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Soft Frequency Reuse Based Spectrum Sharing Scheme in the Integrated Satellite and Terrestrial Network

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The integrated satellite and terrestrial network has become one of the frontier technologies of the next generation mobile communication system. The satellite network is used as an extension and supplement of the ground network to achieve seamless coverage of wireless mobile communications. The spectrum sharing of the integrated satellite and terrestrial network is realized from the perspective of spectrum planning, considering the number of co-frequency terminals and the distance between the terminal and the center of the satellite beam. The existing spectrum sharing schemes use the concept of geographic isolation, which will limit the available bandwidth of the terrestrial network. Therefore, the concept of time domain isolation is proposed, and a soft frequency reuse based spectrum sharing scheme in the integrated satellite and terrestrial network is designed. The allocation of time slots increases the degree of spectrum isolation and improves the signal to interference ratio of the network. In addition, due to the increase in the utilization rate of the satellite spectrum, the capacity of the satellite system is improved.

Keywords: integrated satellite and terrestrial network, frequency reuse, spectrum sharing, time domain isolation, signal to interference ratio

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1 INTRODUCTION

With the rapid development of the global economy, the realization of "seamless communication" on a global scale has become an inevitable requirement for future mobile communications. In addition, terrestrial and satellite mobile communication systems have developed rapidly as an important part of the global information infrastructure. The terrestrial mobile communication system has experienced 1G, 2G, 3G, and 4G. At present, 5G has entered the stage of full industrialization and commercialization. With the application of high throughput and multi-beam technologies, satellite mobile communication systems have also made considerable progress in recent years Konstantinos et al. (2017). Commercial satellite mobile communication systems such as Inmarsat, Thuraya, O3b, Iridium, Globalstar, Orbcomm have been upgraded to provide effective solutions for maritime, emergency and personal mobile communication scenarios. Companies such as OneWeb and Starlink combined satellite communication services with Internet services and proposed the concept of building a low earth orbit satellite internet of things constellation Wang et al. (2018).

However, due to the limitations of terrain and economic factors, terrestrial mobile networks have been unable to cover most areas of the world, such as oceans and remote areas. As the highest base station in the world, satellites are not restricted by geographical environment and have wide area coverage capabilities. In addition, satellites mainly rely on line of sight transmission and cannot provide effective coverage for densely populated urban areas. ground communication facilities may be destructively damaged in disasters such as earthquakes and hurricanes, causing the disaster area to lose communication with the outside world. Because the satellite is at a high altitude and is not affected by natural disasters, it can quickly provide communication services to the disaster area. Therefore, the satellite network and the terrestrial mobile network can complement each other to build a "Integrated satellite and terrestrial network," which is an effective solution to achieve the goal of "online anywhere and anytime" Guidotti et al. (2019), Boero et al. (2018), Gopal and BenAmmar (2018).

In the integrated satellite and terrestrial network, the terrestrial network and satellite network share the same frequency band, and the terrestrial network also deploys dense micro-cells to increase system capacity. Therefore, in order to achieve spectrum sharing, reliable spectrum planning is required to meet complex ground coverage requirements scenarios. Reference Giambene et al. (2018) studies the problem of spectrum sharing in the integrated satellite and terrestrial network. However, the algorithm is based on a static spectrum sharing strategy and does not consider the dynamic distribution characteristics of user traffic in the coverage area. Reference Umehira and Ohtomo (2009) proposed a new frequency sharing algorithm to improve the frequency utilization rate of the uplink between the ground mobile communication system and the multi-beam satellite system, and reduce the interference of satellite users to the uplink of the ground communication system. Reference Sub et al. (2011) proposed a simple system model to study the feasibility of frequency sharing between satellite network and terrestrial network. The simulation results show that through the comprehensive design of the network structure and business model, the spectrum sharing between the satellite network and the ground network can be realized.

Reference Umehira (2011) studies two kinds of spectrum sharing schemes for integrated satellite and terrestrial network based on the analysis of the integrated network architecture. One scheme is based on full frequency reuse method, and the other scheme is based on partial frequency reuse method. The research results show that compared with full frequency reuse, partial frequency reuse can improve system capacity and spectrum utilization more efficiently, but it also faces more technical challenges. References Awoseyila et al. (2013a) studies ground base stations sharing the frequency spectrum of OFDMA-based multi-beam satellite communication systems. In order to reduce the mutual interference between the satellite network and terrestrial network, the ground base station adopts beam multiple access technology. Reference Kim et al. (2011) studied the strategy of sharing the mobile satellite service frequency band (2 GHz) in the integrated satellite and terrestrial network based on the LTE system, which shows that the terrestrial network has serious interference to the satellite uplink. On the other hand, downlink frequency sharing is feasible in the coverage areas of pedestrian microcells and vehicle-mounted macrocells. In addition, dynamic radio resource allocation combined with interference coordination can be used to optimize the performance of the integrated satellite and terrestrial network. Reference Awoseyila et al. (2013b) proposed the idea of Exclusive Zone (EZ) to realize spectrum sharing, but it did not analyze the influence of the size of isolation area on frequency sharing efficiency. The geographical isolation of the existing integrated satellite and terrestrial network will limit the available bandwidth of the terrestrial network. Therefore, this paper introduces the concept of time domain isolation, and designs a spectrum sharing scheme based on soft frequency reuse for the integrated satellite and terrestrial network. At the cost of algorithm complexity, the allocation of time slots increases the degree of isolation, improves the signal to interference ratio (SIR) of the network, and increases the capacity of the satellite system.

