISL subnetwork significantly increases the complexity of connection-oriented network operation, and has to be tackled by tailor-made routing strategies.

For the networking considerations, it is helpful to take a simplified view of a typical end-to-end connection between a mobile user MUa and a fixed partner FUb, as illustrated in Figure 2

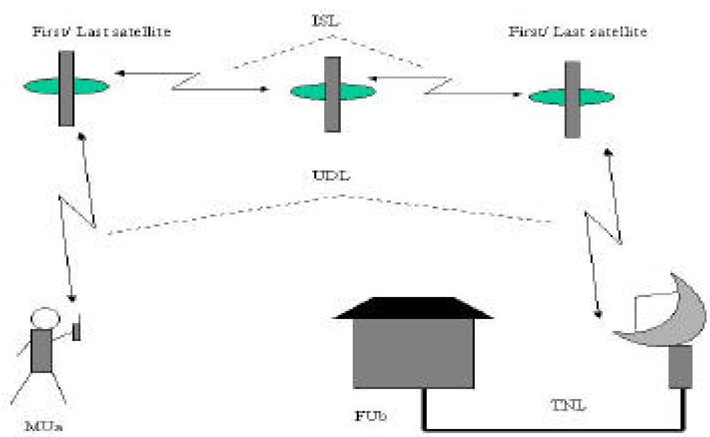

Figure 2: A Typical end-to-end connection in a satellite PCN with ISLs

In this system, three major connection segments can be defined; *intersatellite link (ISL)* segment, which comprises the radio links between pairs of satellites, essentially forming a dynamically meshed subnetwork in space, *up/downlink (UDL)* segment which incorporates the uplink between mobile user and the origin satellite and the downlink between the destination satellite and the fixed earth station. The up/downlinks change their status according to the direction of traffic flow. The third connection segment is *terrestrial network link (TNL)* segment.

4. ISL Routing

In this system, the end-to-end routing task is divided into two phases: UDL routing and ISL routing. In UDL routing there are two main steps to be taken. In the first step, a responsible satellite selection procedure (RSSP) takes care of providing continuous service to two end users by at least one start and end satellite out of the respective clusters. In the second step, between start and end satellites a hitless handover between predefined or preselected momentary paths must be guaranteed in order to avoid forced connection termination. This task is essentially performed by a change of path translation tables in the corresponding start/end satellites. The UDL routing problem is not within the scope of this study.

In our problem, on the other hand we focused on the ISL routing phase or the routing process. The situation encountered in ISL subnetworks of LEO satellite constellations is quite different from classical networks with respect to network topology. Permanent topological changes are an inherent characteristic of those networks, and new routing strategies are required to enable continuous operation in the connection-oriented mode. For that purpose a discrete time network model is defined in the following subsection.

4.1. Network Model

The ISL subnetwork has the following characteristics:

- The number of network nodes *N* is constant.
- A single node is never unconnected (in a graph-theoretical sense).
- With the above restrictions, the network topology is subject to changes due to
  - discrete-time activation/deactivation of links,
  - continuous-time distance variations between nodes.
- The complete topology dynamics is periodic with period *T*.

