

Chapter 2

Beamforming Transmission

Multi-beam Satellites have been widely adopted in current satellite communication systems due to its energy efficiency and potential for frequency reuse. Recently, array multi-beam antennas have drawn more attention for the possible applications of digital beamforming techniques. In this chapter, we discuss the main challenges when applying beamforming to satellite communication systems and introduce several prospective applications of satellite beamforming technology. Then, a multimedia multicast beamforming method for the integrated terrestrial-satellite network is proposed, in which base stations (BSs) and the satellite work cooperatively to provide ubiquitous service for ground users. Due to the content diversity of multimedia services, users that require the same contents will be served as a group using multicasting. With multiple transmit antennas, multicast beamforming is executed among groups while reusing the entire bandwidth. Finally, a practical work of Smart Communication Satellite (SCS), the Chinese first low-earth-orbit communication satellite, is presented briefly.

2.1 Beamforming in Satellite Communication Systems

The deployment of multi-beam satellites has increased during the last few years to cover designated areas with the minimum effective isotropic radiated power (EIRP). By projecting higher power density, narrow spot beams can provide higher data capacity for small user terminals. In recent developed multi-beam satellite systems, a large number of beams were employed, such as 228 beams in Inmarsat-4 and 500 beams in SkyTerra-1 [1]. Meanwhile, frequency reuse is possible in multi-beam satellite systems as long as the inter-beam interference can be carefully managed, which can significantly increase the spectrum efficiency [2]. Three types of multi-beam antennas have been utilized in today's multi-beam satellite systems: reflector multi-beam antenna, lens multi-beam antenna, and array multi-

beam antenna, among which the reflector multi-beam antenna and lens multi-beam antenna have been widely deployed due to the mature solutions and effortless realization. Recently, array multi-beam antennas are drawing more and more attention for their superior performance of aperture efficiency and leakage loss. What is more attracting for array multi-beam antennas is the possible application of digital beamforming techniques, which can flexibly construct beams of different shapes/sizes in different cases. Beamforming is one of the array processing methods of antenna arrays. By adjusting the weighting factors on antennas, it can steer nulls to mitigate co-channel interferences and forming independent beams toward different directions, which contributes to improve the performance of mobile communication systems [3]. Generally, it is not practical to equip user terminals with antennas arrays, while satellites and base stations are more applicable to do so. In mobile communication systems, transmit beamforming is a powerful mean of interference mitigation and capacity improvement by providing isolation among users in different directions [4].

The application of beamforming in satellite communication systems is confronted with multiple challenges caused by the special characteristics of satellites [5, 6], which can be summarized as follows.

- The Long and Variable Delay of Channel State Information (CSI)

Adopting beamforming techniques generally requires CSI of desired users and sometimes also the interference users, such as the typical zero-forcing (ZF) or regularized ZF (RZF) beamforming [7]. However, different from terrestrial networks, there is a long time delay between the satellite and terrestrial users due to the long communication distance. Under such a circumstance, it is difficult to obtain the real-time CSI, especially in frequency division duplexing (FDD) scenarios, which is widely utilized nowadays. Some special beamforming algorithms are required in satellite communication systems to adapt to the long time delay of CSI. For instance, the blind beamforming technique can be executed when no information of the source direction or signals is available [8]. Also, since the earth is not a perfect sphere, the delay of CSI would be variable as the satellite is moving. Thus, in time division multiple access (TDMA) systems, accurate time controlling methods are required to ensure system performance.

- The Small Channel Fluctuations

There is generally a strong main path between the satellite and terrestrial users. In such a case, the channel model is regarded as either an additive white Gaussian noise (AWGN) channel or a Rician channel with a dominant line-of-sight path in most of the cases. Apparently, both of the two channel models experience small channel fluctuations. When the terrestrial users distribute close to each other, their channel matrices would have low spatial orthogonality, making it difficult to separate the terrestrial users by means of beamforming. Opportunistic beamforming techniques can be considered in this case, which can induce large and fast channel fluctuations so that spatial orthogonality can be utilized for beamforming [9]. Moreover, when terrestrial users distribute relatively far from each other, the spatial orthogonality can also be exploited since the channels would have low relevance due to the sparse distribution.

- **Heterogeneous Users with Individual Features**

For the terrestrial cellular networks, although there are various types of mobile phones and various standards, the communication architectures are all identical. In such a case, the beamforming models in cellular networks are also universal for different users and situations. However, the user types of satellite networks are heterogeneous with various features, which can be hand-held terminals, aircrafts, ships, and earth stations. Moreover, in some specific application scenarios, different types of users may be served simultaneously. While hand-held terminals may only be equipped with a single antenna, earth stations are able to afford large-scale antenna arrays. Instead of a universal beamforming technique for a single type of users, the beamforming models should be different according to the types of serviced users, or a universal solution is expected to address all these different cases. Besides, in satellite systems, constant envelope modulation are employed for the sake of maximizing the efficiency of EIRP. It would also be a challenge to generate constant envelope signals for heterogeneous users with individual features.

- **High Mobility of Satellites**

Except geostationary earth orbit (GEO) satellites, the satellites generally move at a high speed relative to the earth, especially in terms of LEOs. For example, the period of the Iridium system at the orbit of 780 km is about 100 min, which means an angular velocity of $3.6^\circ/\text{min}$. The beams of the satellite need to change in a fast manner according to the relative location between the satellite and terrestrial users. Moreover, when the user is out of the coverage range of beamforming, the link would be terminated, and thus a high-efficient handover is also required. In cases of LEO and MEO, the fast moving of the satellite would also cause large doppler shift, which may significantly deteriorate the system performance, particularly for narrowband signals. Doppler shift compensation techniques need to be adopted to ensure reliable communication.

2.1.1 Multi-Beam Joint Processing

As stated in the introduction, frequency reuse is possible in multi-beam satellite systems as long as the inter-beam interferences can be carefully controlled. In current multi-beam satellite systems, the typical frequency reuse factor of four is generally adopted for the sake of inter-beam interference limitation, as illustrated in Fig. 2.1a. Full frequency reuse, as illustrated in Fig. 2.1b, can exploit higher spectrum efficiency with the reuse factor of one. However, the inter-beam interference may significantly deteriorate the system performance, especially in the overlap area of adjacent beams.

