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PERFORMANCE ANALYSIS AND ROUTING TECHNIQUES IN LEO SATELLITE SYSTEMS

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ABSTRACT

In this paper, we survey techniques for routing and performance analysis of Low Earth Orbit (LEO) systems. We first review the basic structure of LEO satellite communications and present the main characteristics of LEO systems. The dynamic characteristics of LEO systems make the performance analysis and routing problem quite complicated. In this study, we review some of the proposed solutions to these problems. We explain the two main criteria for the calculation of performance analysis: blocking probability of ongoing calls during handover and the new call blocking probability. Then we mention which way is the most preferable and what are done during the calculation process.

Keywords: *LEO, satellite, performance, routing.*

1. INTRODUCTION

1.1. Context

The communication revolution that is currently taking place has increased the demand for a broad ranges of telecommunication services and also for wireless access solutions. Satellite communication Systems, especially Non-Geostationary Satellite Systems are the best candidates for providing communication services globally in a cost effective manner. Non-Geostationary Satellite Systems will form a mobile telephony and data transmission network that would work without the need for complex ground-based infrastructures which is one of the key components of existing land-based cellular schemes. Therefore, it will be possible to reach areas without cellular infrastructure world-wide. The cost of the installation is fixed and there is no relationship between cost and distance. For example, linking every home to internet with fiber links costs 300 billion dollars while via satellite it costs only 9 billion dollars [1].

By using satellites at low altitudes, Low Earth Orbital Satellite Systems can reduce power requirements on-board and on the ground. This

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results in lightweight low power radio telephones with small low profile antennas. Besides of these, low altitude means minimized transmission delay nearly equal to land-based networks. A more detailed description of Mobile Satellite Communication Systems can be found in [2] and [3].

Satellite Communications for commercial purposes started in the mid-80s. Several corporations introduced direct-to-home (DTH) satellite broadcasting before cable TV was being established. Nowadays, we are witnessing a lot of companies especially telephone companies investing to satellite industry. As a result of this huge market potential, today there are more than 200 satellites distributed over geostationary arc.

Improvements in fiber optic technology and switching structures decreased the importance of geostationary satellites' role in connecting long distance telephone exchanges for international calls. Instead of using satellites as primary medium for communication, they started to be seen, for telephone companies, as a backup for ground links. On the other hand, for television companies, it was still an important broadcast medium. As a consequence, geostationary satellites became a medium for are non-interactive broadcast applications, but lost its importance for two way communication applications. The advances on satellite technology, made it possible launching tens of similar satellites to low earth orbits. These systems would provide a service as good as fiber optic networks. As a consequence, starting from the early 90s telecommunication industry witnessed a lot of proposals for Low Earth Orbital Satellite Systems. Some of the well-known schemes are Globalstar, Orbcomm, Iridium, and Teledesic. Further informations about these systems can be found in [4] – [9].

There are different types of orbits. However the scope of this survey will be Low Earth Orbit Systems. Therefore, we will not take into account other satellite systems.A detailed information about orbit types can be found in [10] and [12].

1.2. Structure of the Survey

The organization of this paper is as follows. In section 2, the architecture of satellite networks will be given together with some notations. Section 3 is devoted to performance evaluation of LEO satellite systems. In section 4, proposed routing algorithms will be explained. The survey will be concluded in section 5.

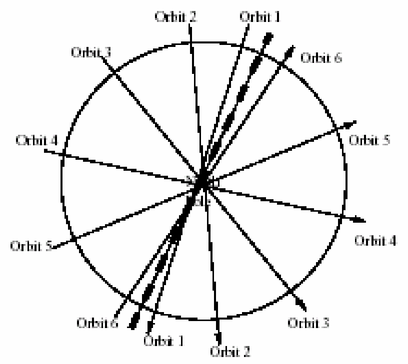

Figure 1. Schematic Polar View of The Iridium Satellite Constellation

2.NOTATION AND ACHITECTURE

Satellite Constellation: According to Husson [11], a constellation of satellites is a set of identical satellites, launched in several orbital planes with the orbits having the same altitudes.

Orbit Period: The time a satellite completes one full rotation around the earth within its own orbit is called the *Orbit Period*.