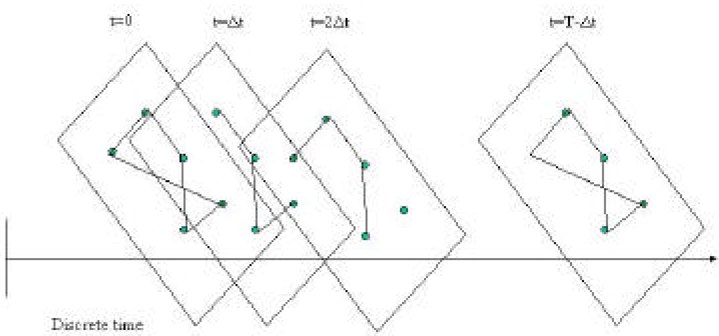

Figure 3: Discrete-time Topology Approach

The routing concept is based on a discrete-time topology approach as illustrated in Figure 3. The dynamic network topology approach is considered as a periodically repeating series of *K* topology snapshots separated by step width $\Delta t=T/K$. Each of the snapshots at $t=k\Delta t$, $k=0,...,K-1$ is modeled as a graph $G(k)=(V,E(k))$ where $V=1,...,N$ is the constant set of nodes and $E(k)$ represents the set of undirected links $(i,j)_k=(j,i)_k$ between neighboring nodes i and j, existing at $t=k\Delta t$. Associated with each link are its cost $c_{ij}(k)$ according to an appropriate cost metric.

In this study, each momentary link between two satellites is provided with a link weight (*LW*) showing its expected costs at the regarded time interval. Considering real-time services, it is obvious that propagation delay should dominate the cost metric. Consequently, in the simulations the *LW* is mainly determined by the distance between two satellites: the greater it is, the higher is the *LW* attached to the link.

In addition, permanently active ISL's should be given preference over those being temporarily switched off. This will in general reduce the number of forced path handovers and consequently enhance the overall path continuity over time. The permanence of ISL's is introduced into the cost function as parameter *perm*, assigning lower costs to permanent ISL's and thus resulting in preferential routing over such links.

The third component of the *LW*, *geogr* represents the geographical position of the satellites. Satellites covering medium latitude or land mass regions will probably collect more calls from ground than satellites crossing polar regions or oceans, thereby directly imposing a corresponding traffic demand on their ISL's. This unequal traffic demand imposed from earth suggests traffic distribution shaping in space for the sake of overall traffic routing performance. An efficient handling of this task will of course require some sophisticated traffic adaptive routing during system operation. However, based on the above considerations, it is possible to roughly capture the major effects already at the stage of off-line path search. This is done by the parameter *geogr*, which assigns lower costs to ISL's of satellites covering regions with lower traffic demand.

Considering these components, the link costs are calculated according to the following formulae

$$LW(t_i) = \{distance\ /\ C\} * \{1 / perm\} * \{1 / geogr\}$$

where C is speed of light.

In accordance with the scaling proposed in this function both *perm* and *geogr* reasonably take values from 0 to 1. However, in our simulations, we took these parameters equal to 1 which means we only dealt with propagation delays.

Once the calculation of all *LWs* is completed the total cost of the path at the given time interval is calculated as follows

$$TLW_j(t_i) = d_{switch} * hops + \Sigma_{for\ all\ links}\ LW_k(t_i)$$

In our case, switching delay is 10ms at each satellite on-board switch.

4.2. Routing Process

The routing process is divided into three steps. On the first step, for each interval, the momentary ISL topology is defined, especially including exact geometrical information on satellite points, and distance between satellites. This information is kept in different database files. The procedure first of all, chose from this database the information necessary for that time interval. To keep track of this information, two kinds of files are formed. In the first one, the geographical positions of the satellites are kept and in the second one, the connectivity of the satellites is recorded. From these data, the simulator first calculates the network topology and the cost matrix for each ISL.

On the second step, a path search procedure is implemented for connecting the given start and end satellites. In other words, for each time interval, according to the newly formed ISL topology, a new routing process is run between the start and end satellite. This process produces best max. number of paths between the start and end satellites using the DSPA. In our simulations, the max. number is three.

The last step of the routing process is the optimization process. Over one constellation period, an optimization procedure is performed in terms of minimizing the occurrence of path handover situations by choosing respective paths from the given sets. In this part of the process, we used the greedy optimization algorithm. The total process is illustrated in Figure 4.

5. Implementation of the Algorithm

5.1. Data Structures Used In The Program

Connectivity matrix used to represent the ISL topology. That means, this matrix shows which satellite is connected to which satellites.

Dist matrix used to store the cost metrics for each link. Shortest paths are calculated according to that matrix.