Multi-beam joint processing, which is based on the technique of digital beamforming, provides a possible way of full frequency reuse without significant performance loss [2]. Instead of each beam serving its users separately, signals of all users of all beams are joint precoded by means of beamforming, and then

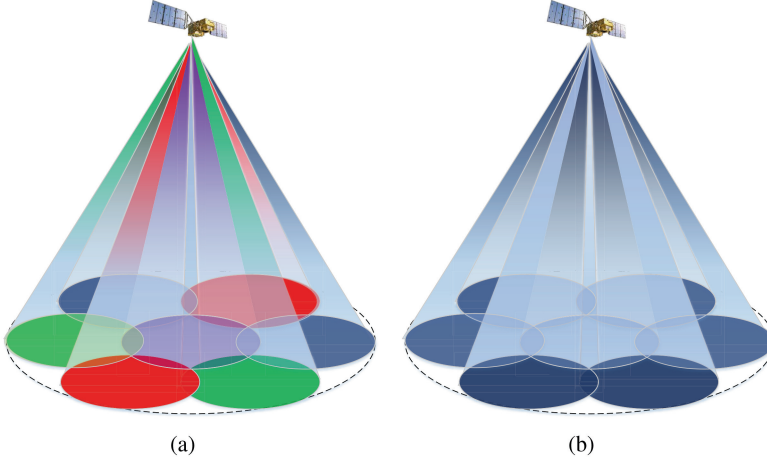


Fig. 2.1 The beams with the same color use the same frequency. Thus in (a), four different frequencies are used among beams, while in (b) only one frequency is used among all beams

transmitted by all beams with full frequency reuse. The inter-beam interference can be mitigated by adjusting the beamforming weighting factors on antennas at the transmitting with the help of CSI. By utilizing the spatial orthogonality of users, higher spectrum efficiency can be exploited when digital beamforming techniques are adopted. Generally, the multi-beam joint processing is more potential to be adopted in the uplink case than the downlink case. For the downlink transmission of satellites, due to the power constraints, it may not be practical to serve all users with full frequency reuse simultaneously, in which user scheduling techniques need to be considered combined with frequency reuse techniques to optimize the system performance.

2.1.2 Multigroup Precoding

The channel between the satellite and terrestrial users is usually modeled as an AWGN channel or a Rician channel, which experiences small channel fluctuations. When terrestrial users distribute close to each other, it is difficult to separate different users by means of beamforming with full frequency reuse. In this case, instead of employing beamforming for each user separately, we can divide the users into groups according to the location distribution and employ multigroup precoding. As illustrated in Fig. 2.2, terrestrial users are divided into groups according to their locations and serviced by the satellite. For users in different groups, spatial orthogonality can be utilized, and beamforming is employed between groups when full frequency reuse is adopted. For users within the same group, since beamforming is difficult to be exploited due to small channel fluctuations, other multi-access techniques may be considered, such as time division multiple access (TDMA) or frequency division multiple access (FDMA).

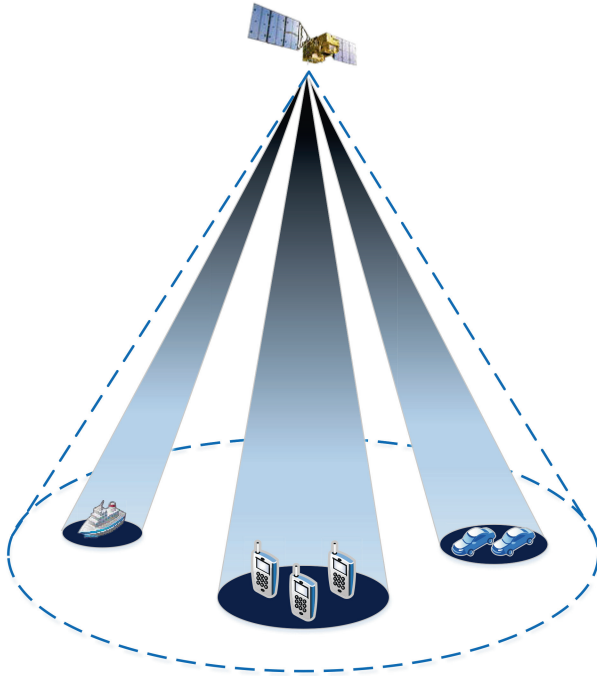


Fig. 2.2 Multigroup precoding satellite system

Although beamforming techniques is difficult to be employed within each group to achieve frequency reuse, this problem can be avoided when it comes to multicasting. Multicast multigroup precoding is studied for satellite communication systems [10], in which users are divided in to groups and the same symbol is broadcasted to multiple users in the same group. Also, for users in different groups, digital beamforming techniques are employed to achieve full frequency reuse. Moreover, user scheduling methods can be exploited in this system to achieve higher multiuser diversity gaining.

Digital beamforming techniques are based on antenna arrays and CSI is needed when calculating the weighting factors on antennas. In next generation wireless systems, massive MIMO is attractive for its potential high data rates and energy efficiency based on large antenna arrays. However, when it comes to large antenna arrays, there exist several challenges especially in frequency division duplexing (FDD) cases. When the scale of antenna arrays increases, the number of CSIs required for beamforming also increases, leading to a large number of training symbols for channel estimation. Furthermore, in FDD systems, the CSI feedback will become a prominent problem if large scale of antenna arrays are equipped. To overcome these problems, the method of two-stage beamforming is proposed to reduce the CSI needed for beamforming in large antenna arrays systems [11]. Terrestrial users are divided into groups with approximately the same channel

Table 2.1 ITU-R table of allocations in Ka band

Frequency bands	ITU-R region 1	ITU-R region 2	ITU-R region 3
17.3–17.7 GHz	FSS (space-Earth)	FSS	FSS
	BSS (feeder links)	BSS	BSS
	Radiolocation	Radiolocation	Radiolocation
17.7–19.7 GHz	FSS (space-Earth)	FSS	FSS
	BSS (feeder links)	FS	BSS
	FS		FS
27.5–29.5 GHz	FSS (Earth to space)	FSS	FSS
	FS	FS	FS
	MS (mobile services)	MS	MS

covariance matrix, and the beamforming process is then decomposed into two stages: the outer beamforming and the inner beamforming. In the two-stage beamforming, only the inner beamforming requires actual CSI, which has much smaller dimensions compared with the initial problem.

2.1.3 Cooperative Beamforming in Terrestrial-Satellite Networks

The rapid growing data traffic brings more and more pressure to the wireless network, which is predicted to increase by over 10,000 times in the next 20 years. Spectrum sharing has shown great potential for improving the capacity performance. For example, in the S-band, 1885–1980, 2010–2025 and 2110–2170 MHz are allocated to the terrestrial communication systems IMT-2000 (International Mobile Telecom System-2000), while 1980–2010 and 2170–2200 MHz are allocated to satellite communication. Since the service in satellite systems is usually scheduled instead of burst, it is possible for terrestrial systems to share the satellite frequency band when the satellite frequency band is not occupied. Moreover, in the next generation wireless networks, the millimeter-wave (mm-wave) band of 30–90 GHz has drawn great attention for the large amount of possible bandwidth. Meanwhile, satellite communications have also shown interest in the mm-wave band for the sake of the increasing traffic demands, especially the Ka band of 26.5–40 GHz [12]. Table. 2.1 gives the ITU-R table of allocation in 27.5–29.5 GHz, part of the Ka band. We can observe that parts of the Ka band has already be allocated to the satellite service. It can be envisioned that the developing of mm-wave in both terrestrial and satellite communications may result in spectrum conflict in the future, and thus the spectrum-sharing techniques would be rather important.

