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Spectrum Trading for Satellite Communication Systems with Dynamic Bargaining

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Abstract—With the rapid development of modern satellite communications, broadband satellite services are experiencing a period of remarkable growth in both the number of users and the available bandwidth. More efficient spectrum management schemes require deeper investigation in order to meet the ever-increasing demand for broadband spectrum. In this paper, we propose a band allocation method for multibeam satellite systems by introducing a market-driven pricing mechanism. Instead of adopting static and fixed band selling, we consider a satellite network operator that utilizes the mode of price bargaining to trade the unused band with terrestrial network operators. By applying market-based mechanism to support satellite spectrum allocation, higher spectrum efficiency can be attained in order for satellite systems to meet the increasing demands for satellite bandwidth at an affordable cost. Besides, for the one-to-many bargaining case without terrestrial operator involved in, a differential spectrum pricing solution is devised to address heterogeneous users' spectrum preferences. In a typical price bargaining model, market participants (i.e. terrestrial network operators) are assumed to know exactly their needs dynamically, which is hard to achieve in near real-time; thus, our approach approximates it with a sub-optimal estimation on the network operators' benefit threshold. To be specific, we obtain the optimal pricing at every round of bargaining by predicting the overall benefits of terrestrial network operators and reaching the Nash equilibrium. Essential discussions and proofs for the pricing rationality are provided. Numerical results are given to evaluate the impact of the pricing scheme on the profits of satellite systems.

Index Terms—Satellite communication systems, spectrum allocation, market-based mechanism

I. INTRODUCTION

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SATELLITE communication systems play an important part in the development of the pervasive internet infrastructure of the cyberspace due to their unique ability to establish a reliable network coverage across the globe, including remote and isolated rural areas [1]-[4]. In remote rural areas, where land-based communication infrastructures are prohibitively costly to provide, the availability of high bandwidth at affordable price has made satellite internet access an essential communication service that connects not only specialized users such as security surveillance and field mining, but also for ordinary users to take advantage of internet applications such as e-banking, navigation and Geosynchronous Orbit (GEO) positioning. As the worldwide demands for broadband satellite services have been growing at an unprecedented rate, the licensed spectrum of wider band for exclusive use, both for uplink and downlink, even in the Ka band has been shown to be insufficient [5]-[7].

With the rapid development of broadband satellite services, the need for improving bandwidth efficiency in satellite communications has become critical and attracted much attention from researchers and industry practitioners [8]-[10]. Furthermore, a variety of techniques including multiple spot beams, Orthogonal Frequency Division Multiplexing (OFDM), spectrum reuse and dynamic spectrum access, have been widely explored to facilitate broadband applications [11]-[15], wherein efficient satellite resource allocation plays a central role and always requires deep and full investigations. In specific application scenarios, when satellite systems use multiple beams to increase the total system capacity, each beam competes with one another for resources such as transmit power and bandwidth in order to achieve satisfactory communication. Hence, the satellite system requires a certain degree of flexibility in allocating its wireless resource to efficiently match the requested dynamic traffic [16]. For spectrum reuse in satellite cells, effective resource allocation is essential to managing inter-cell interference and enhancing system performance [17]. Besides, traditional satellite architectures were designed to cater for circuit traffic of fairly long duration and will be unsuitable to schedule burst data traffic, especially over time-varying channel capacities [18].

While plenty of resource allocation schemes have been proposed to fulfill the goal of improving bandwidth efficiency in satellite systems, most existing algorithms proposed for satellite networks employ centralized control [19]. Wherein, the large propagation delay inherent in satellite links and the large number of users needed to be served in emergency situations should be focused on. Indeed, flexible resource

allocation needs to take into account the factors of individual communication requirement, user priority, transmission diversity as well as service type in real time. Besides, working mainly in time division mode with flexible network schemes, such satellite systems manage their wireless resources by rationally allocating time slots, transmit power as well as spectrum band to address the aforementioned concerns. Various efforts have been reported in the literature to improve both energy and spectrum efficiency [20][21]. Resource allocation approaches that support dynamic spectrum and power allocation are likely to allow multibeam satellite systems to be more resource-efficient in complex network circumstances. Furthermore, allocation of spectrum band in satellite systems, especially cognitive satellite communications, that supports spectrum sharing among multiple terrestrial network operators have attracted plenty of interest [22]. In this case, the satellite spectrum is needed and shared by a number of, otherwise isolated, terrestrial network operations.

