INTRODUCTION TO SATELLITE TECHNOLOGY AND ITS APPLICATIONS

CHAPTER 3: INTRODUCTION TO LOW EARTH ORBITAL (LEO) SATELLITES

3.1. Introduction

Revolutionary changes are being observed in telecommunication systems. These revolutions have changed how service and industrial organizations operate, are transforming society, and are profoundly affecting the daily life of everyone. Communication systems based on LEOS, low earth orbit satellite, are an exciting and fascinating endeavor in reorganizing the services that global communication network provides. In developing LEOS systems, huge investments are made and still, a very large amount is required to continue the operations. In the last decade, many systems based on LEOS have been announced. Out of many systems under development, a few are Orbcomm, Iridium, Teledesic, and Globalstar. All the systems target the masses and aim to provide them global communication services (Fossa et al., 1998; Del Portillo et al., 2019). In managing and developing mobile communication systems based on a large-scale commercial satellite, very limited experience exists, this makes it an extremely risky business. The designers of these systems face numerous challenging, interesting, and open research issues. LEOS-based communication systems are presented in this chapter. Here, we will analyze their economic viability and will also discuss some of the potential research areas that are involved in their configuration, development, operation, management, and maintenance (Ware et al., 1996; McDowell, 2020).

LEOS providing global communication services is one of the exciting and new development. LEOS systems are based on the concept of having multiple satellites that orbit in low orbits. They have sophisticated equipment for transmitting, processing through antennas, communicating to and from hand-held user terminals present on the ground. With users in a cell, one or more satellites serve these users, and Earth is divided into cells. As implied by low earth satellite orbits, the satellites move continuously relative to the ground, disappearing and again appearing from the user's sight, compelling recurring hand-offs of users among beams of the antenna within a satellite and also from present satellite to upcoming serving satellite (Pratt et al., 1999).

It is expected that LEOS will be providing wireless mobile communication services around the world. Out of many advantages they have, one is their transcending ability, they transcend the artificial boundaries imposed by regional, state, and local governing bodies. LEOS capably provide instant communication services in regions where telecommunication infrastructures are missing or are underdeveloped, i.e. South America, Africa, Asia, and

Eastern Europe. These systems will be supporting wireless communication in areas that are not covered by geostationary or cellular phone systems, i.e. earth poles, wilderness areas, deserts, or oceans. They will be supporting a huge range of services, such as data communications, phone, paging, messaging, data communications, video services, broadcasting, positioning, monitoring, narrowband, and wideband broadcasting and communication services (Chang et al., 1998).

In the deployment, assembly, and development of LEOS, significant investments are made. Ongoing operational costs that range to several billion dollars/year will be incurred by LEOS. This cost is required to ensure that the operation continues, to replace dead satellites, and for management and marketing costs. It is expected that LEOS will complement and support the global communication system's other components as well, such as the wireless system that consists of data communication and cellular phone services and geostationary satellites, and wire-based (fiber and copper) system. Considering the perspective of the end-user, LEOS will give a lot of benefits and will improve the available telecommunication technologies.

LEOS system's basic components include hand-held communication devices, satellites orbiting in low orbits (mostly the altitudes is between 700 and 5000 kilometers), and gateways to and from the ground-based communication systems. Satellites in low orbits implicit that the satellites, relative to the earth, are not stationary; they keep moving while staying in their orbits with the rotation time in between 100 to 120 minutes/rotation. This time depends on their altitude and trajectory. Moreover, even the orbits are moving relative to the earth (having a cycle time of almost 24 hours per rotation). For ensuring that every single point receives continuous coverage as well as communication, at least one satellite has to be above the minimum threshold of angular elevation level (at any point of interest) and within the line of sight. For a particular system, the selected satellite configuration has to provide uninterrupted service and coverage even under external interference, or components and satellite failure conditions (Leo & Brown, 2000).

Numerous systems based on LEOS are under development. The systems have different characteristics, as shown in Table 3.1 (numerous satellites, communication technologies, satellite weight, constellations, antenna types, trajectories, types of offered communication services). Different approaches to using these new technologies are represented by them. Significant investments are required by each of these systems. These investments might be of multibillions of dollars. Moreover, being an untested and new technology, system designers have to address many operational and technical challenges to make these operations successful and economically viable (Leo, 1998).

