Design of GEO/LEO Double-Layered Satellite Network Based on Rateless Code for Global Information Distribution

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Abstract. This paper proposes a double-layered satellite network based on the rateless code, which can globally distribute the information with a few satellites. The satellite network is composed of Geostationary Earth Orbit (GEO) and Low Earth Orbit (LEO) satellites. The GEO satellites which cover the low and middle latitudes serve as the backbone network, whereas the LEO satellites are considered the enhanced network to make up for the shortage of the backbone network. Due to the interruption tolerance of the rateless code, only a few satellites are employed to achieve worldwide information distribution in the design of the satellite network. The coverage performance and the average elevation angle of the user are simulated, and results demonstrate that the network can achieve globally information distribution.

Keywords: Satellite communication · Rateless code · Double-layered network · Information distribution

1 Introduction

Compared with other communications, the satellite communication has the inherent characteristics, especially the broad coverage which can support global services. With the continuously increasing requirement of information business, the satellite communication can contribute to alleviating the pressure, such as distributing information globally. It is necessary to design a network that can achieve worldwide information distribution.

Satellites can be divided into Geostationary Earth Orbit (GEO), Medium Earth Orbit (MEO) and Low Earth Orbit (LEO) satellites according to the orbital altitude. They show different characteristics in the communication

Supported by National Natural Science Foundation of China (No. 91338201, 91738201 and 91438109).

M. Jia et al. (Eds.): WiSATS 2019, LNICST 280, pp. 13–24, 2019.
https://doi.org/10.1007/978-3-030-19153-5_2

system, as listed in Table 1. It reveals that there are respective advantages and disadvantages, and the restrictions are difficult to overcome in the single-layered satellite network.

Table 1. Advantages and disadvantages of different satellites.

Satellites	Advantages	Disadvantages
GEO	The broad coverage	Unable to cover the high latitudes
	The mature manufacturing technology	Large propagation loss and delay
	Easy to keep aligned with the satellite	Large manufacturing and launch risk
	Communicate without frequent switch	Vulnerable to jam and physical destruction
	The negligible doppler shift	The scarce orbital position resource
MEO/LEO	The small launch risk	The limited single satellite capacity
	Small propagation loss and delay	The complex network control
	Cover the Earth globally	More satellites required
	Backup and anti-interference ability	The severe doppler shift
	The small user terminal	Large total investment and operating cost

Consequently, the double-layered satellite network was proposed, which combines with the pros and cons of different satellites [1–4]. Compared with the single-layered network, the double-layered network has more advantages, e.g., the coverage of multiple satellites, the high elevation angle of the user and the flexibility in choosing satellites. Furthermore, some researchers proposed the multi-layered satellite network [5,6]. However, many satellites are required to achieve worldwide information distribution, and the networking between satellites is very complicated.

This paper proposes a double-layered satellite network based on the rateless code to address the challenge, which can achieve worldwide information distribution with fewer satellites. The network is composed of the GEO constellation which acts as the backbone network and the LEO constellation which serves as the enhanced network. The backbone network distributes information in the low and middle latitudes, whereas the enhanced network provides enhanced support through the multiple coverage in low and middle latitudes and the supplemental coverage in the high latitudes and the polar regions. Along with the characteristics of reliable, fast and interruption tolerant of the rateless code, the double-layered satellite network can achieve an efficient and reliable information distribution.

The rest of the paper is as follows. Besides briefly introducing the characteristics of the rateless code, Sect. 2 depicts the double-layered satellite network. Next, Sect. 3 designs the backbone network and the enhanced network. Section 4 analyzes the coverage performance and the average elevation angle of the user. Finally, Sect. 5 concludes the paper.

2 Satellite Network Architecture Based on the Rateless Code

The satellite communication is a useful platform for distributing information around the globe. However, the channel condition may be deteriorated by the bad weather, the interference or the invisibility between the source and the receiver, which will cause a sharp rise in the bit error rate. The packet error rate will arise as well during the data distribution. Therefore, it is necessary to take measures to guarantee the reliability of the information distribution. Lots of techniques are put forward to solve the problem, such as network code [7], block code [8], FUN code [9] and rateless code [10]. Among them, the rateless code possesses some excellent characteristics, which is an effective encoding method for both unicast and multicast system, and plays an essential role in the satellite communication, especially for those without feedback from the receiver.