The paper is organized as follows. In **Section 2**, we introduce the spectrum sharing technologies of integrated satellite and terrestrial network based on spectrum planning. In **Section 3**, a spectrum sharing algorithm for satellite and terrestrial integrated network based on soft frequency reuse is proposed. The performance of the spectrum sharing algorithm is verified in **Section 4**. Finally, the conclusion is provided in **Section 5**.

2 SPECTRUM PLANNING BASED SPECTRUM SHARING SCHEMES IN INTEGRATED SATELLITE AND TERRESTRIAL NETWORK

In the integrated satellite and terrestrial network, the satellite network and terrestrial network sharing the same frequency band can effectively improve the spectrum utilization. However, sharing the same frequency band will cause interference between satellite and ground components, which will seriously affect communication quality. Therefore, effective sharing between two or more communication systems using the same frequency band, and interference within the tolerable range is the key to spectrum management.

2.1 Conventional Spectrum Sharing Schemes in the Integrated Satellite and Terrestrial Network

Conventional Frequency Reuse (CFR) is more common in terrestrial networks. In terrestrial cellular systems, frequency reuse requires a certain geographic isolation to reduce interference to a tolerable range. In addition, in order to efficiently use spectrum resources, the satellite system adopts a geographical isolation method to reuse frequency bands. In the integrated satellite and terrestrial network, the spectrum sharing scheme between multi-beam satellites and ancillary terrestrial component (ATC) is shown in **Figure 1**. The horizontal axis of the coordinate axis is the 7 frequency bands allocated by the system, and the vertical axis is the 7 beams of the GEO satellite. Taking beam 1 as an example, the satellite network uses the frequency band F1, and the terrestrial network uses the frequency band F2–F7. The terrestrial cell in

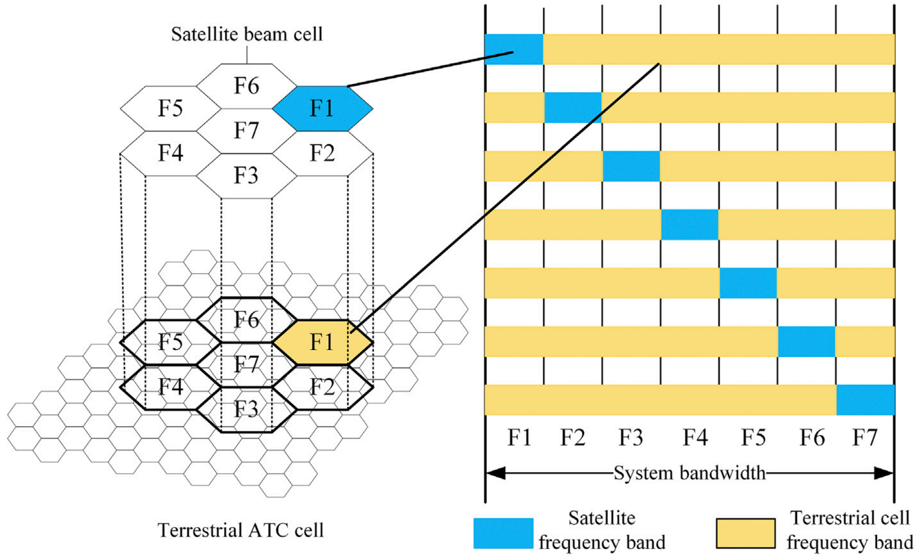

FIGURE 1 | CFR based spectrum sharing scheme.