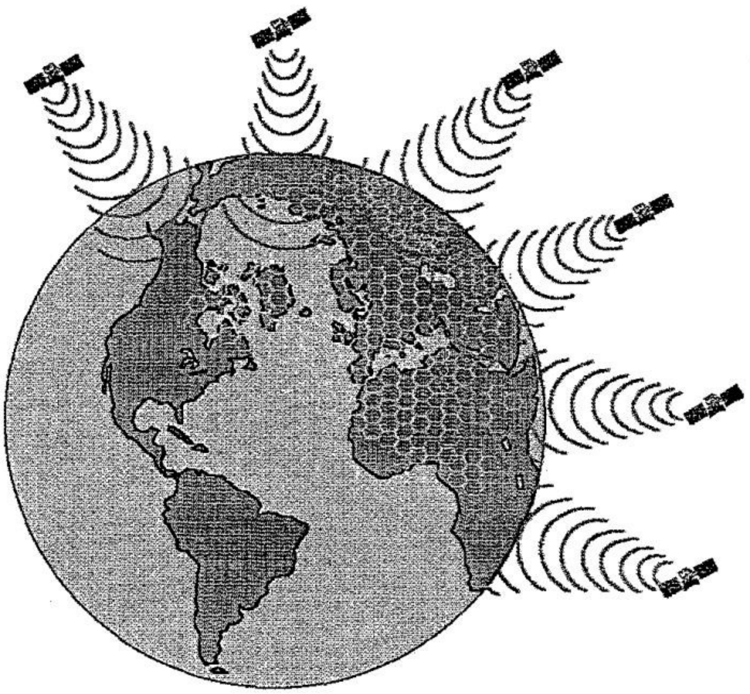

Figure 3.1. A global LEOS communication system

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This chapter aims of introducing the major problems and present their initial results to grab the research opportunities in the potential fields. It is not possible to provide a complete review of all the analysis and modeling efforts of such dynamic and complex systems. The LEOS consortium has undertaken all extensive development and research efforts. Unfortunately, because of their high financial risks and the novelty involved, similar companies protect such models as commercial secrets. Their publication is not encouraged. Recently, details of some models have been published in several papers. Wherever appropriate, we refer to public domain papers, containing the both, analysis and modeling aspects of LEOS. Early discussions regarding LEOS analysis issues can be seen in Gavish (1995a,b).

3.2. LEOS economic viability

In global communication systems, LEOS presents innovative and new development. With this unproved and new technology, investors face many risks. Mostly the question that arises is: Whether the designed systems will ever be successful or not in the marketplace? Some concerns regarding the viability of LEOS are addressed in this section.

The following issues should be addressed by any technologically risky and new system (Leo et al., 1998; Díaz-de-Baldasano et al., 2014):

1. Whether the system is technologically feasible or not? Irrespective of the revenues collected and costs by the system, can we find a feasible design?
2. What are the managerial and political considerations and what sort of environment supports them? The frequency allocation by the regulatory agencies for a particular service or system can be taken as an example of discussed geopolitical consideration. If the regulatory bodies do not approve the frequency required for the system's successful operation, it is useless to have a remarkable technically viable design.

For approving the frequency spectrum, many promises and compromises are supposed to be made to convince most of the members of a regulatory body. For minimizing the cannibalization of existing services, incentives such as assurances are required. These existing services can be cellular phone services, they can be orders of materials or other services that suppliers offer, especially in countries that support the project. Questions that arise are: Who can become a shareholder or can invest in the system? The satellites will be launched by whom? Who will be responsible for manufacturing the different satellite components? Who will be launching the satellites? At what percentage the revenues will be shared?

3. The system's economic viability: After such a huge investment, will the return be high enough that it will be able to provide the system's long-term economic viability? Will the price of services (that user will be paying) be low enough that it attracts a larger user community so that the system operation and development costs can be recovered?

For analyzing the system's economic viability during its lifetime, the system's basic cost components are identified. For better comparison, the cost of the main system under steady-state- conditions are analyzed. For example, the Iridium configuration is used to calculate the system's annual lifetime costs.

4. *Satellite replacement and launch costs:* For the iridium system, as per the plan, there should be 66 operational satellites in orbit. In-orbit satellites have a limited lifetime and due to this, it is expected that satellites had to be launched into orbit in a steady state to replace dying or dead satellites. Considering the expected lifetime of a satellite to be of five years, we can calculate the average number of satellites needed to be replaced yearly which is 66/5=13.2. Satellites and rockets are not perfect, hence there exists a possibility that they might fail after or during the launch process. The success probability for commercial rockets is between 0.8 to 0.96 (Gavish and Kalvenes, 1997b, 1995). This probability depends on the launch method, cost, payload, and rocket type. Considering the launch failures after and during launch may lead to the need of launching at least 15 satellites per year (Andriulli et al., 2004).

- *Launching cost* is estimated while keeping 15 satellite launches/year, for ten million dollars for each launch. So in total, $150 million is estimated for each year.

- *Satellite replacement cost* is also estimated while keeping 15 satellites in consideration, so almost twenty million dollars for one satellite. So in total, $300 million is estimated for each year.

5. *Operation and gateways costs* are estimated at $100 million each year.
6. *Billing, marketing, management, and accounting costs* are estimated at $100 million each year.
7. The system's largest cost component is constituted by *financing charges*. It includes the recovery of development and research costs, financing the inventory of the ground satellites and of the ones in orbit, gateways, rockets, and spare parts required to keep the system running and up. As per estimations, the finance charges for the Iridium system will be around $300 million each year.

Gathering the different cost components, the total cost sums up to $950 million per year. Assuming that this system will be able to achieve 1000000 subscribers, still, each one of them will have to pay $1000 each year to keep it going for the long run. The Iridium system has declared to achieve a target of 10000000 subscribers, then in this ideal case, each one of them will be paying almost $10 each month (for recovering the annual costs). If the subscribers are charged ten dollars each month, this will raise the number of users, making the system attractive for everyone. This might even exceed the demand to the point that it exceeds the system's capacity. Hence, the actual system capacity and the number of subscribers have to be carefully balanced. Based on these considerations, the Iridium system seems to solve political and technical questions. If this system reaches its stated goal (the number of subscribers), it will turn out to be a huge success.

3.3. LEOS research issues

There is a huge profit potential in services based on LEOS and this has attracted investments and attention by large international concerns. For having a proper understanding of the promised benefits, many operational and technical questions have to be answered. These systems provide fertile and new grounds for research-related activities. A few of these challenging issues that one might face in LEOS-based systems are discussed in the following sections.

