Chapter 2
Satellite Network Constellation Design

2.1 Introduction

Satellite constellation design plays an important role in satellite network robust QoS routing technology. Although robust QoS routing technology should not depend on constellation design, constellation design can affect the system cost, the effective communications of the entire network, and the effective and convenient management of the satellite network. At the same time, it is the basis of the implementation of routing strategies and routing algorithms. Constellation design is defined as follows in [1]: distribution of satellites of similar types or with similar functions in similar or complementary orbits to accomplish a specific task under shared control. The thought of using satellite constellation to provide wireless communications service can be traced back to 1945. British scientist Clarke published a paper in Wireless World, and first proposed a scheme of using three GEO satellites to provide continuous coverage for the equatorial region [2]. This scheme can be deemed as the first constellation design scheme.

Although a GEO satellite can cover low latitude regions well, it cannot provide good service for the high latitude areas. Besides, the power requirement of the terrestrial terminal and the quality requirement of the receivers are very high in a GEO communication system, which means the terrestrial terminal is hard to be made handheld. This is because the orbit of GEO satellite is extremely high which leads to a long round trip time (RTT) and a heavy link loss. For some business with high real-time requirement, GEO satellites sometimes are difficult to guarantee the quality of service. The emergence of non-geostationary orbit satellites such as LEO, MEO satellites greatly compensates the disadvantage of GEO satellites. Compared with GEO satellites, LEO and MEO satellites have smaller communication delays and link loss. The application range of LEO and MEO satellites is larger than GEO satellites. Regional coverage, intermittent coverage, and global seamless coverage can be achieved by adjusting the parameters of LEO and MEO constellations. LEO and MEO satellites make constellation design more complex, and non-geostationary orbit constellation design has gradually become the focus of constellation design.

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Since the 1960s, great achievements have been made in terms of non-geostationary orbit constellation design. Some representative examples are as follows: LEO polar orbit constellations, the δ Constellation proposed by Walker, the Rosette Constellation proposed by Ballard, the Ω Constellation and the σ Constellation, etc. The researches of Walker, Ballard, Rider, Hanson et al. are more influential. Their proposed constellation design schemes [3–11] have been widely adopted by later researchers, and become classic in non-geostationary orbit constellation design [12].

Although the efforts of Walker et al. have solved the inherent disadvantages of GEO satellite constellations, such as limited coverage, long communication delays, and large link loss, the drawbacks of vulnerability and limited constellation resources are still unsolved. The emergence of satellite over satellite (SOS) architecture [13] makes the collaboration between different layers come true. It enhances the invulnerability of satellite network systems, and lightens the burden of routing of LEO satellites, and also makes the design of non-geostationary orbit satellite constellation more complicated. Constellation design has thus been shifted from a single layer to multilayers. The representative works on multilayered constellation design are also presented in [14–17]. These works not only take into account constellation coverage, but also consider constellation failure robustness, the total system cost, and many other factors.

The principles and methods of non-geostationary orbit constellation design are systematically expounded in [12], and two classic constellation design methods, the Orthogonal Circular Orbit Constellation Design and the Common Ground Track Regional Constellation Design, are proposed. The Orthogonal Circular Orbit Design uses geostationary satellites and polar-orbiting satellites to provide service for terrestrial users. This design takes full advantage of continuous band coverage of geostationary satellites in low latitudes and continuous crown coverage of polar orbit satellites. It considers the population-weighted average elevation angle, latitude average elevation, and also the distribution of average elevation angle. The design improves the coverage in mid- and low latitude regions, especially the low latitude regions, while keeping good coverage in high latitude areas. This also makes the coverage characteristics of the whole constellation more consistent with the global population latitude distribution characteristics, and improves the overall coverage performance.

The disadvantage of the Orthogonal Circular Orbit Design is that, when the total number of constellation satellites, the number of orbital planes and the number of satellites in each orbit are all fixed, the orbit altitude required by the Orthogonal Circular Orbit Design to achieve global coverage is higher than polar orbit constellations. The Common Ground Track Regional Constellation Design draws on the idea of the common ground track continuous coverage design proposed in [18]. The constellation design in [19] is of this kind. It considers the regional population distribution of China and can provide seamless coverage for the whole territory of China.

A simple encoding identifier that can completely describe the parameters of common ground track constellations was first proposed in [18]. The equivalent condition between common ground constellations is then discussed, and the common optimization design method to realize regional satellite mobile communication is given. In the end, it makes an adjustment of the parameters of a constellation program based on the time varying characteristics of business distribution density. The parameters are further optimized by the genetic algorithm.

Besides, there is a lot of other literature on multilayered constellation design. These constellation designs are conceived from the point of view of robustness, system cost, and coverage performance, etc. This book does not focus on constellation design. The constellation design mentioned in this chapter is intended to provide an application model for the implementation of satellite network routing schemes and robust QoS routing algorithms, and a useful research method for multilayered constellation design. Therefore, the constellation design objectives considered in this chapter are as follows [19]:

(1) 100 % earth coverage by LEO layer satellites.
(2) 100 % earth coverage by MEO layer satellites.
(3) 100 % coverage of LEO satellites by MEO layer satellites.
(4) 100 % coverage of mid-low regions of the earth by GEO layer satellites.
(5) The access satellite link duration time of any user (no switching) $\geq$5 min.
(6) The duration of continuously covering one ground station by one satellite $\geq$8 min.
(7) The system cycle of a constellation is minimum.
(8) The number of satellites and orbits is minimum.