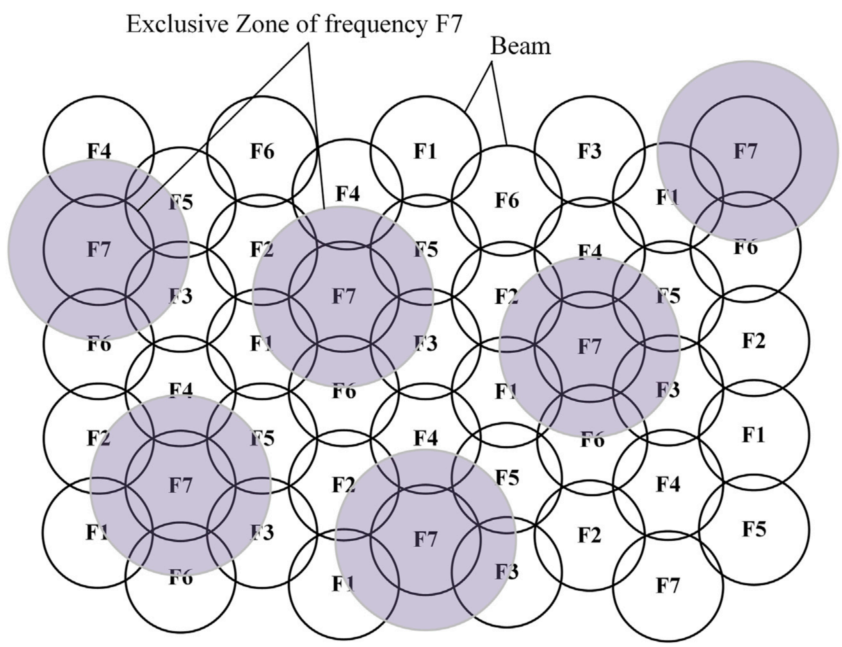

FIGURE 2 | Exclusive zone based spectrum sharing scheme.

the adjacent satellite beam overlaps the frequency band of the current beam, which will cause serious interference. Because the number of ground users is relatively large, the main interference is caused by the uplink of the ground user terminal to the satellite communication system. Therefore, there is not only serious interference in the beam, but also serious inter-beam interference between the terrestrial cell and adjacent satellite beams. It is the simplest method to apply the conventional frequency reuse scheme of the terrestrial cellular network to the integrated satellite and terrestrial system, but the performance is the worst.

2.2 Exclusive Zone Based Spectrum Sharing Scheme in the Integrated Satellite and Terrestrial Network

Reference Awoseyila et al. (2013b) designed the spectrum allocation strategy in the terrestrial cell and satellite beam

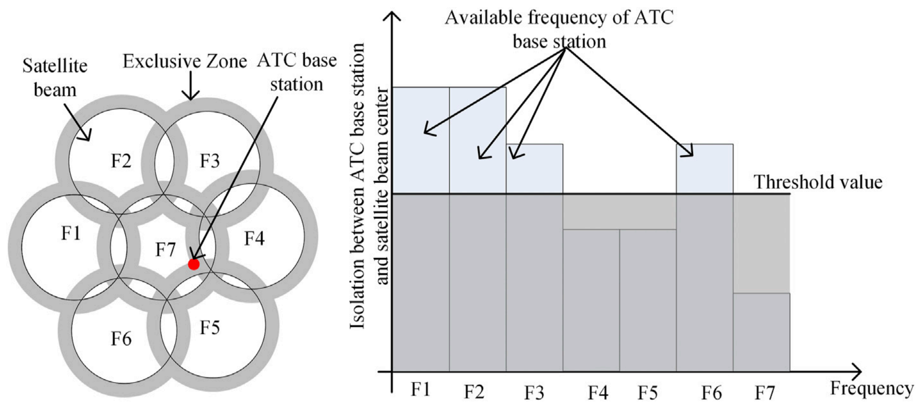

FIGURE 3 | Available frequency of terrestrial network in Exclusive Zone scheme.

based on the concept of the EZ. According to the Friis transmission equation, if the terminal is far from the beam center of the satellite, the satellite antenna reception gain is very small. Therefore, increasing the frequency isolation between the terrestrial network and the satellite network can reduce the number of interfering terminals and the antenna receiving gain. In the N-color frequency multiplexing satellite network, each satellite cell uses $1/N$ of the total frequency spectrum for information transmission. In **Figure 2**, each beam uses 1/7 of the available spectrum (F1–F7), and the gray area represents the Exclusive Zone of frequency F7. At this time, the frequency F7 can be reused by all ground systems in the white area.

If this concept is applied to all beams, **Figure 3** can be obtained. Then evaluate the isolation between the ATC base station in the figure and the satellite beam. The simulation results show that the isolation between the ATC base station and the satellite beams using frequencies F4, F5, and F7 is too low, and the base station is not allowed to be used. Therefore, ATC base stations within the EZ range cannot use the corresponding satellite system frequency bands, and only those outside the EZ range can be used. In addition, the size of the EZ will directly affect the interference between the satellite network and the terrestrial network. The higher the value of EZ, the lower the interference between systems, and will reduce the available frequency of terrestrial ATC system. The size of the EZ will directly affect the capacity of the terrestrial cell and the received SIR of the satellite. The -3 dB beam width is considered as the beam edge, and the range of EZ is as follows:

$$G\left[\arctan\left(\frac{\sqrt{3}\,R}{h}\right)\right] \le G(EZ) \le G_m - 3\,(\mathrm{dB}) \tag{1}$$

where EZ is considered as the off-axis angle of the satellite spot beam, $R = 95\,km$ is the radius of satellite spot beam (km), $h = 36{,}000\,km$ is the height of geostationary satellite, G_m is the maximum gain of satellite multi-beam antenna (dB) and the $\sqrt{3}R$ is the distance between two nearby beam centers.

