Minimum Flow Maximum Residual Routing in a LEO Satellite Network Using Routing Set

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Abstract

Satellite networks are used as backup networks to the terrestrial communication systems. In this work, we tried to find a routing strategy over dynamic satellite systems to better utilize the capacity of the network. The satellite networks are not affected by natural disasters, therefore they can be used widely during and after disasters. The Minimum Flow Maximum Residual (MFMR) routing algorithm over the Routing Set boundaries is proposed in order to better utilize the capacity of the system by distributing the load over the shortest path alternatives of the system. We assumed the satellite network as having finite states and formulated the problem by using Finite State Automation concept along with earth-fixed cell strategy by using a virtual satellite network model. The routing problem in satellite networks is previously studied in the literature and it is conjectured that the problem is NP-Hard. The online and offline problems are stated and the MFMR algorithm is described in detail. The algorithm is compared with alternatives by simulating the network on Opnet Modeler. Finally, the performance analysis of different scenarios is given in this work.

1. Introduction

The operators of new satellite systems give more importance to communication satellite networks than broadcasting systems since, they believe that on the average 50% of the world population will be living in rural areas in the 21st century [1]. Moreover, this population will need services that could be given on satellite networks such as health care, distance learning, crisis management, environmental monitoring, electronic commerce, e-mail and Internet access [2, 3]. Satellite systems can satisfy various QoS requirements for different communication needs such as bulk transfers, video broadcasts, video conferencing, interactive computing, voice calls, distance learning [4, 5]. Satellite networks are intended to augment the existing terrestrial and cellular networks [6]. Also, these networks are thought as a backup communication system where land based communication networks exist, because the satellite systems do not suffer from natural disasters (earthquake, flood, etc) and continue to give service globally. Satellites also provide global connectivity infrastructure, a natural broadcast medium, high data rate and new terminal addition with a low cost [7].

The satellites are grouped into two categories: bent pipe and onboard processing/switching [8]. The bent pipe satellite works as a repeater. It amplifies the incoming signal and reflects it to the ground-switching center; therefore, it has the simplest architecture. Onboard processing satellites are more "intelligent" and they may have knowledge of the overall network and do the switching according to their connection information controlled by themselves or from the ground control centers. Both type of satellites cover a big cell on earth in the footprint and may divide this area into simple micro cells or hierarchical cells [9].

This paper will introduce a new packet routing mechanism over interconnected satellite networks that will be based on the Routing Set (RS) concept and will give simulation results of some scenarios. It is known that the continents where communication can occur are located around the equator, namely, below the 50th latitude. This means that the inter-satellite link lengths are approximately equal in the communicating regions. Hence, the communication's propagation delay is determined by the number of satellite hops on the communication path. The RS method proves that all of the alternative shortest paths between source and destination pairs have the same length. This means that the propagation delay is the same for all path alternatives of the communication pairs. Our path finding algorithm tries to minimize the maximum flow over the RS. This method implies the knowledge of the flows over the RS (not all of the network). The resulting network is a better-utilized and balanced flow network that reduces at the same time the processing delay and minimizes the buffer requirements of the switching nodes.

The second section categorizes and describes the satellite networks briefly. Section 3, introduces the Routing Set concept. Section 4 deals with the Minimum Flow Maximum Residual (MFMR) routing algorithm and the problem formulation. Section 5 describes the test network, the related scenarios that are used in the simulations for evaluating the performance of the MFMR algorithm. Section 6 concludes the paper.

2. Satellite networks

It is known that, in an interactive communication the delays above 400 msec are "annoying" [1]. The delay is related to various factors. The most important factor in a satellite network is the propagation delay. In fact, the delay is an appropriate measure to use in evaluation of several routing algorithms in an application independent manner. Since the propagation path is long compared to land based systems, the satellite networks are inherently slower than other networks. Moreover, the altitude of the satellite constellation affects the path, thus, it affects the propagation delay.

In the bent-pipe satellite networks, the system sends the messages to a ground switching-center. The center routes the message over wired networks and broadcasts the packet at the destination satellite. The destination satellite, broadcasts the message to its footprint area and the destination terminal receives the message. In onboard switching satellite networks, the satellites have switching capabilities over their inter-satellite links. These satellites can route the packets in the air. The routing information can be static or dynamic. In static routing, all of the routing information for all source-destination pairs is decided and uploaded to the satellite nodes. In dynamic routing on satellite networks, theoretically, the paths are rediscovered every time a new call (in circuit switching) or packet arrives (in datagram routing). Moreover, the routing can be grouped into proactive or reactive routing [10] where in proactive routing the routes are computed independently of traffic arrivals and in reactive routing routes are discovered on-demand. The routing information can be discovered by a ground-switching center or by the satellite itself. In both cases, the satellites have to forward the packets along their inter-satellite links. The satellites in the same orbit do not change their position relative to the others in the orbit. Thus, they keep the same inter-satellite links (ISL) 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 [11].

The satellite network architecture looks like a Twisted Manhattan network given in [12]. In fact, the real network has small differences that affect the optimal routing in this mesh architecture. The architecture converted to 2D representation is given in Figure 1. The upper right and the down left sides of the network are neighbors. However, since they move in opposite directions, they continuously break their inter-orbital links and reconnect with the next arriving satellite.

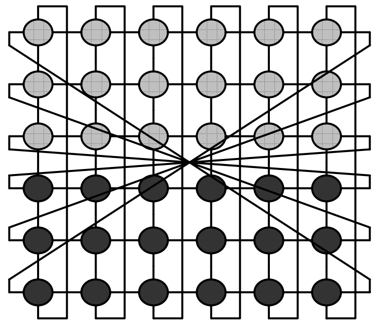

Figure 1. Satellite network topology

In Figure 1, the ground relative positions can be thought as fixed and the routing can be done accordingly. This means that, the routing can be done according to source-destination pair positions on earth. If we consider an instant and think the network as static, the routing can be done easily. According to our assumption, we associate the routing information with the current coordinates of the node it is found. The coordinate of the satellite is given by *(x, y)* where *x* is the position of the satellite in the orbit counting from North Pole and *y* is the orbit number. For the next instant of time, where a new satellite comes to the position, the recent satellite can forward the routing and active connection information over the ISL. We can specify the network with the number of orbits and the number of satellites per orbit. Because of the spherical shape of the network, there exist more than one path to the destination node. The discovery of the shortest path depends on the direction where the destination is searched. In order to find the direction, a virtual network is introduced in the next chapter.

3. Routing Set

Since the satellites cover smaller areas in LEO systems, the traffic requirements may become unbalanced [13] due to high population in cities in contrast to 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. Previous research includes Dogleg, Parallel Highway and Polar Hop routing methods [14]. In Dogleg routing, the packets go first horizontally until they reach the destination satellite's longitude and then vertical to the destination node or the reverse (vertical first and then horizontal), but never both at the same time. In Parallel Highway routing, the flow is routed over a parallel path to the shortest paths. This is used to distribute the high flow outside of the crowded regions. The last one is the Polar Hop. In this method, all of the connections are routed over the path that passes through the polar region.

The footprints of LEO satellites move faster than any terminal on earth that causes to frequent handovers of terminals from a satellite to the other. This is called satellite-fixed cell system. The alternative of satellite-fixed cell is the earth-fixed cell system [15]. 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. However, if the orbit period is divided into convenient small time intervals, the network can be thought as fixed during these intervals. The routing can be done according to this static network, since the newly arriving satellite will take the place of its ancestor. In some previous work, this network is considered as having finite states (Finite State Automation - FSA) and all the routing decisions are pre-calculated for all states (static routing.) In [16], it is shown that static routing gives better results than dynamic routing. In [17], [18] and [19] the FSA model is used to calculate the blocking probability. In [20], it is believed that the FSA assumption is not realistic and the path has to do handover in every moment where the underlying network architecture changes due to the satellite motion and the routing must be done according to the probabilistic model that chooses the least probable handover ISLs as the most convenient path. This is called the Probabilistic Routing Protocol (PRP). However, this method assumes that the link cost is a function of the time- and location-homogeneous traffic load [21]. Whereas, this assumption is not realistic since the traffic is not time-homogeneous. New traffic can easily congest the PRP path and leave the other paths underutilized. The maximal resource requirement of a path is determined by the hop count and by using a minimum hop count path will reduce the maximum resource consumption [22].