2.2 Principle of Constellation Design

2.2.1 Constellation Structure Selection

The satellite network system mentioned in Sect. 1.2 can be divided into the geostationary orbit system and the non-geostationary orbit system. The altitude of a geostationary orbit is 35,800 km, so the value of RTT is large, and the transmitting power required by a ground personal terminal is relatively high. Currently, most of the satellite systems in use are in non-geostationary orbits. The non-geostationary orbit satellites can be divided into circular orbit satellites and elliptical orbit satellites according to the orbit type. An elliptical orbit satellite has good coverage of high latitude areas. However, the elliptical orbital inclination must be 63.14 in order to make the satellite apogee fixed under disturbance conditions, which is very unfavorable to the coverage of mid-low latitude areas. As a result, only circular orbit satellite constellations are considered in this book. The inclination of a circular orbit can be chosen between 0 and 90°. A circular satellite network system can be either an LEO or MEO satellite network according to the orbital altitude.

In the composition of a multilayered constellation, usually the number of GEO satellites is the smallest. The orbital altitude of GEO satellites is the highest and the link loss is the heaviest, hence the required user terminal's effective isotropic-radiated power (EIRP) and G/T[1] value is the highest. The number of MEO and LEO satellite is usually larger. The orbital altitudes of MEO and LEO satellites are lower and the link loss is relatively small, which makes lower EIRP and G/T requirements of the ground station. Compared with GEO satellites, LEO and MEO satellites are more conductive to the communication between ground users and the satellite. However, in order to achieve the design objectives of (1)–(3), the required number of LEO and MEO satellites are much larger, which makes a higher cost than a GEO system. At the same time, LEO and MEO satellites also have the disadvantages of more complex satellite switching control and the serious Doppler Effect. These problems are particularly prominent in an LEO constellation. The combination of GEO MEO and LEO satellites can effectively make up for the disadvantages of a single-layered satellite constellation.

In order to test the performance of the various constellation structures, we designed two simulation experiments. Both of them adopt the satellite network routing strategy and the routing algorithm proposed in [14]. The first experiment compared the end to end delays of satellite nodes of an LEO constellation, an LEO/MEO constellation, and an LEO/MEO/GEO constellation all under a low network load. The LEO single-layered constellation adopts the constellation parameters of Iridium [20], the LEO/MEO double-layered constellation uses the parameters of Iridium and ICO [21], and the LEO/MEO/GEO triple-layered constellation adopts the parameters of Iridium, ICO and three evenly distributed GEO satellites. The second experiment compared the end to end delays of three constellations all under a high network load. In our simulation, link utilization less than 95 % is deemed as low network load, and conversely, high network load. Link utilization is set by adjusting the link background traffic. Beijing (116°23′E, 39°54′N) is chosen as the central ground station in this simulation, the latitudes of the other 12 test nodes remain the same, and their longitude interval is 15° eastward from Beijing successively. The end to end delay between the nodes is the average value of the 24-h simulation time, and Figs. 2.1 and 2.2 show the simulation results.

As shown in the figures, the performance of the LEO single-layered constellation is superior to that of both the LEO/MEO double-layered satellite constellation and the LEO/MEO/GEO triple-layered constellation for the transmission delay plays a decisive role under the low network load (link utilization 90 %).

[1] The G/T value of ground station performance index is an important technical indicator which reflects the performance of a ground station receiving system. Where G is the receiver antenna gain, T is the equivalent noise temperature of receiving system noise performance. A larger G/T value reflects a better performance of the ground receiving system. At present, ground stations with G/T $\geq$ 35 dB/K are defined as A-type standard stations, ground stations with G/T $\geq$ 31.7 dB/K are defined as B-type standard stations, while the stations with G/T $<$ 31.7 dB/K are called nonstandard stations internationally.

