An Appropriate Traffic Routing Scheme for Node-to-Node Communications in LEO Satellite Network Using Hybrid Mesh Topology

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Abstract

Since Low Earth Orbit (LEO) satellites provide short round trip delays, they are becoming increasingly important for real-time applications such as voice and video traffic. Several strategies have been proposed for routing in a LEO satellite system. Some of them are based on the Internet Protocol (IP), the Asynchronous Transfer Mode (ATM) switching, and the Routing Sets (RS).

This paper will introduce an improving for the new packet routing mechanism over inter-connected satellite networks that is the Minimum Flow Maximum Residual (MFMR) algorithm that will be based on RS concept and will give simulation results of a certain scenario. Our proposed algorithm is based on the Hybrid mesh topology (one of many mesh topologies used in LEO satellite routing). The algorithm is developed and implemented using a software simulation in Matlab. The proposed algorithm tries to minimize the maximum flow over a given set of shortest paths from the source to destination, and also, generates minimum propagation delay paths. The propagation delay we get is less than that of MFMR algorithm, i.e., improving the performance of the LEO satellite network by using Hybrid topology.

Key words: LEO satellite, ATM, MFMR, RS, and Hybrid Algorithm.

الخلاصة

بما ان الاقمار الصناعية في المدار المنخفض (LEO satellite) توفر زمن تاخير قصير، لذلك أصبحت بصورة متزايدة مهمة للتطبيقات الانية مثل نقل الصورة والصوت. قدمت عدة استراتيجيات لدراسة مرور الاشارة في أنظمة الـ (LEO satellite). قسم منها يعتمد على بروتوكولات الانترنيت، وطور التحميل الغير متزامن (ATM)، ومجاميع المرور (RS) .

هذا البحث يقدم تطوير لتقنية المرور الموجودة حاليا، وهي الـ (MFMR) والتي تعتمد على مفهوم الـ (RS) وسوف نعطي نتائج تمثيلية لسيناريو معين. التقنية المقدمة تعتمد على توبولوجية الشبكة المهجنة (Hybrid mesh topology) وهي أحدى التوبولوجيات المستخدمة في الـ (LEO satellite).التقنية المقدمة في هذا البحث طورت ونفذت باستخدام الـ (Matlab) ، وتعمل على تقليل الحد الاعلى لـ (Flow) على مجموعة من المسارات القصيرة في شبكة الـ (LEO satellite) من المصدر الى المستلم، وايضا تقليل زمن الانتشار. وزمن التاخير الذي تم الحصول عليه اقل من الذي تم الحصول عليه باستخدام تقنية الـ (MFMR)، وذلك يعني تحسين أداء شبكة الـ (LEO satellite) وذلك باستخدام (Hybrid mesh topology) .

1. Introduction

In today's community exists a growing demand and necessity for really global voice and data communication. To provide connections for these applications, two main technologies are in used today: direct cable connections and radio transmission. Cables are (at least for

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long distances, and especially between continents), expensive to deploy and hard to maintain, and they cannot reach every desired position [1].

Satellite networks can meet a variety of data communication needs of businesses, government, and individuals. Due to the wide-area coverage characteristics and ability to deliver wide bandwidths with a consistent level of service, satellite links are attractive for both developed and developing countries [2]. The satellite network suffers from the propagation delay. It is known that in an interactive communication the delays above 400 msec become "annoying". The delay is related to various factors.

The most important is the propagation delay. Since the propagation path is long compared with land based systems the satellite networks are inherent slower than other networks. The altitude of the satellite constellation affects the delay. Due to Van Allen Radiation Belts the satellite networks can be at 3 different ranges of altitudes (orbits): Low Earth Orbit (LEO) satellite networks, below the first bell (500-1500 km); Medium Earth Orbit (MEO) satellite networks, between the first and second belt (5000-12000km); and Geosynchronous Earth Orbit (GEO) above the second belt (20000- ... km).