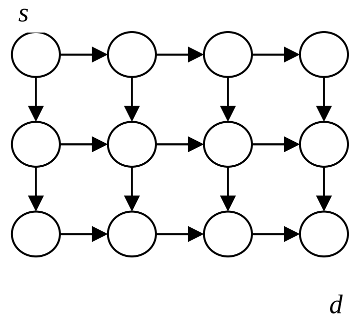

Figure 2. Paths from the source s to dest. d.

In our work, we will use this assumption. If we consider the network presented in Figure 1, 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). All directions toward the destination are located on a shortest path from the source to destination.

In Figure 2, all possible paths are shown. The length of inter-orbital and intra-orbital links can be assumed to be equal length above 50th latitude (this can be calculated from the formulations given in [17]). With this assumption, it can be proven that all of the paths using any one of the links with the specified directions are equal and are shortest paths. It can also be proven that the paths using these directions are loop-free.

Claim 1: The number of possible loop-free paths is equal to

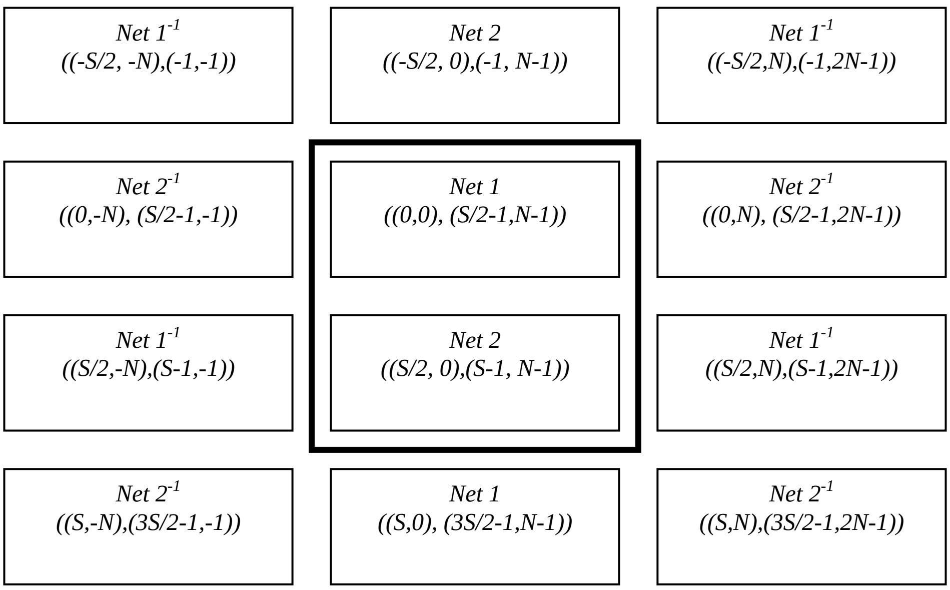

Figure 3. The real and virtual satellite network representation. The rectangle in the middle is the real network. As the world is spherical the bottom nodes are above the top of the real network that is presented by a virtual network. Similarly the rightmost nodes are on the left of leftmost nodes.

$\frac{(x+y)!}{x!y!}$, where x is the difference of abscissa between the source and destination and y is the difference of ordinates between the source and destination.

Proof: If we take an example network as in Figure 2, all of the loop-free paths have to be a combination of x times the direction (→) and y times the direction (↓). Any combination of these directions will reach to the destination. A path would have $(x+y)$ possible moves on the first and $(x+y-1)$ on the second and so on. This brings $(x+y)!$ divided by the possible combination of the directions within themselves that is $x!y!$. The same proof can be made also by induction. Moreover, all of these paths are loop-free, since in order to have any loop the path has to contain at least one of the directions that are opposite. The directions (→) and (↓) are called allowed moves and are represented with 1 in the matrix $\boldsymbol{X}$ in (11) for the nodes in the routing set.

Claim 2: If all the links and nodes are identical in a Routing Set R, all of the loop-free paths formed by taking allowed moves from $\boldsymbol{X}$ are also shortest paths.

Proof: If all the allowed links and nodes are identical in a loop-free path all of the alternative paths will have the same length and it will be equal to the shortest path.

In the following sections, the routing problem for a satellite system will become a "shortest path" discovery problem within a RS. The LEO satellite network is spherical and there exist many RS between the source and destination and most of them pass through the polar region or through the horizontal plane. A virtual network has to be considered while finding the right RS.

We assume N orbits and S satellites per orbit. Because of the spherical shape of the earth, the first and the N^{th} orbits are neighbors in both sides. The nodes between the borders of these orbits are called seams. The border orbit satellites of different seams that are neighbors are counter-rotating. The satellite network will look like the topology shown in Figure 1, if we ignore the spherical shape of the earth. The network can be represented as in Figure 4.

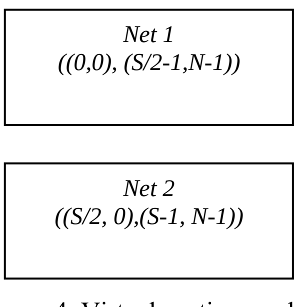

Figure 4. Virtual routing model.

Along with the satellite network given in Figure 3, a virtual routing model of the whole network is presented in Figure 4. In the virtual routing model, all the real source and destination pairs are located in the center rectangle, namely in *Net 1* and/or *Net 2*. The routes will be calculated on this virtual network and mapped back to the real connections. Suppose we have the source in *Net 1* and the destination in *Net 2*. The destination node will be placed, according to a mapping function, virtually in all *Net 2* and *Net* 2^{-1}. All the routing sets will be formed according to single source and multiple virtual destinations pairs. The minimum number of hop RS will be selected as primary RS since it includes the shortest path candidate. In this virtual network, the minimum hop count for routing sets L_R can be calculated by the following formula:

$$L_R = |x_d - x_s| + |y_d - y_s| \qquad (1)$$

We assume that satellite positions are given by the pair (x, y) where x represents the axis and y the ordinate on the coordinate plane. All routes are calculated based on these node positions. The satellite can route a message to the destination node over nine different RSs. These RSs are the rectangles to nine different satellite nodes (one real and eight virtual locations of the same destination satellite located in different *Net*'s) having the same source node as a corner. The eight virtual locations are as follows: (in Figure 3) three virtual networks at the top of the figure, two on the left and right of the real network, and three at the lower part of the figure. For the shortest path, the RS with the minimum length $L_{R\min}$ (called the Minimum Cardinality RS) is chosen and the routing path to be used for the call is found in this RS. The Minimum Cardinality RS is calculated by the evaluation of Equation (1) for these nine different RSs (namely nine addition operations.) The path is selected within this RS and mapped back to the real ISLs. The shortest path in our network is chosen by a flow distribution mechanism that will be described in the next section.

4. Minimum Flow Maximum Residual (MFMR) path

We have chosen the boundaries of the solution space for the communication path up to now. Every alternative path has the same length. During this step a routing algorithm has to be chosen. The algorithm has to [23]:

- Be of an average complexity,
- Do loop-free routing,
- Converge,
- Have minimum computational overhead,
- Have minimum storage overhead.