In 1998, Byers and Luby firstly proposed the concept of rateless code in binary erasure channel [10]. The definition of the code length does not exist for the rateless code, which means that the code length tends to be infinity. Correspondingly, the definition of the code rate does not exist, so it is called rateless code. The basic idea of the rateless code is that the source node continuously generates encoded packets, and as long as the receiver receives sufficient encoded packets whose quantity is slightly larger than the original packets, it is possible to recover the original information, regardless of what the specific packets it receives. Specifically, the source node transmits sufficient packets encoded from k original packets, and when the receiver receives arbitrary $k\,(1+\varepsilon)$ encoded packets, the decoder can recover all original packets at a high probability, where ε is the decoding overhead. It should be noted that the decoding overhead of the elaborately designed rateless code can be very small, and the encoding and decoding algorithm can be simple as well. In addition, the rateless code can also improve the channel capacity and the network robustness.

In satellite broadcast, when users can not continuously receive the information from one satellite, the information can be transmitted from different satellites with the help of the rateless code, which can significantly improve the efficiency of the broadcast. We propose the GEO/LEO double-layered satellite network to achieve reliable, efficient and interruptible information distribution based on the rateless code. The rateless code shows the following characteristics when adopted in satellite broadcast:

- Reliability: If the Automatic Repeat Request (ARQ) mechanism is adopted to distribute data to users in heterogeneous channel conditions, it may result in ACKnowledgement (ACK) storm because each user has been reporting the ACK. If the Forward Error Correction (FEC) is chosen, it cannot ensure the reliability because of the deteriorated channel condition. If the rateless code is adopted, there is only one ACK when the entire data are completely received. Therefore, the information can be reliably distributed to all users.
- Fastness: Since the user only confirm once after the entire data have been received, the number of ACK or retransmission is reduced compared with the

ARQ mechanism. Therefore, the transmission delay is effectively shortened. The information transmission is fast.
- High efficiency: As long as the receiver receives arbitrary $k\,(1+\varepsilon)$ encoded packets, original packets can be recovered at a high probability. Recently, some elaborately designed rateless code whose decoding overhead approaches zero has been proposed [11,12]. The number that the receiver needed is almost the same as the original. Thus the efficiency is high.
- Interruption tolerance: During the transmission, the user can access the network and download the data at any time. In addition, the downloading can be interrupted, and the user can access the network later to continue the downloading. When the quantity of the received packet is enough, the original information can be obtained as well.
- Large chunks of data: The encoding and decoding complexity of ordinary code increases exponentially with the data size, while the relationship between the encoding and decoding complexity and the data size reaches linear in Raptor [13]. So the rateless code is very suitable for the transmission of large chunks of data.

The study presents a double-layered satellite network based on the rateless code. The GEO satellites cover the low and middle latitudes, and the LEO satellites cover the high latitudes and the polar regions as a supplement. The rateless code is used for broadcasting information between the backbone network and the enhanced network and between the network and the user. The asynchronous and intermittent reception can be realized With the help of the interruption tolerance. In other words, the user can access, quit and rejoin the network at any time. Therefore, the information can be distributed efficiently and reliably. Furthermore, the total number of satellites can be effectively reduced by using the rateless code. Because even if the entire network cannot achieve seamless global coverage, the region that is not covered temporarily can be broadcasted by the next satellite because of the interruption tolerance. Therefore, as long as the network can achieve periodical coverage globally, it can achieve worldwide information distribution.

The architecture of the double-layered satellite network is shown in Fig. 1. It consists of three parts, i.e., the space segment, the control segment and the user segment. The space segment is made up of the GEO constellation and the LEO constellation. The GEO constellation is comprised of three evenly distributed GEO satellites, and the Inter Satellite Link (ISL) is established between each GEO satellite. The LEO constellation is comprised of LEO satellites which are distributed in polar orbit. The GEO constellation serves users in the low and middle latitudes whereas the LEO constellation is responsible for users globally, especially in the high latitudes. The control segment is made up of the Network Control Center (NOC) and gateways, and it is responsible for the monitoring and control of the space segment, the network operation management and the user management. The user segment includes different types of user terminals and the information source.