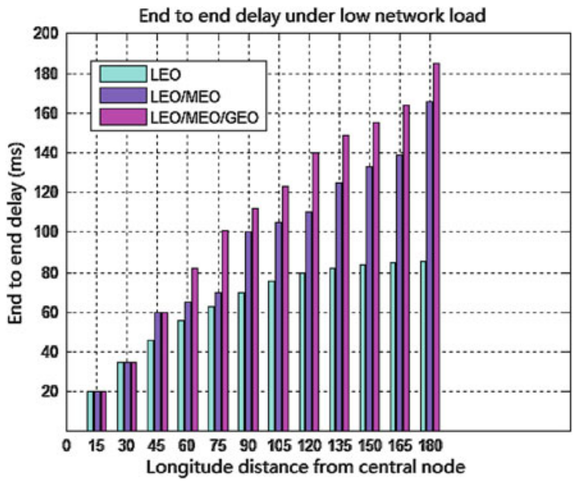


Fig. 2.1 End to end delay when link utilization at 90 %

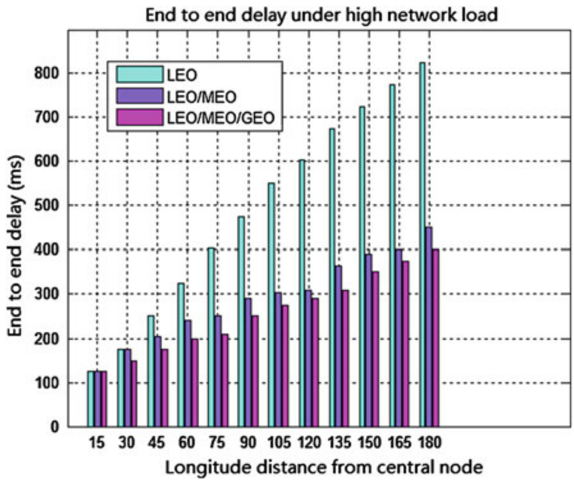
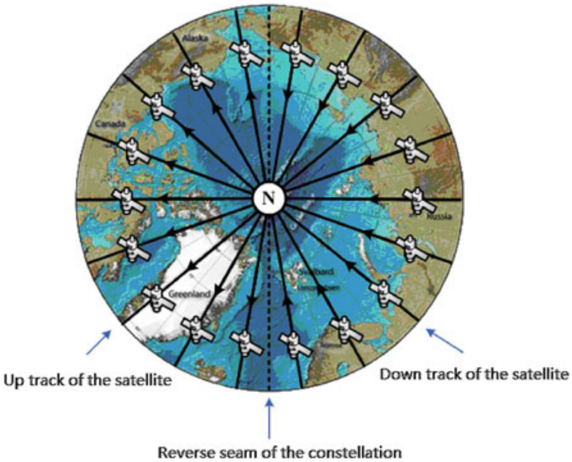


Fig. 2.2 End to end delay when link utilization at 98 %

However, when the network load is high (link utilization 98 %), the queuing delay, processing delay, and the probable congestion delay play a decisive role. At this time, the advantages of high bandwidth, multiple path, high processing ability, and high reliability of double-layered and triple-layered constellations start to show, and make their performances superior to the single-layered constellation.

As known from the requirement analyses and service experience of the operational constellations, the business types of a satellite network are varied and the traffic is huge [20, 21]. So an LEO/MEO/GEO triple-layered satellite constellation is chosen as our experimental model. Since there does not exist a constellation model that fits all business types, the performance of the LEO/MEO/GEO triple-layered satellite constellation may be inferior to that of a double or single-layered

Fig. 2.3 Top view of a polar orbit constellation



satellite constellation under certain circumstances. The constellation design must be in compliance with user requirements and the business type.

2.2.2 Orbit Type Selection

This book discusses circular orbit constellations only. As mentioned before, circular orbits can be divided into polar orbits and inclined orbits. The orbital inclination angle of a polar orbit is equal or close to 90°. A polar orbit is so-called because the satellite in it periodically crosses the north and south poles. The orbital inclination angle of an inclined orbit is less than 90°. Among the operational constellation systems, both Iridium [20] and Teledisic [22] use a polar orbit, while the Globalstar [23] constellation and the ICO [21] constellation adopt an inclined orbit.

A top view and a lateral view of a polar orbit constellation are shown in Figs. 2.3 and 2.4, respectively. Figure 2.3 shows the polar orbit constellation seen from above the Arctic polar region. Satellites east of the North Pole run up approaching the North Pole and the satellites west of the North Pole run along their tracks away from the North Pole. The satellites in the track 10° northeast of the North Pole and the satellites in the track 10° northwest of the North Pole run in opposite directions. Similarly, the satellites in the track 10° southeast of the North Pole and the satellites in the track 10° southwest of the North Pole also run oppositely. The dotted line in Fig. 2.3 shows the reverse seam of the polar orbit constellation track, satellites on both sides of the seam running reversely. Figure 2.4 shows a side view of a polar-orbiting constellation. Every single polar-orbiting satellite maintains four ISLs, two of which connect the adjacent satellites within the same orbit and the other two connect the adjacent satellites in two adjacent tracks. ISLs connecting the adjacent

Fig. 2.4 Side view of a polar orbit constellation

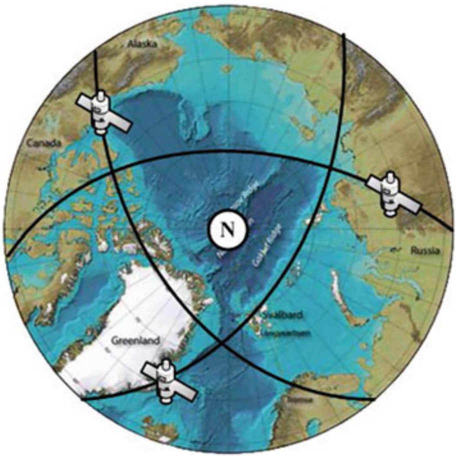
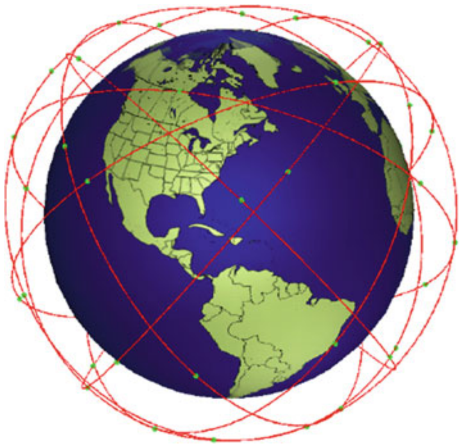


Fig. 2.5 Top view of an inclined orbit constellation

satellites in the same orbit are permanent links. ISLs connecting the adjacent satellites in adjacent orbits will be temporarily closed when crossing the Polar Regions, for the antennas cannot track the neighboring satellites in time during the high-speed swap of satellite relative positions. Satellites in both sides of the reverse seam maintain only three ISLs. This is because the satellites in both sides of the seam move reversely at an extremely high speed, and not suitable for the establishment of ISL. Although a polar orbit constellation has the disadvantage of sparse coverage of the low latitude regions, it is very suitable for the implementation of the virtual node routing strategy, which will be discussed in the following chapters.