In [11], the minimum propagation delay is taken as the basis for routing and the number of hops is not considered. In the same work, the length of ISLs near the pole is shorter than those near the equator. Moreover, routing over the polar ISLs causes to less propagation delay. However, in

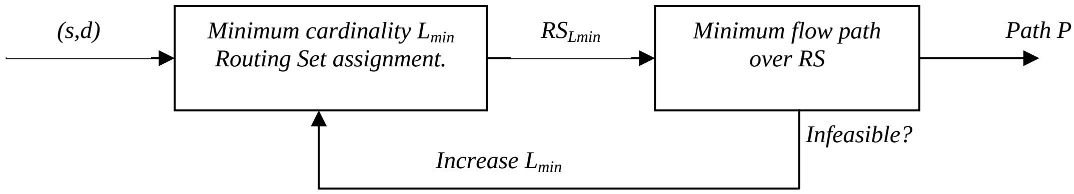

Figure 5. Finding the path over the minimum cardinality RS.

the method presented in [12], the polar ISLs will suffer from congestion. Also, more of the population is near the Equator when compared to the Polar Regions. Thus, most of the ISLs within a RS have approximately the same length and choosing the least propagation delay path will congest the link whereas the other links will remain unused. This method will minimize at the same time the call blocking probability that is one of the main constraints in [16]. In our method, it is assumed that all the ISLs have the same length in order to give the same priority to all the paths.

In [21], the satellite network topology is considered as changing during time because of the constant motion of satellites. However, as the number of satellites grow (e.g., 66 for Iridium and 288 for Teledesic) with the FSA assumption, at a given instant, all of the satellites have their four ISLs connected to their neighbors and the topology can be considered as described in Figure 1.

In [10], various routing strategies according to knowledge oracles are given. These oracles include local knowledge, local or global queuing status or traffic demand in future. In MFMR algorithm, only the RS node link status will be used in order to find most convenient path. Therefore, the global link state knowledge, which has a big overhead of status messaging that wastes the network resources, can be reduced to RS link state knowledge.

In our work, we believe that if we distribute the traffic on the highly utilized links over all other available paths, this will balance the traffic load on the overall network. Based on this assumption, the satellite routing problem can be modeled as a topology discovery and a flow assignment on the discovered topology. The satellite network being a spherical mesh has many alternative paths from a specific source to the destination. Actually, the destination node can be represented by one real and eight virtual nodes (on the virtual network) all in different directions. The route assignment phase should also decide on the optimum path's direction (or the RS) out of the alternative directions. Therefore, the problem is to find the optimum topology and the optimum path on this topology. The parameters used in the problem definition are given in Table 1.

Table 1. Known parameters in the formulation of the problem

Notation	**Meaning**
$G(N,A)$	Graph *G* with satellite nodes *N* and inter-satellite links (arcs) *A*
u_{ij}	Connectivity matrix between nodes *i* and *j*. 1 if ISL *(i,j)* is included in the topology.
K	Maximum number of ISL for a node
f_{ij}	Flow on link *(i,j)*
f_{ij}^{mn}	Flow on link *(i,j)* because of traffic requirement between source-destination pair *(m,n)*
C_{ij}	Link capacity of *(i,j)*
T^{mn}	Traffic requirement between source-destination pair *(m,n)*

We define;

$$Z_{ij} = \sum_{m,n} f_{ij}^{mn} \qquad \forall m,n \in N \text{ and } \forall (i,j) \in A \quad (2)$$

Let,

$$Z = \max\{Z_{ij}\} \quad (3)$$

The routing problem P_1 becomes;

$$Min\ Z \quad (4)$$

Subject to,

$$\sum_j u_{ij} \le K \qquad \forall i \in N \text{ and } \forall (i,j) \in A \quad (5)$$

$$u_{ij} = u_{ji} \qquad \forall i,j \in N \quad (6)$$

$$f_{ij} \le c_{ij} u_{ij} \qquad \forall i,j \in N \quad (7)$$

$$\sum_{\{j:(i,j)\in A\}} f_{ij}^{mn} - \sum_{\{j:(j,i)\in A\}} f_{ji}^{mn} = \begin{cases} -T^{mn} & if\ i = m \\ T^{mn} & if\ i = n \\ 0 & \text{otherwise} \end{cases} \qquad \forall i,m,n \in N \quad (8)$$

$$f_{ij}^{mn} \ge 0 \qquad \forall i,j,m,n \in N \quad (9)$$

$$u_{ij} \in \{0,1\} \qquad \forall i,j \in N \quad (10)$$

The objective is the minimization of the maximum flow on any link. The link capacities are assumed to be different from each other. This is because of the fact that the satellite network can be formed by different types of satellite nodes and link capacities. Inequality (5) limits the number of chosen links for a node with the maximum number of ISL of a satellite node. In order to be chosen for a link, there are some requirements; the link should be included in the arc set *A*, and it should be included in the topology. Equation (6) states that the links are bi-directional. (7), (8) and (9) are the usual flow constraints. The problem P_1 is a difficult optimization problem. Similar problems given in [24] and [25] are formulated as Mixed Integer Linear Programming (MILP) problems which is known to be NP-Hard.

The satellite networks tend to give better service quality by increasing the elevation angle of the footprints. This results in smaller coverage area in the footprint and increased number of satellites for the global coverage. The Teledesic network was designed to use 840 satellites [26]. In addition to the satellite network, the High Altitude Long Operation (HALO) networks are under development [27]. These networks are consisting of airplane nodes flying at an altitude of 51,000-60,000 ft. This altitude will result in increased number of nodes in the sky. Increasing the number of intermediate nodes will increase the number of alternative paths between the source-destination pairs. This will increase the search time for an available path to distribute the flow over the network in a balanced way. In order to reduce the search time, we will use a heuristic. We will divide the problem into two sub problems: a topology assignment and a routing problem over the given topology. The topology will be chosen as the minimum cardinality routing set from the source to destination where a feasible solution exists. The search phase is represented in Figure 5. The flow distribution on the available paths become more important in real time communication over single or multi-layered satellite networks as in [28] where High Altitude Platforms (HAP) and LEO networks are inter operated.

The search procedure will assign the minimum cardinality RS from the source to the destination and with the given topology, a feasible solution should be found in the next step, namely the minimization of the maximum flow over the RS. The complexity of the first step is nine addition and comparison operations. The output of the first phase is a matrix ***X*** that describes the minimum cardinality RS. The matrix ***X*** is calculated for all possible links and directions between router nodes in order to limit the number of candidate paths from source to destination and to give a boundary to our search space of possible paths. The matrix is given in (11). Table 2 defines the notation used in the matrix.

Table 2. Notation used to define the RS.

Notation	Meaning
χ^{mn}	Available links matrix from source *m* to destination *n*
$X_{ij}^{mn} = \{0,1\}$	1 if link from node *i* to node *j* is included in the rectangle from source node *m* to destination *n* 0 otherwise.

$$\chi^{mn} = \begin{bmatrix} x_{00}^{mn} & x_{01}^{mn} & . & . & . & . \\ x_{10}^{mn} & . & . & . & . & . \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ . & . & . & . & . & . \\ . & . & . & . & . & x_{NN}^{mn} \end{bmatrix} \qquad (11)$$

The link availability matrix, χ^{mn}, is used in the formulation of the problem. The role of the matrix is to make available all the links in the routing set that are towards the destination. This idea is explained in more detail in the following parts. The elements of χ^{mn} are calculated using (12). The node numbers are referred as the coordinates of the satellite node in the network. Thus, the source, destination and intermediate node indices are converted to coordinates in order to give the necessary formulation to calculate the matrix. The conversion can be done by using the *mod()* and *rest()* functions that give the abscissa of the node by taking the modulus of the node number with the number of orbits in the network and the ordinate of the node by taking the remainder of division operation of the node number to the number of orbits, respectively.

Table 3. Notation used to define χ^{mn}.