Pathlist which is a three dimensional data structure and is used to store three shortest path for each time interval. The greedy optimization algorithm uses this matrix to minimize the path handovers.

TLW is used to store the total cost of each path during a whole system period. n is the number of satellites. dswitch is the switching time.

Topology vector is used to store the geographical positions of each satellite.

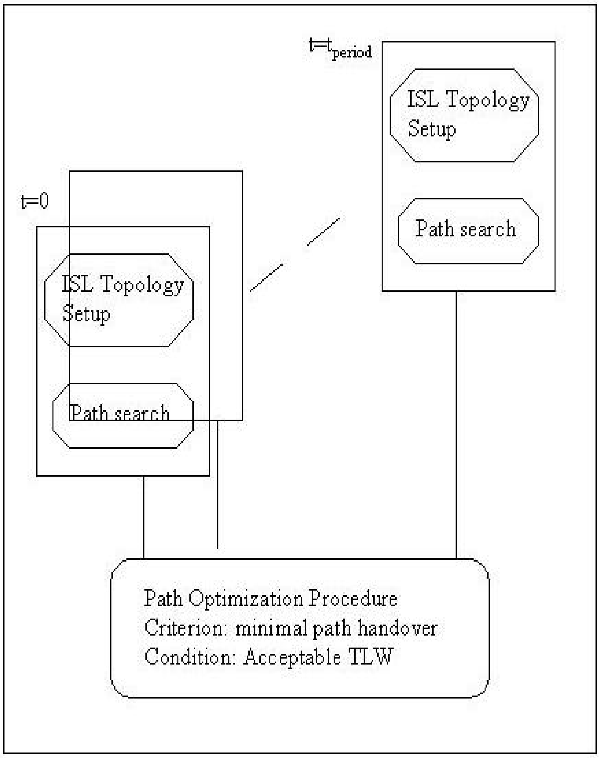

Figure 4: Optimization Process

The program is designed independent of a satellite constellation. For that purpose, the constellation specific parameters are kept in different files and read from them at the beginning of the program. In order to use the same program for a different satellite constellation, only the necessary files are needed. Therefore, the program is flexible and can be easily adapted to other satellite constellations.

5.2. Implementation

The algorithm is shown in Figure 5.

In our program the period duration is chosen as nine minutes. To complete a whole period, 11 different time intervals are defined, and the satellite constellation for each time interval is restored in 11 different files. At the beginning of the each time interval, two files are read: One for the geometrical positions of the satellites, and the other for the presence

```
Greedy Optimization Algorithm

1.  Begin
2.  limit = 2 * PERIOD                          // Initialization step
    1.  acceptcounter = 0
    2.  bestHO = PERIOD
    3.  CANDIDATE = BEST = rand mod 3
3.  While acceptcounter < limit
    1.  CANDIDATe = BEST
    2.  HOcounter = 0
    3.  row = rand mod 11
    4.  CANDIDATE(row) = rand mod 3
    5.  pidold = CANDIDATE(0)
4.  For (i==1;i<+PERIOD;i++)
    1.  pidnew = CANDIDATE(i)
5.  If(!comparepath(pidold,pidnew)) Hocounter ++
    1.  pidold = pidnew
6.  If(Hocounter<+bestHO)
    1.  acceptcounter = 0
    2.  bestHO = Hocounter
    3.  BEST = CANDIDATE
7.  Else acceptcounter ++
8.  End while
```

Figure 5: Optimization Algorithm in order to Optimize Number of Handovers During an ISL Routing

of ISL's. Afterwards, the program calculates the cost matrix according to the given cost metric. Once the cost matrix is found, three different paths between the starting and ending satellites are found. The next step is calculating the *TLWs* of each path. This process is repeated for each time interval. Once the setup and path search phases are finished, the optimization process starts. During the optimization phase, a greedy optimization algorithm is used.