Top and side views of an inclined orbit constellation are shown in Figs. 2.5 and 2.6, respectively. Figure 2.5 shows a polar orbit constellation seen from above the Arctic polar region. The constellation shown in Fig. 2.5 was proposed by Walker first, and named the δ Constellation for three satellite tracks compose the Greek

Fig. 2.6 Side view of an inclined orbit constellation



alphabet Δ as shown in the top view. The side view of the inclined orbit constellation is shown in Fig. 2.6. In the inclined orbit constellation, each satellite keeps two ISLs connecting two adjacent satellites on the same orbital plane. These two ISLs are permanent links as in a polar orbit constellation. Since the distance between two adjacent satellites in two adjacent orbital planes changes greatly and rapidly in an inclined orbit constellation, ISLs are usually established near the intersection point of two orbital planes and information is then exchanged when the link is established. Although uniform global coverage can be achieved by an inclined orbit constellation through proper arrangement, its coverage area is not regular and the changes of connections are more complex than a polar orbit constellation. Therefore, the virtual node routing strategy (which will be discussed in the following chapters) is not suitable for an inclined orbit constellation.

In practice, different layered satellites usually collaborate with one another. The LEO-layered satellites are usually used as entrance/exit satellites, which connect and communicate with terrestrial gateways directly. A polar orbit constellation is usually chosen for the LEO layer for the easy implementation of the virtual node strategy. MEO-layered satellites are usually used as the manager of the LEO satellites. The inclined orbit constellation is sometimes used in the MEO layer to provide a uniform coverage of the Earth and also the LEO-layered satellites.

2.2.3 *Selection of Orbit Altitude*

The orbit altitude is an important factor in the design of a satellite constellation. All of the design goals mentioned in Sect. 2.1 are directly related to the orbit altitude. In addition, EIRP and G/T value of ground terminals are also related to the orbit altitude. A higher orbit altitude means higher requirements of EIRP and G/T value. However, the required number of satellites to achieve the goals (1)–(8)

Table 2.1 Possible choice of LEO orbit altitude

N	K_1	h (km)
1	13, 14	1248, 896
2	25, 27, 29	1461, 1070, 725

is fewer with a higher orbit altitude, which means a lower construction cost. The choice of orbit altitude usually requires a compromise between the construction cost and the quality of service; meanwhile, the following two environmental restrictions are also needed to be considered.

(1) The influence of the Earth's atmosphere: In general, the orbit altitude of an LEO satellite should not be lower than the altitude of the top of the atmosphere, or the oxygen atoms of the upper atmosphere will erode the body of the satellite seriously, and shorten the service life of the satellite. At the same time, the disturbance of the atmosphere will also affect the normal operation of the satellite. The disturbance and damping of the atmosphere can be ignored only when the orbit altitude is greater than 1000 km.
(2) The influence of the Van Allen belts: As mentioned in Sect. 1.2, the Van Allen belts are named after their discover Van Allen. They are two radiation belts surrounding the Earth. They are composed of high-energy charged particles, and present strong electromagnetic radiation. The Van Allen belts are divided into the inner belt and the outer belt located at an altitude of 1,500–5,000 km and 13,000–20,000 km, respectively. When designing the LEO and MEO constellations, the altitude of an orbit should avoid being located in the two Van Allen belts so as to keep away from the strong electromagnetic radiation of these two belts.

For the ease of computing, the constellation should be able to return to the initial state after a period of time. If the constellation is made up of LEO-layered satellites and MEO-layered satellites, the running cycle of LEO satellites T_L and MEO satellites T_M should satisfy the following equation:

$$T_L \times K_1 = T_M \times K_2 = T_E \times N,$$

where T_E is the rotation period of the Earth, and K_1, K_2, N are all integers.

According to the Kepler's third law:

$$T = 2\pi (R_E + h)\sqrt{(R_E + h)/GM}, \tag{2.1}$$

where T is the running cycle of satellite, R_E is the radius of Earth, h is the satellite orbit altitude, G is the universal gravitational constant, M is the weight of Earth. $R_E = 6378.14$ km, $G = 6.67 \times 10^{-11}\ \text{m}^3\ \text{kg}^{-1}\ \text{s}^{-2}$, $M = 5.97 \times 10^{24}$ kg.

For the LEO satellites, according to the environmental constraint on the satellite orbit and the definition of the LEO satellite orbit in Sect. 1.2, the possible choice of LEO orbit altitude can be calculated by Eq. (2.1) as shown in (Table 2.1).

Table 2.2 Possible choice of MEO orbit altitude

N	K_2	h (km)
1	4, 5	10390, 8042
2	7	11912

$N = 1$ means the constellation will return to the initial state after 24 h of running of the LEO-layered satellites, while $N = 2$ means the constellation will return to the initial state after 48 h of running of the LEO-layered satellite. For the ease of computing, the situations when $N > 2$ are not considered in this book.

Similarly, for the MEO satellites, the possible choices of orbit altitudes as shown in (Table 2.2).

Besides the environmental constraint and the repetitiveness of the constellation initial state, the running cycle of the entire constellation should also be considered when choosing the orbit altitudes of LEO and MEO satellites. If the terrestrial gateway is considered, the system cycle of the multilayered constellation should be the least common multiple of the running cycle of the satellites of each layer and the rotation period of the Earth. And if only the space-based network is considered, the system cycle of the multilayered constellation should be the least common multiple of the running cycle of the satellites of each layer. Since the running period of the GEO satellites equals the rotation period of the Earth, in order to satisfy the design goals (7) mentioned above, the least common multiple of the running period of LEO and MEO-layered satellites should be minimum and should not exceed 24 h. Therefore, 896 km is chosen as the LEO orbit altitude, and the running cycle is 12/7 h accordingly. 10390 km is chosen as the MEO orbit altitude and accordingly the running cycle is 6 h. The system cycle of the whole constellation is hence 24 h.