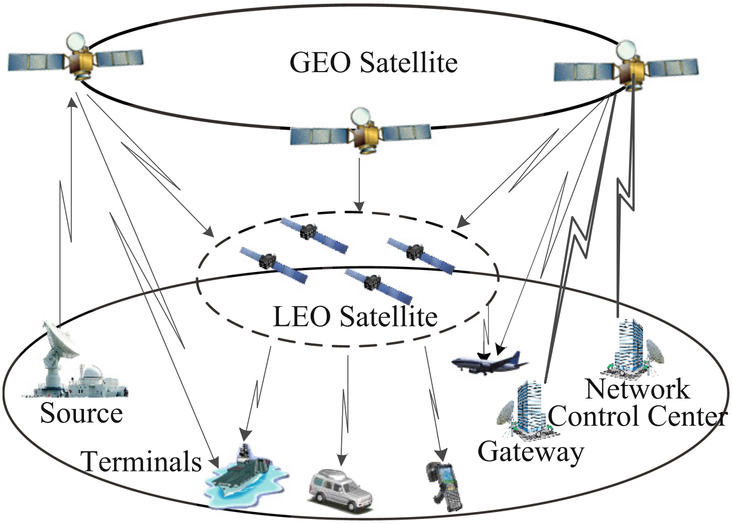

Fig. 1. The architecture of the double-layered satellite network.

3 Design of the Double-Layered Network

The double-layered satellite network consists of a GEO constellation which works as the backbone network and an LEO constellation which works as the enhanced network. In extreme cases, only a GEO satellite and an LEO satellite can realize worldwide information distribution based on the rateless code. However, if then, most of the regions in the world are covered shortly, and the network capacity is notably limited. Therefore, the design of GEO and LEO constellations is required. We should balance between the number of satellites and the coverage performance to achieve better performance with fewer satellites.

3.1 Design of the Backbone Network

According to the features of the GEO satellite, the backbone network is set to use three GEO satellites. The three satellites evenly distribute in orbit, and the longitude of each differs 120°. The fixed ISLs are built between GEO satellites for the information exchange. Figure 2 shows the coverage performance of the backbone network when the user's elevation angle is 10°, where the green denotes that the zone is covered by single satellite with 100% time; the yellow represents two satellites, and the white denotes it cannot be covered with 100% time. Figure 2 shows that the backbone network can cover areas within 50° north and south latitudes, which are about 468 million km^2, as large as 91.75% of the global surface.

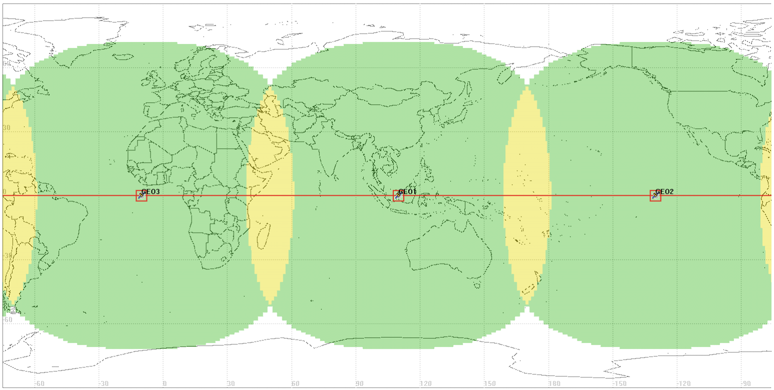

Fig. 2. The coverage performance of the backbone network.

3.2 Design of the Enhanced Network

The backbone network can cover most of the global surface, but the regions near the north and south poles are not covered. We decide to use polar LEO satellites to compose the enhanced network. Firstly the orbit altitude is optimized, and the selection of orbit altitude should take the following two factors into account:

(1) avoid the Van Allen radiation belts and the atmospheric drag [14]

The Van Allen radiation belts are two high-energy particle radiation belts around the earth, in the range of 1500–5000 km and 13000–20000 km. They will cause damage to the electronic circuit, so the two ranges should be excluded. Furthermore, when the orbit altitude is less than 700 km, the atmospheric drag will slow the velocity of the satellite and shorten the lifetime of the satellite. Therefore, the orbit altitude of the LEO satellite should be in the range of 700–1500 km.