The algorithm uses two lists; one for the best paths for the whole system period, and one for the candidate paths which changes during the search. First a random path is chosen. Then at each step of the search, one of the paths is changed and the number of handovers is counted, if it is less than the previous path list then, this list is accepted as the best path list for the whole system period. Otherwise the search continues by changing another path.

6. Results

In this study we run the program several times with different start and end satellite configurations. In the following figures the starting satellite is 21 and ending satellites are 0, 1, 10, 22, 23, 31, 32, 33, 41, 42, and 43 respectively. As an example case the output of the program is as follows:

Interval 0
Path 0 : 21,32,42,41
Path 1 : 21,32,22,43,42,41
Path 2 : 21,11,22,32,42,41
Interval 1
Path 0 : 21,32,31,41
Path 1 : 21,20,31,41
Path 2 : 21,32,42,41
Interval 2
Path 0 : 21,20,31,41
Path 1 : 21,32,31,41
Path 2 : 21,32,42,41
Interval 3
Path 0 : 21,20,31,41
Path 1 : 21,20,19,30,31,41
Path 2 : 21,20,31,30,40,41
Interval 4
Path 0 : 21,22,32,31,41
Path 1 : 21,22,33,43,42,41
Path 2 : 21,20,19,30,40,41
Interval 5
Path 0 : 21,22,33,43,42,41
Path 1 : 21,20,32,43,42,41
Path 2 : 21,20,32,31,30,40,41

Interval 6
Path 0 : 21,22,32,43,42,41
Path 1 : 21,20,32,43,42,41
Path 2 : 21,22,33,43,42,41
Interval 7
Path 0 : 21,22,33,43,42,41
Path 1 : 21,20,32,31,42,41
Path 2 : 21,22,32,31,30,41
Interval 8
Path 0 : 21,20,32,43,42,41
Path 1 : 21,20,19,31,30,41
Path 2 : 21,10,9,20,32,43,42,41
Interval 9
Path 0 : 21,20,19,31,42,41
Path 1 : 21,20,19,18,30,41
Path 2 : 21,11,22,32,31,42,41
Interval 10
Path 0 : 21,32,31,30,41
Path 1 : 21,20,19,18,30,41
Path 2 : 21,11,22,43,42,41

So far, the best three paths between the given source and destination satellites are shows for each time interval during a whole period. Then the best paths for each time interval is chosen with the greedy optimization algorithm. If we compare the performance of our optimization method with the case without optimization, we can see that without optimization the handover cases occur at passing from time interval 0 to 1, 1 to 2, 2 to 3, 3 to 4, 5 to 6, 6 to 7, 7 to 8, 8 to 9, and 9 to 10, that means nine times. The paths chosen after the optimization are as follows:

Handovers = 5:
Interval = 0:
21,32,42,41
Interval = 1:
21,32,42,41
Interval = 2:
21,20,31,41
Interval = 3:
21,20,31,41
Interval = 4:
21,22,33,43,42,41
Interval = 5:
21,22,33,43,42,41
Interval = 6:
21,22,33,43,42,41
Interval = 7:
21,22,33,43,42,41
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Interval = 10:
21,32,31,30,41