Compared to the study of resource allocation on terrestrial networks, the research work on satellite systems is not investigated very well. As the resource allocation in wireless networks always needs to balance the benefits of different participants which lets the activity more like a zero-sum game, market-driven mechanism consisted of auction-based or pricing-based approach is often under consideration in terrestrial networks. Thus, market-based method can more efficiently redeploy the scarce resource, balance the demands and even attract potential participants. However, to our knowledge, few related work is available for the satellite systems yet. Only several pricing-based methods for resource allocation in satellite communication networks have been proposed before [23]-[25].

In this paper, a market-based approach is introduced to solve the difficult problem of spectrum allocation in satellite networks. Instead of adopting the approaches based on differential traffic distribution, user demands and priority classification, or simple and direct pricing in the light of spectrum bandwidth, the proposed method applies a market-driven mechanism to balance the band requirements and needs of both the supplier and consumers, and completes the process of price bargaining by rounds of dynamic benefit prediction and price offering. The proposed scheme aims to maximize the profits of the satellite network through devising a proper pricing strategy and, at the same time, meets the band requirements of the terrestrial network operators at affordable costs. The satellite system offers a band price for every round of bargaining, then waits for the dealing decision from the band users until the last round of trading. During the spectrum price bargaining, the satellite network needs to revise its prediction of the overall benefits of the terrestrial networks after every round of bargaining so as to gradually and better approach a rational band price in the next round.

To better describe and illustrate the trading process, we use the model of Nash bargaining solution, which is a form of cooperative game to analyze the choice of a particular point on the Pareto efficiency. After identifying the Nash equilibrium, we obtain the optimal price for every round of bargaining to improve the satellite system's profits. Furthermore, the

proofs for the rationality of proposed spectrum price and unique existence of the Nash equilibrium are given. Numerical tests' results are provided to illustrate the impacts of various algorithm parameters on the optimal pricing and satellite systems' profits.

The contributions of this paper can be highlighted as follows.

- A novel pricing-based method for spectrum allocation in satellite communication networks is proposed, through introducing a market-driven concept into traditional fixed band allocation to satellite users.
- A Nash bargaining model is used to manage the resource negotiation interaction between the satellite network and terrestrial networks, and facilitates the optimal spectrum pricing for every round of bargaining.
- As the satellite network cannot exactly determine the satellite user's parameters, such as transmit power, users' active factor and dynamic distribution, which are essential to evaluate the terrestrial networks' benefits as the basis of the band price, our proposal rolls back to detect the benefits by estimating the upper thresholds of these parameters. The upper thresholds mean the maximum permitted values.
- After proposing an one-to-one pricing solution between the two bargaining agents, we further study the one-to-many spectrum pricing where differential user preferences are taken into account. We focus on the cases that terrestrial users' spectrum preferences comply with the normal and linear distributions, then propose corresponding spectrum algorithms to optimize satellite systems' profits.
- We further prove the rationality of the optimal spectrum pricing for every round of bargaining and the existence of an unique Nash equilibrium at this game.

The rest of this paper is organized as follows. We give the system model of band allocation for satellite networks in Section II. Then, the pricing algorithm based on Nash bargaining model is proposed in Section III. In Section IV, numerical results are provided to elucidate the performance of our proposal. We summarize this paper in Section V.

II. SYSTEM MODEL

A. Satellite Networks with Spectrum Sharing

In this paper, we consider a geostationary satellite network which employs a transparent architecture operating in the Ka-band. As the scenario involves flexible resource allocation and interference management, it is assumed that the satellite payload is equipped with the necessary modules, such as multiport amplifiers, flexible traveling wave tube amplifiers, etc.