(2) facilitate the operation of the satellite control

We choose the quasi-regression orbit to facilitate the satellite control, which means that the satellite passes the same place on the ground every day or every several days. The orbit period T_s follows the formula:

$$\frac{T_s}{T_e} = \frac{k}{n} \tag{1}$$

where k and n is the integer. T_e is a sidereal day, and the value is $T_e = 86164$ s. According to Kepler's Third Law, the relationship between the orbit altitude and the period confirms:

$$h = \frac{{T_s}^{\frac{2}{3}} \mu^{\frac{1}{3}}}{(2\pi)^{\frac{2}{3}}} - R \tag{2}$$

where μ is Kepler Constant, and $\mu = 3.986 \times 10^{14}$ $\mathrm{m^3/s^2}$. R is the radius of the Earth, and $R = 6371$ km. After simulation, we choose $k/n = 2/25$, which means that the sub-satellite point will return to the same position after 25 laps around

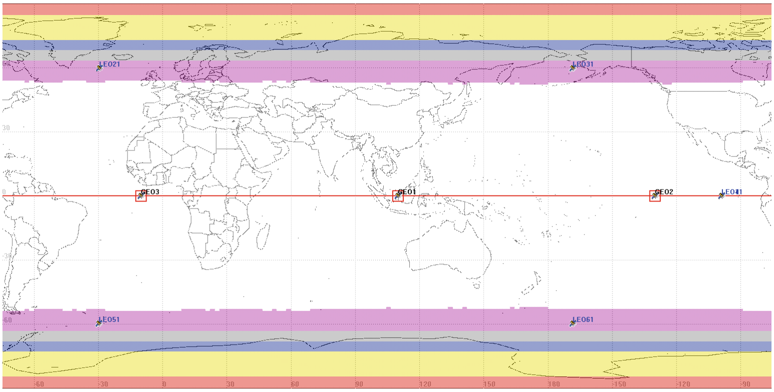

Fig. 3. The coverage performance of the enhanced network (6 satellites). (Color figure online)

the Earth in 2 days. $T_s = 6893\,\text{s}$ according to (1), and then substitute into (2). We get $h = 1457\,\text{km}$, and the value meets the requirement 700–1500 km.

The diameter of the LEO satellite coverage area is $D = 5943.5\,\text{km}$ when the elevation angle is 10°. If fewer satellites are used to cover the polar regions, the overlapping region between satellites should be minimized. The minimal number of satellites needed can be calculated by:

$$S = \left\lfloor \frac{2\pi R}{D} \right\rfloor \tag{3}$$

After calculation, we get $S = 6$. The six LEO satellites are distributed in different orbit planes to cover the polar regions evenly. It is known that when the quantity of the polar orbit planes is more than 2, satellites may collide over the polar regions. Therefore, the inclination angle from 80° to 100° (except 90°) is usually used, and the inclination angle is set 84.5°.

After the design, we use the LEO satellite with 1457 km orbit altitude, 84.5° inclination angle to compose the enhanced network, and the quantity of the orbit plane is 6. It should be pointed out that the total number of LEO satellites is flexible. If the excellent coverage performance is required, the quantity can be large. If the cost is low, the quantity had better be small.

Figure 3 shows the coverage performance of the enhanced network when the enhanced network is composed of 6 LEO satellites, where the red denotes that the zone is covered above 90% time, the yellow zone above 80% time, the blue zone above 70% time, the gray zone above 60% time, the purple zone above 40% time, and the white zone below 40% time. Figure 3 shows that 6 LEO satellites can provide periodic coverage for regions above 50° north and south latitudes. When the enhanced network is composed of 24 LEO satellites, the satellites follow the Walker constellation with the parameter of 24/6/3. The coverage performance is shown in Fig. 4, where the green denotes that the zone is covered by with 100% time, the red zone above 90% time, the yellow zone above 80% time, the blue