System Period: In a constellation, satellites move in a synchronized way in trajectories relative to the earth. The position of all the satellites in a satellite constellation at some instance of time, repeats itself after a predetermined period which is usually several days. This period is called the *System Period*. System period is calculated as an integer common multiple of the orbit period and the earth rotation time (sidereal day) which is 23 hours, 56 minutes and 4.1 seconds.

Seam: As seen in Figure 1, the satellite in Orbit 1 moves from north pole to south pole and then from south pole to north pole. The satellites at Orbit 1 and Orbit 6 move in opposite directions. For that reason, there is a seam in between these two orbits, and this seam indicates a change of direction. With respect to this seam, the constellation comprises two hemispherical areas of co-rotating orbits, each extending from the north to the south pole.

Intersatellite Link: A direct connection between two satellites based on line of sight. Intersatellite Links (ISL) permit two mobile or fixed points on earth in different footprints to communicate without the need of terrestrial systems. Of course, this feature necessitates the solution of complex handover problems. Adding ISLs also introduces flexibility in routing, builds inherent redundancy into the network, and avoids the need for visibility of both user and gateway by each satellite in the constellation.

Footprint: The spherical area of the earth covered by a satellite with an elevation angle equal to or greater than a certain minimum elevation angle.

Elevation Angle: The angle between the line from the earth's surface to the satellite and the tangent at that point considered.

Cell: To improve the bandwidth and frequency efficiency, the satellite footprint area is divided into smaller cells. For each cell within a footprint area, a specific beam of the satellite is used.

Satellite Fixed Cell Coverage: If the satellite antenna sending beams is fixed, then as the satellite moves in its orbit, together with its footprint, the cells also move. This constellation is said to have satellite-fixed cell coverage.

Earth-Fixed Cell Coverage: Unlike the satellite-fixed cell coverage, in earth-fixed cell coverage, the beam transponders are not fixed. The earth surface is divided into cells, as in cellular systems, and a cell is serviced by the same beam while that area is within the footprint area of that satellite. Hence, each cell will be associated with a given geographical area on the earth, and the users are referenced to the cell they are located in as it is in the cellular systems independent of the beam and satellite passages.

Beam Steering: In order for the same beam to be fixed onto the same cell on the earth, the satellite's antenna should steer in the opposite direction of its motion.

Cell Switching: When it becomes not possible for the satellite to steer the antenna, then cell switching occurs. The steering of the beam can be mechanical or electronic. In LEO systems, where the satellite motion relative to earth cells is high, electronic steering is preferable.

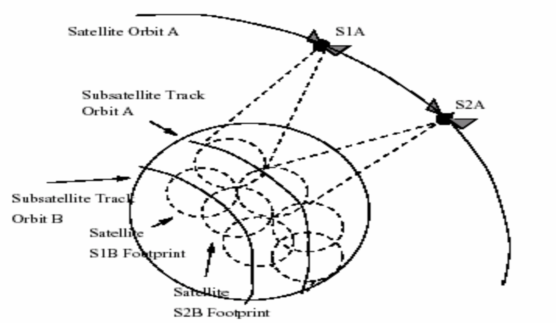

Figure 2. Streets of Coverage

Streets-of-Coverage: A street of coverage is a line of overlapping footprints of satellites within the same orbit. This is illustrated in Figure 2[1]. As seen in the figure, a street is like a strip of earth aligned along and centered about the subsatellite earth track. For the global coverage, streets of coverage should be overlapped from different orbital planes.

3. PERFORMANCE EVALUATION

In performance analysis, the main concern is usually calculation of the blocking probability of ongoing calls during handover. That is, a call during a handover can not find empty channels on the next satellite and forced to terminate. This process decreases the reliability of the system. The second performance criterion is the new call blocking probability. A new call can get blocked because there is not enough channel to carry it. Increasing new call blocking decreases the throughput of the system. Therefore, there is usually a trade-off between new call blocking and handover call blocking. From the point of quality of service, it is usually preferable to choose decreasing the handover call blocking without increasing new call blocking drastically. Therefore, most of the studies performed about the performance of LEO satellite systems were concentrated on calculation of handover call blocking probabilities. In this section, we will give different types of approaches used on performance evaluation of LEO systems. For that purpose, we categorized those studies in two main groups: the first group are the studies dealing with traffic characterization and performance evaluation. The second group of studies deals with the handover problems.

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[1] This figure is similar to the one in [25].