2.2.4 Selection of the Numbers of Orbits and Satellites

2.2.4.1 Selection of the Number of LEO Orbital Planes and Satellites

As mentioned in Sect. 2.2.2, polar orbit LEO satellites are selected as our LEO-layered satellites. These satellites are evenly distributed in different LEO orbital planes, and the LEO orbital planes are evenly distributed according to their longitudes. The LEO layer of the constellation considered in this section is like the LEO polar constellation shown in Fig. 2.4. The selection of the number of LEO orbital planes should be considered first. The global coverage is the only factor needed to be considered in the LEO layer constellation design. The coverage of the LEO polar orbit constellation is dense in high latitude areas and sparse in low latitude areas. Therefore, if the LEO constellation can completely cover the equatorial area, it can achieve global coverage. Figure 2.7 shows the cross-sectional profile of an LEO satellite's coverage of the equatorial region.

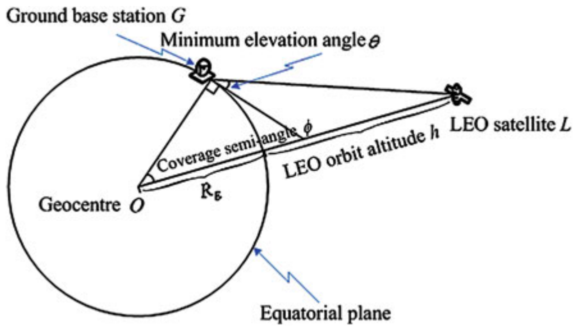


Fig. 2.7 An LEO satellite's coverage of to the equatorial region

As shown in Fig. 2.7, the longitudinal range of an LEO satellite's coverage area can be obtained by calculating the coverage semi-angle ϕ. The required number of LEO orbital planes for full coverage of the equatorial region can hence be calculated. Given that $OG = R_E = 6378.14$ km, $OL = h + R_E = 895.5$ km $+$ 6378.14 km $=$ 7273.64 km, the minimum elevation angle $\phi = 10°$. GL can first be obtained by the law of cosines:

$$OL^2 = OG^2 + GL^2 - 2OG \cdot GL \cdot \cos\angle OGL. \tag{2.2}$$

Substitute OL, OG, $\angle OGL$ into Eq. (2.2), according to the root formula, GL can be obtained by omitting a negative root:

$$GL = 2560.1 \text{ km}.$$

And then, ϕ can be obtained by the law of sines.

$$GL/\sin\phi = OL/\sin\angle OGL. \tag{2.3}$$

Substitute GL, OL, $\angle OGL$ into Eq. (2.3), ϕ can be obtained by omitting an obtuse angle solution.

$$\phi = 20.25°.$$

As a result, an LEO satellite can cover $2\phi = 40.5°$ longitudinal range of the equatorial region. That is to say, $\lceil 360^{\circ}/4\phi \rceil = 5$ LEO orbital planes are needed to achieve the full coverage of the equatorial region.

The selection of the number of LEO satellites in each orbital plane is similar to the selection of the number of LEO orbits. Assuming that all of the LEO satellites have the same orbit altitude, an LEO orbital plane's full coverage of the corresponding longitudinal circle is the only factor needed to be considered to achieve full coverage of the Earth. Figure 2.8 shows the longitudinal profile of an LEO satellite's coverage of the certain longitudinal circle.

As shown in Fig. 2.8, an LEO satellite's coverage range can be obtained by calculating the coverage semi-angle ϕ'. The number of LEO satellites needed to fully cover that longitudinal circle can be thus obtained. Similar to the deduction

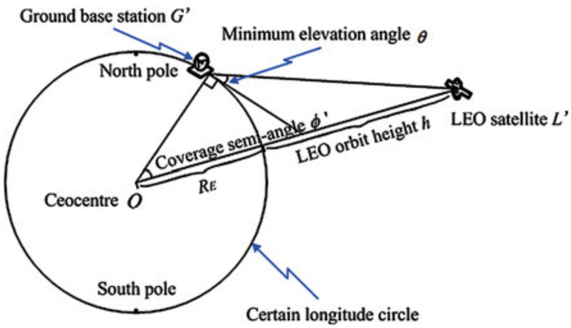


Fig. 2.8 Coverage of LEO satellite to certain longitude circle

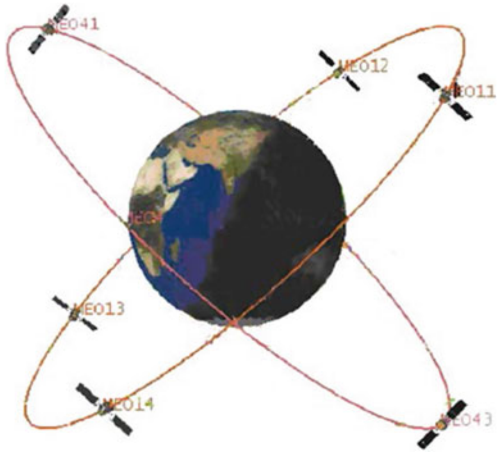


Fig. 2.9 Schematic diagram of the ICO constellation

of ϕ, we can get $\phi' = 20.25°$. That is to say, an LEO satellite's longitudinal coverage range is $2\phi' = 40.5°$. Therefore, $\lceil 360^\circ/2\phi' \rceil = 9$ LEO satellites are needed to fully cover the whole longitudinal circle.