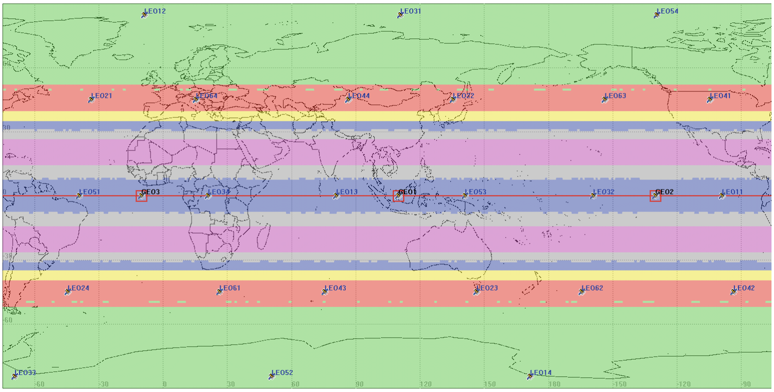

Fig. 4. The coverage performance of the enhanced network (24 satellites). (Color figure online)

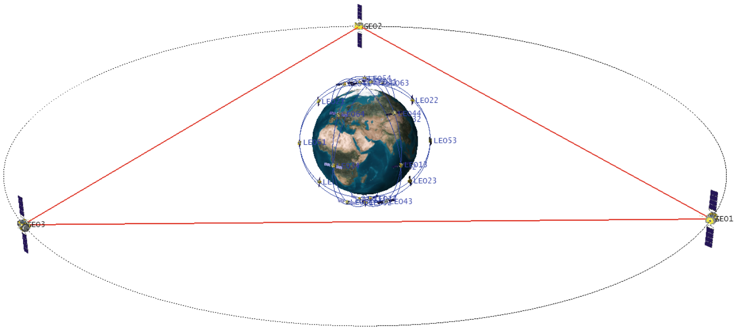

Fig. 5. The configuration of the double-layered satellite network (24 LEO satellites).

zone above 70% time, the gray zone above 60% time, and the purple zone above 40% time. Figure 4 shows that 24 LEO satellites can achieve seamless coverage for regions above 50° north and south latitude.

In practice, the configuration of the double-layered satellite network is quite flexible. A primary network that consists of 3 GEO and 6 LEO satellites can be first established in the initial stage. It can achieve worldwide information distribution with the help of the rateless code. Then LEO satellites can be added at any time to shorten the interruption time. If the seamless coverage is required, the quantity of LEO satellites can be increased to 24 or higher. Figure 5 shows the configuration of the double-layered satellite network when 24 LEO satellites are used.

4 Simulation Analysis

The longitudes of the ascending node of the three GEO satellites are 110° E, 10° W and 130° W, and the fixed ISLs are built between the GEO satellites. Then

Table 2. The ephemeris data of the GEO and LEO satellites.

Satellite	Perigee altitude	Apogee altitude	Inclination angle	Argument of perigee	RAAN	True anomaly
GEO1	35786 km	35786 km	0°	0°	110°	0°
GEO2	35786 km	35786 km	0°	0°	230°	0°
GEO3	35786 km	35786 km	0°	0°	350°	0°
LEO1	1457 km	1457 km	84.5°	0°	0°	0°

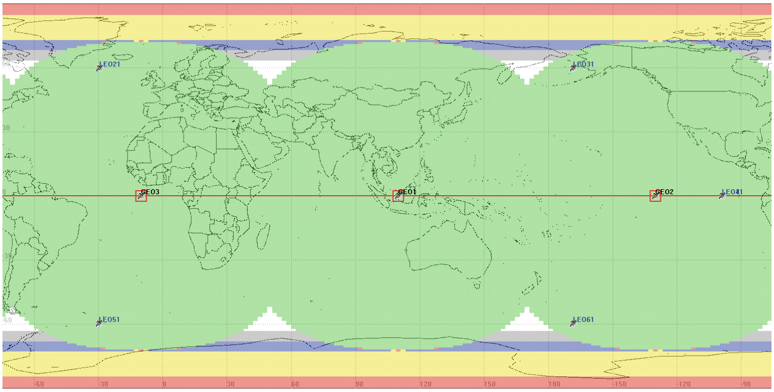

Fig. 6. The coverage performance of the double-layered network (6 LEO satellites). (Color figure online)

generate three GEO and one LEO satellites by the software Satellite Tool Kit (STK) according to the ephemeris data of the GEO and LEO satellites listed in Table 2. The other satellites are created based on 6/6/1 constellation parameter When the enhanced network is composed of 6 LEO satellites. The user's elevation angle is set to be 10° in the simulation. The coverage performance of the double-layered satellite network is shown in Fig. 6, where the green denotes that the zone is covered by with 100% time, the red zone above 90% time, the yellow zone above 80% time, the blue zone above 70% time, the gray zone above 60% time, and the purple zone above 40% time.