The resulting end-to-end propagation delays from ground to ground are 20 – 25 msec for a LEO, 110-130 msec for MEO and 250-280 msec for GEO systems [1]. Thus, satellite systems can be categorized according to their orbits. The Geosynchronous orbit satellites are located over the equator and have the same angular speed as the earth. This mean that a geosynchronous satellite keeps its place at the same point in the sky for a reference point on the earth, its service area is constant and is called a footprint. The MEO and LEO orbits being closer to the earth in order to keep their satellites at the same altitude have to do a bigger angular motion compared to earth. This results in a motion of a satellite seen from a reference point over earth. In order to give a continuous service with a LEO or MEO satellite the system has more than one satellite nodes and they are moving on the same orbit with the same direction and angular speed. In such constellations the system can have two types of network architectures. In the first architecture bent pipe satellites are used and the system sends the messages to a ground switching center and the center routes the message over wired networks and broadcasts the packet at the destination satellite which, in turn it broadcasts the message to its footprint area and the destination terminal receives the packet. In the second type of architecture the satellites have switching capabilities and inter-satellite links and can route the packets in the air [1,3,4].

2. The Concept of LEO Satellites

There are two classes of LEO satellites: little LEOs, which are used for non-real time communications, sometimes also referred to as real-enough-time service. Applications for these are data transfer like paging or everything that can be done by electronic mail, whereas big LEOs also provide voice transfer (cellular telephony) or even networking. Little LEO satellites are quite small with a weight of 50-100 kg. The other class is build of big LEOs with a height of up to 500 kg and a diameter of not more then a few meters [1,3].

Satellites in low orbits can only cover a small earth surface area at a time. The area which is covered by a single satellite with a certain minimum elevation angle taken in consideration is called its footprint. The footprint between two adjacent satellites in each orbit is overlapping, and so are the footprints of two adjacent orbits. If one inscribes a hexagon into each footprint, then we can speak of the effective footprint of the satellite and you we cover the surface of the earth with them without any gaps [1,2].

LEOs based communication systems have multiple satellites orbiting in low orbits. Earth is divided into cells with users in a cell served by one or more satellites. LEOs are expected to provide wireless mobile communication services from any place to any other place on earth and support wireless communication from and to areas not covered by cellular or geostationary phone systems [5,6].

The LEO satellite constellation consists of a set of satellites orbiting the earth with high constant speed at a relatively low altitude. Each satellite is equipped with a fixed number of antennas that allow it to communicate with ground transmitters/receivers and with other satellites. On the other hand, two major issues arise due to their low altitude. First, a single satellite can only cover a small footprint at the earth surface, many satellites being thus required to provide globe coverage. Second, the footprint of each satellite moves continuously, implying a high mobility of the whole network, in contrast with other cellular systems.

A closer look at the feasible types of orbits shows that unless the orbits have the same altitude and inclination, their relative position change so often that ISLs can hardly connect them for a sufficient amount of time.

The basic structure of a constellation consists in a set of orbits that are deployed along a semicircle when viewed from a pole, as shown in Figure (1). The satellites are placed along the orbits so as to obtain a maximum coverage of the earth's surface. The deployment of satellites along with their footprints is shown. We can see that in a constellation there are two extreme orbits which are adjacent, but whose satellites move in opposite directions. As a result, a seam appears, that divides the network into, two parts: those satellites moving from south to north and those are moving from north to south [7].

When a satellite is leaving the visible area of its client during an existing connection, this connection must be given to another satellite. This process is called handover and requires rerouting of inter-satellite links as shown in Figure (2) [1].

The advantages of LEO satellites and the increasing congestion of GEO satellites, suggest the future development of orbiting satellites [8]. A large set of satellite constellations has been proposed to address communication services with worldwide coverage. Due to the progress in satellite communication technologies, it is now feasible to build a mobile communication network using LEO satellites [5].