Cognitive ratio (CR) technique is considered as one of the spectrum-sharing techniques in terrestrial-satellite networks, in which the second user dynamically utilizes the spectrum when managing the interference caused to the main user. In CR

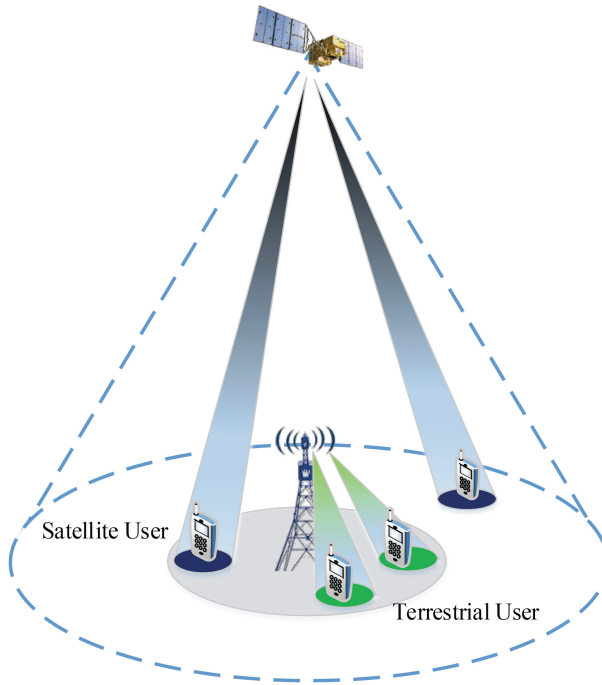


Fig. 2.3 Cooperative beamforming in terrestrial-satellite networks

networks, co-channel interference (CCI) management is the key problem, and thus interference mitigation techniques play an important role in the system performance. The digital beamforming technique, which is based on antenna arrays, can be exploited for interference mitigation in terrestrial-satellite networks by utilizing the spatial orthogonality [12]. Cooperative beamforming is employed at the satellite when both the satellite users and terrestrial users are taken into consideration as constraints for beamforming. By carefully adjusting the weighting factors on antennas at the satellite, the satellite can share the spectrum with terrestrial networks while limiting the interference caused to terrestrial users, as illustrated in Fig. 2.3. Since the satellite generally has limited computation capability, for the sake of reducing complexity, one semi-adaptive beamforming technique is proposed for OFDM based terrestrial-satellite mobile system [13].

2.2 Multicast Beamforming

Due to the rapid development and popularity of mobile devices, such as smartphones and tablets, as well as the development of mobile communication, wireless data service is extended from conventional text messaging or web browsing to multimedia

services such as video streaming, music streaming, and mobile TV [14]. Compared with conventional services, multimedia services generally require larger data traffic, which adds more pressure to the wireless networks. On the other hand, the same multimedia services may be required by multiple users simultaneously, especially for popular videos or TV programs, which is called as content diversity in [15]. Considering both the large data traffic and content diversity, one efficient technique for multimedia services is multicasting. Instead of providing service via point-to-point transmission, multicast transmission delivers the same content to multiple users simultaneously, which can significantly improve the system performance.

A typical max-min fair problem for multicast transmission was discussed in [16], in which multiple groups were served by one base station (BS), and the optimal beamforming vectors were calculated when maximizing the minimum rate of all users under the total power constraint. In [17], coordinated multicast beamforming was investigated for multicell networks, when only one group of users were served by each BS. The problem of minimum power multicast beamforming was investigated in [18], in which the non-orthogonal multiple access technique was adopted within groups. In [19], a content-centric multicast beamforming model for cache-enabled cloud RAN was proposed. In the cloud RAN, all BSs were connected to a central processor, and worked cooperatively to provide multicast transmission for multiple groups. Then, the multicast transmission for satellite communications was also studied in [20], in which the system capacity was maximized under per-antenna power constraints.

While the terrestrial networks can achieve high-speed data service at low cost [21, 22], in the next generation of wireless communication, satellite based access is one way to complement terrestrial based networks to ensure ubiquitous, 100% geographic coverage [23]. The coexistence and cooperation of terrestrial and satellite networks have been investigated in recent works. In [24], the author applied the technique of Cognitive Radio (CR) into terrestrial-satellite networks, enabling dynamic spectrum access for the satellite. Then, in [25], the scenario of the hybrid satellite terrestrial relay network (HSTRN) is investigated, in which a relay with single antenna is utilized to assist the transmission of the satellite in the presence of co-channel interference (CCI).

In this part, we consider a multimedia multicast integrated terrestrial-satellite network, in which the BSs and satellite cooperatively provide ubiquitous coverage for ground users. Due to the content diversity of multimedia services, multicast transmission can be utilized to serve multiple users that require the same contents simultaneously. For both BSs and the satellite, users will be divided into groups according to the required contents, while beamforming is executed among groups reusing the entire bandwidth. Taking both the system performance and user fairness into consideration, we maximize the total capacity of the system while introducing a minimum capacity constraint for the satellite. Then, by means of the successive convex approximation (SCA) approach and the Lagrangian dual method, we obtain the optimal power allocation scheme for the system.



Fig. 2.4 System model of the multimedia multicast integrated terrestrial-satellite network

2.2.1 System Model

Consider a multimedia multicast network as shown in Fig. 2.4, in which L BSs and a satellite cooperatively provide service for ground users. The BSs are equipped with N antennas, and can provide high speed data transmission for high density populations in urban areas. On the other hand, the satellite, equipped with M antennas, can provide extra data service for those users without coverage of BSs, such as users in suburban areas or mountain areas.

All users are assumed to be equipped with a single antenna, and will be grouped according to the required contents. Considering the content diversity of multimedia services, multicasting can be utilized to improve the system performance. The users that require the same contents, such as video streaming or mobile TV, will be divided into the same group for multicast transmission. With multi-antennas, each BS will serve N groups with N different requiring contents within its coverage, when beamforming is executed for reusing the entire bandwidth. The user set of group J in the coverage of BS I is represented by $U_{B,I,J} = \{u_{B,I,J,1}, \dots, u_{B,I,J,|U_{B,I,J}|}\}$, in which $|U_{B,I,J}|$ is the total user number of user set $U_{B,I,J}$. Also, the satellite will provide multicast transmission for M groups, and the user set of group J of the satellite is $U_{S,J} = \{u_{S,J,1}, \dots, u_{S,J,|U_{S,J}|}\}$, in which $|U_{S,J}|$ is the total user number of satellite group J . Note that the entire bandwidth is reused in the whole system, and thus there will exist CCI among groups and also between two systems.

2.2.2 Problem Formulation

In the multimedia multicast integrated terrestrial-satellite network, each BS provide multicast transmission for N groups when beamforming is executed. The transmit signal of BS I is

$$\mathbf{x}_I = \sum_{j=1}^N \boldsymbol{\omega}_{I,j} \sqrt{P_{B,I,j}} s_{B,I,j}, \quad (2.1)$$

in which $\boldsymbol{\omega}_{I,j}$, $||\boldsymbol{\omega}_{I,j}|| = 1$, is the beamforming vector, $P_{B,I,j}$ is the transmit power, and $s_{B,I,j}$, $E[|s_{B,I,j}|^2] = 1$, is the multicast signal for all the users in group j . As stated in the system model, all users in the same group require the same contents, and thus for each group only one multicast signal is transmitted.

Since there are multiple users that experience distinct channels within each group, we cannot completely cancel the interference among groups. In conventional point-to-point transmission, the beamforming vectors of maximum ratio transmission (MRT) is designed as

$$\boldsymbol{\omega}_i = \frac{\mathbf{h}_i}{||\mathbf{h}_i||}, \quad (2.2)$$

where $\mathbf{h}_i$ is the channel from the transmitter equipped with multi-antennas to the corresponding user with single antenna. We extend this to point-to-multipoint transmission, and then the multicast beamforming vectors based on MRT is:

$$\boldsymbol{\omega}_{I,j} = \frac{\sum_{k=1}^{|U_{B,I,j}|} \mathbf{h}_{I,j,k}}{||\sum_{k=1}^{|U_{B,I,j}|} \mathbf{h}_{I,j,k}||}, \quad (2.3)$$

where $\mathbf{h}_{I,j,k}$ is the channel from the BS I to user k in group j .