3 SOFT FREQUENCY REUSE BASED SPECTRUM SHARING SCHEME IN THE INTEGRATED SATELLITE AND TERRESTRIAL NETWORK

Although EZ based spectrum sharing scheme can effectively reduce the interference to satellite network, the improvement in spectrum utilization is not obvious, and the available bandwidth of the terrestrial network is limited. For this reason, the idea of time domain isolation is introduced, and the spectrum sharing scheme of the integrated satellite and terrestrial system based on soft frequency reuse is designed. This solution reduces the interference between satellite and ground components from the perspective of time domain isolation. The frequency allocation method is shown in **Figure 4**. First, the entire frequency band is divided into seven sub-bands, and the satellite cell is divided into internal and external parts. Satellite users at the edge of the satellite cell use one of the seven sub-bands, while the satellite cell terminal in the central area uses the remaining six sub-bands. At the same time, we divide each frame into two parts, time slot 1 and time slot 2. In time slot 1, the user at the center of the beam uses six sub-bands for information transmission. In slot 2, users at the edge of the beam use the remaining one sub-band.

Figure 5 shows the frequency band allocation scheme for ground components in spectrum sharing based on soft frequency reuse. In the terrestrial network part, a frame is divided into two time slots, and the edge and center of the network are also divided. For example, the terrestrial cell center user in satellite beam 1 uses F7 in time slot 1, and the terrestrial cell edge terminal uses frequency bands F1-F6 in time slot 2. However, three-color frequency reuse is used at the edge of the terrestrial cell, and two sub-bands can be used in the edge area. When the edge of the terrestrial cell is not fully loaded, frequency allocation based on the users' location is used to meet the communication needs. Since the ephemeris of the satellite is known, the position of the satellite can be calculated in advance. In addition, the ground base station is fixed, and time synchronization can be achieved

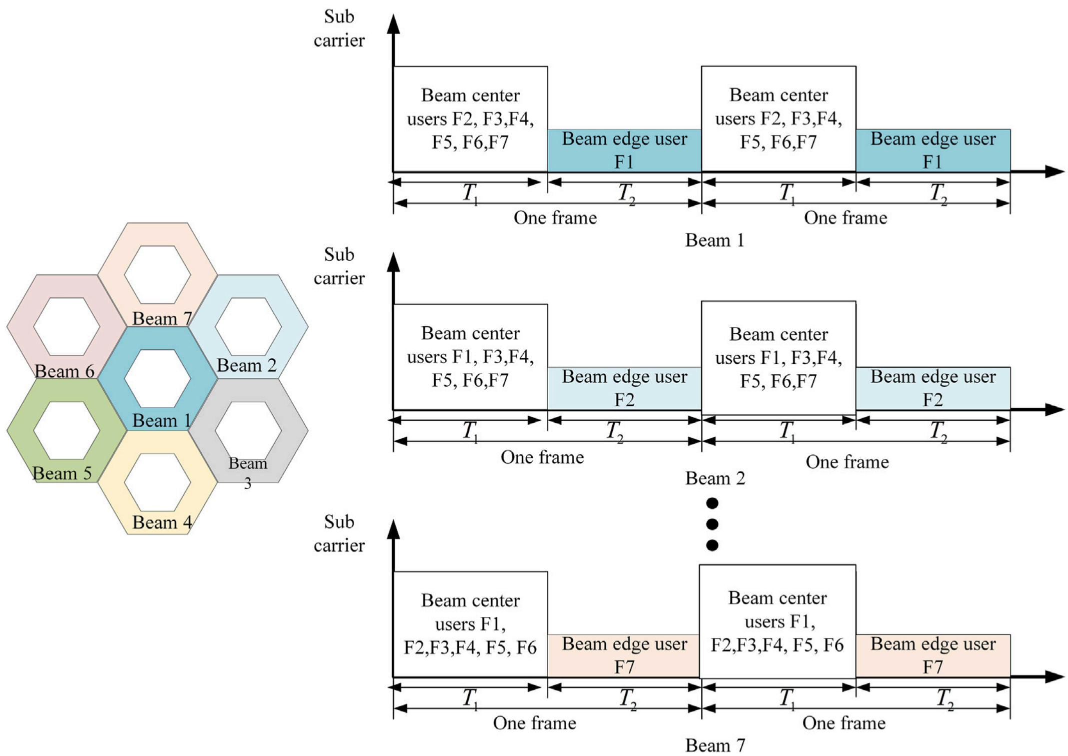

FIGURE 4 | Frequency reuse scheme of satellite.

through a centralized gateway station based on location information management and scheduling.