Fig. 1 illustrates the application scenario proposed in this paper, where the satellite system and multiple terrestrial users coexist. The satellite networks carry out the satellite spectrum deal by exchanging useful information with the terrestrial cluster head, which performs the band trading on behalf of a group of end users. In this situation, the terrestrial users/terminals behave like general satellite ground terminals.

Fig. 1. System model

During the course, the terrestrial terminals carry transceiver compatible to both cellular and satellite data transmissions. So, the cluster head could communicate with the cluster members via the cellular air interface when the satellite connectivity has not yet been established. In another word, we do not restrict the terminals involving in this trading to satellite communications. They may have the authorities to access terrestrial cellular networks even the main point we focus in this paper lies in their activities of satellite transmission. The cluster head represents these users like an agent to perform price bargaining with the satellite systems no matter it is a base station or a common wireless terminal. The satellite systems will offer a continued band of idle spectrum as the leased spectrum. In this paper, we investigate the satellite spectrum trading in cases of one-to-one and one-to-many bargaining between terrestrial terminals and satellite systems. The satellite spectrum is scheduled to sell and the terrestrial users without monetary payment are not allowed to utilize the bands. During the course, any private deal or speculations should be avoided, and a spectrum bargaining in trust can be proceeded. Due to the limit of space, this paper is not inclusive of more complex situations.

Specifically, in order to improve spectrum efficiency in satellite networks, multibeam antenna technology is adopted in this system model where band reuse is generally deployed. In the course of spectrum reuse, a typical four-color spectrum reuse pattern is employed which is a practical scheme to avoid coverage conflict and improve spectrum efficiency as shown in Fig. 2.

Generally, when investigating resource allocation and interference management in multibeam satellite systems, the earth surface can be considered as a plane, on which each cell is approximated by an orthographic projection of the satellite beam. Thus, a cone is formed by a cell and the corresponding beam. We also take into account, during the design phase of satellite networks, that signal strength near the border of a beam is weaker than that in the center. Hence, in this work, we

Fig. 2. Spectrum reuse in multibeam satellite systems

suppose that most of the cells in the proposed system model, are not working under the mode of orthographic projection, but a oblique projection which makes the bottom of the cone similar to an ellipse. Moreover, the cell's shape will change with the angle between the central line and the bottom.

B. Interference Model & Terrestrial User's Utility Function

In terrestrial communication system, the strength of inter-cell interference mainly depends on the distance between adjacent cells, especially those reusing the same band. If the orthogonality between the terrestrial cells is perfect, less interference will be caused by the other cells. However, in mobile satellite communication system, the satellite antenna performs the role of spatial filter. Generally, the angular selectivity of beams is not ideal in practice, and the interference strength is also affected by the angle between the selected user's position and the central line of the corresponding beam, as shown in Fig. 3.

Thus, when taking into account the oblique projection, the subastral point does not match the cell's center well. In this case, the angle θ describing the deviation angle between user $(\beta, 2)$ and cell center o can be expressed as

$$\theta = \arccos \left(\frac{\{(d_o^s)^2 + (d_{\beta 2}^s)^2 - 2R^2[1 - \cos(d_{\beta 2}^o/R)]\}}{(2d_o^s d_{\beta 2}^s)^{-1}} \right) \quad (1)$$

where d_o^s denotes the distance between cell center o and the satellite as shown in Fig. 3. $d_{\beta 2}^s$ denotes the distance between user $(\beta, 2)$ and the subastral point, $d_{\beta 2}^o$ denotes the distance between user $(\beta, 2)$ and cell center o , and R means the earth radius.

In the GEO satellite communication system proposed in this paper, we adopt the communication mode of channelized Time Division Multiplexing (TDM). In general, in a channelized TDM system, an user in any single cell will suffer from interference caused by users working in other cells which share the same band. As for the number of users affected by interference, it depends on the network pattern and whether the cell is fully loaded. As shown in Fig. 2, user $(\beta, 2)$ denotes the