Similarly, the transmit signal of the satellite is

$$\mathbf{x}_S = \sum_{j=1}^M \mathbf{v}_j \sqrt{P_{S,j}} s_{S,j}, \quad (2.4)$$

where $\mathbf{v}_j$, $||\mathbf{v}_j|| = 1$, is the beamforming vector, $P_{S,j}$ is the transmit power and $s_{S,j}$, $E[|s_{S,j}|^2] = 1$, is the multicast signal for group j .

For simplification, in the grouping scheme of the satellite, the satellite users will be grouped according to both the required contents and the geographic locations. The users that require the same contents in the same small area will be divided into one group. Due to the small channel fluctuations of the satellite channel, the

channels of the users in one group can be approximately viewed as the same. Then, zeroforcing beamforming (ZFBF) can be utilized to cancel interference among groups. Let $\mathbf{g}_{S,1}, \mathbf{g}_{S,2}, \dots, \mathbf{g}_{S,M}$ be the channel from the satellite to the satellite users of different groups, $\mathbf{G} = [\mathbf{g}_{S,1}, \mathbf{g}_{S,2}, \dots, \mathbf{g}_{S,M}]^H$. The ZFBF vectors can be calculated by

$$[\mathbf{v}_1, \dots, \mathbf{v}_M] = \mathbf{G}^{-1} \mathbf{D}, \quad (2.5)$$

where $\mathbf{D}$ is the normalization diagonal matrix, and $\mathbf{D}^2 = \text{diag}\{\frac{1}{(\mathbf{G}^{-H} \mathbf{G}^{-1})_{1,1}}, \dots, \frac{1}{(\mathbf{G}^{-H} \mathbf{G}^{-1})_{N,N}}\}$, where $(\mathbf{H})_{n,n}$ is the n th element of the diagonal of $\mathbf{H}$.

Then the received signal of the BS user K in group J of BS I is

$$\begin{aligned} y_{B,I,J,K} &= \mathbf{h}_{I,J,K}^H \boldsymbol{\omega}_{I,J} \sqrt{P_{B,I,J}} s_{B,I,J} + n \\ &+ \mathbf{h}_{I,J,K}^H \sum_{j=1, j \neq J}^N \boldsymbol{\omega}_{I,j} \sqrt{P_{B,I,j}} s_{B,I,j} + \mathbf{g}_{B,I,J,K}^H \sum_{j=1}^M \mathbf{v}_j \sqrt{P_{S,j}} s_{S,j}, \end{aligned} \quad (2.6)$$

where $\mathbf{g}_{B,I,J,K}$ is the channel from the satellite to the BS users, and n is the additive white Gaussian noise (AWGN). The SINR can then be calculated as

$$\gamma_{B,I,J,K} = \frac{|\mathbf{h}_{I,J,K}^H \boldsymbol{\omega}_{I,J}|^2 P_{B,I,J}}{\sum_{\substack{j=1, \\ j \neq J}}^N |\mathbf{h}_{I,J,K}^H \boldsymbol{\omega}_{I,j}|^2 P_{B,I,j} + \sum_{j=1}^M |\mathbf{g}_{B,I,J,K}^H \mathbf{v}_j|^2 P_{S,j} + \sigma_n}, \quad (2.7)$$

where σ_n is the AWGN power.

The received signal of the satellite user is

$$\begin{aligned} y_{S,J,K} &= \mathbf{g}_{S,J}^H \sum_{j=1}^M \mathbf{v}_j \sqrt{P_{S,j}} s_{S,j} + n \\ &= \mathbf{g}_{S,J}^H \mathbf{v}_J \sqrt{P_{S,J}} s_{S,J} + n. \end{aligned} \quad (2.8)$$

Since the satellite users are located in areas without coverage of BSs, we ignore the interference from the BSs. The SINR can then be calculated as

$$\gamma_{S,J,K} = \frac{|\mathbf{g}_{S,J}^H \mathbf{v}_J|^2 P_{S,J}}{\sigma_n} \quad (2.9)$$

Based on the Shannon's theorem, the capacity of the whole system can be calculated as

$$\begin{aligned} C_B + C_S &= \sum_{I=1}^L \sum_{J=1}^N \sum_{K=1}^{|U_{B,I,J}|} C_{B,I,J,K} + \sum_{J=1}^M |U_{S,J}| C_{S,J,1} \\ &= \sum_{I=1}^L \sum_{J=1}^N \sum_{K=1}^{|U_{B,I,J}|} \log_2(1 + \gamma_{B,I,J,K}) + \sum_{J=1}^M |U_{S,J}| \log_2(1 + \gamma_{S,J,1}). \end{aligned} \quad (2.10)$$

Due to the different channel conditions of users as well as the co-channel interference among users, it is of great importance to allocate the power reasonably to achieve optimal system capacity performance. However, since the satellite will cause interference to all the BSs users within its coverage, it may lead to a relative small capacity for the satellite if we simply maximize the total capacity of the system. Thus, taking fairness into consideration, we introduce the minimum capacity constraint for the satellite to protect the performance of the satellite. Then, the optimization problem can be formulated as

$$\max_{\mathbf{P}_B, \mathbf{P}_S} C_B + C_S \quad (2.11)$$

$$C1 : C_S \geq C_{S,0},$$

$$C2 : \sum_{J=1}^N P_{B,I,J} \leq P_{B,I,\max}, \forall I,$$

$$C3 : \sum_{J=1}^M P_{S,J} \leq P_{S,\max},$$

$$C4 : P_{B,I,J}, P_{S,J} \geq 0,$$

where C1 is the minimum capacity constraint for the satellite, C2 is the maximum transmit power constraint for the BSs, and C3 is the maximum transmit power constraint for the satellite.

2.2.3 Optimal Power Allocation Algorithm

We have formulated the maximum capacity optimization problem based on the minimum satellite capacity constraint as (2.11). However, problem (2.11) is non-convex due to the non-convex objective function C_B . In this section, by means of the successive convex approximation (SCA) approach [26], we transform the non-convex problem into a series of convex subproblems, which are then solved using the Lagrangian dual method.

2.2.3.1 Transformation of Optimization Problem

The original optimization problem in (2.11) is a non-convex problem of high complexity. To overcome this problem, we adopt the successive convex approximation (SCA) approach proposed in [26], which transforms the non-convex problem into a series of convex subproblems by approximating the non-convex function using some convex function around the feasible point and then solves the subproblem iteratively.