4 SPECTRUM SHARING SCHEME PERFORMANCE SIMULATION AND ANALYSIS

The satellite system bandwidth is 180 kHz, the equivalent noise temperature of the satellite receiver is 559 K. In terms of satellite links, line of sight propagation loss, atmospheric loss, and polarization errors should be considered. The line of sight loss model used is:

$$L_f = 92.45 + 20log_{10}d + 20\log_{10}f \tag{2}$$

where, f is the operating frequency band in GHz, we consider using the 2 GHz, and d is the distance between satellite and terminal in km. The satellite antenna model is based on ITU-R S.672-4, which is the radiation pattern of the satellite antenna used in the fixed satellite service of the geostationary satellite.

$$G(\psi) = \begin{cases} G_m - 3(\psi/\psi_0)^2 & \psi_0 \le \psi \le a\psi_0 \\ G_m + L_s & a\psi_0 \le \psi \le b\psi_0 \\ G_m + L_s + 20, -, 25\log(\psi/\psi_0) & b\psi_0 \le \psi \le \psi_1 \\ 0 & \psi_1 \le \psi \end{cases} \tag{3}$$

where $G(\psi)$ is the antenna gain in dBi, G_m = 50 dBi is the maximum main lobe gain, ψ_0 = 0.15 is the half of 3 dB beam width, a = 3.16, b = 6.32 the constant numeric values, ψ_1 is the angle when $G_m + L_s + 20, -, 25\log(\psi/\psi_0)$ equals 0 dBi, and L_s = −30 is the required near-in-side-lobe level (dB) relative to peak gain. As shown in **Figure 6**, the direction angle of the satellite antenna beam increases, and the antenna gain decreases. Therefore, the farther the interference is from the beam center, the lower the interference intensity received by the satellite.

Take the terminal located at the sub-satellite point of the GEO satellite as an example to calculate the uplink budget. The detailed link loss parameters are shown in **Table 1**. The transmit power of the satellite terminal is 5 W, the transmission loss is 0.1 dB, and the mismatch loss is 0.5 dB. At the same time, the polarization loss and pointing deviation loss of the antenna are also considered. The receiver sensitivity is set to −120 dB, and the minimum allowable signal-to-noise ratio (SNR) of the system is 4 dB. Therefore, the calculated link budget is 9.68 dB.

4.1 Performance Analysis of Signal to Interference Ratio

In the integrated satellite and terrestrial network, the interference of the terrestrial cell terminal to the satellite is considered, and the main interference source is located in the main lobe coverage area. The interference between satellite network and terrestrial network components can be measured by the SIR of the signal received by the satellite. The terrestrial system user antenna adopts the omnidirectional antenna and

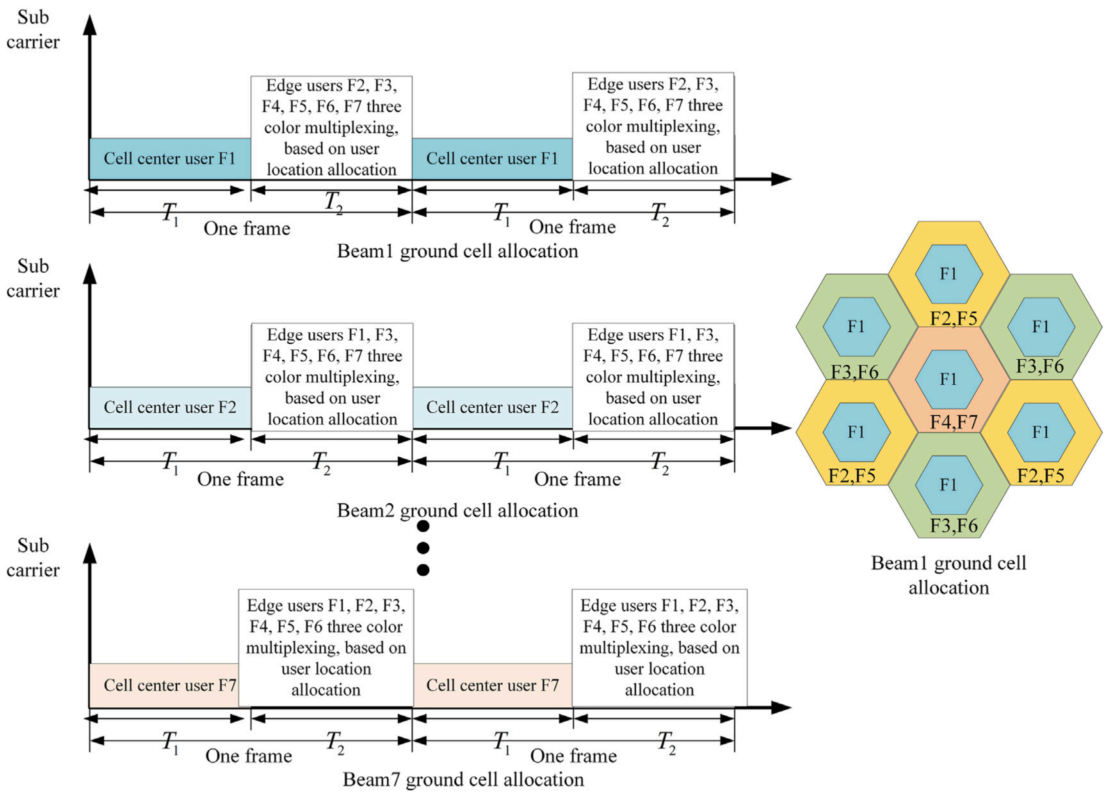

FIGURE 5 | Frequency reuse scheme of terrestrial cell.