Fig. 3. Orientation angle with oblique projector

user causing interference to user $(\alpha, 1)$. Then, for the uplink channel, the carrier power can be obtained as

$$C = \frac{p_{\alpha 1} g_{\alpha 1}(\varepsilon_{\alpha 1}) G_{\alpha}(\theta_{\alpha 1}^{\alpha})}{(4\pi d_{\alpha 1}/\lambda)^2 f_{\alpha 1}(\varepsilon_{\alpha 1})} \quad (2)$$

where $p_{\alpha 1}$ denotes the transmit power of satellite terminal $(\alpha, 1)$, $\varepsilon_{\alpha 1}$ denotes the elevation angle from user $(\alpha, 1)$ to the satellite system, $g_{\alpha 1}(\varepsilon_{\alpha 1})$ denotes the antenna gain of terminal user $(\alpha, 1)$ at the direction $\varepsilon_{\alpha 1}$, $\theta_{\alpha 1}^{\alpha}$ is the derivation angle from user $(\alpha, 1)$ to the central line of cell α . $G_{\alpha}(\theta_{\alpha 1}^{\alpha})$ is the satellite antenna gain of cell α at the direction $\theta_{\alpha 1}^{\alpha}$. $d_{\alpha 1}$ is the straight-line distance between the user $(\alpha, 1)$ and the satellite system. λ denotes the wavelength, and $f_{\alpha 1}(\varepsilon_{\alpha 1})$ denotes the channel fading of user $(\alpha, 1)$ at the direction $\varepsilon_{\alpha 1}$.

Thus, interference among the terrestrial cells can be given as

$$I = \sum_{\beta=1}^k \frac{p_{\beta 2} g_{\beta 2}(\varepsilon_{\beta 2}) G_{\beta}(\theta_{\beta 2}^{\beta})}{(4\pi d_{\beta 2}/\lambda)^2 f_{\beta 2}(\varepsilon_{\beta 2})} \mu_{\beta 2} \rho_{\beta}^{\alpha} \quad (3)$$

where k denotes the number of the cells sharing the same frequency with cell α , $p_{\beta 2}$ denotes the transmit power of satellite terminal $(\beta, 2)$, $G_{\beta}(\theta_{\beta 2}^{\beta})$ is the satellite antenna gain of cell β at the direction $\theta_{\beta 2}^{\beta}$, $d_{\beta 2}$ is the straight-line distance between the user $(\beta, 2)$ and the satellite system, λ denotes the wavelength, and $f_{\beta 2}(\varepsilon_{\beta 2})$ denotes the channel fading of user $(\beta, 2)$ at direction $\varepsilon_{\beta 2}$. $\mu_{\beta 2}$ denotes the active factor of user $(\beta, 2)$ which is related to the user's service type. ρ_{β}^{α} is the polarization isolation factor between cell α and β . Then, the uplink Signal to Interference plus Noise Ratio (SINR) can be

expressed as

$$\text{SINR}_1 = \frac{p_{\alpha 1} g_{\alpha 1}(\varepsilon_{\alpha 1}) G_{\alpha}(\theta_{\alpha 1}^{\alpha})}{d_{\alpha 1}^2 f_{\alpha 1}(\varepsilon_{\alpha 1}) \sum_{\beta=1}^k \frac{P_{\beta 2} g_{\beta 2}(\varepsilon_{\beta 2}) G_{\beta}(\theta_{\beta 2}^{\beta}) \mu_{\beta 2} \rho_{\beta}^{\alpha}}{(4\pi d_{\beta 2}/\lambda)^2 f_{\beta 2}(\varepsilon_{\beta 2})} + N_0(\varepsilon_{\alpha 1}) B_1} \quad (4)$$

where N_0 is the spectral density of noise power which depends on the receiver antenna and equivalent noise temperature along with the climatic conditions over the coverage area as the noise temperature is aggravated by rain fading. B_1 denotes the bandwidth obtained by the satellite user 1 working at cell α .

When the satellite system agrees to share its dedicated band with users in terrestrial networks, it is understandable that the former wishes to realize steady profits from the activity. In this case, the spectrum pricing raised by the satellite system is supposed to be carefully designed and should be subject to the overall benefits expected by the terrestrial networks. Otherwise, the spectrum trading will be declined by the potential customers. Therefore, for the satellite system, a key task is to predict the terrestrial users' benefit accurately.