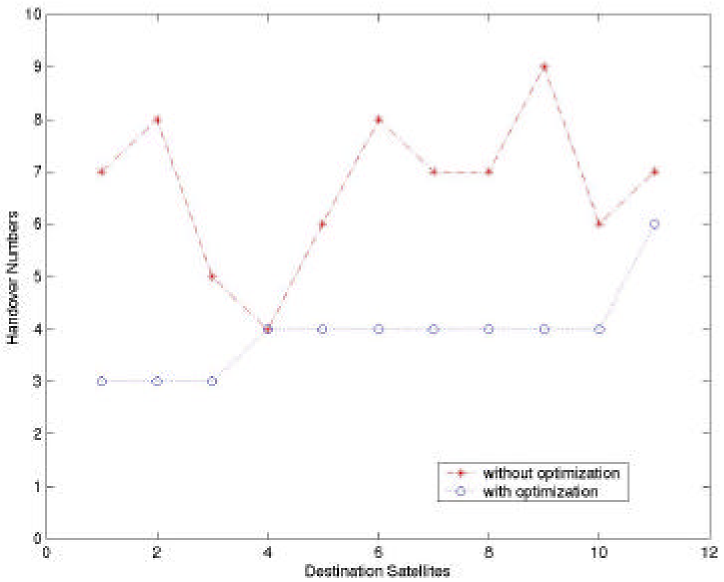

Figure 6: Handover numbers with and without handover optimization

Here it is easily seen that the number of handovers occurs only five times. That means an improvement of 4 handover over nine can be obtained with our optimization procedure. To illustrate this situation in Figure 6, we compared the number of handovers with and without optimization for the start and end satellites mentioned beforehand.

As seen in Figure 6, our optimization improves the performance of the routing process in each start end connections. Only connecting satellites 21 to 22, we can not make any minimization which is resulted from the fact that these two satellites can see each other with a direct link nearly in all time intervals, so whether to choose the shortest path or not it is not possible to minimize the number of handovers.

To demonstrate the success of our optimization process we used Figure 7 where the percentage decrease of the number of handovers at each time interval is illustrated. Again the start satellite is 21 and the destinations are as listed beforehand.

In Figure 7, we can see that only in the connection between 21 and 22 there is no improvement as mentioned earlier. On the other hand, there is always an improvement in the number of handovers. The most optimization can be obtained in the connection between 21 and 1 where the ISL constellations changes nearly at each time interval. Therefore, the paths between the start and end satellites also change at each time interval. Our optimization performs better in situations where the number of path changes increases with time.

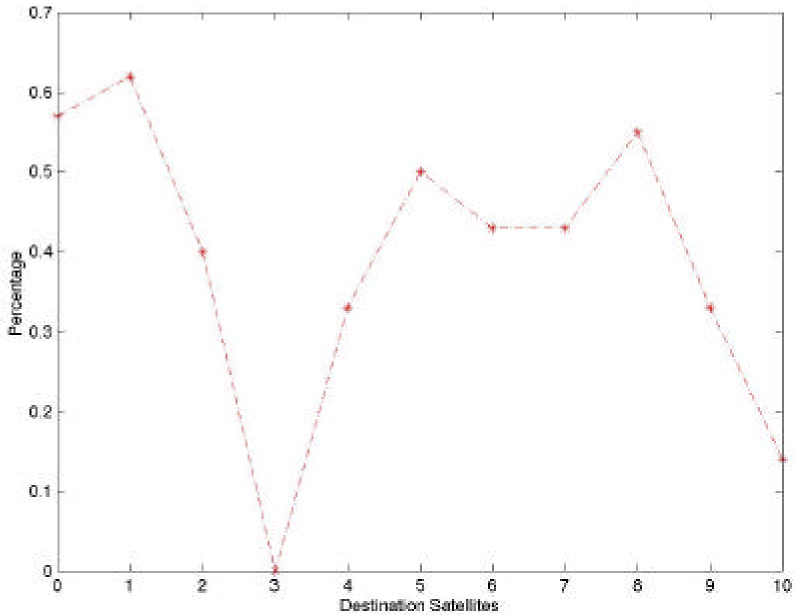

Figure 7: Percentage improvements in handover situations

So far, we only tried to improve our handover numbers, that means minimize it. In fact, without any delay constraints, this problem becomes infeasible. To make the problem a little bit more realistic, we add a delay constraint. In that case, we tried to choose the paths without increasing delay more than 50 percent. In other words, in this case, the end to end delay of the current path and the previous one should not change more than 50 percent. Using this delay constraint, we tried to re-obtain the best paths with a small modification in our program. Figure 8 shows the percentage changes in the handover numbers with delay constraint.