Notation	Meaning
$x_{ef,gh}^{ab,wz}$	Link availability state over the link from node *(e,f)* to node *(g,h)* caused by the connection from source *(a,b)* to destination *(w,z)*.

$$X_{ef,gh}^{ab,wz} = \begin{cases} 1 & if\ (a \le w) \text{and} (g = e+1) \text{and} (f = h) \\ 1 & if\ (a \ge w) \text{and} (g = e-1) \text{and} (f = h) \\ 1 & if\ (b \le z) \text{and} (g = e) \text{and} (h = f+1) \\ 1 & if\ (b \ge z) \text{and} (g = e) \text{and} (h = f-1) \\ 0 & \text{otherwise} \end{cases} \qquad (12)$$

where the nodes $(a,b),(w,z),(e,f),(g,h) \in N$

Given the routing set RS, the second problem becomes a minimization of the maximum flow over the routing set chosen by the first phase of the problem. The problem P_2

is defined as (The notation of Table 1 is used in the formulation);

$$Min\, Z \qquad (13)$$

Subject to,

$$f_{ij} \le \begin{cases} c_{ij} & \text{if } u_{ij} = 1 \\ 0 & \text{otherwise} \end{cases} \qquad \forall i, j \in N \qquad (14)$$

$$\sum_j f_{ij}^{mn} - \sum_j f_{ji}^{mn} = \begin{cases} -T^{mn} & \text{if } i = m \\ T^{mn} & \text{if } i = n \\ 0 & \text{otherwise} \end{cases} \qquad \forall i, m, n \in N \qquad (15)$$

$$f_{ij}^{mn} \ge 0 \qquad \forall i, j, m, n \in N \qquad (16)$$

The problem P_2 assumes that the topology is fixed and it minimizes the maximum utilization over the links. The problem is known to be polynomial. Thus, by using some simplifying assumptions as Routing Sets instead of solving a difficult optimization problem (P_1) a polynomial problem (P_2) is solved.

Some other search methods can be proposed for this problem. One of the solutions is the Variable Depth Search (VDS) [25]. However, VDS's complexity is much higher than the proposed heuristic. Other heuristics such as Simulated Annealing and Genetic Algorithms can be used in order to solve the minimization of the maximum flow problem. These methods are used in [24] in order to decrease only the maximum flow on the network links and do not deal with the propagation delay of the communication path discovered.

4.1. The MFMR algorithm

Dijkstra's shortest path algorithm is used in order to find an initial shortest path and then other proposed algorithms modify this path in order to find a better alternative or the best promising path (e.g. in PRP [20]). However, in our case, we modified Dijkstra's algorithm to give a final result that is relevant to our case. In this algorithm, the shortest path is defined as the minimum flow path. The costs are taken as the link flows. In the algorithm, it is assumed that the flows are non-negative (this assures loops not to be chosen as shortest paths. Though, the loops are not present in the directed graph, namely, the routing set from the source to the destination due to χ^{mn} matrix.) In Table 4, the notation used in the MFMR algorithm is given. The MFMR algorithm is given in Figure 6.

Table 4. Notation of MFMR algorithm

Notation	Meaning
SS	Set of nodes.
SS'	Inverse of *SS*.
NN	Set of all nodes.
d(i)	Distance of node *i* to *sc*. Here, the minimum flow to *i*.
r(i)	Maximum residual flow to *i* from *sc*.
c_{ij}	Capacity of link *(i,j)*
f_{ij}	Flow of link *(i,j)*
pred(j)	Predecessor of node *j* of minimum flow path.
A(i)	All of the valid outgoing arcs from node *i*.

```
{
  SS = ∅; SS' = N
  d(i) = ∞ for each node i∈NN
  d(sc) = 0 and pred(sc) = 0
  r(sc) = ∞ for each node i∈NN
  while /SS/≤/NN/ do
  {
    Let i∈SS' be a node for which d(i)=min{d(j): j∈SS'}
    SS = SS∪{i}
    SS' = SS'-{i}
    For each (i,j)∈A(i) do
      If d(j)>max{d(i), fij}
      {
      d(j) = max{d(i), fij}
      pred(j) = i
      r(j) = max{r(i), cij-fij }
      }
      else if d(j) = max{d(i), fij}
      if r(j)<max{r(i), cij-fij }
      {
                pred(j) = i
                r(j) = max{r(i), cij-fij }
      }
  }
}
```

Figure 6. The Minimum Flow Maximum Residual (MFMR) path algorithm

The algorithm takes the minimum flow label node *i* from *SS'* and transfers it to *SS*. In each iteration, all of the outgoing arcs of the chosen node are processed to correct the label of the nodes in *SS'* to have the minimum flow. This means that the minimum flow node *i* in the set *SS'* does not have any intermediate node in its path in *SS'*. We have to show that the minimum flow path from *sc* to *i* has to have at least *d(i)*. Consider any path *H* from source *sc* to node *i* that contains some node in *SS'* as an intermediate node. The path *H* can be decomposed into two segments H_1 and H_2: the path H_1 does not contain any node in *SS'* as an intermediate node but terminates at a node *k* in *SS'*. By the second induction hypothesis, the node has to have a minimum flow label as *d(k)*. The node *i* having the minimum flow label in *S'* should have *d(i)* ≤ *d(k)*. Moreover, if *d(i)=d(k)*, then *r(i)* ≤ *r(k)*. Therefore, the path H_1 has the maximum flow label as at least *d(i)*. Additionally, since the flows on arcs are nonnegative, the flow on path H_2 is also nonnegative. As a result, the path *H* has at least a minimum of the maximum flows with value *d(i)*. This implies that the minimum of the maximum flows path label of node *i* has *d(i)* as a label.

5. Performance Evaluation of the MFMR Algorithm

5.1. Sample Topology and Scenarios

During our simulations, we worked on an example topology with 6 orbits and 12 satellites on each orbit. All the population is assumed to live in continents, so the transmitting and receiving nodes are placed over the continents or close to a continent and not over the oceans. The significant satellite locations (sources and/or destinations) and their coordinates can be seen on Figure 7 presented as white dots.

Figure 7. Satellite locations used in test scenarios.

These sets of satellites are chosen as compatible with the work in [14]. Since there are not enough measurement results published yet, the traffic parameters are taken to be as generic as possible. There can be more than one call from a source node to a destination and they are considered as single flows. The flows are non-bifurcated, that means the calls are circuit switched. Thus, the routing is done at the call initiation and in circuit switching time. Important parameters here are the call holding time and the load of the call as in [21]. The nodes generate calls with exponentially distributed inter-arrival times from a source to a destination. In many previous works, the call holding times are ignored and packet loads are considered. Whereas, in our model, the call durations and the communication load requirements of these specific calls are considered. In the simulation, the loads of the calls are taken as exponentially distributed according to three load levels that are specified for every scenario: light, normal and heavy. In some previous studies (e.g. [6]), the load distributions are taken as uniform or non-uniform (in the sense that some of the sources have different loads compared to the others, but the nodes are still geographically distributed uniformly.) However, uniform distributions are not realistic for a satellite communication (though it is specified as unrealistic in the same paper [6]) where the nodes are distributed over the Earth and there is time zone difference between the source-destination pair. The exponential inter arrival time is based on [9, 29, 30]. The scenarios and the traffic parameters are described in Table 5 through Table 10. First two scenarios have the same configurations with different load levels, therefore are considered the same scenario with different loads, namely, Scenario I Light Load (LL) and Heavy Load (HL)

Table 5. Scenario descriptions.

Scenario	Description
I.LL	Communication within continent, no inter-continental calls, short calls
I.HL	Communication within continent, no inter-continental calls, long calls
II	Communication out of continents, no intra-continental calls, long calls
III	Communication intra and inter continental calls at the same time
IV	Disaster in a country (2,2), hot spot to that node, short calls, light load
V	Hot spot in every continent, short calls, heavy load

Table 6. Parameters for Scenario I.