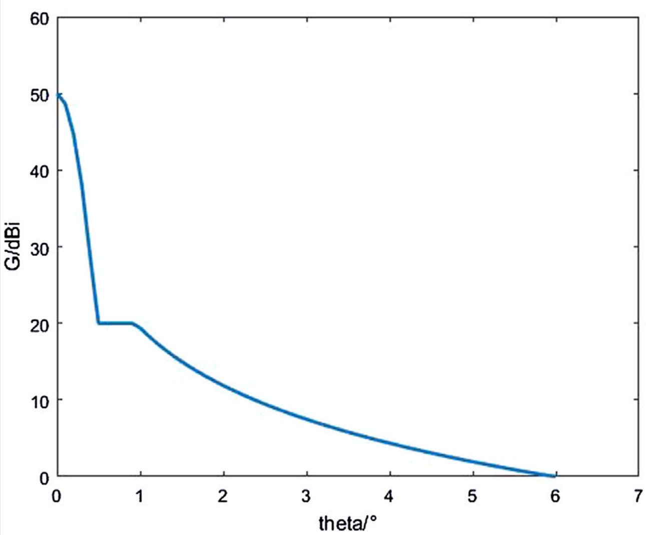

FIGURE 6 | Multi-beam pattern of satellite antenna.

the satellite system user antenna adopts the directional antenna. The transmission power of terrestrial network users P_i is between -30 and 24 dBm. Considering the propagation loss of the terrestrial link and the distance between the user and the ground base station, we take the partial power control formula to compensate.

$$SIR = \frac{P_d G_{d-tx} G_{d-rx} / L_d}{\sum_i P_i G_{i-tx} G_{i-rx} / L_i} \quad (4)$$

where P_d = 37 dBm and P_i are the transmission power of the useful signal and the interference signal, respectively. G_{d-tx} and G_{i-tx} are the transmission gains of useful and interfering signals, respectively. G_{d-rx} and G_{i-rx} are the reception gains of useful and interfering signals at the satellite, respectively. L_d and L_i are channel loss models of useful and interfering signals, respectively.

The hybrid satellite and terrestrial system adopts 7 satellite spot beams, 8,911 terrestrial cells with the radius of 1 km, and 40 users in each cell. Because the number of terminals in the satellite network is huge and the location is different. Therefore, the signal transmission experience different link attenuation, such as rain attenuation, cloud attenuation. Therefore, the influence of shadow fading and free space attenuation is mainly considered in SIR calculation, and the SIR of terminal equipment is analyzed by mean operation. The SIR we discussed in the paper is the average SIR of the total terrestrial terminals. The cumulative probability distribution of the SIR of the spectrum sharing scheme is shown in **Figure 7**. In soft frequency reuse based spectrum sharing scheme, the time slots and frequencies used by the beam center and the beam edge are different, and the SIR of the beam center and the beam edge are respectively simulated. In

TABLE 1 | Link budget table.

Link budget	Value
Transmitter power	5 W (37 dBm)
Satellite terminal antenna gain	3 dBi
Transmission Losses	0.1 dB
Tx Impedance mismatch	0.5 dB
EIRP	37 + 3–0.1–0.5 = 39.4 dBm
Free-space basic transmission loss	189.6 dB
Atmospheric loss	0.18 dB
Polarization loss	3 dBi
Basic transmission loss	−189.6–0.18–3 = −192.78 dB
Satellite Antenna Gain	50 dBi
Unpointing loss	1 dB
Rx Impedance mismatch	0.51 dB
Received power	39.4–192.78 + 50–1–0.51 = −104.89 dBm
Margin with sensitivity	−104.89–(−120) = 15.11 dB
Noise	−118.57 dBm
SNR	−104.89–(−118.57) = 13.68 dB
SNR Minimum	4 dB
Margin	13.68–4 = 9.68 dB

the soft frequency reuse based spectrum sharing scheme, the SIR at the center and edge of the beam is significantly improved compared to conventional frequency reuse. The SIR at the center of the beam is 2.5 dB higher than the scheme based on EZ (EZ = 7.6 dB), and the SIR at the edge of the beam is lower than the scheme based on EZ (EZ = 7.6 dB). However, in the scheme based on EZ, the larger the exclusive zone, the smaller the available bandwidth on the terrestrial network, while the soft frequency reuse scheme does not have this problem.