By analyzing the users' transmission Quality of Service (QoS) during satellite communications, it can be concluded that the terrestrial user 1 is required to achieve the transmission capacity as

$$C_1 = B_1 \times \log_2(1 + \frac{p_{\alpha 1} g_{\alpha 1}(\varepsilon_{\alpha 1}) G_{\alpha}(\theta_{\alpha 1}^{\alpha})}{d_{\alpha 1}^2 f_{\alpha 1}(\varepsilon_{\alpha 1}) \sum_{\beta=1}^k \frac{P_{\beta 2} g_{\beta 2}(\varepsilon_{\beta 2}) G_{\beta}(\theta_{\beta 2}^{\beta}) \mu_{\beta 2} \rho_{\beta}^{\alpha}}{(4\pi d_{\beta 2}/\lambda)^2 f_{\beta 2}(\varepsilon_{\beta 2})} + N_0(\varepsilon_{\alpha 1}) B_1}) \quad (5)$$

For terrestrial users, this is the utility function which can be used to describe their benefits based on the bandwidth obtained through the spectrum trading. Meanwhile, we assume the cluster head of the terrestrial users will reallocate the leased band to the other users, and all of the terrestrial users can work on the band by frequency division mode. In order to maximize the overall benefits of the terrestrial networks, we consider the satellite users involved in this work share the spectrum honestly and cooperatively.

In our proposal, the terrestrial users working in the satellite networks need to send all the essential parameters, such as user QoS and satisfactory degree, to the cluster head. Then, the cluster head, who represents the users to make bargaining with the satellite system, will pursue the most rational trading scheme.

III. PRICING ALGORITHM BASED ON NASH BARGAINING

A. Satellite Spectrum Pricing

This paper focuses on designing a theoretical method for guiding the process of spectrum trading in order to allocate satellite spectrum efficiently. We consider a scenario of dynamic interactions between the satellite system and different terrestrial network operators as shown in Fig. 1, wherein terrestrial users aim to take advantage of the satellite network's idle spectrum. In such circumstances, satellite bands are traded dynamically on a short-term basis. In the course of spectrum

trading, the satellite system broadcasts the essential information including the specific position of the leasing band, leasing price, transmission mode and internet protocol, etc, to assist the potential satellite users to make decisions. On the other hand, since terrestrial users are generally randomly distributed with stochastic number, the satellite system will not be able to obtain the complete user information for formulating a proper price policy once and for all. If the terrestrial users may take advantage of this informational asymmetry, and offer to use the satellite spectrum in low cost, the satellite network might be unwilling to participate in the trading in cooperative mode due to the potentially low benefit through this kind of spectrum sharing.

To avoid such unfair incidents and to incentivize satellite networks to participate in dynamic spectrum sharing with other terrestrial users, our work proposes a non-cooperative spectrum sharing model. The satellite systems offer a bid to conduct the cooperation with satellite users wherein the participants need to reach a coherent sharing agreement by constant bargaining. Thus, the satellite systems have the initiative of formulating the spectrum price and the terrestrial users cannot permitted to use the satellite band through other modes, such as dynamic spectrum access in underlay or overlay way without the authority of satellite systems, which safeguard the satellite systems' benefit in case of asymmetry trading information.

As mentioned in the previous section, satellite networks are not assumed to be smart networks equipped with highly intelligent resource management analysis devices, they cannot detect very detailed parameters of the terrestrial users. The spectrum trading is not a symmetric transaction for both sides. However, the satellite networks still need to evaluate the terrestrial network's benefit so as to offer a proper pricing to smoothen the trading process. To be specific, it is supposed that the satellite networks can estimate the values of G_i , k , $f_i \in i$ and ρ_i . Yet, the other parameters such as p_i , μ_i and $d_{\beta 2}$ are not easy to obtain. In this case, in order to precisely estimate the whole benefits of the terrestrial networks, our proposal considers to detect the benefits by estimating the upper thresholds of these parameters. In this case, the upper thresholds mean the maximum permitted values of these parameters. In other words, even if we cannot obtain the dynamic transmit power p_i of every user, we estimate the maximal power p_i^{max} . Similarly, we can also obtain the thresholds of minimal transmission distance between transmitter and receiver denoted as d_{min} . Since the satellite networks are only capable of estimating the upper threshold of the terrestrial networks' utility function which is expressed as U_{max} , it can be envisioned that the actual utility function of the networks is subject to $U_A \in [0, U_{max}]$. In the following deductions, we will consistently approach the actual utility U_A by adjusting U_{max} at every round of bargaining, then offer a proper price based on the latest estimation of the user's utility function.