In recent years, there have been several proposals to use networks of satellites in LEO for communications. A big advantage of LEO satellites networks over GEO satellites is much smaller delay. However, the lower altitudes also introduce disadvantages including much shorter orbit periods, typically a few hours, and smaller footprints. This results in constant motion of the satellites with respect to the earth's surface, and the need for more satellites to provide full coverage of the earth. LEO satellites can be used to supplement terrestrial networks by providing links between points on the surface that would be difficult or too expensive to connect with terrestrial links. A more ambitious approach is to replace large parts of terrestrial networks by using inter-satellite links to inter-connect a number of satellites into a LEO satellite network, as shown in Figure (3), three satellites in a single orbit connected with ISLs [4,6].

There are two types of inter-satellite links; intra-orbital and inter-orbital satellite links. The former connect consecutive satellites on the same orbits, while the latter connect two satellites that are on different orbits. In Figure (4) we show three possible patterns that can be obtained by using inter-orbital links between adjacent orbits: the "W" pattern and the "inclined" pattern in Figures 4(a)-(b) use four ISLs per satellite (hybrid topology), while the pattern in Figure 4(c) uses only three ISLs [7,9].

The routing information can be discovered by a ground switching center or by the satellites itself. In both cases the satellites have to forward the packets along their Inter-satellite Links (ISLs). The satellites in the same orbit do not change their position relative to the others in the orbit. Thus, they keep the same ISLs with their neighbors. These links are called intra-orbital links. They may have other links to the neighboring orbits. These links are called inter- orbital links (see Figure (4)) [1,3,4].

Since the satellites cover smaller areas in LEO systems, the traffic requirements become unbalanced due to high population in cities and low at rural areas. The communication requirements between high population areas are larger. This problem can be resolved by distributing the flow in a balanced way over all possible ISLs between the communicating nodes.

The footprints of satellites move faster than any terminal on earth. This causes to frequent handovers of terminals from a satellite to the other. This is called satellite-fixed cell system. The alternative of this is the earth-fixed cell system. In this method the cell on earth is fixed and the satellite's antenna beams are steered so as to point toward this fixed cell during some interval of time. In either way the source-destination pair and the path between them are transferred to new satellites coming to the positions where the path was passing through. In a network where the intermediate nodes are changing all the time in a constant way the path handover becomes important.

If we consider the hybrid topology model network in Figure (5), we can see that there exists more than one shortest path from the source to the destination. We call all the nodes in the rectangle, where the source is a corner and the destination is the other on the diagonal, a Routing Set (RS). If there are K routing set, we called it, K-set, where K is the number of paths between source and destination. All the directions toward the destination are located on a shortest path from the source to destination.

Again in Figure (5), all possible paths are shown in hybrid mesh topology. All of the paths using any one of the links with the specified directions are equal and are shortest paths. Also, the paths using these directions are loop-free. Thus, the routing problem for a satellite system becomes the "shortest path" discovery problem. However, since the network is spherical and there exist many RS between the Source (S) and Destination (D) and most of them pass through the polar region on through the horizontal plane a virtual network has to be considered while finding the right RS [3].

3. The Presented Work

3.1 Part One

The first part of our work is to investigate and design the ISL hybrid topology to be implemented. This is an important step to guarantee efficient networking in the operational system and to ensure the routing sets. In the following we present a simple approach to the LEO ISL topology design.

A closer look on the planar projection of the constellation in Figure (6), facilitates the first step in the ISL hybrid topology design. Due to the perfect symmetry of the constellation it is sufficient to consider generic types of ISLs between satellite 0 and its neighbors as an example. These are then applicable to all other satellites pairs correspondingly. This topology was shown in [10], but group 1 was not included.

Studying the relative time values of all ordered paths in a K-set for various source-destination pairs and various steps, one observes that the paths can be easily grouped according to its time ranges, as illustrated in below.

Typically, one time range corresponds to a certain number of ISL hops forming the respective path; the paths belonging to the first four groups of the considered case are displayed in Figure (7), and the relationship between hop count and path group becomes obvious.