While constraints C1–C4 are all concave or linear, problem (2.11) is non-convex because of the non-convex function $C_{B,I,J,K} = \log_2(1 + \gamma_{B,I,J,K})$ in the objective function. We approximate this non-convex function by logarithmic approximation [27]:

$$\ln(1 + \gamma_{B,I,J,K}) \geq \theta_{B,I,J,K} \ln \gamma_{B,I,J,K} + \beta_{B,I,J,K}, \quad (2.12)$$

which is tight at $\gamma_{B,I,J,K} = \bar{\gamma}_{B,I,J,K}$ if the approximation parameters are selected as:

$$\theta_{B,I,J,K} = \frac{\bar{\gamma}_{B,I,J,K}}{1 + \bar{\gamma}_{B,I,J,K}}, \quad (2.13)$$

$$\beta_{B,I,J,K} = \ln(1 + \bar{\gamma}_{B,I,J,K}) - \frac{\bar{\gamma}_{B,I,J,K}}{1 + \bar{\gamma}_{B,I,J,K}} \ln \bar{\gamma}_{B,I,J,K}.$$

Apply the logarithmic approximation to both C_B and C_S , and change the variables by $\hat{\mathbf{P}}_S = \ln \mathbf{P}_S$, $\hat{\mathbf{P}}_B = \ln \mathbf{P}_B$, the lower bound of the objective function is obtained as follows:

$$\begin{aligned} C_B + C_S &\geq C_B(e^{\hat{\mathbf{P}}_B}, \boldsymbol{\theta}_S, \boldsymbol{\beta}_S) + C_S(e^{\hat{\mathbf{P}}_S}, \boldsymbol{\theta}_S, \boldsymbol{\beta}_S) \\ &= \sum_{l=1}^L \sum_{j=1}^N \sum_{K=1}^{|U_{B,I,J}|} \left[\frac{1}{\ln 2} (\theta_{B,I,J,K} \ln \gamma_{B,I,J,K}(e^{\hat{P}_{B,I,J}}) + \beta_{B,I,J,K}) \right] \\ &\quad + \sum_{j=1}^M |U_{S,J}| \left[\frac{1}{\ln 2} (\theta_{S,J,1} \ln \gamma_{S,J,1}(e^{\hat{P}_{S,J}}) + \beta_{S,J,1}) \right], \end{aligned} \quad (2.14)$$

in which

$$\begin{aligned} \gamma_{B,I,J,K}(e^{\hat{P}_{B,I,J}}) &= \frac{|\mathbf{h}_{I,J,K}^H \boldsymbol{\omega}_{I,J}|^2 e^{\hat{P}_{B,I,J}}}{\sum_{j=1, j \neq J}^N |\mathbf{h}_{I,J,K}^H \boldsymbol{\omega}_{I,j}|^2 e^{\hat{P}_{B,I,j}} + \sum_{j=1}^M |\mathbf{g}_{B,I,J,K}^H \mathbf{v}_j|^2 e^{\hat{P}_{S,j}} + \sigma_n}, \\ \gamma_{S,J,1}(e^{\hat{P}_{S,J}}) &= \frac{|\mathbf{g}_{S,J}^H \mathbf{v}_J|^2 e^{\hat{P}_{S,J}}}{\sigma_n}. \end{aligned} \quad (2.15)$$

Then, substituting the objective function with the lower bound as well as doing the variable transformation, we can obtain the approximate subproblem as

$$\min_{\hat{\mathbf{P}}_B, \hat{\mathbf{P}}_S} \left[C_B(e^{\hat{\mathbf{P}}_B}, \boldsymbol{\theta}_S, \boldsymbol{\beta}_S) + C_S(e^{\hat{\mathbf{P}}_S}, \boldsymbol{\theta}_S, \boldsymbol{\beta}_S) \right] \quad (2.16)$$

$$C1 : C_S(e^{\hat{\mathbf{P}}_S}, \boldsymbol{\theta}_S, \boldsymbol{\beta}_S) - C_{S,0} \geq 0,$$

$$C2 : P_{B,I,\max} - \sum_{J=1}^N e^{\widehat{P}_{B,I,J}} \geq 0, \forall I,$$

$$C3 : P_{S,\max} - \sum_{J=1}^M e^{\widehat{P}_{S,J}} \geq 0.$$

Note that we have transformed the problem into the standard form of convex optimization. According to [28], the log-sum-exp function is convex, and thus it is easy to prove that the subproblem (2.16) is a standard convex optimization problem. However, problem (2.16) is only the lower bound approximation of the original problem. To obtain the solution of the original problem, we update the approximate parameters in (2.13) using the results of the subproblem. Then, the updated parameters will be used for the calculation of the next iteration until the results converge.

2.2.3.2 Lagrangian Dual Method

In the last section, we have transformed the original non-convex optimization problem into a series convex subproblems by utilizing the SCA approach and logarithmic approximation. Then, in each iteration of the SCA approach, we solve the transformed subproblem in (2.16) by means of the Lagrangian dual method. The Lagrangian function of problem (2.16) is as follows:

$$\begin{aligned}
 L(e^{\widehat{\mathbf{P}}_B}, e^{\widehat{\mathbf{P}}_S}, \eta, \boldsymbol{\mu}, \lambda) & \quad (2.17) \\
 = & -C_B(e^{\widehat{\mathbf{P}}_B}, \boldsymbol{\theta}_S, \boldsymbol{\beta}_S) - C_S(e^{\widehat{\mathbf{P}}_S}, \boldsymbol{\theta}_S, \boldsymbol{\beta}_S) \\
 & - \eta \left[\sum_{J=1}^M |U_{S,J}| C_{S,J,1}(e^{\widehat{P}_{S,J}}, \theta_{S,J,1}, \beta_{S,J,1}) - C_{S,0} \right] \\
 & - \sum_{I=1}^L \mu_I (P_{B,I,\max} - \sum_{J=1}^N e^{\widehat{P}_{B,I,J}}) \\
 & - \lambda (P_{S,\max} - \sum_{J=1}^M e^{\widehat{P}_{S,J}}),
 \end{aligned}$$

where $\eta, \boldsymbol{\mu}$ and λ are the Lagrange multipliers of constraints C1, C2 and C3 in (2.16).

The dual function is

$$D(\eta, \boldsymbol{\mu}, \lambda) = \inf_{\widehat{\mathbf{P}}_B, \widehat{\mathbf{P}}_S} \{L(e^{\widehat{\mathbf{P}}_B}, e^{\widehat{\mathbf{P}}_S}, \eta, \boldsymbol{\mu}, \lambda)\}. \quad (2.18)$$

Then the Lagrangian dual problem is

$$\begin{aligned} \max_{\eta, \mu, \lambda} D(\eta, \mu, \lambda) \\ \text{s.t. } \eta, \mu, \lambda \geq 0. \end{aligned} \quad (2.19)$$

By solving $\frac{\partial L}{\partial P_{B,I,J}} = 0$ and $\frac{\partial L}{\partial P_{S,J}} = 0$, we can obtain the optimal solutions as

$$\begin{aligned} P_{B,I,J} = e^{\widehat{P}_{B,I,J}} &= \left[\frac{\sum_{K=1}^{|U_{B,I,J}|} \theta_{B,I,J,K}}{\mu_I \ln 2 + \sum_{\substack{j=1 \\ j \neq J}}^N \sum_{k=1}^{|U_{B,I,j}|} \theta_{B,I,j,k} \frac{|\mathbf{h}_{I,j,k}^H \boldsymbol{\omega}_{I,J}|^2}{I_{B,I,j,k}[t]}} \right]^+, \\ P_{S,J} = e^{\widehat{P}_{S,J}} &= \left[\frac{(1 + \eta) |U_{S,J}| \theta_{S,J,1}}{\lambda \ln 2 + \sum_{i=1}^L \sum_{j=1}^N \sum_{k=1}^{|U_{B,i,j}|} \theta_{B,i,j,k} \frac{|\mathbf{g}_{B,i,j,k}^H \mathbf{v}_I|^2}{I_{B,i,j,k}[t]}} \right]^+, \end{aligned} \quad (2.20)$$

where $(x)^+ = \max(0, x)$, and we define

$$I_{B,i,j,k}[t] = \sum_{l=1, l \neq j}^N |\mathbf{h}_{i,j,k}^H \boldsymbol{\omega}_{i,l}|^2 e^{\widehat{P}_{B,i,l}[t]} + \sum_{l=1}^M |\mathbf{g}_{B,i,j,k}^H \mathbf{v}_l|^2 e^{\widehat{P}_{S,l}[t]}, \quad (2.21)$$

which is calculated using the results of last iteration.