Figure 6 demonstrates that the double-layered network can cover the low latitudes with 100% time, and the area occupies 91.75% of the global surface when the enhanced network consists of 6 satellites. Besides, it can cover 96.29% of the global surface above 80% time. Thus we know that although it cannot achieve seamless coverage globally, the polar regions that are not completely covered can be covered periodically, and the interruption time is short. The information distribution can continue through the next satellite based on the interruption tolerance of the rateless code after the interruption.

When the enhanced network is composed of 24 LEO satellites, the enhanced network is a Walker constellation with the constellation parameter of 24/6/3. The other simulation conditions are the same. Figure 7 shows the coverage performance of the double-layered satellite network, where the green denotes that

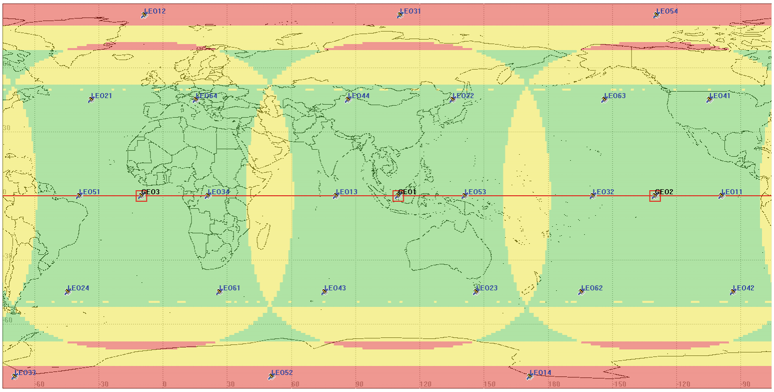

Fig. 7. The coverage performance of the double-layered network (24 LEO satellites). (Color figure online)

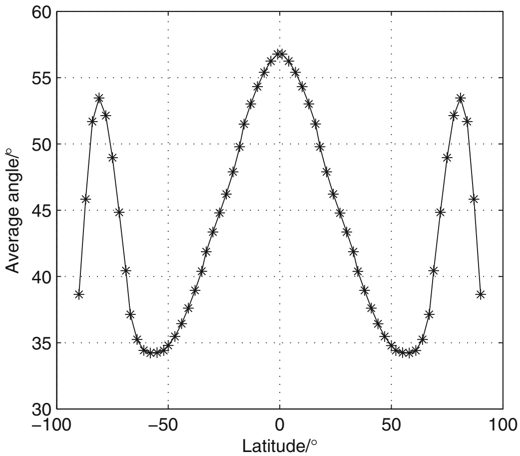

Fig. 8. The average elevation angle versus the latitude.

the zone is covered by single satellite with 100% time; the yellow represents two satellites, and the red represents three satellites. Figure 8 shows the average elevation angle of global users versus the latitude.

Figure 7 demonstrates that the double-layered satellite network achieves seamless coverage globally when the enhanced network consists of 24 satellites. Besides, it achieves multiple coverage in the high latitudes. In addition, the double-layered satellite network provides good communication elevation angle for users, especially in the low and high latitudes according to Fig. 8. Therefore, the designed network can improve the system availability, and alleviate the problem of information distribution in valleys, mountains, high latitudes and polar regions.

5 Conclusion

The multi-layered satellite network can combine characteristics of different typological orbits and utilize varieties of spatial resources to the uttermost, which indicates a significant development direction in the future. This paper proposes a double-layered satellite information distribution network combined of the GEO satellites and LEO satellites, which is based on the disruption tolerance of the rateless code. The designed network can use fewer satellites to achieve global information distribution. This paper simulates the coverage performance and the average elevation angle of the designed network, and the results prove that the network performs well, and the system availability is high.

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