3.2 Part Two

The hybrid mesh topology given in the first part of section 3 is an essential step to investigate the formulation of the new routing sets. In fact most of the following formulated equations given in [3,5,10], but the last modification was done in [3] and it is called "Minimum Flow Maximum Residual (MFMR)" algorithm. Here, we present a modified version of these equations by implementing our new mesh topology given in part 1 (we called this modification by "Hybrid Algorithm HA" for simplicity).

First, the general link matrix for any routing sets is given by:

$$X^{mn,pq} = \begin{bmatrix} X^{mn,pq}_{00,00} & X^{mn,pq}_{00,10} & . & . & . & . & . & . \\ X^{mn,pq}_{10,00} & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & X^{mn,pq}_{OS,OS} \end{bmatrix}$$

where:
(m,n) : Coordinates of source
(p,q) : Coordinates of destination
O : Number of orbits
S : Number of satellites per orbit
$X^{mn,pq}$: Available links matrix from (m,n) to (p,q)

According to our mesh topology, we can decompose the above matrix into two matrices, we called them for simplicity the odd and the even matrices, and we get the following two new matrices:

The odd matrix is:

$$Y^{mn,pq} = \begin{bmatrix} Y^{mn,pq}_{00,00} & . & Y^{mn,pq}_{00,20} & . & . & . & . & . \\ . & . & . & . & . & . & . & . \\ Y^{mn,pq}_{20,00} & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & Y^{mn,pq}_{OS,OS} \end{bmatrix}$$

and the even matrix is:

$$Z^{mn,pq} = \begin{bmatrix} . & . & . & . & . & . & . & . \\ . & Z^{mn,pq}_{10,10} & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & Z^{mn,pq}_{(O-1)(S-1),(O-1)(S-1)} & . \\ . & . & . & . & . & . & . & . \end{bmatrix}$$

where:

$Y^{mn,pq}_{ij,kl} = \{0,1\}$: 1 if link from node (i,j) to node (k,l) is included in the rectangle from source node (m,n) to destination (p,q).
0 otherwise.

$Z_{ij,kl}^{mn,pq} = \{0,1\}$: 1 if link from node (i,j) to node (k,l) is included in the rectangle from source node (m,n) to destination (p,q).
0 otherwise.

The main reason for sorting the general link matrix into two parts; that instead of searching the minimum distance between two nodes in big matrix, the presented algorithm try to find the minimum distance in one of the yielding matrices after sorting. If it does not find the minimum distance, it tries the other one.

Therefore, the delay time per hope would be minimized, i.e., the time of the algorithm we used would be minimized and that led to less time delay per hop in the satellite on board processing.

Then we must minimize the maximum flow on any link that is given by:

$$Min_z = Max\left\{ \frac{\sum_{(m,n)} \sum_{(p,q)} f_{ij,kl}^{mn,pq}}{C} \right\}$$

where:

$f_{ij,kl}^{mn,pq}$: Flow from node (i,j) to (k,l) due to source (m,n) to destination (p,q).

C : link capacity.

But, the above equation must and should be subjected to the following constraints:

$$f_{ij,kl} \le C.X_{ij,kl}^{mn,pq} \qquad \forall (m,n),(p,q),(i,j),(k,l)$$

$$\sum_{kl} f_{kl,ij}^{mn,pq} - \sum_{kl} f_{ij,kl}^{mn,pq} = \begin{cases} -T^{nm,pq} & if \quad (i,j)=(m,n) \\ T^{nm,pq} & if \quad (i,j)=(p,q) \\ 0 & otherwise \end{cases}$$

where:

$T^{mn,pq}$: Traffic requirement from (m,n) to (p,q)

The simulation is programmed using Matlab software package. In order to accept the results, we must compare our modified algorithm with the one used in [3]. And also, we must use the same worked data used in [3]. Our modified algorithm also, takes the current flow on link as the path's cost (time) and chooses the least cost path having the most residual capacity.

In order to test this part, the following are used:

1. We worked on 6 orbits and 12 satellites in each orbit
2. All the population is assumed to live in continents.
3. The transmitting and receiving nodes are placed over the continents or close to continent and not over sea.