The optimal solution of the power allocation scheme is in the form of the Lagrange multipliers. Since $D(\eta, \mu, \lambda)$ in (2.18) is not differentiable. We calculate the Lagrange multipliers using the subgradient method:

$$\begin{aligned} \eta[t_\delta + 1] &= [\eta[t_\delta] - \delta_\eta[t_\delta + 1](C_S(\boldsymbol{\theta}_S, \boldsymbol{\beta}_S) - C_{S,0})]^+, \\ \mu_I[t_\delta + 1] &= \left[\mu_I[t_\delta] - \delta_{\mu_I}[t_\delta + 1](P_{B,I,\max} - \sum_{J=1}^N P_{B,I,J}) \right]^+, \forall I, \\ \lambda[t_\delta + 1] &= \left[\lambda[t_\delta] - \delta_\lambda[t_\delta + 1](P_{S,\max} - \sum_{J=1}^M P_{S,J}) \right]^+, \end{aligned} \quad (2.22)$$

where t_δ is the iteration step, and $\delta[t_\delta + 1]$ is the step size in each iteration of subgradient method.

Algorithm 1 Optimal power allocation algorithm

```

1: Initialize  $t = 1, \theta_B = \theta_S = 1, \beta_B = \beta_S = 0$  and  $\mathbf{P}_B[1] = \mathbf{P}_S[1] = 0$ 
2: repeat
3:   Initialize  $t_\delta = 1, \eta > 0, \mu > 0, \lambda > 0$ 
4:   Initialize  $\mathbf{I}_B$  referring to (2.21)
5:   repeat
6:     for  $l = 1$  to  $L$  do
7:       for  $J = 1$  to  $N$  do
8:         Update  $P_{B,l,J}$  referring to (2.20)
9:       end for
10:    end for
11:    for  $J = 1$  to  $J = M$  do
12:      Update  $P_{S,J}$  referring to (2.20)
13:    end for
14:    Update  $\eta, \mu, \lambda$  referring to (2.22)
15:    Update  $\mathbf{I}_B$  referring to (2.21)
16:    Set  $t_\delta = t_\delta + 1$ 
17:  until  $\mathbf{P}_B, \mathbf{P}_S$  converge
18:  Set  $\mathbf{P}_{B,l}[t] = \mathbf{P}_{B,l}[t + 1]$ 
19:  Update  $\theta, \beta$  referring to (2.13)
20:  Set  $t = t + 1$ 
21: until  $\mathbf{P}_B, \mathbf{P}_S$  converge

```

The optimal power allocation algorithm is summarized as Algorithm 1. We initiate the algorithm from a feasible point $\mathbf{P}_B[1], \mathbf{P}_S[1]$. In each iteration of the outer loop, we calculate the approximate parameters based on the results of last iteration and transform the original problem into a convex subproblem by logarithmic approximation. Then, in the inter loop, we solve the convex subproblem by means of the Lagrangian dual method. By solving the transformed subproblems iteratively, the results will converge to the optimal solution of problem (2.11).

2.2.4 Performance Evaluation

In this section, we provide the simulation results to evaluate the performance of the proposed power allocation algorithm. The satellite is assumed to be a LEO with a orbit of 1000 km. For simplification, we assume the total user number in each group is the same, and all users are uniformly distributed in the network. The carrier frequency is set as 2 GHz while the bandwidth B is set as 10 MHz. The AWGN power can then be calculated by $\sigma_n = BN_0$, in which $N_0 = -174$ dBm/Hz is the AWGN power spectral density. The maximum transmit power of all BSs are uniformly set as $P_{B,max} = 43$ dBm. The radio frequency (RF) power of the satellite is 80 W, and the transmit antenna gain is assume to be 50 dBi. The channels from BSs to users experience Rayleigh fading, and are modeled according to [29], while

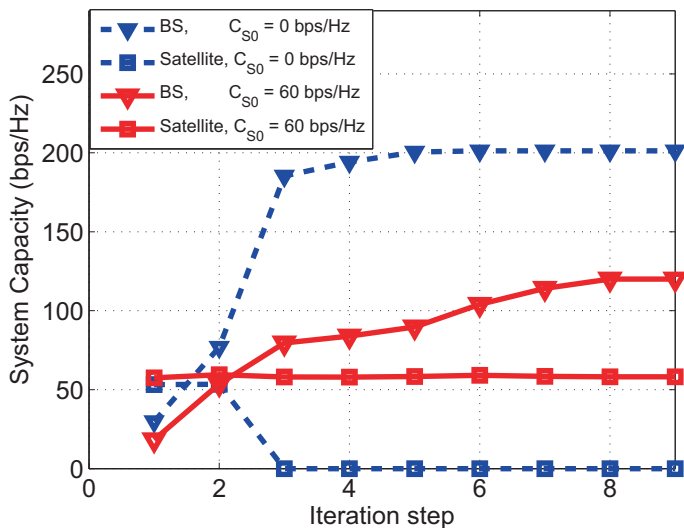


Fig. 2.5 The convergence process over iterations

the channels from the satellite to users are modeled as Rician channel according to [30]. Also, two other power allocation strategies are considered for comparison in the simulation, which are referred to as “Suboptimal Searching Algorithm” and “Greedy Algorithm”.

Figure 2.5 shows the convergence process of the proposed Algorithm 1, in which the BS number is set as $L = 3$, the group size is set as $|U_{S,j}| = 3$, the antenna numbers are set as $N = 2$ and $M = 2$. We can observe that for different settings of minimum capacity constraints $C_{S,0}$, the algorithm converges fast within ten steps. Also, since the satellite will cause interference to all BS users, the satellite capacity converges to almost zero if we set the minimum satellite capacity $C_{S,0} = 0$ bps/Hz.

Figure 2.6 gives the total capacity of the system of different BS numbers, in which we set the minimum satellite capacity constraint $C_{S,0} = 60$ bps/Hz, and the group size $|U_{S,j}| = 3$. We can observe that the total capacity almost increases linearly as BS number increases in all the cases, which indicates that introducing new BS to the system will not deteriorate the system performance. Also, with more transmit antennas, the system capacity will be improved, and we can see that increasing the antennas of either BSs or the satellite can achieve similar improvements. The system capacity increases by about 31.7% when both the BSs antennas and the satellite antennas increase from 2 to 4.