2.2.4.2 Selection of the Number of MEO Orbital Planes and Satellites

For the MEO layer satellite orbit design, the two MEO orbital planes of the ICO constellation system are adopted in this book. Both of these two MEO orbital planes form a 45° included angle with the equatorial plane. Their phase difference is 180°. Since the ICO constellation is a commercial system already in use, its orbit layout is reasonable, and is adopted as our MEO orbits in the multilayered constellation. The ICO constellation is shown in Fig. 2.9. The constellation includes two orthogonal orbital planes each with five evenly distributed MEO satellites (one backup MEO satellite is not included). Each MEO satellite keeps two ISLs connecting two adjacent MEO satellites. Meanwhile, each MEO satellite establishes an ISL with the adjacent MEO satellite in the adjacent orbital plane to

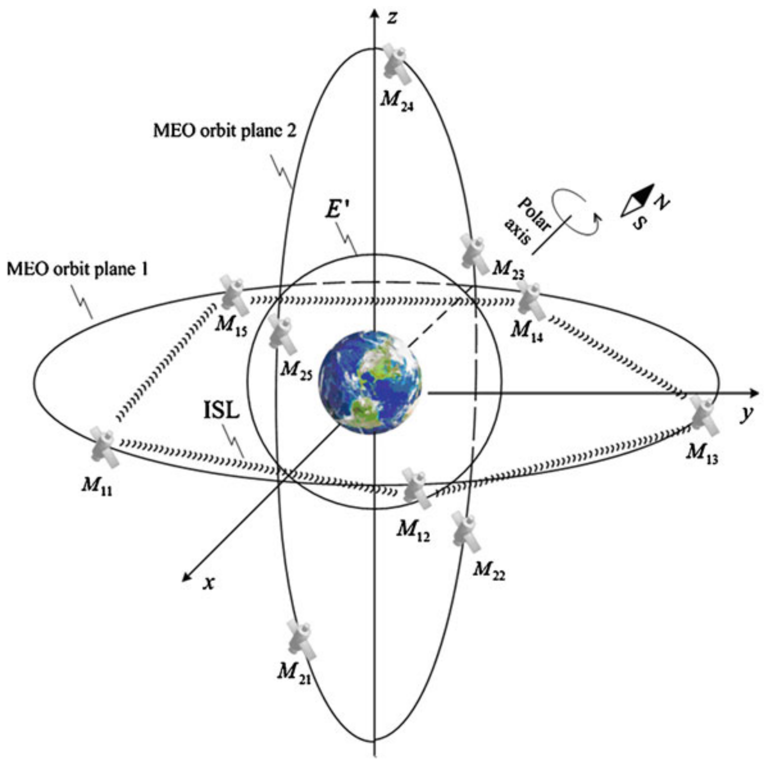


Fig. 2.10 The ICO planes in new coordinate

exchange data when it bypasses the cross point of two orbital planes. The ICO system was initially used to provide satellite mobile communications service for navigation management and distress alerting in the maritime industry.

Below we will investigate if the arrangement of orbits and satellites of the ICO system can satisfy the design goals (2) and (3). Since the polar orbit constellation design is used in the LEO layer, all of the tracks of the LEO layer form a sphere concentric with the Earth, referred to as Ball E'. Intuitively, if the MEO layer satellites can completely cover the surface of E', they can also fully cover the surface of the Earth. The process of proving this is omitted.

For the ease of computing, only one MEO orbital plane is used as the *xoy* plane to establish a coordinate system, as shown in Fig. 2.10. First, let us investigate the orbital plane 1 satellite coverage of E'. Using plane *xoy* as the cross section, we draw a sectional view of the coverage of MEO satellite M_{1x} over E' as shown in Fig. 2.11. The MEO satellite coverage of E' can be obtained by calculating the coverage semi-angle ϕ of the MEO satellite over E' As mentioned in Sect. 2.2.3, the radius of the LEO orbit $R_L = OL = 7273.64$ km, the radius of the LEO orbit $R_M = OM = 6378.14 \text{ km} + 10390 \text{ km} = 16768.14$ km. If the minimum

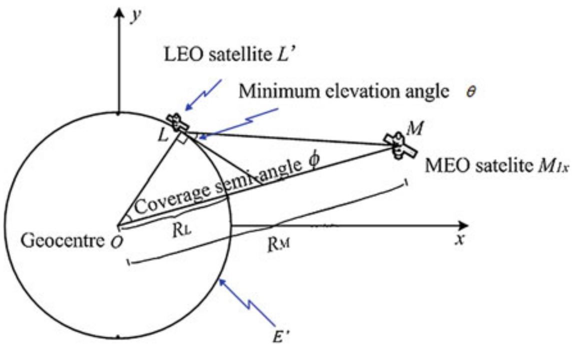


Fig. 2.11 The cross-sectional view of the MEO coverage of the LEO

elevation $\phi = 10°$, we have $\angle OLM = 90° + \phi = 100°$. *LM* can be obtained by the law of cosines as follows:

$$OM^2 = OL^2 + LM^2 - 2OL \cdot LM \cdot \cos \angle OLM. \tag{2.4}$$

Substitute *OL*, *OM* and $\angle OLM$ into Eq. (2.4), according to the root formula, LM can be got by omitting one negative root.

$$LM = 13898 \text{ km}.$$

ϕ can be got according to the law of sines.

$$LM/\sin\phi = OM/\sin\angle OLM. \tag{2.5}$$

Substitute *LM*, *OM* and $\angle OLM$ into Eq. (2.5) and omit an obtuse angle, we have:

$$\phi = 54.72°.$$

As a result, an MEO satellite can cover a $2\phi = 109.44°$ spherical range. To achieve the full coverage of E' on the *xoy* plane, at least $\lceil 360^{\circ}/2\phi \rceil = 4$ MEO satellites are needed in MEO orbital plane 1. Similarly, to achieve the full coverage of E' on the *xoz* plane, a minimum $\lceil 360^{\circ}/2\phi \rceil = 4$ MEO satellites are needed in MEO orbital plane 2. So, the arrangement of orbits and satellites of the ICO constellation system can achieve the design objectives (2) and (3).