3.3.1. Constellation configuration

There is an impact of the number of orbits and satellites present in them, orbit altitude, and orbits type on overall operating costs and system configuration. When designing a constellation for these systems, the main objective is to ensure that all the satellites stay within the line of sight. These satellites have to be within the line of the interested service points on earth. For highly populated areas, the coverage should be increased by the constellation, while for lightly populated areas, there should be a lower level of coverage. Constellations might vary from rosette constellations for polar-based trajectories to different combinations of various configurations. A few of the commonly used configurations classes include (Hongzheng & Chao, 2011):

1. Polar orbits: such constellations where the orbital planes (relative to the poles) have a slight inclination or pass over the poles. Each satellite is in a position that is highly predictable which simplifies the communication control structures required for the system. For the regions close to the poles, a high coverage degree is provided by polar orbits. This high degree of coverage is regarded as a major disadvantage. However, over the globe, considering the actual termination locations of communicating parties and distribution of origination, we can conclude that polar orbits are advantageous when we incorporate power management issues as the design factor. In regions where high power consumption and traffic are expected, multiple coverages are provided by polar orbits.
2. Constellations, which have highly inclined orbits relative to the equator are termed Rosette constellations. They provide a high coverage level for all parts of the globe except for polar areas. In polar areas, they provide a lower coverage level. In a rosette constellation, it is difficult to maintain interstate links. Any of the LEOS (announced so far) has not proposed the use of a rosette constellation.
3. Another constellation is Equatorial constellations. It provides excellent coverage at the equator but offers no coverage in areas that are away from the equator.
4. A minimum number of satellites are required by Polyhedral orbits to offer continuous global coverage. Polyhedral orbits achieve this at the expense of higher satellite altitudes and complicated orbits. They have complex orbital structures, hence maintaining up and down communication links and supporting space-based routing is difficult. It makes polyhedral orbits unattractive for the systems based on LEOS.

Depending upon many design factors, the constellations from above are selected. Some designs use a combination of the above configurations. For a LEOS system, three possible constellations are shown in Figure 3. 2: a rosette constellation, a polar constellation, and the one consisting of an equatorial and rosette constellation, named as a mixed constellation. The type of constellation affects both, the number of satellites required to provide full earth coverage and the launch costs of satellites that are required for the initial configuration, as well as for the maintenance of the system (Fallon & Oestreich, 2015).

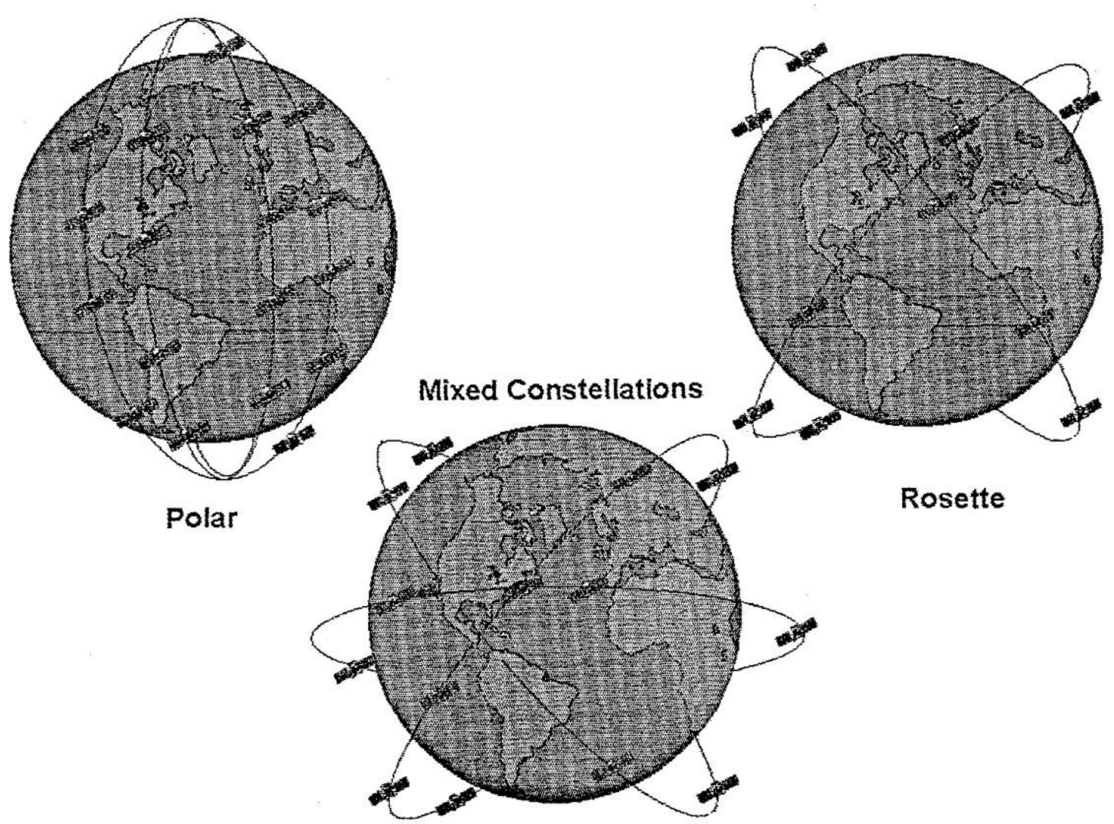

Figure 3.2. Examples of satellite constellations

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The early studies regarding configurations guaranteeing a coverage level encompass the papers by Beste (1978), Ballard (1980), and Perrotta (1991). Beste used classical optimization methods for finding the minimum number of satellites required for both multiple and single coverage in polar orbits. Ballard studied rosette constellations. studied rosette constellations compared to elliptical and circular orbits. Other papers related to trajectory design include Kaniyil et al. (1992) and Adams and Rider (1987). The used nonlinear optimization for designing polyhedral orbits that may have a minimum number of satellites to provide complete coverage of the earth. Furthermore, other investigators include Rider (1985, 1986), Maral et al. (1991), Markowic and Hope (1992), and Sheriff and Gardiner (1993).