In Fig. 2.7, the influence of different group size on the system capacity is illustrated, in which the BS number is set as $L = 5$, the minimum satellite capacity constraint is set as $C_{S,0} = 60$ bps/Hz, and the group size is set as $|U_{S,j}| = 3$. Similar to the case of BS numbers, the total capacity also increases almost linearly with the group size. In the satellite system, since ZFBF is executed among groups, the satellite capacity is proportional to the group size. However, in the BSs system,

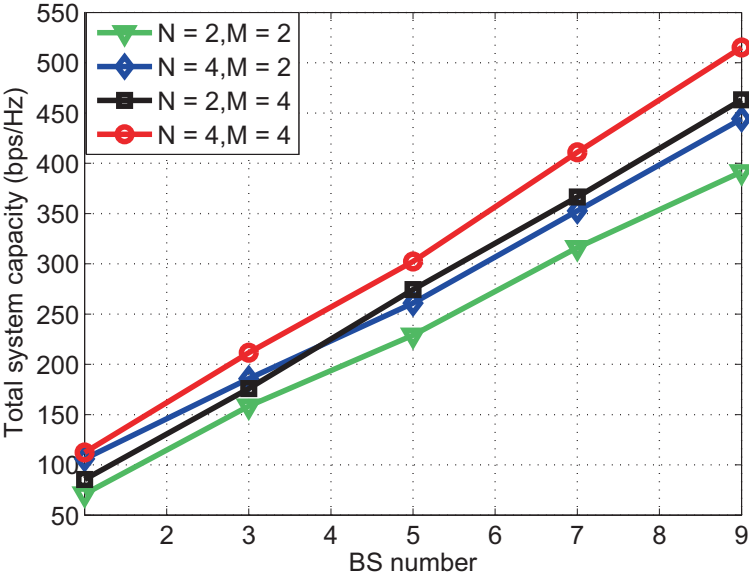


Fig. 2.6 Total system capacity of different interference temperature limit and antennas

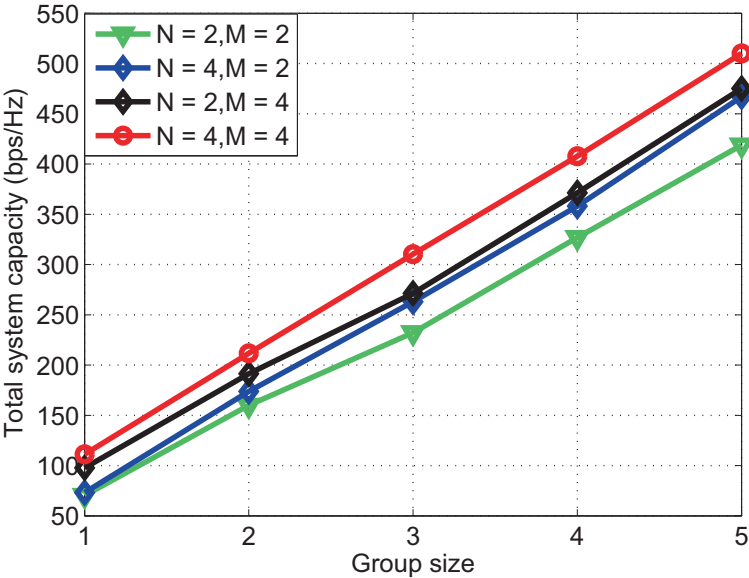


Fig. 2.7 Total system capacity of different group size

larger group size may cause larger inter-group interference, since the designing of beamforming vectors need to balance among all the users. On the other hand, larger group size also provides larger multi-user diversity gaining, which compensates

for the loss from inter-group interference. In multimedia multicast networks, the main system performance gaining comes from multicast transmission to groups. The linear increasing system performance indicates the potentials of multimedia multicast networks.

Finally, with $L = 3$, $N = 3$, $M = 3$, $C_{S,0} = 60$ bps/Hz, and $|U_{S,J}| = 4$, the comparison results with two other strategies are illustrated in Fig. 2.8. In the “Suboptimal Searching Algorithm”, a capacity-maximizing based searching is executed separately for each group to obtain the suboptimal power allocation scheme, while the water filling algorithm is adopted according to the channel conditions under the satellite capacity constraint in the “Greedy Algorithm”. We can observe that for different maximum BS transmit power, our proposed algorithm can achieve higher capacity performance, outperforming the two algorithms quite well. Due to the inter-group performance, the water filling algorithm cannot achieve satisfying performance, in which there is about 70% capacity loss compared to the optimal algorithm. The “Suboptimal Searching Algorithm” can achieve much better performance than the greedy strategy, since each group is optimized separately taking the inter-group interference into consideration. However, since only the suboptimal results are obtained, there is still about 15% loss of performance compared with the optimal algorithm.

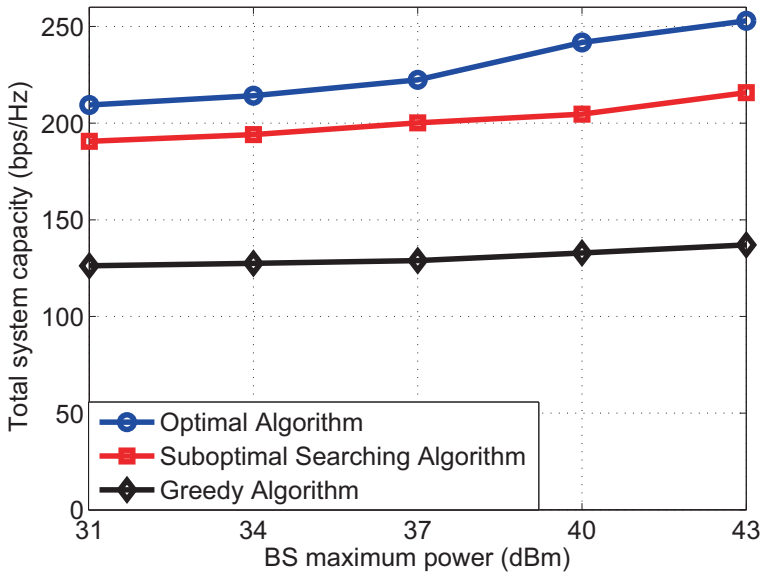


Fig. 2.8 Comparison of system performance with the heuristic strategy

2.3 Smart Communication Satellite

The satellite internet provides for both terrestrial and space users the communication and internet access services via communication satellites on different orbits. In the past few years, the satellite internet has evolved into a hot topic that captures the attention of both scientific research and industry operation all over the world. Google, SpaceX, and some other giants have all initiated their own satellite internet plan aiming to provide internet coverage, globally or specifically, using space network nodes such as medium earth orbit (MEO) satellite, e.g., O3b plan, and low earth orbit (LEO) satellite.