The satellite locations and coordinates can be seen in Figure (8). The traffic parameters are taken to be as generic as possible.

Important parameters here are the call holding time and the load of the call as in [3]. The nodes generate calls that inter-arrival times are exponentially distributed. Also, the loads of the calls are also exponentially distributed according to three load levels that are specified for every scenario: light, normal, and heavy. The scenarios are described in Table (1).

The routing set algorithm is evaluated in Matlab. As the objective of the routing was to minimize the maximum flows on the links, the scenario is evaluated for their link flows. The maximum flow of the network is represented by the link with the maximum flow during the overall simulation time. The simulation durations are also chosen as 2000 sec, and run 20 times and the maximum of the result is chosen.

The maximum flows in each group are close or equal to the ideal case. The flow requirement of the group is the sum of individual flows of the nodes in the group. The MFMR is below the total flow requirement of the network. This last means that the flows are distributed over the RS and no additional flow from the other groups is routed over the specified RS.

In Figure (9), the maximum flow is decreased, and in the same time we maintain the shortest paths (the routing sets) in all groups, due to the using of hybrid mesh topology.

In Figure (10), we notice that as the number of hops is increased, the end-to-end delay time is increased, due to the increasing in the total distances between the source and destination satellites.

Apparently, we get less time delays in all hops as compared with [3], due to the sorting of the link matrix into two parts that led to decrease the overall delay time between two nodes. And also, the use of PC with 3 GHz processor enhanced the performance of searching the minimum distance between nodes.

Also, it can be seen that even for the worst case (5 hops) the end-to-end delay from ground to ground is still below 400 msec.

The RS routing method gives better results when the RS is bigger. In the global communication case, the system can chose as an RS for all satellites, which results in better distribution of the total flow. The RS algorithm intends to distribute the flows over all the available shortest path routes in order to reduce the link utilization and prevent the congestion.

4. Conclusions

This work has primarily focused on Routing Set analysis for a LEO satellite network. In this work, we proposed a new LEO satellite routing algorithm that is the "Hybrid algorithm". The new scheme is based on the Routing Sets.

The Hybrid routing algorithm helps to improve the LEO satellite network availability by using alternate routes. This routing scenario is implemented and simulated in Matlab. The LEO network that is considered in the simulations consists of 6 orbits and 12 satellites on each orbit.

For the studied case, it is seen that the system tries to minimize the maximum flow and keeps the end-to-end delay from ground to ground under the upper boundary of interactive communication (400 msec), and thus we get a low delay times as compared with the lastly proposed algorithm that is the MFMR.

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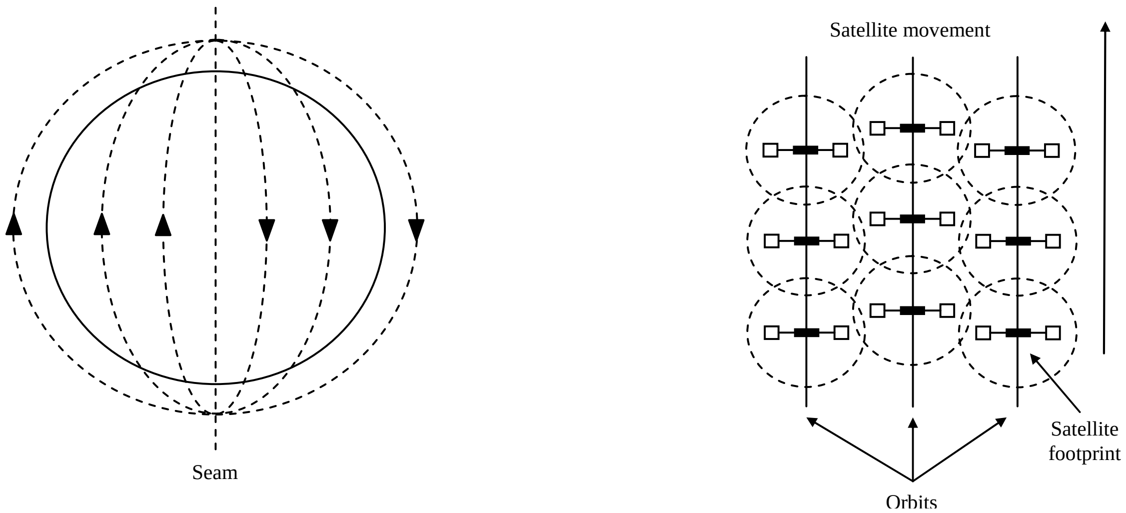