The cost of offering a stated level of coverage is not provided by the above-discussed studies. Higher coverage will result in higher system costs. This is because the system complexity and the number of satellites in orbit will increase. Decreasing the coverage level will possibly reduce system costs. We can find such an example in the Iridium system, where the in-orbit satellites were reduced to 66 (instead of 77) satellites at the cost of few minutes every 24 hours by not covering the areas that were near to the equator. By doing this, around 15% of system cost was reduced. It is purely an example of a worthwhile trade-off.

In selecting any configuration, the following decisions are included (Shi et al., 2018):

5. *The number of in-orbit satellites:* The cost (finance) of the system is increased by a higher number of satellites. It also increases the inventory and in-orbit system power reserve.
6. *The number of orbital planes:* If the number of orbits is higher, the distance among satellites adjacent orbits decreases, resulting in reducing the energy requirements and signal propagation time of inter-satellite links.
7. *The inclination of orbital planes:* If the orbits are more inclined, the likelihood of satellite collisions is observed to be low when they pass near or over the poles.
8. *The orbital plane's angular spacing* determines the cross-seam distance among orbits.
9. *The number of satellites present in each orbital plane:* If a high number of satellites are present, the in-orbit propagation times are decreased between adjacent satellites.
10. *Satellite's relative spacing* within an orbital plane.
11. *Satellite's Angular inclination* among adjacent orbital planes.
12. *Level of coverage:* several planned systems, i.e. Teledesic, needs multiple coverages of the terminal. It is required so that the satellites can effectively operate their communication system.
13. *Storage potential and power collection:* A nonlinear model was developed by Gavish and Kalvenes (1996) that links power generation, satellite altitude, and storage to the total weight that is allocated for power generation and storage on a satellite concerning the overall system capacity. By capacity, we refer to the number of calls that the system supports. The phone call duration is also provided by the same model. Their calculations demonstrate that in configuring LEOS systems, the power storage capacity for each unit of weight is an essential factor (Li et al., 2010).
14. *Satellite altitude:* A much high degree of frequency reusability is implied by a lower altitude. However, the atmospheric drag is increased on the satellite by a lower altitude. On other hand, the expected useful lifetime of a satellite is decreased. The satellite launch cost is also reduced (but as the orbit lifetime of the satellite is reduced,

the per-day launch cost may increase). The number of satellites required for covering the earth is decreased by a higher altitude. Contrary to it, higher altitude increases the power requirements for the equipment transmitting it, weight of the satellite, the satellite launch costs and it may also decrease the lifetime of equipment present in the satellites (this is because of ionosphere provides lower protection level and the Van Allen effect).

15. *Elliptic vs circular trajectories:* From points on earth, small changes in altitude are offered by circular trajectories. This makes the signal acquisition and positioning simpler. Intersatellite communications within orbit are also simplified by circular orbits (Budianto & Olds, 2004).

3.3.2. Physical satellite configuration

It includes the types and numbers of antennas utilized in direct user communication (multibeam/spot beam/ single); movable antennas vs. fixed ones for up and downlink communications; the types and numbers of antennas used in gateway communication; the type (optical or electromagnetic) and the number of inter-satellite communication links that will provide support (the inter-satellite links under development in the systems are in between zero to eight; Figure 3.3 shows an example of a system having eight inter-satellite links named as the Teledesic design); energy storage devices along with their types; energy collection surface areas; satellite propulsion/ maneuvering subsystems; energy collection control mechanisms; and switching, receiving multiplexing, and transmission technologies (Girard et al., 2015; Radhakrishnan et al., 2016).

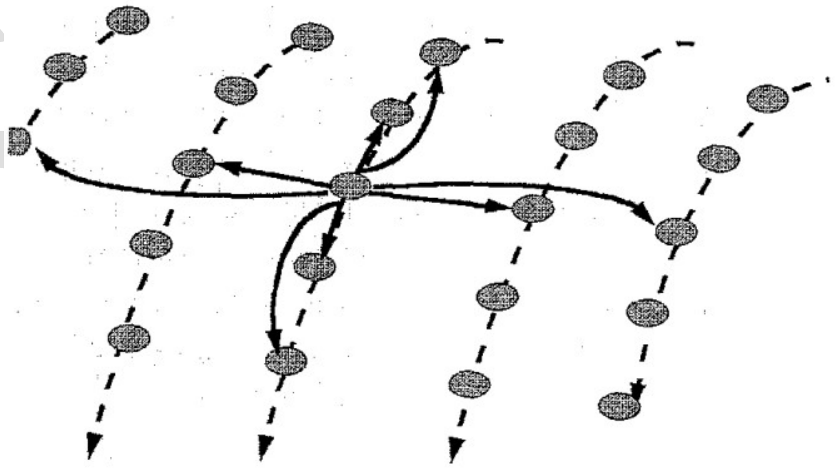

Figure 3.3. Example of a satellite along with its immediate eight inter-satellite links

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The design decisions are intertwined. Mostly, the technical specifications of many components directly affect the design of other components, this collectively affects the overall weight and expected lifetime of the satellite. Considering the limited lifetime of some components (such as solar panels), it is of no use to design other satellite components for a time that is far greater than the expected lifetime of the components having a shorter lifetime (Smith et al., 1992; Powell et al., 2006). Corresponding to it, redundancies have to be included so that a failure of one component does not result in a complete satellite failure. The components, subjected to random failure, possess built-in triplication or duplication, or in some scenarios, it allows graceful degradation of the capabilities. Reliable design models, like the one designed in Shogan (1978) and Sanso and Soumis (1991) help design complex components, which may subject-to-failure.