Grp	Transmit	Receive	Call Dur. (sec)		Call load (10^3pk/sec)
			V. 1	V. 2	
1	(0,2), (1,1), (2,1), (1,2), (2,2)	(0,2), (1,1), (2,1), (1,2), (2,2)	40	120	High flow: 10
2	(1,2), (2,2), (1,3), (2,4)	(1,2), (2,2), (1,3), (2,4)	40	120	Light flow: 4
3	(4,1), (3,2), (4,2)	(4,1), (3,2), (4,2)	40	120	Normal flow: 7
4	(0,9), (5,3), (5,4)	(0,9), (5,3), (5,4)	40	120	High flow: 10
5	(3,10), (3,9), (4,9), (5,8), (5,7)	(3,10), (3,9), (4,9), (5,8), (5,7)	40	120	Light flow: 4

Scenario I is the Intra-Continental Scenario. It assumes that most of the time the satellite communication is used by the nodes located on the same continent and there is no inter-continental traffic requirement. In the simulation, it is assumed that the average call duration is 40 seconds long. In the second version of Scenario I call durations are taken as 120 seconds. The simulation parameters are given in Table 6. In the scenario, it is assumed that there are three different traffic loads:

- Heavy load: 10,000 pk/sec
- Normal load: 7,000 pk/sec
- Light load: 4,000 pk/sec

Table 7. Parameters for Scenario II.

Grp	Transmitting	Receiving
1	(1,1)	(3,10), (4,9), (5,8), (4,1), (0,9), (5,4), (5,3), (3,2), (2,2), (2,4)
2	(4,1)	(2,1), (0,9), (5,3), (5,4), (2,4), (1,2), (5,7), (4,9), (3,10)
3	(4,2)	(0,9), (5,3), (2,4), (2,2), (2,1), (1,3), (5,8), (5,7), (3,10), (4,9)
4	(5,4)	(0,9), (4,2), (3,2), (4,1), (3,10), (3,9), (4,9), (5,8), (5,7), (1,3), (2,4), (0,2)
5	(2,2)	(4,1), (1,1), (5,3), (5,4), (0,9), (1,3), (5,8), (3,9), (3,10)
6	(2,4)	(5,4), (4,2), (4,1), (2,2), (1,1), (0,2), (5,7), (5,8), (3,10), (4,9)
7	(5,8)	(3,9), (3,10), (1,1), (1,2), (4,1), (3,2), (0,9), (5,3), (5,4), (1,3)
8	(4,9)	(5,8), (5,7), (1,1), (4,1), (2,2), (1,3), (2,4), (4,2), (0,9), (5,3), (5,4)

Scenario II is designed to simulate inter-continental calls. There are specific nodes in the continents that communicate with heavy loads (6,000 packets/second) to nodes located in the other continents for an average call duration of 120 seconds. Scenario II corresponds to the case that satellite communication is preferable for inter-continental calls; intra-continental calls are more economical when public switched telephone network (PSTN) is used. In this scenario, the RSs will be bigger than the intra-continental cases. Hence, the network balance will be easier to form than the first two scenarios, since there will be many more possible paths to distribute the flow between the source and destination pairs. The simulation parameters are given in Table 7.

Table 8. Parameters for Scenario III.

Grp	Transmit	Receive	Call Dur. (sec)	Call Load (10^3pk/sec)
1	(3,9), (3,10), (4,9)	(3,9), (3,10), (4,9)	40	High flow: 7
1	(4,9)	(5,7), (2,1), (2,4), (4,1), (5,4)	80	Normal flow: 5
2	(5,8), (5,7)	(5,8), (5,7)	80	High flow: 7
2	(5,7)	(4,9), (2,1), (2,4), (4,1), (5,4)	120	Light flow: 3
3	(1,1), (2,1), (1,2), (2,2)	(1,1), (2,1), (1,2), (2,2)	80	High flow: 7
3	(2,1)	(4,9), (5,7,), (2,4), (4,1), (5,4)	80	Normal flow: 5
4	(1,3), (2,4)	(1,3), (2,4)	120	Light flow: 3
4	(2,4)	(4,9), (5,7,), (2,1), (4,1), (5,4)	120	Light flow: 3
5	(4,1), (3,2), (4,2), (0,9)	(4,1), (3,2), (4,2), (0,9)	120	Normal flow: 5
5	(4,1)	(4,9), (5,7,), (2,1), (2,4), (5,4)	120	Light flow: 3
6	(5,3), (5,3)	(5,3), (5,3)	40	Light flow: 3
6	(5,4)	(4,9), (5,7,), (2,1), (2,4), (4,1)	120	High flow: 7

In Scenario III, it is assumed that the satellite network is economical to use for inter-continental and intra-continental calls. This is the combination of the first two scenarios. The nodes are grouped again by the continents they operate on (the group numbers are given in Table 8 under the column "Grp".) The nodes within the group communicate with each other and one of the nodes communicates with the other groups. In Scenario III, three types of load (light, normal, high) are used. The source and destination pairs can have communications with different durations. Namely, short, medium and long calls with 40, 80 and 120 seconds respectively. The simulation parameters are given in Table 8.

Table 9. Parameters for Scenario IV.

Grp	Transmitting	Receiving
1	(0,2), (0,9), (1,1), (1,2), (1,3), (2,1), (2,4), (3,2), (3,9), (3,10), (4,1), (4,2), (4,9), (5,3), (5,4), (5,7), (5,8)	(2,2)

Scenario IV is reflecting a natural disaster case in a country. In this scenario, the earthquake in Turkey is taken as an example. The communication system collapsed with the traffic requirements for a short period of time. In Scenario IV, there exist a hot spot at node (2,2). All the other nodes try to reach to the hot spot for a short (on the average 40 seconds long) and low quality (light flow with 5,000 packets/second) call. The configuration of the scenario is represented in Table 9.

Table 10. Parameters for Scenario V.

Group	Transmitting	Receiving
1	(3,10), (3,9)	(4,9)
	(5,7)	(5,8)
3	(1,2), (2,2), (1,3)	(2,4)
4	(0,2), (1,1), (1,2), (2,2), (3,2)	(2,1)
5	(3,2), (4,2), (0,9)	(4,1)
6	(0,9), (5,3)	(5,4)

Scenario V represents the continental hot spots. This can be represented by a war case where in each continent there are multiple calls initiated from surrounding satellites towards centers. In this situation, it is expected that there will be small RSs and the network will try to distribute the flows in a small number of paths to the destination. The calls are taken to be short (40 seconds) but traffic flow requirements are designed to be high (15,000 packets/second). The parameters are given in Table 10.

5.2. Result of the simulations

The MFMR routing is evaluated on a simulator, Opnet Modeler. The scenarios are run 10 times [31] for 2,000 seconds (this value is found to be sufficient for the simulation in order to have more than 50 successive routing decisions from a single source to a single destination) with different seed values and the average/maximum values of the runs are recorded and plotted on the graphs. In the results, the sample mean values of these 10 runs are calculated. The confidence interval is taken as 95% and calculated by Student t-Distribution. The warm-up period is taken as 200 seconds (this value is considered as sufficient for the system to come to a steady state.) In the first scenario, besides the max flow, the end-to-end delay for various number of hops are evaluated. In the second simulation, the max flows over the links of the critical nodes over inter-continental communication paths are evaluated. These satellite nodes are aligned on three virtual lines. These lines are shown in Figure 8 and Table 11. For Scenario III, the same inter-continental lines are used to measure the flow on these nodes. In the Scenario IV, all the network nodes are evaluated for their max flow and buffer requirements. In Scenario V, the maximum flows in the satellite groups are given.