Figure (1): The basic structure of LEO constellation (Hybrid topology)

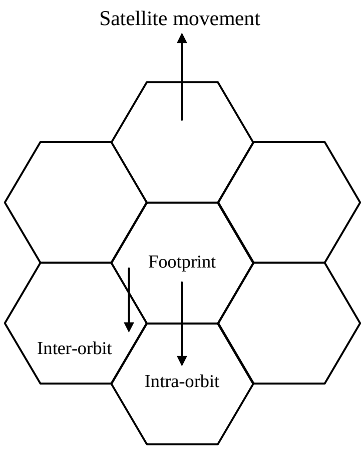

Figure (2): Footprint and handover

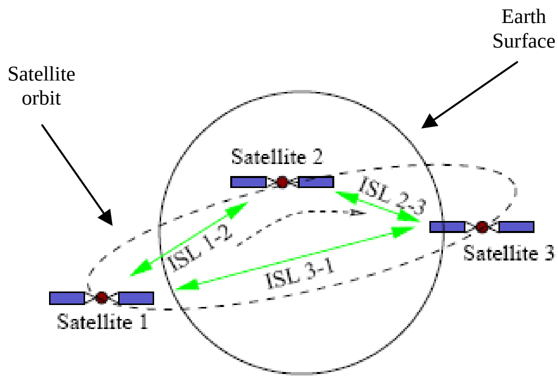

Figure (3): Basic ISLs

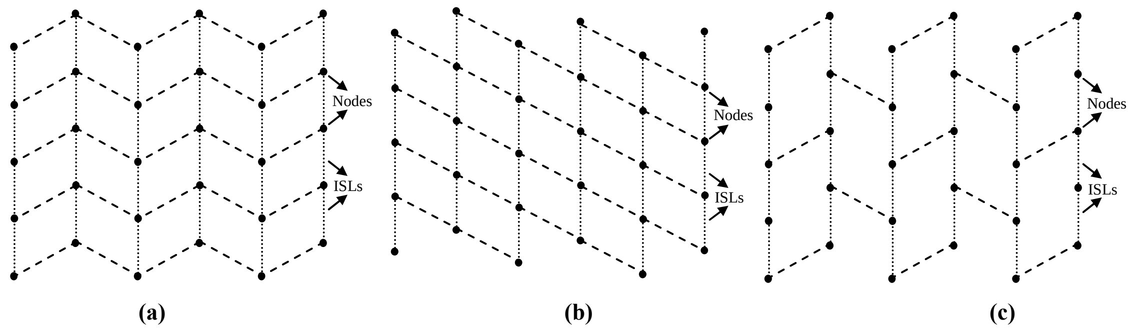

Figure (4) : Some ISLs patterns

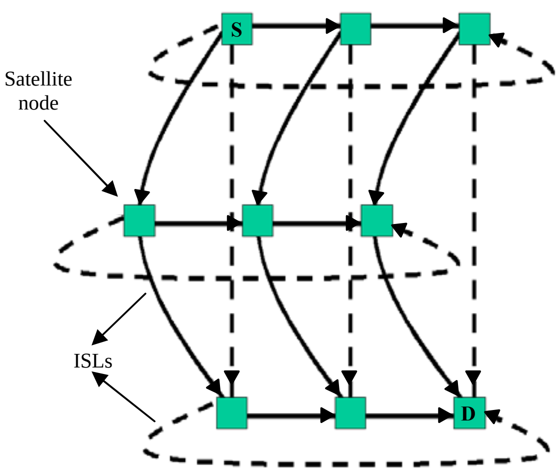

Figure (5): 3 x 3 hybrid topology model

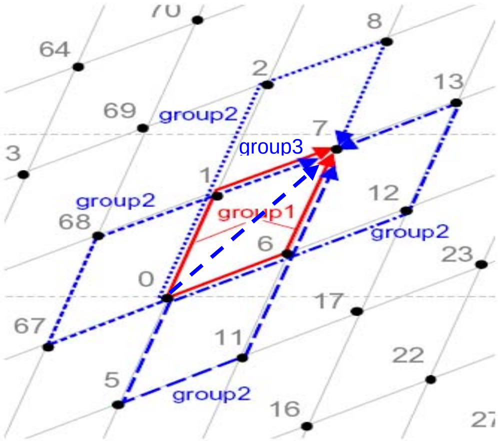

Figure (6): Hop-based path grouping between sat_0-sat_7 for hybrid topology

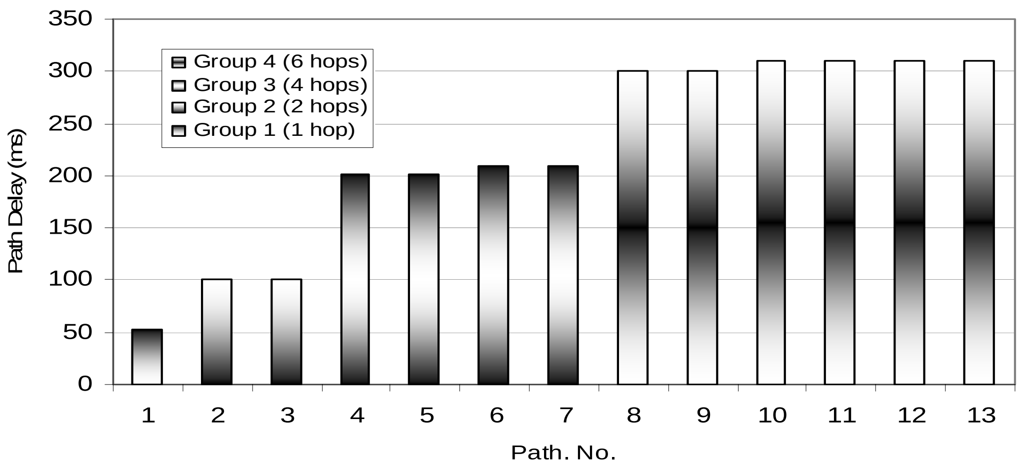

Figure (7): Path delay vs. path no. between sat_0 and sat_7 for hybrid topology model

Table (1): Scenarios descriptions

Group	***Transmitting***	***Receiving***	***Call (sec)***	***Load (10^3 pk/sec)***
1	(0,2), (1,1), (2,1), (1,2), (2,2)	(0,2), (1,1), (2,1), (1,2), (2,2)	40	H. flow: 10
2	(1,2), (2,2), (1,3), (2,4)	(1,2), (2,2), (1,3), (2,4)	40	L. flow: 4
3	(4,1), (3,2), (4,2)	(4,1), (3,2), (4,2)	40	N. flow: 7
4	(0,9), (5,3), (5,4)	(0,9), (5,3), (5,4)	40	H. flow: 10
5	(3,10), (3,9), (4,9), (5,8), (5,7)	(3,10), (3,9), (4,9), (5,8), (5,7)	40	L. flow: 4