3.3.3. Intersatellite links

The forthcoming issue is the operation and configuration of inter-satellite links. Should the system support space-based routing? On earth-based services, the dependence of the system is reduced by space-based routing provided by telcos. However, adding up to the cost and complexity of the system and satellites. For space-based routing, various technologies are possible through inter-satellite links, which add up to the power and weight requirements of the systems (Werner et al., 1997; Wang et al., 2019). They differ in the maximal angular change rate among the satellite's relative positions and their distance, which they can support. Satellite interconnection's different possible patterns are shown in Figure 3. 4. These patterns head to various end-to-end means and sometimes may lead to worst-case delays affecting the overall performance. In LEOS systems, communication links between adjacent satellites (same-orbit). It uses polar circular orbits. As within the orbit, the relative positions of satellites are not changing, it is easy to support communication links having polar circular orbits. In adjacent orbits, inter-satellite links between satellites are comparatively difficult to support. This is because their relative position changes (the rate of angular change, at some latitudes, is that much high that inter-satellite links in adjacent orbits are supposed to be shut off). Within and between elliptic orbits, inter-satellite links are very extremely difficult to support, hence, most of the systems planning to use elliptic orbits depend mostly on ground-based routing (Bertossi et al., 1987).

In space-based routing, a prominent issue to be addressed are cross-seam links. Between the orbits, seams are formed when satellites move in opposite directions in two adjacent orbits. Among polar-based systems, this happens twice. Communication between satellites moving over the seams (in opposite directions) is comparatively difficult to support. We can handle cross-seam communications by routing their messages to the other side (over the pole), two satellites moving in the same direction. Long propagation delays and various hops in the routes are implied by such over-the-pole routing. The designer has to depend on new inter-satellite communication technologies for supporting cross-seam communications if they aim of providing cross-seam communication links.

Limited research, regarding the inter-satellite link technology's impact, crosslink operational policies, and crosslink configuration patterns on overall system performance, is published. Models of inter-satellite links were developed by Gavish and Kalvenes (1997a). They used this model for analyzing the effect of various crosslink configuration patterns. Gavish and Kalvenes used shortest path routing models and also calculated the worst case and overall end-to-end delay. The end-to-end delay and worst-case are illustrated in Figure 3.5. In Figure 3.4, pattern B of crosslink configuration, about end-to-end delay, is more preferred than other tested patterns (Wu et al., 2014).

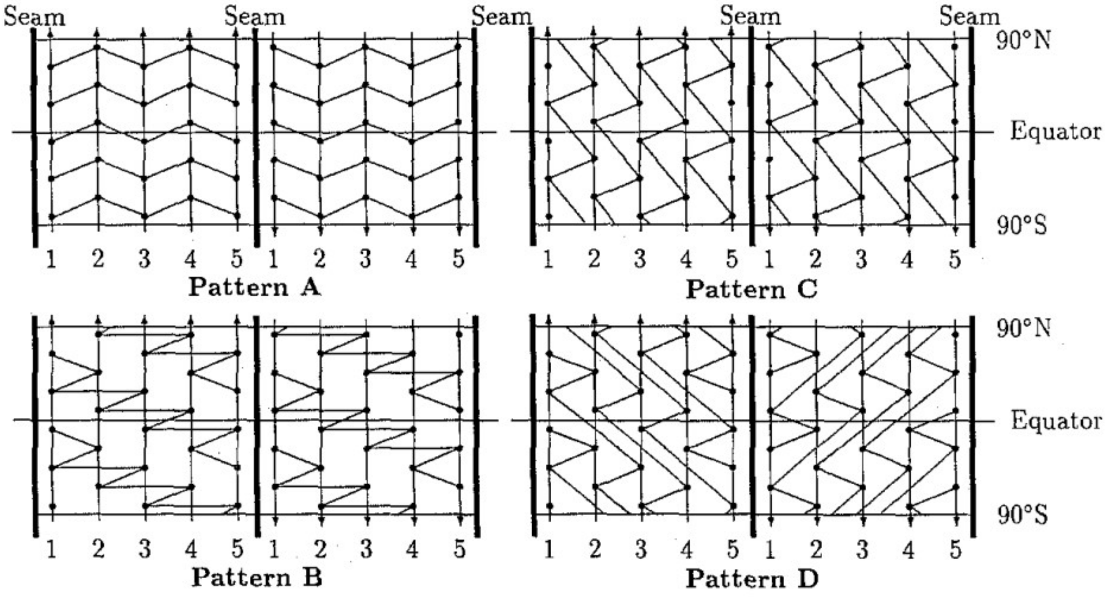

Figure 3.4. Different satellite interconnection patterns.

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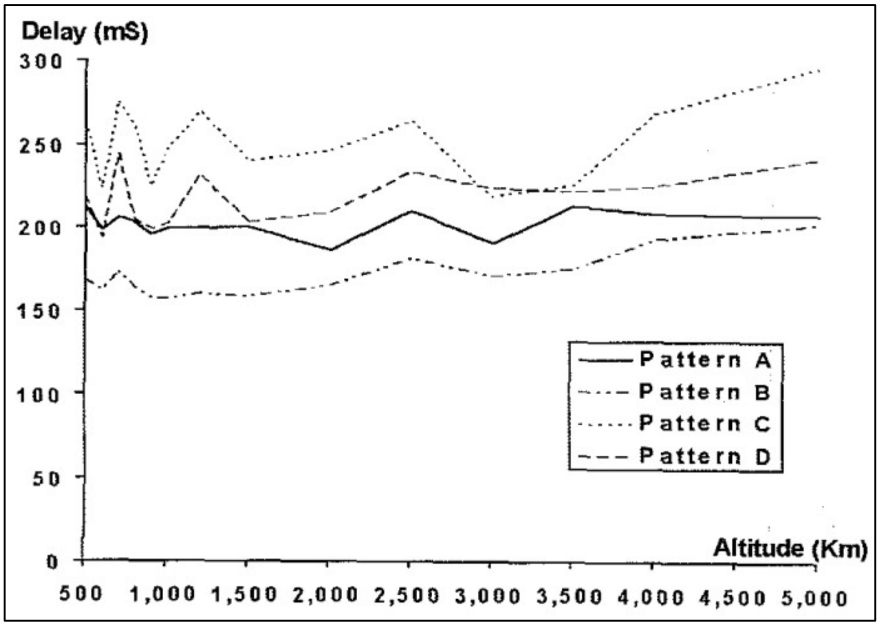