When comparing Figure 7 with Figure 8, it is obvious that, our optimization decreased together with the addition of our delay constraint which is expected. That means, in that case, our program can find some best path combinations which could use even longer paths and rejected because of our constraint. Especially going from 21 to 10, we can not improve our handover numbers without violating the delay constraint. In 9, a much more strict delay constraint is used to choose our best path combinations. In that case, it is obvious that our optimization process can not make an improvement more than 50 percent. That means the stricter the delay constraints, the lower is our improvements.

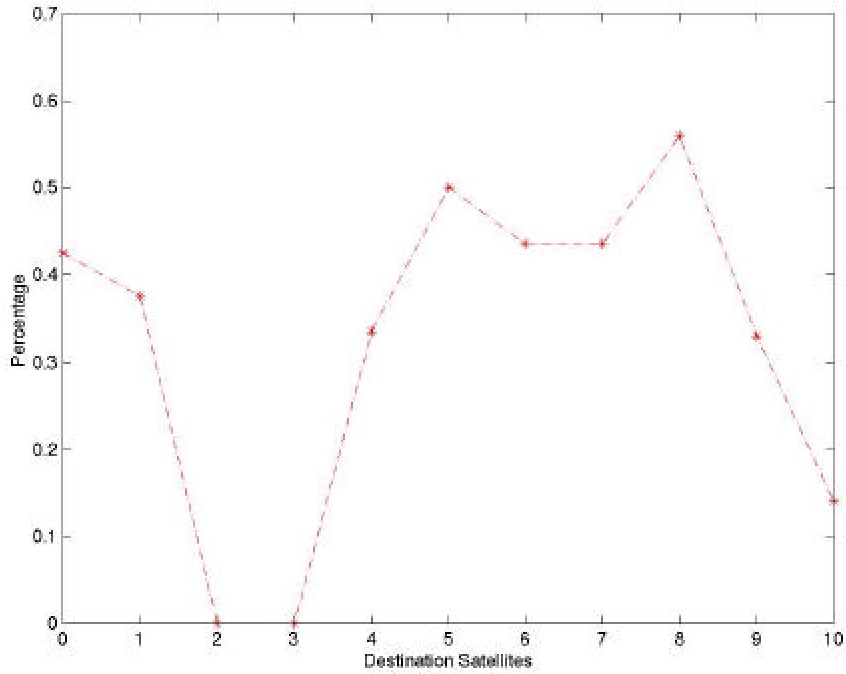

Figure 8: Percentage improvements in handover situations with delay constraint=50

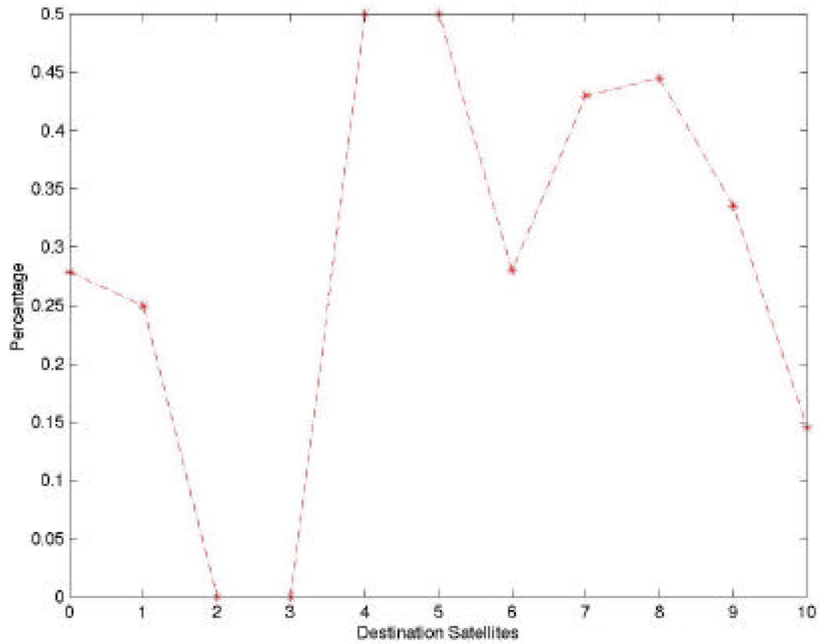

Figure 9: Percentage improvements in handover situations with delay constraints = 10