The main factors affecting the SIR of the satellite beam center signal are the ratio of the beam center radius to the beam radius R_{cen}/R and the terrestrial cell radius R_{ter}. The main factor affecting the SIR at the edge of the satellite beam is the radius of the terrestrial cell. The simulation result of the satellite beam center SIR with R_{cen}/R is shown in **Figure 8**. As R_{cen}/R increases, the SIR of the received signal decreases. This is because the larger the beam center radius, the larger the antenna half-beam angle, and the lower the isolation between the ground terminal and the satellite beam center. When R_{cen}/R is lower than 0.37, the radius of the terrestrial cell R_{ter} has little effect on the SIR, indicating that the beam center and the terrestrial cell in the adjacent beam have a high degree of isolation. When the radius of the terrestrial cell R_{ter} increases, the number of ground co-frequency terminals decreases, and the SIR at the center of the satellite beam increases.

The variation of the SIR of the satellite beam edge with R_{ter} is shown in **Figure 9**. With the increase of the radius of the terrestrial cell, the SIR of the three schemes has increased. This is because the radius of the terrestrial cell directly affects the number of the co-frequency terminals in the satellite coverage area. When the radius of the terrestrial cell is 5 km, the number of ground co-frequency terminals drops sharply. However, the terrestrial cell radius R_{ter} cannot be too large, which will affect the received SIR of the terrestrial cell terminal and the user capacity of the system.

4.2 Throughput Performance Analysis

Since different frequencies are used to transmit information in different time slots and geographical areas, spectrum resources will be wasted and network throughput will be reduced. The spectrum sharing scheme of soft frequency reuse improves spectrum efficiency as much as possible by flexibly planning time and space resources. From the perspective of satellite system capacity, when the spectrum sharing scheme of integrated satellite and terrestrial system is determined, the channel power and system bandwidth of the beam are determined. Therefore, when other noises are not considered, the user throughput can be calculated as follows:

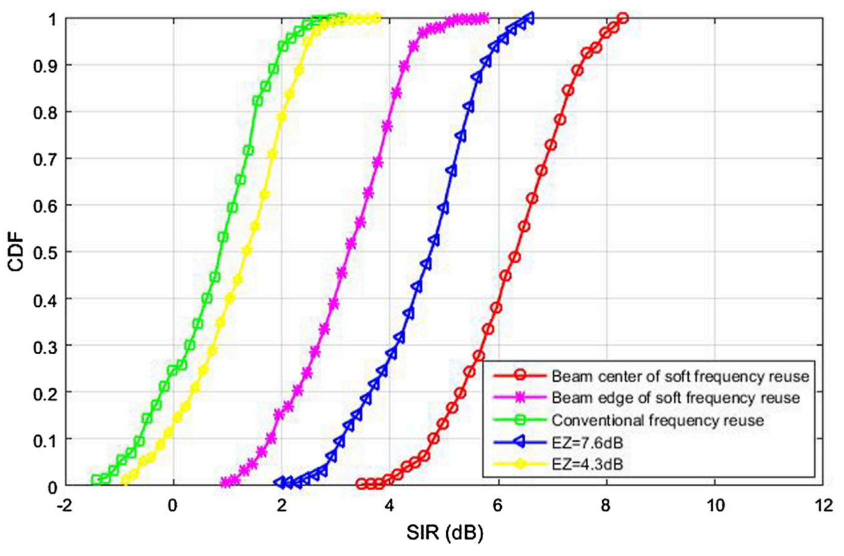

FIGURE 7 | The cumulative distribution function of SIR.

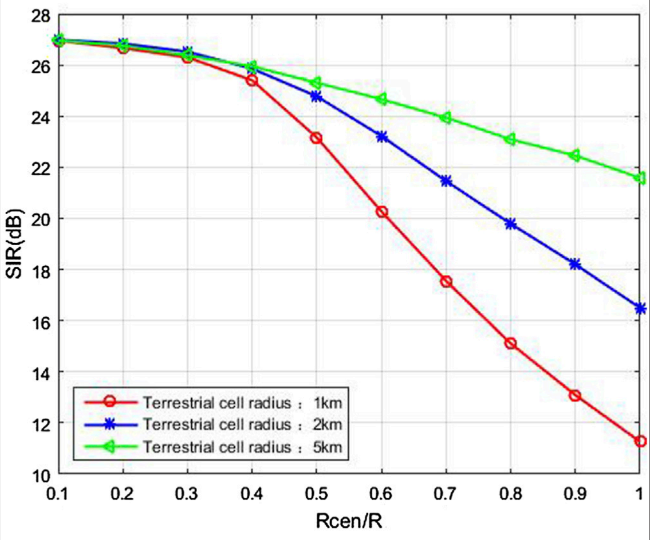

FIGURE 8 | SIR of satellite beam center with R_{cen}/R.