Figure 3.5. Worst-case delay. It is a function of satellite altitude and crosslink patterns.

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Surprisingly, all the systems based on polar orbit use an inferior pattern (pattern A). Using a combination of numerical simulation techniques and shortest path algorithms (see Lawler, 1976 and Bertsekas, 1995a), Gavish and Kalvenes also investigated the effect of using expensive technologies to delay the crosslink's shutoff point to higher latitudes, and the cross-seam links effect that supports direct communications among satellites. The analysis gives insight into the economic futility (or worthiness) of investing in expensive and new technologies to extend inter-satellite communications (Newman et al., 2012).

3.3.4. Communication methods and services

What transmission methodologies or their combinations should be preferred by the channels? What sort of communication services shall be provided/supported by the system? All these services add to the system management complexity, software, and hardware, and the revenues and costs collected. They will have potential services in many fields which include: paging, positioning, mobile/cellular phone services, targeted TV broadcasting (in a small geographic area) and video broadcasting, remote telemetry, data communication, tracking, and security services, videoconferencing, and videophone. For each of these services, appropriate software and equipment need to be installed on both, the satellite and ground side. What services given LEOS configuration should offer and the interaction between system configuration and service capabilities are interesting subjects of research for LEOS potential providers and designers (Mikkonen et al., 2002; Hinami et al., 2009).

3.3.5. Routing methodologies - space vs. ground-based routing

Orbits are moving relative to the earth, while satellites move within orbits. Inter satellite links, beams, satellites, and antennas may be switched off or again, depending on many physical and operational constraints. A combination of earth-based components and space-based components may compose routes. End-to-end communications with bounded variability and an acceptable delay, under many failures and operational conditions, should be ensured by the system. Considering all this, the fact of developing new routing methodologies cannot be denied (Bhalaji, 2019). These methodologies should be reliable and robust in a dynamic environment. In LEOS-based systems, routing has to provide sustenance for continuously changing topologies and stochastic demand. For handling these complex operational routing questions, stochastic routing models have to be developed. Gavish and Neuman (1992) developed such a model.

In a LEOS system, each satellite covers a limited area at any point. Two distant communicating entities are covered by different satellites. Resultantly, it is required to route the message to a destination satellite (from an origin satellite). For interconnecting the destination and source points, LEOS architects have suggested two competing approaches. The first approach depends on the cable system (existing on the ground) for routing the message. In the routing approach based on earth, assuming the communicating entities to be dependant on satellite communications, a source user interacts with a satellite, relaying its message to a gateway present on the earth station. At this point, the ground-based wire plant is used for transferring those messages to another gateway that is present near the destination point. This point beams the message to the other satellite and finally, this satellite sends it to the destination (Zaitchik et al., 2010). Considering all this, some interesting research issues arise such as the placement of gateways, numbers of gateways that should be present in the system, the type of gateway that should be used in each location. Numerous concerns have to be taken into consideration while designing, these concerns include, the stochastic user demand, the ground (gateway routing and operation) based charges dependant on ground-based operator and gateway, the possibility of component and satellite failures. Location models like the ones developed by Deng and Simchi-Levi (1991), Bitran et al. (1981), and Cattrysse and Van Wassenhove (1992) can be used for addressing a few of the issues regarding the gateway placement.

For interconnecting two communicators, the second approach uses communication links based on inter-satellite space, in order for transferring messages directly between satellites.

Between the satellites, the transfer of messages is repeated until it reaches the destination satellite. Figure 3.6 depicts space-based vs. earth (or ground) based routing.

As compared to space-based routing, ground-based routing is less complex (technically). It is dependant on inter-satellite links. For satellites, the stabilization of inter-satellite links is relatively easy in the same circular orbit. This is because the satellites' relative positions do not change over time (Lienig et al., 2002). In different orbits, it is technically challenging to support inter-satellite links between satellites. This because of the continuously changing positions and orientation of satellites. Spaced-based routing has a major advantage; its system is self-contained, so it does not depend on services that are being provided by organizations such as independent and regional phone companies, and PTTs). Political independence is increased in the case of using space-based routing. Similarly, for the LEOS system owners, the portion of revenues collected is increased. Taking the operational side into consideration, multiobjective routing models have to be developed. An example of such a model can be the one in Henig (1986, 1984). Different criteria have to be balanced i.e. satellites power consumption, end-to-end delay, revenues, and costs of the entities that are involved in the quality of service provided and the particular route. Methods such as multiobjective routing and multi-criteria optimization play an essential part in such routing problems. In LEO systems, a more complete analysis and exposition of routing issues are presented in Gavish (1997b).