In Figure 10, the result of the last test is illustrated. In this test, average change in delay resulted from our optimization process is calculated. As shown in the figure, our delay changes are mostly below 6 percent. Only in two connections which are the connections between 21 to 41, and 21 to 42, the delay increases more than 6 percent. That means, our optimization can find the path list that causes the least number of handovers without improving the end to end delay. That means our algorithm can be used for data traffic which requires QoS guarantees.

7. Conclusion

In this study, we investigated the effect of ISL's and tried to improve the routing process from the point of handover situations. As shown in the previous section, our optimization process performs fairly well, that means nearly at all source destination pairs, some percentage of improvements can be obtained. Another contribution to the ISL routing process is made by adding a delay constraint to the process. This constraint can be useful in case of time sensitive applications for long durations. The delay constraint idea may also be used for traffic characteristics that requires QoS guarantees. In these situations, our optimization can be used with the given delay constraint. As this constraint is also an end-to-end delay, it is quite well used as a QoS guarantee. As a conclusion, it can be seen that our ISL routing algorithm can find the best paths between a given source and destination satellite pairs for a whole orbit period. On the other hand, to make the problem applicable to more realistic situations, UDL routing phase also should be solved. Therefore, as a future study, UDL routing part can be added to our optimization process. Another contribution to that study would be taking into account the traffic requirements. Even if in this study, traffic requirements are taken into account as a parameter in our cost metric, it is only some kind of approximation. Therefore, a more detailed analysis of this subject need to be done.

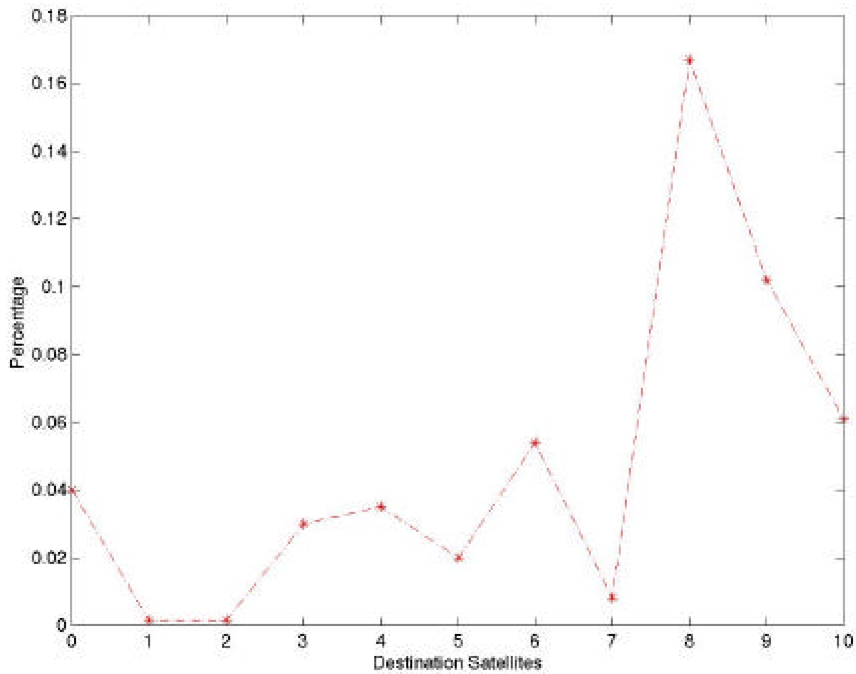

Figure 10: Average delay increases resulted from the optimization

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