3.1. Performance Analysis

Single M/M/K/K Queue Analysis: In [13], Ganz *et al.* investigated system performance of low earth orbit satellite systems. In this paper, system performance is expressed in terms of the *distribution of the number of handovers* occurring during a single transaction time and the *average call drop probability*. Both beam to beam and satellite to satellite handovers are taken into account. The variables used in performance calculation are the system constellation, the satellite speed and direction, the cell size and the average transaction duration. First average number of handovers during the call duration is calculated with adapting the results obtained for cellular systems.

The next step is the calculation of the channel occupancy distribution. For that purpose, the hypothesis that the channel occupancy time distribution is exponential, has been tested with Kolmogorov-Smirnov goodness-of-fit test. An event-driven simulator generated outputs according to a fitted exponential distribution where the exponential distribution parameter is equal to the sum of average call duration and the average time spent by a user in a given cell. Then the difference between simulation and exponential distribution is tested.

With the assumption that the number of handover calls entering a cell is equal to the number of handover calls leaving the cell, the number of calls in a cell is the number of calls generated by the cell. In this system, each cell can be modeled as an M/M/K/K queue where K denotes the number of channels per cell. Therefore, the call blocking probability is given as:

$$P_b = \Pr ob[Kchannelsarebusy] = \sum_{n=0}^{K}[(\lambda\theta)^n \frac{1}{n!}]^{-1}(\lambda\theta)^K \frac{1}{K!} \quad (1)$$

where θ is *fitted exponential*. Since average number of handovers (h_c) involved in each call is known, the call dropping probability is: $P_d = 1-(1-P_b)^{h_c}$.

The last parameter is the system capacity. It is calculated as the crosslink capacity per hop and determined according to the average number of hops between two users per call and the number of channels at each crosslink.

Coverage and Interference Related Analysis: In [14], Jamalipour A., Katayama M. and Ogawa A. investigate traffic characteristics of LEOS-Based Systems. They defined three important area: coverage or footprint area in which users communicate with the specified satellite, interference area defined by the final line of sight and observed area consists of the coverage area of three adjacent satellites. The distribution of users within the observed area is defined with the following probability density function:

$$P(\alpha) = \frac{A}{w}\exp(-\frac{\alpha^2}{2w^2}) \quad (2)$$

where α is the location of users in terms of relative angle from origin, w is the traffic uniformity parameter and A is the probability of existence of a user in the predetermined area. Performance measures for the system are throughput and average delay on uplink channels. The throughput for each satellite is calculated as the ratio of the expected number of successful packets to the expected number of users served by that satellite. To define the traffic characteristics of the whole system, the normalized throughput for the observed area is calculated as the fraction of the sum of expected number of successful packets for three adjacent coverage area to the sum of the expected number of users on three adjacent coverage area. The expected number of users can be calculated using the probability density function given in equation 2. Average delay is also defined as the elapsed time from the generation of the packet to the completion of the transfer of that packet. As the traffic is not uniform, the average delay at different coverage areas will not be the same. Therefore, a normalized average delay is defined. The normalized average delay is the average delay over an observed area and is given in the following equation.

$$E(T) = \frac{E(T_{i-1})E(N_{i-1}) + E(T_i)E(N_i) + E(T_{i+1})E(N_{i+1})}{E(N)} \quad (3)$$

Complete Analytical calculations of average delay and throughput can be found in [14].

Analysis By Simulation: In [15], Papapetrou *et al* prepares a simulator to analysis LEO systems. The simulator is designed based on the Motorola's Celestri System. However, it can be modified to other systems easily. Inputs to the simulator are orbit altitude, orbit period, number of satellites, number of orbits, inclination, intraplane ISL per satellite, interplane ISL per satellite, right ascension and phase shift. System uses Dijkstra's shortest path algorithm for each time interval and based on Werner's Dynamic Routing Algorithm which will be explained in section 4.1, choose the shortest path from a predefined set of shortest paths. If at the next interval, the new shortest path does not increase the cost more than 30%, the old path is kept for the sake of decreasing the number of path handovers. In this simulator, they use two different traffic types, Poisson, and Self-Similar. Two of the performance criteria are the end-to-end delay for different traffic distributions and the loading of the most loaded satellite which is defined as the number of cells carried by the most loaded satellite.