Satellites on various kinds of orbits, high, medium, and low, all can be used as transmission nodes in the satellite internet. Generally, high earth orbit (HEO) and MEO satellites cover the ground area through beamforming using multiple spot beams. However, due to their long distance (a few thousand to tens of thousands of kilometers) to the earth, HEO and MEO satellite systems suffer from high link loss, thus imposing high G/T and EIRP requirements on the ground terminals. For LEO communication satellite, e.g., Iridium and Globalstar, the distance between the earth and satellite is greatly reduced, and hence the link loss is low, so that direct communication between the satellite and small ground terminals can be supported. Nevertheless, the low orbit altitude limits the coverage area of one single LEO satellite. To meet the wide coverage requirement, multiple LEO satellites are usually arranged in accordance with a certain shape and rule to form a LEO satellite constellation, each satellite serving the ground in a uniform-coverage way. With the development of internet services, it is more and more difficult for LEO satellites with uniform coverage to meet the continually increasing requirements on communication rate. Though the energy of spot beams is more concentrated, using them naively would significantly reduce the coverage area. As such, under the limited energy constraint, the contradiction between coverage area and communication rate for LEO satellite becomes increasingly prominent.

Smart Communication Satellite (SCS), the first low earth orbit (LEO) mobile communication experimental satellite of China, developed by Tsinghua University and Beijing Xinwei Telecom Technology Inc., was launched on September 4, 2014 [31]. In order to solve the contradiction between data rate and cover range of LEO satellite communication, SCS exploits smart antennas on the LEO satellite, which produce fast-switched dynamic spot-beam, to meet the requirement of large coverage and high communication rate. In line with the current developing trends of small satellites, SCS makes a lot of efforts in communication-oriented satellite design. Through tackling a series of challenges under the constraints of size, cost, and energy, SCS developed a payload centric technique and accomplished the 100 kg-class weighted micro-satellite applicable to communication and navigation services. Firstly, SCS demonstrates the concept of smart beamforming for small satellite. Secondly, by using large numbers of industrial-grade components, SCS achieves low-cost facilities from altitude determination to the house-keeping system, as well as the communication payload. Finally, SCS accomplishes the file management, software upgrading and Internet access by a Linux operating system, making it naturally with the ability for evolution with Internet development.

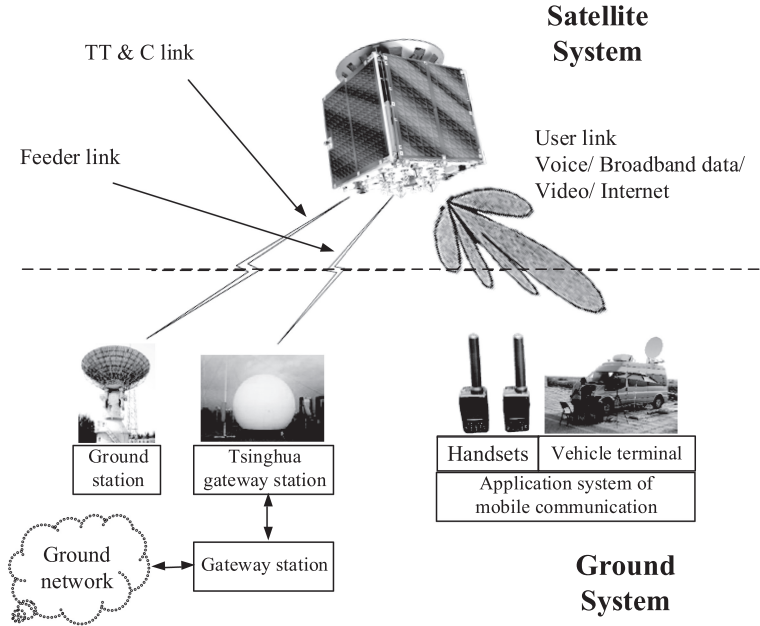


Fig. 2.9 The composition of SCS experiment system

2.3.1 System Design

The composition of SCS experiment system is presented in Fig.2.9. The entire experiment system can be divided into two parts: the satellite system and the ground system. The satellite system contains the platform system and the payload system, while the ground system contains the application system of payloads, ground station and gateway station. There are three links between the satellite and ground: S band TT&C link, C band feeder link and S band user link. TT&C link carries the tele-control and telemetry information. Feeder link produces the high speed data download passageway for the flight logs and experimental data. Meanwhile, the feeder link connects the mobile communication payload and Tsinghua gateway station. The customer link employs smart beam, which is created by the mobile communication payload, to build a smart space communication system. If there is no support from ground station, the satellite forms communication links between users under its footprint through on-board switching.

The SCS is formed by payloads and platform. The payloads contains multimedia mobile communication payload based on smart antenna (with C band feeder link), and spectrum scan payload. The platform contains power subsystem, Tt&C subsystem (S band transponder and Tt&C unit), house-keeping subsystem (OBC and GPS), attitude determination and control subsystem (ADCS), structure subsystem and thermal subsystem.

2.3.2 Smart Beamforming

The satellite communication has the feature of non-uniform services and uncertainty in user distribution. In the vast sea, land and space, the user requests are relatively concentrated but area-uncertain. SCS does not adopt the uniform coverage scheme as in the traditional mobile satellite communication system. Instead, after the users initiate the service request, it would calculate and adjust the beam direction in real time according to the position information of the satellite and the user. Then, by allocating the time, space, and frequency resources, the on-demand beamforming in vast coverage area is achieved, which is called as the smart beamforming. The smart communication system can be described as “Smart beam, On-demand coverage”, by which the Internet access and communication between the handsets users and vehicle terminals users under coverage area can be built. By providing directional services, SCS effectively increases the user’s transmission rate, and meanwhile efficiently exploits the limited energy of small satellites. Table 2.2 gives the onboard experimental results of SCS.

The onboard mobile communication payload is composed of antenna, radio frequency subsystem, and baseband subsystem. The circular array, embedded on the side facing the ground, consists of twelve 4-arm helical antennas and is shared by both the transmitter and receiver. By on board autonomic computing and adaptive digital phase control technique, SCS reduces the effect of orbit change and attitude deviation on the precise beam direction during the high-mobility process of satellite, and hence the signals in the user receiver can be coherently superposed exactly all the time. The spectrum resource applicable for LEO communication satellite is highly deficient at present. To address this problem, SCS uses spectrum scanning payload to acquire real-time information of the current electromagnetic spectrum environment, whereby it provides support for the future spectrum sensing communication.

Table 2.2 The onboard experimental results of SCS

Test project	Test results
Minimum elevation angle of devices	24°
Intranetwork call setup time of handheld devices	≤300 ms
Internetwork call setup time of handheld devices	≤400 ms
Delay of vehicle devices	≤100 ms
Uplink rate of handheld devices with single code channel	8 kbps
Uplink rate of handheld devices with double code channel	16 kbps
Downlink rate of handheld devices	Max 56 kbps
Uplink rate of vehicle devices	1024 kbps
Downlink rate of vehicle devices	1024 kbps

2.4 Summary

In this chapter, we discuss the main challenges when applying beamforming to satellite communication systems and introduced several prospective applications of satellite beamforming technology. Then, a multimedia multicast beamforming method for the integrated terrestrial-satellite network is proposed. Finally, a practical work of Smart Communication Satellite (SCS), the Chinese first low-earth-orbit communication satellite, is presented briefly.

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Terrestrial-Satellite Communication Networks

Transceivers Design and Resource Allocation

Kuang, L.; Jiang, C.; Qian, Y.; Lu, J.

2018, XIII, 151 p. 72 illus., 51 illus. in color., Hardcover

ISBN: 978-3-319-61767-1