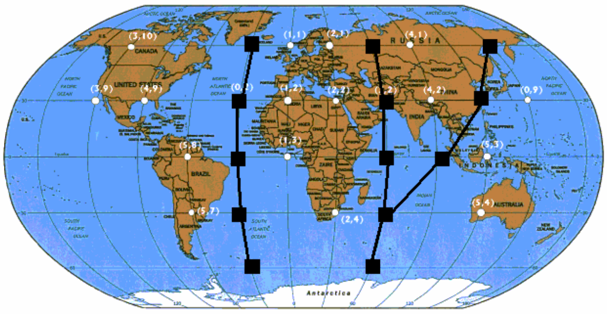

Figure 8. Inter-continental satellite node lines.

Table 11. Satellite nodes over inter-continental lines.

Line	Satellites	Separates
1	(0,1), (0,2), (0,3), (0,4), (0,5)	Europe and Africa from America
2	(3,1), (3,2), (3,3), (3,4), (3,5)	Europe and Africa from Asia
3	(3,4), (4,3), (5,2), (0,10)	Europe and Africa from the Australia and Japan

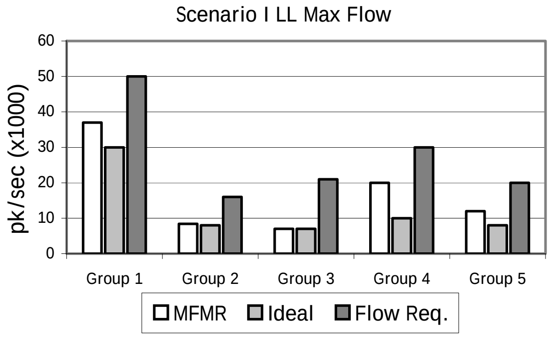

Figure 9. Comparison of the maximum flows for Scenario I. LL

The Ideal Case results are the lower bounds for the traffic matrix over the given network groups discovered over the RS boundaries. The Ideal Case is the maximum flow within the group calculated by using exhaustive search over the RSs. During the calculation, the average flow requirements of sources to destinations are taken into consideration. Thus, the Ideal Case forms a lower bound to the problem over the RS concept. The RS concept will reduce the search space to a minimum cardinality rectangle that will decrease the search time and the complexity. The exhaustive search is relevant for only small RS with 10-20 nodes. The Flow Requirement bars in Figure 8 represent the total flow requirement carried by the satellite group. As seen from Figure 8, the first group has more traffic requirements and the nodes in the group are very close to each other. In fact, five out of six nodes are trying to connect to each other. The network, has distributed the flow over the existing network. The flow is between the best case and the total network requirement. This difference comes from the fact that some of the sources try to connect over the same path without knowing each other. Sometimes, they both begin transmitting at the same time. The nodes become aware of such a flow at the time when the first packet of the flow comes to its input links. At the moment where they update their link state tables, another source sends its packets over the same link before the update operation. This is a normal case in the real life, since the nodes will send status reports to the neighboring satellites after a certain interval of time. For such cases, the simulations behave worse than the Ideal Case. However, the algorithm should behave the same as the Ideal Case for a network where all of the nodes are aware of the instantaneous changes in the link states of all the neighboring nodes (which is not a realistic situation.) In the case of Group 5, it can be seen that the recorded maximum flow is closer to the Ideal Case than the total Flow Requirement. This is due to the fact that in the groups where source nodes are less than or equal to non-transmitting nodes, the network has more paths to distribute the flow over. This group has 12 nodes and only four of them are transmitting nodes. As mentioned before, the graph represents the average of ten runs. Therefore, on the average, the routing scheme's performance is the same or very close to the ideal (exhaustive search) case.

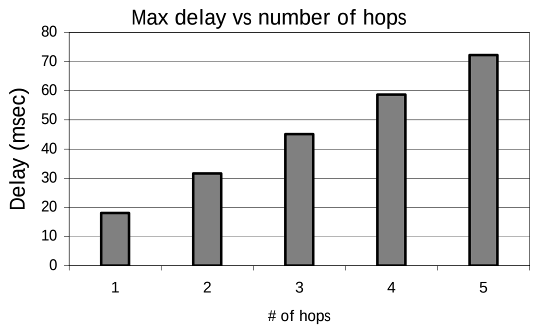

Figure 10. The effect of the number of hop to the end-to-end delay.

In Figure 10, it can be seen that even for the worst case (five hops), the end-to-end delay from ground to ground is below 400 msec, which is the boundary for the interactive communication where the call begins to be "annoying". Moreover, for five hops, on the ideal case where satellite node buffers are empty, the packet has to reach to its destination in 70.75 msec. This is calculated by five times the ISL line propagation delay and two times the up/downlink propagation delay. Dividing the MFMR delay by the ideal case's delay, the delay for five hops is 2% worse than the ideal case (72.24/70.75).

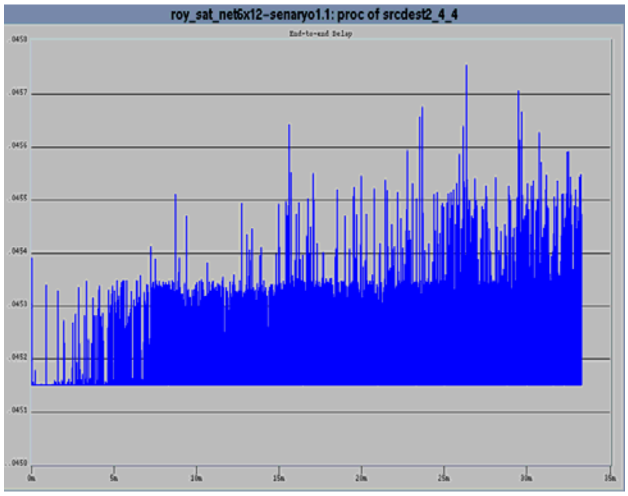

Figure 11. End-to-end delay plot of traffic from (1,2) to (2,4).

We can see from Figure 11 that the delay does not show big variations and on the average is 45 msec for a three-hop path. The lower limit of the graph shows the minimum propagation delay and the fluctuating part is the queuing delays which are around 0.5%.

Scenario I.v.2 is the same as the first version but the average call durations are 120 msec. This is done in order to test the effect of call durations on the maximum link flows and delays.

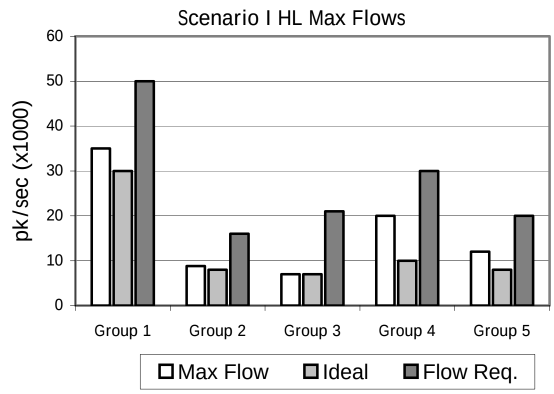

Figure 12. Comparison of the maximum flows for Scenario I HL.

It can be seen by comparing Figure 12 to Figure 9 that there is not much difference between light load (LL) and heavy load (HL). For the normal load cases studied when the length of the calls for all of the nodes are increased, the flows on links did not change. This increase may affect the buffer sizes and delay performance. However, the delay performance of the system behaved the same as the LL, since the flows were distributed and the buffers were not overloaded.

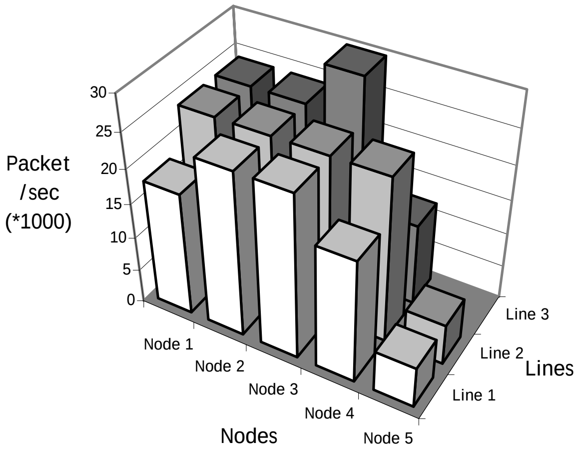

Figure 13. Comparison of inter-continental line maximum flows (MFMR).