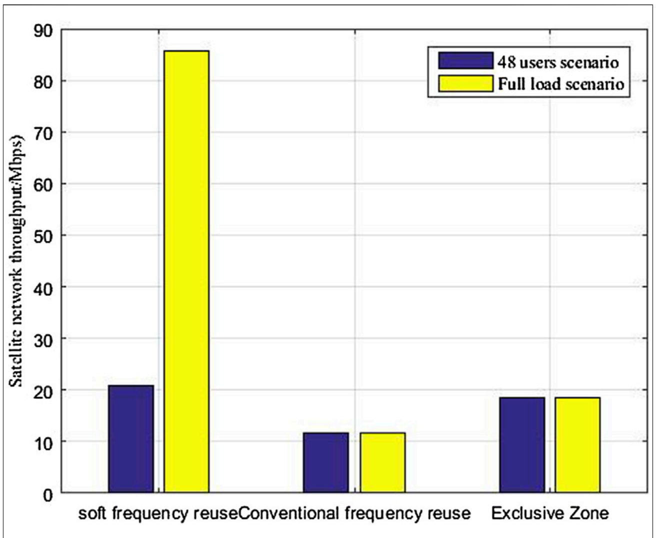

FIGURE 10 | Satellite network throughput.

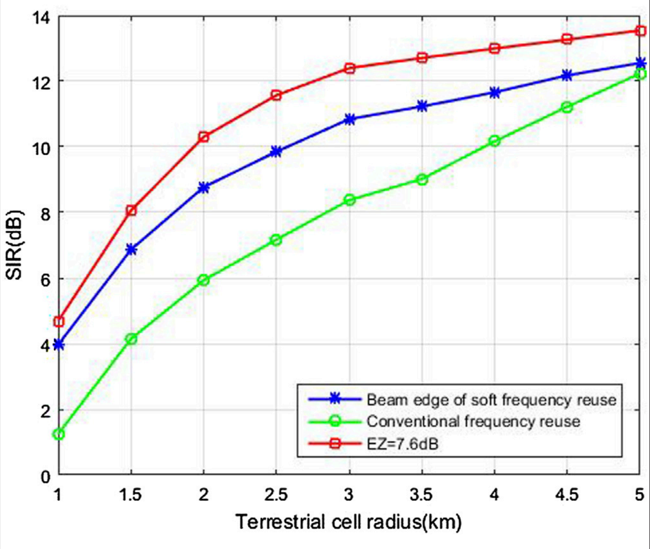

FIGURE 9 | SIR of satellite beam edge with R_{ter}.

$$C_{if} = B\log\left(1 + SIR_{if}\right) \tag{5}$$

where,B is the system bandwidth. Then the capacity of the beam f is:

$$C_f = \sum_{i=1}^{K_f} C_{if} = \sum_{i=1}^{K_f} B\log\left(1 + SIR_{if}\right) \tag{6}$$

When the number of satellite cell users is 48 and the satellite cell is fully loaded, the satellite throughput is shown in **Figure 10**. For conventional frequency sharing and EZ based spectrum sharing schemes, both time slot 1 and time slot 2 can accommodate 24 users. The spectrum sharing scheme based on soft frequency reuse can accommodate 144 users at the beam center of time slot 1, and 24 users at the beam edge of time slot 2 for information transmission, that is, 168 users can be accommodated when fully loaded. The simulation results show that when the number of satellite cell terminals is 48, the soft frequency reuse based spectrum sharing scheme has the highest system throughput. This is because the SIR of the beam center and the beam edge has increased. When the satellite cell is fully loaded, the number of users based on the soft frequency reuse scheme is greater than the conventional reuse scheme and the EZ based spectrum sharing scheme, and its throughput will also be significantly improved.

5 CONCLUSION

Through the introduction of the existing conventional frequency reuse scheme and the EZ based spectrum reuse scheme in integrated satellite and terrestrial network, we understand the concept of geographic isolation used in these two solutions. The spectrum sharing solution of the integrated satellite and terrestrial network based on the EZ is an extension of the conventional spectrum sharing scheme. Although the spectrum sharing scheme based on the EZ can effectively reduce the interference of the ground terminal to the satellite link, but it limits the available bandwidth of the terrestrial network. Then based on the idea of time domain isolation, a spectrum sharing scheme based on soft frequency reuse for integrated satellite and terrestrial network is proposed. The solution does not limit the available bandwidth of the terrestrial network, and the simulation results show that the SIR and satellite throughput have been improved. In addition, the larger the ratio of the satellite beam center radius to the beam radius, the higher the spectrum utilization rate. However, the SIR of the beam center is reduced, and the size of the beam center needs to be considered in the system design. The satellite system and the terrestrial system need to be accurately synchronized to use the soft frequency multiplexing spectrum scheme, but the propagation delay of the signal and the dynamic movement of the satellite and ground users will produce time deviations. Therefore, we will consider the solution to the synchronization problem between systems in the follow-up research.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

The work was developed as a collaboration among all authors. MY designed the system model of the software frequency reuse scheme. The manuscript was mainly drafted by GX, and the authors BX and YD revised the manuscript. All authors have read and approved the final manuscript.

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