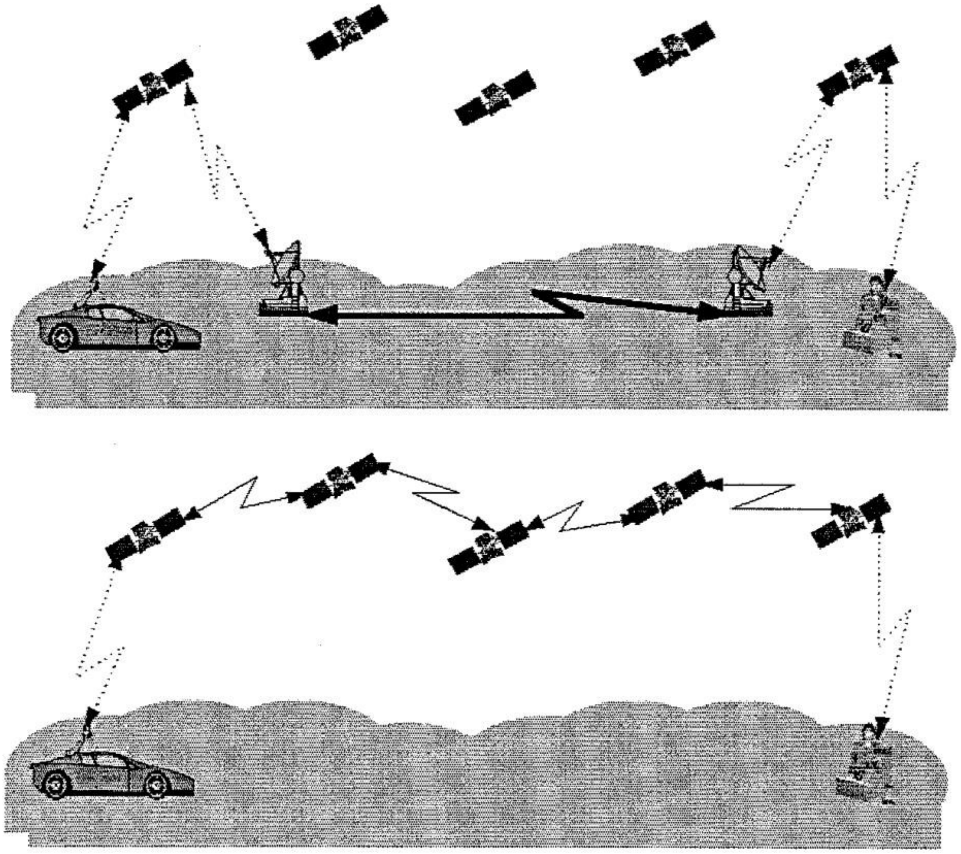

Figure 3.6. Spaced-based vs. ground-based routing.

3.3.6. Bandwidth management and allocation of channel

Bandwidth serves as a limiting agent in the system's capacity. For maintaining the system economically viable, efficient frequency plays an essential part. The most acknowledgeable feature of such systems is high-level channel reusability. In highly dynamic environments, LEOS may cause challenging channel allocation problems. The very high altitude and speed of the satellites (compared to earth) give rise to physical constraints. These constraints need to be addressed when allocating channels. Timeshift between satellites and within a satellite and the Doppler effects impose channel separations between satellites and between adjacent 'cells' (Del Re et al., 1995; Luo & Ansari, 2005). For LEOS systems, significant frequency shifts might be observed and this is because of the planned frequency ranges and satellite velocities for communication systems. The expected frequency shifts for different satellite altitudes and frequency ranges in a polar system are illustrated in table 2. A satellite passes over the total area of the cell in a time-varying from a minimum of few seconds to a maximum of one minute. Different satellites may provide multiple coverages to cells, requiring a decision that which satellite will serve the cell at that point (Shah et al., 2005; Al-Mistarihi et al., 2012). For LEOS-based systems, the essentially important thing for its successful operation is efficient channel management. As a solution to these channel allocation problems, a vital role is played by models such as capacitated fixed charge networks (Wolsey, 1989) and dynamic graph coloring (taking place in real-time).

3.3.7. Power management

Satellites' power consumption is a complex function of numerous factors including stochastic/ fluctuating demand for satellite orbit and telecommunications, weather conditions, satellite household keeping operations, and demand for inter-satellite communications. The solar panels present on a satellite need to be always oriented toward the sun. This ensures the collection of optimal energy and also prevents the panels from burning. During their orbits, satellites pass through the shadow of the earth, and at that time, sunlight does not fall on their solar panels. There are limited energy collection areas on a solar panel of a satellite (Mostacciuolo et al., 2018). As there are weight limitations, the small size of the energy storage capacity of a bounded battery. The energy is consumed by the satellite transmission activities and this may deplete its energy sources. If in case, the stored energy is depleted, the satellite is no longer useful and generally, it cannot be reactivated. In the system operation, satellite activity management for conserving its energy is a crucial factor. It is possible to conserve energy by dividing the tasks of satellites and assigning them to other satellites, or by reducing active phone sessions that a satellite handles, or by shutting off inter-satellite connections or gateway connections, or multi-beam antennas. The operations of power management are handled by simulating many power consumption and storage scenarios, and through testing simple decision rules for managing the system. Further investigation needs to be performed to do this task most efficiently. A combination of stochastic optimization methods (Bertsekas, 1995b; Bellman and Dreyfus, 1962; Howard, 1960) and stochastic control models will be required to form effective power management procedures (Falke et al., 2004).

3.3.8. System capacity

LEOS system investors and designers are concerned about this issue. System capacity determines the number of users that can appropriately use the system, while the quality of service is acceptable. The numbers of effective users determine the number of subscribers that can be efficiently accepted by the service providers. This affects the cost of charges for each subscription and also for the use of the system (Alvarez & Walls, 2016, Chin et al., 2018).