Defining a Queueing Network: This is the only traffic model taking into account the dependencies between calls on different cells. In [16], Zaim *et al* proposed a Markov Process to calculate call blocking probability. The model is an N(N-1)/2 dimensional Markov Chain where N is the number of satellites. They also added a set of traffic constraints to include traffic dependencies between cells and ISLs. The model can give the exact values for up to 5-satellite systems. For larger systems, the authors developed a decomposition algorithm to produce approximate values. As an extension to the study published in [16], the decomposition is extended to a two dimensional system with vertical and horizontal subsystems in [17].

3.2. Handover Problem

In Mobile Satellite systems, channel allocation can be done either in a fixed way or dynamically. The first satellite systems were using fixed channel assignment techniques in which case, the channel are assigned to cells permanently. On the other hand, in dynamic channel assignment, the channels are allocated to cells according to call requests. During channel allocation, two main strategies are used: Queueing Schemes and Channel Reservation Schemes. The aim of these techniques is giving priorities to handover requests to improve quality of service. In this section, proposals related with these two techniques have been investigated. In [18], Santos *et al.* compared these techniques under fixed and dynamic channel allocation. According to Santos *et al.*, combining queueing and guard channels decreases both dropping and handover traffic while increasing the new call blocking.

Queueing Schemes: Del Re *et al.*, in [19]-[21], proposed an analytical model to analyze handover queueing strategies under fixed channel allocation. They compared the results for some dynamic channel allocations. Their method is designed for satellite-fixed cell coverage. First, the probability density function of the user within the cell is calculated. The next step is the calculation of the handover probability of a call. The third step is the calculation of the average number of handover requests per call. Once all these parameters have been calculated, a queueing analysis is performed to calculate the new call and handover call blocking probabilities. Therefore, an M/M/K/K model is used where the arrival and departure rates have been calculated using the parameters found in the previous steps. Two queueing strategies were taken into account, FIFO and Last Useful Instant(LUI).

In [22], Pennoni and Ferroni described an algorithm to improve the performance of LEO systems. They defined two queues for each cell, one for new calls and one for hand-off calls. The calls are held in these two queues for a maximum allowed waiting time. That is, they are dropped if they are not served within this time. The queue for new calls has a maximum waiting time equal to 20 sec. The queue for hand-off calls has a maximum waiting time equal to the cross-over time of the overlapping zone of two adjacent cells. The hand-off queue has higher priority than the new calls queue. The authors developed an analytical method to calculate blocking probabilities. According to that approach, the footprint area of a satellite is thought as a square area and the traffic is distributed over that area. Therefore, a two dimensional traffic intensity distribution over geographical area is obtained. Integrating over the footprint or the overlapping area, the traffic intensity for all calls or for only handover calls are obtained. Then using these values on Erlang-B Formulae, dropping or blocking probabilities are calculated. In [23] , Dosiere *et al.*, used the same model to calculate hand-off traffic rate over a street-of-coverage. Once the hand-off arrival rate has been calculated as in [22], the total arrival rate has been defined as the summation of new call arrival rate and hand-off arrival rate. Call departure rate has also been defined as the sum of call termination and handover rate. These values are then put into Erlang-B formulae to calculate blocking probability. In [24], Ruiz *et al.* used a similar technique with the one used in [22]. However, this time, they used some guard channels for handover calls and they distinguished new arrival rate from handover attempt rate.

Channel Reservation Schemes: In [25], Respero and Maral defined a Guaranteed Handover mechanism for LEO satellite systems with Satellite-Fixed Cell Configuration. In this method, channel reservation is performed according to the location of the user. That is, once the user is at a critical distance from the handover point, it request a reservation from the neighboring satellite. These reservation requests are put into a priority queue. As soon as an idle channel is found, the channel is reserved for that call. The advantage of this method is that the reservation is done only on the next satellite instead of the whole call path. That way, the number of redundant circuitry is minimized and the handover success rate is as high as the static reservation technique.

In [26] Wan *et al.*, defined a channel reservation algorithm for handover calls. In this algorithm, they keep three queues, one for handover requests, one for new call requests and one for available channels. Each request comes with the information indicating the position of the user within the footprint area. The position information is then used to calculate the time of the next handover. Channel queue is also keep track of the channels available together with the availability time of that channel. That is, if this is an idle channel, available time is zero, if this is a channel on use the time is set to the handover deadline. The aim of the algorithm is matching those channels with the handover and new call request queues according to the time criterion.