2.2.5 Selection of Model Parameters of a Multilayered Constellation

Based on the theoretical analysis of various constellation parameters in Sects. 2.2.1–2.2.4, an LEO/MEO/GEO triple-layered constellation is designed for our further experiment and the parameters of this constellation are as follows:

Table 2.3 The parameters of the designed experimental constellation

	Orbit height (km)	Running cycle (h)	Number of satellites	Orbit inclination
LEO	895.5	12/7	6×11	90°
MEO	10390	6	2×5	45°
GEO	36000	24	1×3	0°

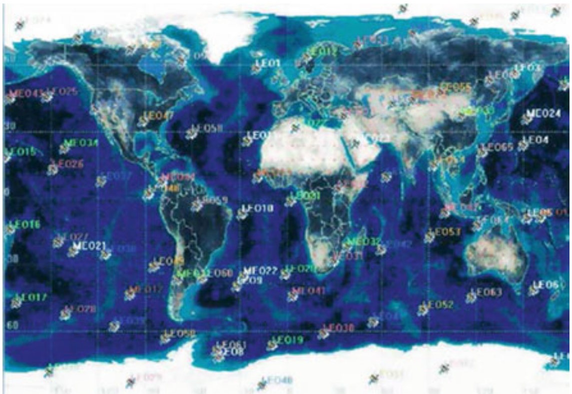


Fig. 2.12 The initial state of subsatellite points of LEO/MEO constellation

Through theoretical analysis, goals (1)–(4) and (7) can be achieved by the triple-layered constellation as shown in Table 2.3. Taking into account the survivability and robustness of the constellation system, the multilayered constellation does not stick to the requirement of goal (8), but adds a small number of redundant satellites. The goals of (5) and (6) are not involved in the theoretical analysis, and will be verified through the simulations in the following section. The constellation shown in Table 2.3 is tentatively named *Tr* in this book.

2.3 Simulation Analysis of Constellation Design

Figure 2.12 shows initial subsatellite points of the LEO and MEO satellites in constellation *Tr* through STKv5.0. The subsatellite points of GEO satellites are not shown in the graph for their relative positions are fixed. Through the simulation, we know that the LEO satellite constellation can achieve global coverage of the Earth in its whole running cycle, which tallies with our theoretical analysis. Since the LEO-layered satellites are usually used as the interface satellites of a terrestrial base station and a space-based network, to satisfy the design goal (6), we only need to investigate if the continuous coverage time of an LEO satellite over a ground base station is no less than several minutes (for an LEO satellite, the time is usually 8 min). The LEO-layered satellites of a multilayered constellation have the shortest time to cover the terrestrial base station. Therefore, the continuous

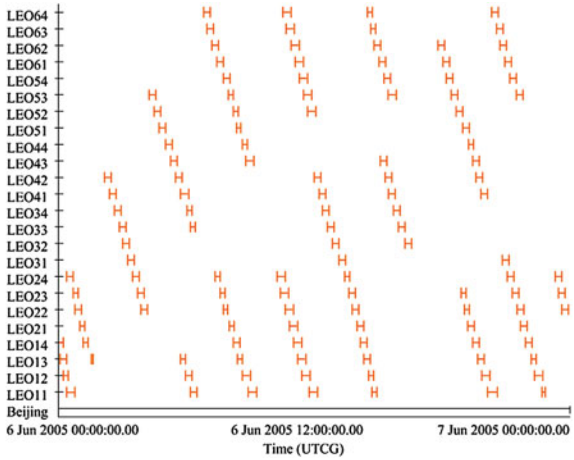


Fig. 2.13 The coverage periods of LEO satellites over Beijing station

coverage time of LEO-layered satellites is critical to the constellation design. If the continuous coverage time is too short, the frequent switching of the interface link will lead to a large protocol overhead and link instability.

Now, let's find out the time during which the LEO-layered satellites continuously cover the ground base station. Taking the ground base station in Beijing as an example, STK v5.0 is used as our simulation tool, the simulation time is set from 0:00 June 6, 2005 to 0:00 June 7, 2005. There are $6 \times 11 = 66$ LEO satellites involved in this simulation. Figure 2.13 shows the coverage time of LEO satellites numbered 1–4 in each orbital plane over the Beijing station. The simulation result shows that at least three LEO satellites can cover the Beijing station, and the maximum number is seven each day. The least continuous coverage time of LEO-layered satellites over the Beijing station is 496 s, which meets the requirement of goal (6).

Theoretically, if an LEO satellite can cover a ground base station, the transmission link between the ground station and the LEO satellite can be established. The access link duration should be equivalent to the coverage time of the LEO satellite over this ground base station. Actually, in order to ensure the link quality, the received power value of the ground station is required to be greater than a certain threshold value. That is to say, some ground stations need to switch to a new interface satellite to get higher received power even if they are still located in the coverage area of their old interface satellite. This leads to the duration time of the access link a little less than the coverage time of the current satellite. Still take Beijing station as an example, the access link duration time is checked in the simulation. Figure 2.14 shows the access link duration time of the 66 LEO satellites covering the Beijing station, where the horizontal axis represents the simulation time and the vertical axis is the minimum link duration time of all the LEO satellites covering the Beijing station at the current simulation time. This is based on the assumption that the receiving antenna of the Beijing station has a gain of 44 dB in the direction of the working satellites.