Very few researches regarding projected system capacity are published. The basic reason behind this might be that there are numerous factors responsible for determining the capacity of the system. A complicated interaction between those factors needs to be considered for determining the capacity of the system. Some of the impacting factors include; channel reusability level, control policies, regulatory bodies allocating frequency, transmission methods, demand patterns for communications while considering their shifts over a 24 hrs cycle, antenna technologies, and power consumption. On the overall system, the power consumption limit's effect was investigated by Gavish and Kalvenes (1997a).

We can reduce the dependency of system capacity on generating and storing power by increasing the number of satellites present in orbit. They need to be increased to a number that falls above the minimum number required to provide continuous coverage to earth. The planned Teledesic system demonstrates this reducing power dependency approach. It sets up 840 in-orbit satellites which are responsible for generating enough energy that can drive the system efficiently at its best of the theoretical capacity (Radhakrishnan et al., 2016).

3.3.9. System availability and reliability

It is possible that with time, different parts of a satellite may undergo failure. As commonly practiced in ground-based systems, we cannot repair the hardware failures by simply sending a repair crew that will replace the failed component. Satellite and system designs should possess built-in redundancies which should be capable enough to cope with in-orbit failures. As there are constraints such as the satellite weight and system cost, only a limited level of redundancy can be added to the system (Crisp et al., 2014; 2015). Similarly, as the effective lifetime of satellites is not so great, so the satellite components that are incorporated should not exceed the lifetime of the satellite by far. The question that may arise is that where such redundancy should be built that subjects to volume constraints, weight, satellite lifetime distribution, power, and budget. Other questions regarding operational issues that may arise are: How the component failures should be handled? What should be the capacity of the system if it encounters different failure conditions? What should be the performance of the system under failing conditions? It should be kept in mind that most of the time, failure, it is meant that the quality of provided service is degraded (not that a system or satellite is shut-off). A combination of economic models and reliability models (Shogan, 1976; Li and Silvester, 1986; Ball, 1979) will be needed to address system availability and reliability issues.

3.3.10. Satellite replacement and launch policies

In a LEOS system, the satellites have a limited lifetime. This lifetime comes from two major sources. The low altitude of the satellite imparts that gravity and drag will attract the satellite towards the earth and will finally burn it in the atmosphere. The more appropriate source responsible for the short lifetime of the satellite is the eventual propellant depletion required for maneuvering the satellite. This maneuvering keeps the satellite in the precise orientation and in the correct orbit that is needed for telecommunication. The satellites in LEOS have an expected lifetime ranging between five to eight years (Cornara et al., 1999). Considering the satellite launch vehicle's limited capacity, the probability of launching failures, in-orbit shortage level of rocket, satellites, and expected revenue losses and satellite costs, the aim is to look for the optimal satellite replacement/ launch policies. For the static case, Gavish and Kalvenes (1997b) addressed this problem. They assumed that they will be already aware of the satellite shortages. Dynamic programming procedures were used by them for computing the optimal satellite launch policies. They also used dominance rules for reducing the exponential state space down to a size that can easily be managed. In Gavish and Kalvenes (1995), the static assumptions are less strict. A difference of ten million dollars per anum was demonstrated while comparing different satellite replacement and launch policies. This was done through stochastic optimal control procedures. In Gavish and Kalvenes (1997b), an interesting question investigated was regarding dark satellites. The dark satellites may be kept parked in space and when active satellites fail, the dark satellites can be moved from parking orbits and can be activated as replacement satellites (Jakob et al., 2019).

3.4. Summary and discussion

There are many research issues, out of which, we have introduced and discussed a few involved in communication systems that are based on LEOS. After analyzing and investigating the economic viability issues of these LEOS systems, we concentrated on the operational and technical aspects of the system. The future operators and designers of LEOS face many challenging questions. Most of the operational and design problems are difficult to solve and are NP-complete (Garey and Johnson, 1979). LEOS systems are a novice so they provide (and will continue to do that) a fertile ground to numerous researchers interested in this emerging and potential field.

Systems based on the geostationary satellite are being used and are providing communication services for around three decades. The services they provide include security services, TV broadcasting, collection of sensing data, VSAT based data communication, monitoring, limited phone service, and paging. Communication systems based on MEOS (at 10,000 to

15,000 km altitude), Medium Earth Orbit Satellite, have been put forward as a superior alternative to geostationary and LEOS satellites, they include systems like ICO and Odyssey. A lot of debate regarding the viability of the LEOS vs. MEOS vs. geostationary satellite-based systems is taking place. All these types have a vital part in global communication systems. The role they play depends on the services and functions offered to the users. We have highlighted a few disadvantages and advantages of each system in Gavish (1997a), and have shown their operational characteristics affecting the choices made concerning the system.

Mobile communication services have been greatly facilitated by cellular communication networks (both satellite and terrestrial). In general, ground-based telecommunication services experience variations in demand because of changes in social and economic activities over days or even longer periods. For communication services, besides the regular variations, mobile systems also undergo stochastic changes, which are due to the mobility of customers. In configuring such systems, the added variability raises new challenges. In the case of satellite-based cellular networks, additional constraints are imposed by the mobility of the satellites. The global reach of such systems (satellite-based) adds many administrative and political considerations to the economic and engineering aspects of these systems. In-demand variability and the need to attain global governmental/ political considerations impose new restrictions and limitations on the operations of the system. For instance, for meeting the revenue targets promised to governmental agencies or PTTs, countries impose operational restrictions over which the satellites pass, in-demand time, and spatial changes for telecommunication services. Taking this type of factor into consideration for the day-to-day operations of the system, it becomes a complex task (Maier et al., 2018).