A similar approach with Wan *et al.* is proposed by Obradovic and Cigoj in [27]. They proposed a dynamic channel reservation scheme. Handover management is performed with two queues one for handover requests and one for new call requests.

4. ROUTING ALGORITHMS

The routing problem is divided into two subproblems: Up-and-Downlink (UDL) routing and Intersatellite Link (ISL) routing. In UDL routing, the objective is to ensure the continuity of the connection by providing at least two end satellites, one starting and one ending satellite, through the entire connection. In ISL routing, a hitless handover between start and end satellites 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. Most of the proposed routing algorithms deal with the ISL routing. User to user routing is taken into account in only a few papers.

4.1. Dynamic Virtual Routing Concept

In papers [28] and [29], only a solution to the ISL routing problem is given. In [30], the performance of that routing protocol is calculated using simulation.

In [28], the cost metric has two main components: number of hops and the sum of link weights LWs. A LW represents propagation delay, ISL permanency, and the traffic load.

Routing is divided into three steps. In the first step, for each interval, the momentary ISL topology is defined. In the second step, new routes are calculated for each pair of start and end satellites, using the ISL topologies that corresponds to the time interval. In [31], a neural network approach is used to calculate the path between a given OD pair. The neural network design is similar to the one used in character recognition. The last step is the optimization. Over one constellation period, an optimization procedure is performed in terms of minimizing the occurrence of path handovers by choosing appropriate paths from each set.

4.2. Virtual Node Routing

In this system, users are mapped onto Virtual Nodes(VN), and each VN is connected directly to its neighbors with virtual connections. These VNs behave like ATM switches. Each VN can communicate with a number of cells on the earth. As a satellite within a given VN passes, the next satellite takes the place of that VN. The same cells continue to communicate with the second satellite physically, but virtually they have not changed their VN. Therefore, routing is performed according to the VN topology representing discrete network topologies.

Different routing methods are used in the VN scheme. More detailed explanation of these routing methods can be found in [32].

4.3. FSA-Based Link Assignment and Routing

In this study, the system period is divided into equal length intervals during which the visibility between satellites, that is the topology of the satellites, does not change. A link assignment algorithm is run for each interval. Therefore, the link assignment problem in LEO satellite system is simplified into a set of link assignment problems for a fixed topology network, one per interval.

A Finite State Automation is designed to represent two different topologies. In FSA, each state represents a topology, which is stable during the time period of that state. When the FSA changes state, the topology of intersatellite links also changes.

In the visibility matrix, each element (i,j) represents the existence of an intersatellite link between satellites i and j. If the (i,j)th location of the matrix is equal to 1, then there is an intersatellite link. If it is zero then the link is not active. Given a visibility and traffic matrix, a link assignment table is created off-line for each state. These tables are stored in each satellite, and during the real time operation of the satellite system, the intersatellite links are established according to these tables.

The aim of the link assignment is obtaining the topology that maximize the minimum residual capacity, i.e. to maximize the residual capacity of the most bottlenecked link. This objective is equivalent to minimizing the maximum link flow. Therefore, this link assignment gives the same performance with the optimal static routing. Simulated annealing is used to solve this optimization problem. More details can be found in [33] and [34].

In [35], comparisons of static and dynamic routings have been performed. In dynamic routing, routing table is updated according to the cost estimation, based on link status information which is broadcasted periodically. According to these results, FSA based static routing performs better than static routing.