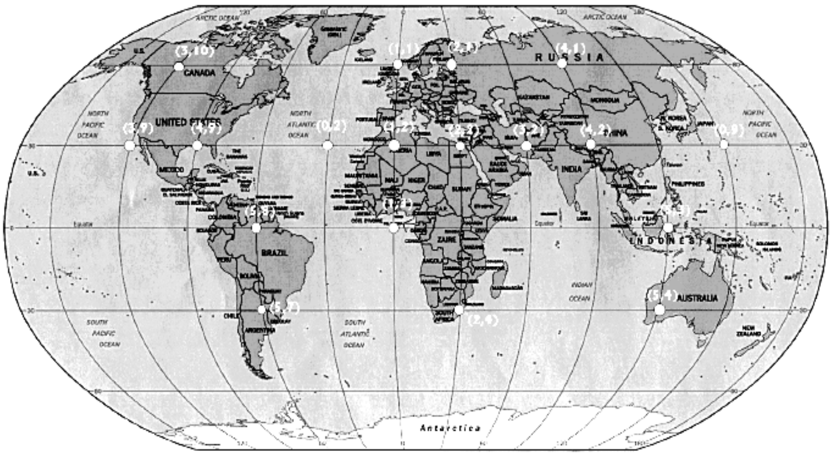

Figure (8): Satellites locations used in test scenarios

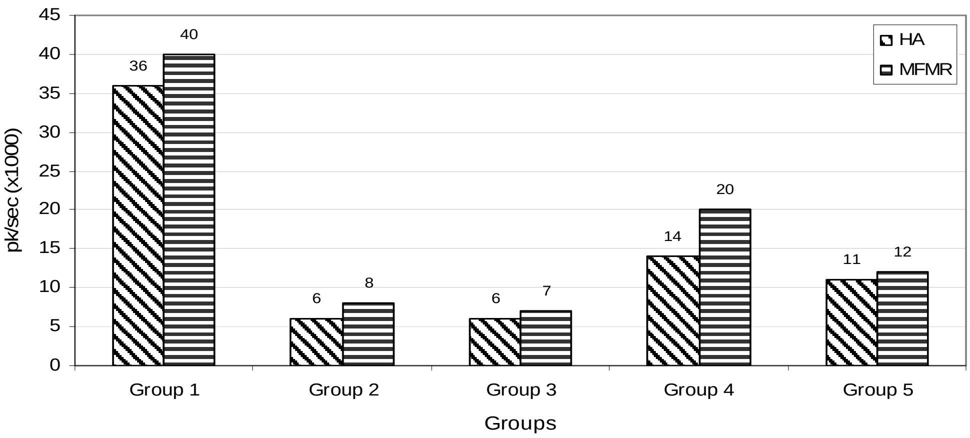

Figure (9): Comparison of the maximum flows

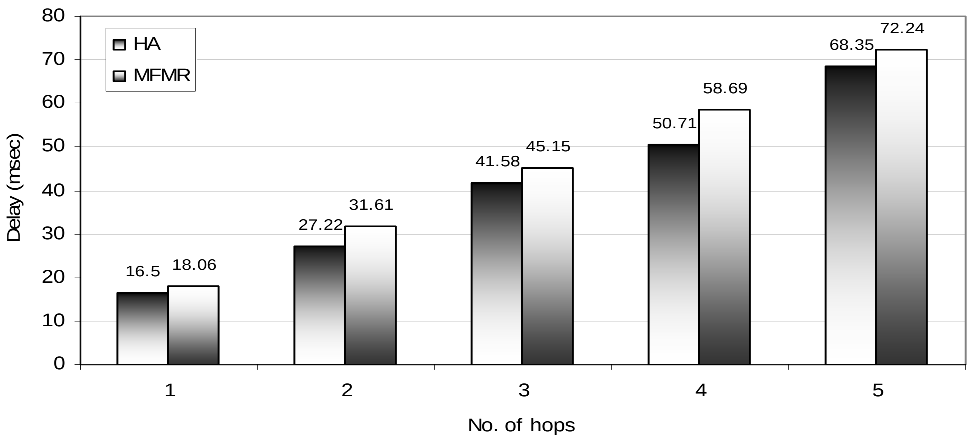

Figure (10): Effect of number of hops to the end-to-end delay