It can be seen from Figure 13 that the loads are heavier on the middle of satellite node lines given in Figure 8. The end nodes of lines are around the Polar Regions. This means that given the continent positions on Earth, most of the time, it is more realistic to use the ISL of satellites that are below the 50^{th} latitude where source and destination pairs are densely located. This means that in the Polar Hop routing scheme all the given flows would try to pass through the Polar Regions and it would result in congested polar links. If the routing scheme would be Dogleg approach the resulting flows would be like in Figure 14.

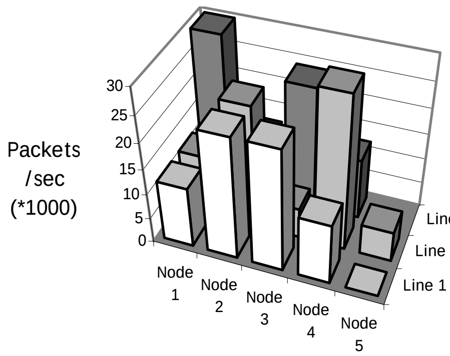

Figure 14. Comparison of inter-continental line maximum flows (Dogleg).

In the Dogleg approach, some of the inter-continental links are used much more than the others. The flows are not balanced and in the case of new connections, the links will suffer from congestion. It should be noted that in the MFMR approach, the links that are not represented in the graphs are also balanced, but the links in the Dogleg approach are not balanced. Especially, in the high traffic regions the Dogleg approach suffers from congestion. For this reason, the Parallel Highway should be combined with the Dogleg. However, the Parallel Highway has a worse delay performance, since it does not use the shortest path. The delay performance of a Parallel Highway can be calculated by adding at least two more ISL links to the shortest path (in the case of the closest parallel path to the Dogleg). This makes around 27 msec additional delays for the network studied.

The satellite node buffers are also recorded in this scenario. The maximum values of the runs are plotted in the graph. The maximum value is the worst case, therefore, for the studied case and traffic requirements, if we take the buffer size of the satellites bigger than these values, we will avoid buffer overflow. The buffer requirements are given in Figure 15. It can be seen from the figure that a buffer size of 3,000 packets is required for the satellite node (we assumed that the satellite can process between 70-80,000 packet headers per second.) In the Scenario III, the inter-continental links are used as well as the intra-continental links. The flow is measured again on the inter-continental group separation lines and represented in Figure 16.

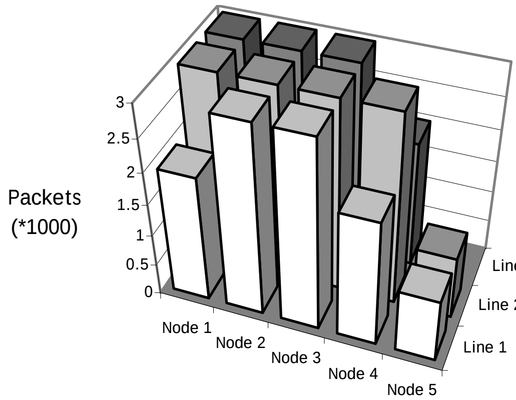

Figure 15. Buffer requirements for inter-continental line nodes.

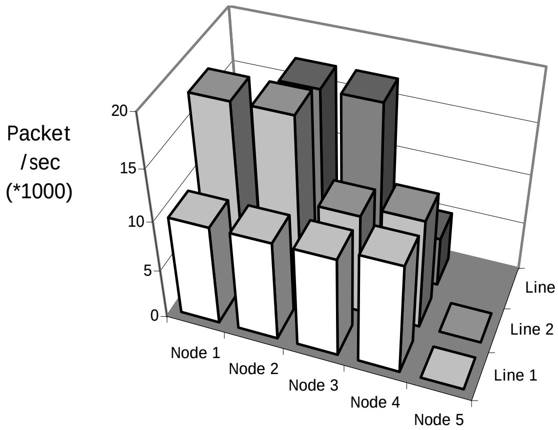

Figure 16. Flows on inter-continental lines for Scenario III.

The flows on the lines are again distributed evenly. In the second line, there is a difference between the first and second couple of nodes. This is due to flow requirements between Groups 3-4 and Groups 5-6. Group 3 uses these two nodes to reach to Group 5 and Group 6. Group 4 uses again the first two nodes to reach to Group 5 and second two nodes to reach Group 6. This makes the maximum flows on links of Node 1 and Node 2 of the second link higher than the others, but the shortest paths are passing through these nodes and there is no other path to choose.

The flows on Node 2 and Node 3 of the third line are high due to the same reason. Group 3 and Group 5 have to send over these nodes to reach to Group 6. That is why the flows are higher than the other nodes on the line. The important point here is that MFMR tries to distribute the maximum flow over the available paths. This can be observed in Figure 16.

In Scenario IV, the natural disaster case is examined. There is a disaster (e.g., earthquake) in the point of (2,2). In an earthquake case, terrestrial network could be damaged or collapsed. Whereas, in a satellite network, with a detailed requirements analysis, these cases can be survived. In our simulation, we considered such a disaster case and this time, all of the source nodes try to reach to the disaster region, namely, to Node (2,2). In this case, the maximum buffer sizes of the surrounding satellite nodes are recorded. It is noticed that, during the simulation, all the surrounding nodes had at most 3,000 packets in their buffers at the same time. This results in the fact that, for the case studied, distributing the flow over the RS reduces the processor utilization on the satellites. The important region in this communication is the surrounding area of the hot spot. The resulting maximum flows over the nodes are given in Figure 17.

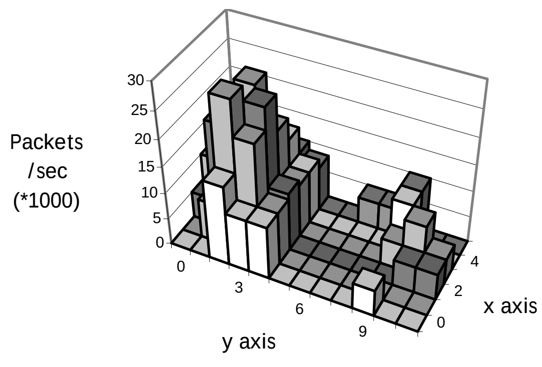

Figure 17. Maximum flows around the global hot spot (2,2).

However, it should be noted that the hot spot is chosen right in the upper middle of the communicating nodes. This position is a place where the nodes are distributed evenly in both directions (horizontal and vertical.) The maximum flow of the overall network is 28,000 pk/sec and it is around the hot spot node. Other approaches such as Dogleg, Parallel Highway or PRP would route all of the flows over the most convenient paths. For the Dogleg and Parallel Highway, these paths would concentrate over the longitude where the hot spot is found. For the PRP, the paths would concentrate over the nodes where a handoff is least probable because of the design issue of PRP. PRP does not try to minimize the maximum flow, but, tries to minimize the rerouting of the assigned path due to satellite motion. Because of this design issue PRP distributes the flow in an unbalanced manner. Compared to PRP, MFMR does not reroute the flows since the most balanced flow is achieved in each flow change and satellite motion is ignored (due to FSA assumption.) Moreover, the PRP will try to use the most convenient path for each flow where the handoff is least probable which will result to congested paths, high blocking probability and unused capacity over the links where handoff is most probable.