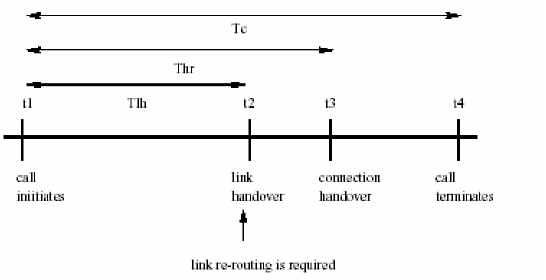

Figure 3. Events Causing to Rerouting

4.4 Probabilistic Routing

In [36], Uzunalioglu *et al* suggested a connection handover protocol for LEO satellite systems called Footprint Handover Rerouting Protocol (FHRP). FHRP is composed of two steps: a Footprint Rerouting (FR) step and an Augmentation step. Footprint Rerouting calculates a minimum cost route between two points on the earth. FR performs this routing process each time it is called. Once a minimum cost route is found, the protocol tries to use it as long as possible using Augmentation method. Let us imagine that, after some time, either the source or the destination satellite handovers to another satellite. If it is possible to find a direct link between that new satellite and the old route, then that link is added to the route. This is called Augmentation. The Augmentation step repeats for a predetermined time period. This time period is calculated in such a manner that the optimality of the route is kept. At the end of each time period, a FR process is triggered. In [37], a routing algorithm based on these ideas is given.
The routing protocol can not be based solely on the dynamics of topology changes. This may be appropriate for the case of connecting two satellites. But for connecting two points on the earth, the algorithm should take into account both the connection and link handovers. A connection handover occurs if the source and destination users change their satellite footprint areas, or in other words, a footprint handover occurs. On the other hand, if the destination satellites do not change, but some of the links connecting these two satellites change, this is called a link handover. Link handover depends on the network architecture and the position of the satellite relative to poles and to the seam. The relation between these three events is illustrated in Figure 3. In this figure, a new call arrives at time t_1 and it terminates at time t_4. Therefore, the

call holding time is $T_C = t_4 - t_1$. At time t_3, a connection handover occurs. At time t_2, at least one of the links on the route experiences a link handover. The rerouting process starts at that moment. Hence, the link handover time is $T_{i,lh} = t_2 - t_1$. If another link handover event does not occur, the next rerouting happens at time t_3.

It is possible to control the number of link handovers by choosing the right links during the routing process. However, the connection handover and call termination events are totally out of control and random. Therefore, the aim of Probabilistic Routing Protocol (PRP) is to use a routing algorithm, which postpones link handover to after a connection handover. By using this method, PRP sets up a route so that, it terminates either because of a call termination or a connection handover, instead of a link handover with a target probability *p*. The drawback of PRP is that it increases the call blocking probability of the network by deleting some links. This high blocking probability can not be accepted for ongoing calls. Therefore, it could only be used on new calls.

4.4. An Optimized Routing Scheme and a Channel Reservation Strategy

Tam *et al.* defined a Revised Mesh Routing Algorithm(RMA) for LEO satellite systems in [38]. In a Mesh Algorithm (MA), the shortest path in three dimension is found. For that purpose, each satellite has been defined by two parameters (x,y) indicating the satellite coordinates. Then absolute x and y coordinate differences are calculated. This shows how many hops on the x-axis and y-axis it is necessary to reach to the destination satellite. That way, it is possible to find all candidate routes between source and destination satellite. The decision criterion is the loading on each ISL. Summing all loads on ISLs, and choosing the route with the least sum gives the best route. In MA, the call is blocked if there is not a minimum hop path between source and destination. RMA, unlike MA, uses the Minimum Cost Algorithm to choose a route in case there is not a minimum hop path between source and destination. Another important idea, Tam *et al.* suggested is ISL channel reservation. In section 3, we saw different channel reservation algorithms. However, all those algorithms take into account, UDL channels. Therefore, this is the first time, a channel reservation for ISLs has been proposed. In this paper, the author suggest to reserve an ISL channel for the next visibility topology before accepting a call. That is, once a channel is requested for a call at time t_0, the algorithm, finds the best route for that discrete time interval taking into account the visibility and usage matrix at time t_0. Meanwhile, it also calculate the best route for time t_l using the visibility matrix at time t_l and the usage matrix at time t_0. The algorithm is then reserve the second path to be used in case of a handover. This process continues for each time interval while the call is active reserving a channel at the next time slot.

5. CONCLUSION

In this paper, we considered some issues that arise in LEO satellite systems. We first explained the terminology used in LEO satellite systems. Then we showed the architecture of a satellite system. Once the general information is given, we focused on two important problems on LEO satellite systems: Performance Evaluation and Routing.

Although performance evaluation and routing are two main problems dealt in communication networks, there are of course some other problems to be solved. One of them is the location management problem. There are some proposals for location management problem in terrestrial mobile networks but in LEO systems, the problem appears to be more difficult. In cellular systems, the location management is necessary for users changing place, and this is a small percentage of the total number of users. However, in LEO systems, even if the users are fixed, they cannot stay on the same footprint area because of the system dynamics. Therefore, there should be a mechanism to detect their locations. Related with this dynamic feature of LEO systems, a second problem, call admission control (CAC) problem becomes more complicated. Hence, a new call admission control mechanism is needed. Another important problem area is of course multiple accessing satellite channels. These problems may be subjects of future studies.

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