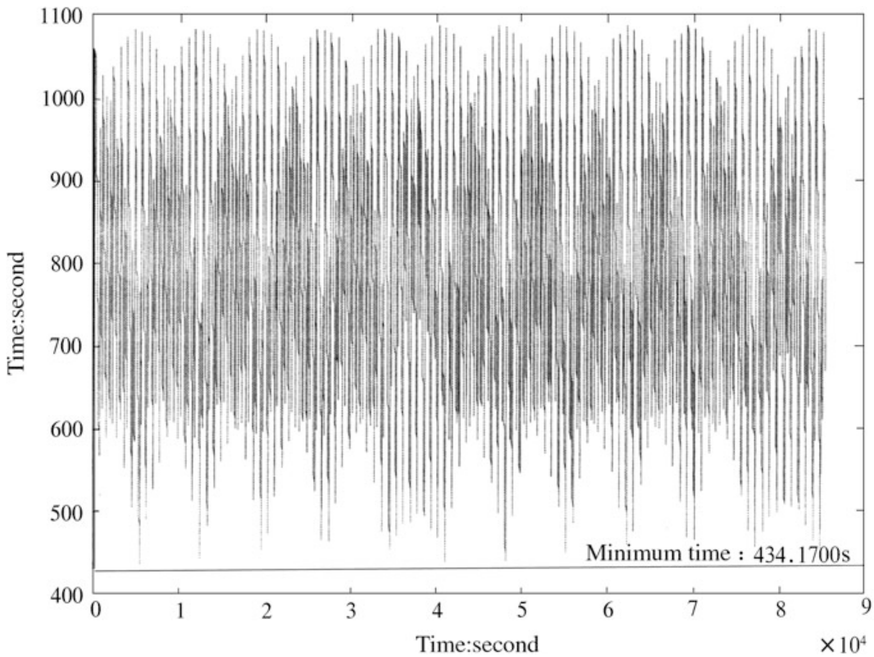


Fig. 2.14 The link duration time of LEO satellites over Beijing station

The simulation results in Fig. 2.14 show that the duration time of the access link is more than 434.17 s, which satisfies the requirement of goal (5), that the access link duration time of any users in any time will last no less than 5 min.

2.4 Analysis of the Constellation Parameters and Their Effect on Routing

The multilayered satellite constellation designed in Sect. 2.2.5 is proved to meet the target (1)–(8) through theoretical analysis and simulation. In order to thoroughly study the needs of constellation design and the implementation of a routing policy, it is necessary to briefly introduce the routing parameters of the constellation.

The routing and switching indicators of the LEO and MEO layers of the multilayered constellation are shown in Table 2.4. Since a GEO layer satellite is usually used as a monitor and backup router in a multilayered constellation, its parameters are not listed here.

The processing capacity of the switching system shown above means the CPU processing power of the onboard router measured by the data packets forwarding rate. The buffer size of the switching system means the buffer size of the onboard router. The above indicators will be different in different constellation systems.

Table 2.4 LEO/MEO satellite routing and switching indicators

	Bandwidth requirements of inter-satellite transceiver (MB/s)	Bandwidth requirements of satellite-ground transceiver (MB/s)	Processing capacity of switching system (kp/s)	Buffer size of switching system (kB)
LEO	$\geq$491	$\geq$380	$\geq$372	$\geq$4.8
MEO	$\geq$191	$\geq$92	$\geq$40	$\geq$0.8

Table 2.5 Service performance of the multilayered constellation system

	Average response time of service (S)	End to end delay (ms)	Delay jitter (s)	IP processing delay (s)
FTP services	41.27	–	–	–
Video services	–	28	1×10^{-3}	–
Voice services	–	19	1×10^{-3}	–
LEO	–	–	–	4×10^{-3}
MEO	–	–	–	1.9×10^{-3}

Under the indicators described in Table 2.4, the performance of FTP services, video services, and voice services provided by LEO and MEO satellites in the multilayered satellite constellation is shown in Table 2.5.

The data in Table 2.5 is based on the indicators in Table 2.4. The Beijing station is used as the receiving station. The ground base station at the same latitude as Beijing and 30° longitude east of from Beijing is used as the sending station. The time of business arrival conforms to the Poisson distribution, and the traffic of business conforms to the simulation data of the terrestrial network in different periods of time. From Tables 2.4 and 2.5, we can see that the requirement of comprehensive indicators of MEO satellites is relatively low, even lower than that of LEO satellites, and the FTP services mainly depend on MEO routing. That means MEO satellites have great potential for the rapid growth of FTP services as well as video and voice services. From the above table, we can see that LEO satellites also work well when their comprehensive performance conforms to the indicators in Table 2.4.

2.5 Summary

This chapter begins with a brief introduction of constellation design and types of constellations, and an analysis of the advantages and disadvantages of different constellations. Then several design goals are proposed to satisfy the QoS requirements of the users. The constellation design is based on these design goals. The effects of layers of a constellation, orbit types, the orbital altitude, the number of satellites, and the arrangement of satellites on the performance of a constellation are all analyzed theoretically. The constellation is designed according to the analysis and is verified through simulation that the design can meet all the design goals. In conclusion, some basic indicators and some basic business processing abilities of onboard routers are given.

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