The MFMR algorithm is compatible with SOS systems or Hierarchical Space Grid Architecture (HSGA) [32] where RS should be extended to cover the hierarchical network as the boundary of search space of MFMR algorithm. However, in HSGA in order to reduce the routing table sizes and the maximum hop number on the path, the network chooses to route the messages over higher layer satellite network. This last reduces the link state messaging overhead of MFMR, but at the same time increases the end-to-end delay. In our simulations, it is assumed that all the inter-satellite links have the same length (i.e. propagation delay) and on the same orbit. Moreover, routing over a MEO layer and then back to a LEO layer node increases the overall path length compared to routing the packets over a single LEO orbit. Therefore, the delay performance of HSGA will be worse than single layer MFMR due to bigger propagation delay values.

In Scenario V, the disaster cases are reduced to continental hot spots. This means that there are continental hot spots that all the other nodes located in the same continent groups try to reach this point. In this case, the flows are taken as the maximum possible. This case is a high quality hot spot communication. The resulting flows are given in Figure 18.

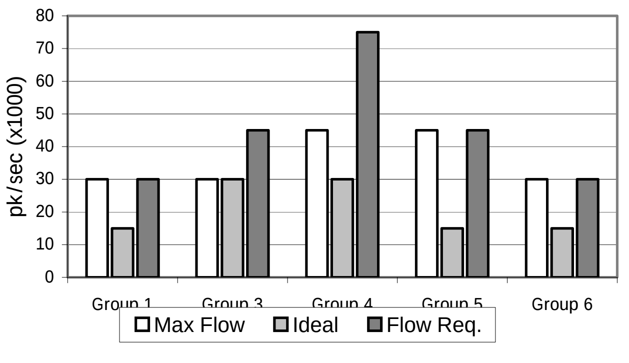

Figure 18. Comparison of continental hot spots.

It can be seen from the figure that the system performs bad in some networks and gives better results in the others. In

Group 1, almost all the network nodes are source nodes and at the worst case the system tries to pass all the flow over the same links. However, it should be noted that this behavior is for small number of calls and the nodes try to find a less crowded path over the RS. The explanation of the worst cases is the same as that of Scenario I: different nodes try to send over the same path before the connection setup packet has been sent, but succeeding calls are distributed over the available paths. The same problem arises in Groups 5 and 6. The results of Group 2 are not presented in the graph, since they are not relevant for the comparison.

The RS routing method gives better results when the RS is bigger. In the global communication case, the system can chose all satellites as a RS, which results in better distribution of the total flow. As the flows are distributed over the RS, the satellite nodes are less utilized and the buffer size requirements are limited to 3,000 packets for the studied case. 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. The algorithm tries to use the underlying network better than the dogleg, parallel highway and polar hop since it uses the shortest path route and the minimum flow link as the most convenient link.

5.3. Comparative Evaluation of the Schemes Under Different Scenarios

In this section, the comparison of the schemes will be given for an example satellite group. The evaluation of the schemes will be done using the delay and the objective function of our formulation, namely, the maximum flow as listed in Table 12 and Table 13.

Table 12. Maximum flow comparison of the schemes.

Scenario	Polar Hop (10^3pk/sec)	Dogleg (10^3pk/sec)	Parallel Highway (10^3pk/sec)	MFMR (10^3pk/ sec)
I Group 2	12	12	12	8
IV	55	30	30	28
V Group 2	45	45	45	30

The flow requirements from the source to destination nodes in the scenarios are taken as average flow values and for each flow value the ideal path of the method is calculated. The maximum flow link of the group is chosen and represented in Table 12. It can be seen from the table that the conventional methods do not distribute the flows as balanced as MFMR for the groups of nodes presented in the results. This means that in MFMR the resources are better utilized and the congestion probability is smaller compared to the other methods considered.

The average delay performance is calculated for different schemes. These values are calculated using 13.33 msec. for ISL propagation delay and 2.05 msec. for satellite up/downlink propagation delay. The results are presented in Table 13.

Table 13. Delay comparison of the schemes.

Scenario	Polar Hop	Dogleg	Parallel Highway	MFMR
I (1,2) to (2,4)	106.64	66.65	93.31	66.65
IV (1,2) to (2,2)	79.98	39.99	66.65	39.99
V (1,2) to (2,4)	106.64	66.65	93.31	66.65

The delay values are calculated assuming that only the propagation delay is effective and the processing delays are negligible. In the studied cases, MFMR and Dogleg performed better than the other methods, since they both use the minimum propagation delay path or more precisely, the shortest path. In the other methods, the propagation delays were bigger than MFMR and Dogleg in all the groups presented in Table 13. It can be deduced that MFMR performs the best for the maximum flow for the scenarios studied. We can deduce also that MFMR is distributing the flow in a balanced manner. In terms of the delay, it performs better or same than Dogleg, Polar Hop and Parallel Highway for all cases studied.

The MFMR can be compared to Minimum Expected Delay (MED), Earliest Delivery (ED), Earliest Delivery with Local Queuing (EDLQ) and Earliest Delivery with All Queues (EDAQ) presented in [10] in the end-to-end delay metric where some of the methods use local or global queuing status and ignore future traffic demand. The MFMR uses the same knowledge oracles and their end-to-end delays will be approximately equal. However, as the MFMR decides on the path according to an additional information: the residual capacity; it will perform better than these methods on distributing the flows on the available path alternatives.

6. Conclusion

The satellite networks are designed to give global coverage and communication services. The system, being far from the mobile terminals located on earth, suffers from the high delay compared to terrestrial wired networks. The satellite system is also a backup network to the land based systems. Moreover, the network is not affected by the natural disasters and is more economical to reach the rural areas where land based communication systems become expensive. Since the system globally covers the earth, the potential number of subscribers is much more than that of land based wireless systems. These large number of users cause high network load on the satellite system. In some previous research, it is assumed that the link propagation delays are the bottleneck of the satellite systems and route accordingly. In this work, the Routing Set concept and the minimization of the maximum flow for satellite systems are designed and simulated. The system assumes that most of the population lives below the 50^{th} latitude on earth which makes it possible to assume that the inter-satellite links between the neighboring orbits are of equal length. This results in the fact that choosing the minimum hop path between the source and the destination pair will reduce the processing delay and, the most importantly, will distribute the maximum flow over underutilized links. This method will keep maximum residual capacity on the links and on the satellite processors.

Three different setups (five scenarios) are implemented and simulated on Opnet. The setups are designed for representing the normal operation (Scenario I, II and III) and the natural disaster case where all of the nodes try to reach the hot-spot area with the simplest service (Scenario IV). In the last setup (Scenario V), the network simulates the continental hot-spot case. For the studied cases, it is seen that the system tries to minimize the maximum flow and reduces the buffer sizes at the satellite nodes.

It is seen that the total end-to-end delay of the system is below the maximum delay of an interactive call. Moreover, MFMR uses the minimum hop RS scheme; this scheme would be extended with the Parallel Highway approach. This means that, in some cases the network has to chose the second or third minimum hop RS in order to distribute the flows over the entire network. This method is expected to perform better than the Parallel Highway, since it uses the same idea as forwarding the flow out of the crowded/congested regions and still minimizes the maximum flow over the second RS. Moreover, a communication priority class concept can be added to the existing system. The highest priority class communication would use the shortest RS and the others the second or third RS. The performance of the disaster cases can be studied under these priority classes.

The RS concept could be extended to work on a satellite network cube composed of LEO, MEO and GEO networks. This is referred as Satellite over Satellite (SOS) network. The system can combine the minimum propagation delay and the minimum flow concept together to form a more balanced and robust network. The RS can be extended to a Routing Cube (RC) for these kind of multilayer satellite networks. The RS, RC and priority classes can be combined to route the low priority calls and data transfers over the higher layers (MEO or GEO) and multimedia interactive calls (or higher priority calls) over the lower layers (MEO or LEO). The system can be extended to work with the high altitude long operational aircraft (HALO) and high altitude platform stations (HAPS) [33] as a lower layer. The HAAP network serves for the metropolitan area users and whenever a long or inter-continental call is needed the system can forward the call over the satellite system.

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