The sharing and allocation of the satellite spectrum contain the following two constant progresses: Firstly, the satellite networks negotiate with the terrestrial networks to identify spectrum pricing and transmission mode. Secondly, the cluster head of the terrestrial networks reallocates the band to the

satellite users. In this paper, we mainly focus on the spectrum pricing scheme involved in the first progress. Before discussing the details of the pricing bargaining, we give several essential and basic settings as follows:

- 1) The maximum number of the bargaining rounds between the two networks is M which satisfies $M \geq 1$. If the cluster head of the terrestrial networks choose to decline the spectrum price offered by the satellite networks at the M th round, an agreement is not reached and the trading is over, which leads to zero benefit for both sides as a result.
- 2) At i th round of bargaining, the satellite networks price the band π_i . If the terrestrial networks accept the offered price, then the deal is done, otherwise $(i + 1)$ th round of bargaining proceeds.

According to the two basic preconditions, and the mode of satellite networks' estimate on terrestrial networks' actual utility, we can obtain the followings conclusions as:

- The spectrum pricing made by the satellite networks is degressive for every new round which can be expressed as $\pi_i > \pi_{i+1}$. To maximize its benefits, the satellite network will set a relatively high price for the spectrum in the initial stages of the bargaining which aims to explore the reaction of the terrestrial networks. If the pricing is resisted by the terrestrial networks, the satellite networks will lower the price in the next round, so that a deal can be made as early as possible.
- Prior to setting a price for every round, the satellite networks need to constantly estimate and update the maximum permitted values of the terrestrial networks' benefits. The i th round estimate of upper threshold can be denoted as $U_i (1 \leq i \leq M)$, where $U_i > U_{i+1}$ due to $\pi_i > \pi_{i+1}$. With the increase of bargaining rounds, which means the terrestrial networks decline the trading scheme proposed again and again, the satellite networks have to adjust its pricing to further approach the actual utility of the terrestrial networks, expressed as $U_i \Rightarrow U_A$. Meanwhile, the spectrum pricing will be updated due to the adjustment of U_i , so as to stimulate the terrestrial networks to accept the deal.
- According to the characteristics of band pricing and estimate threshold, we have the following basic inequation: $0 < \pi_i \leq U_A \leq U_i$. In other words, the spectrum pricing given by the satellite networks should be lower than the actual utility as well as the estimate threshold. As the actual utility of the users is uneasy to determine, we use U_i to approximate it. It is also apparent that U_i is larger than the actual benefits of the satellite networks due to the fact that it represents the upper threshold of the utility function defined in (5). In this case, it is envisioned that the pricing scheme proposed by satellite networks should be rational so as to be accepted by terrestrial networks.
- During the pricing bargaining, the number of the bargaining rounds M is not fixed and unknown to the terrestrial networks. When the time and opportunity costs increase, as a rational market participant, the terrestrial networks are also eager to complete the spectrum trading early.

Then, we define utility functions for both the satellite networks and terrestrial networks to disclose the detailed procedure involved in the spectrum bargaining. Firstly, we give the utility of the terrestrial networks at i th round of pricing as follows

$$T_i = \omega U_A - \pi_i \quad (6)$$

where U_A denotes the actual utility of the terrestrial networks, π_i denotes the band price at i th round and ω is the monetary coefficient which transfers the utility into monetary profits.

Secondly, the utility function of the satellite networks at i th round is defined as

$$S_i = \pi_i - \sigma B \quad (7)$$

where B denotes the spectrum band to be leased and σ is the monetary coefficient.

If the terrestrial networks do not accept the pricing even at the last round of bargaining, the spectrum trading fails and the benefits of both parts result in zero, expressed as $T = 0, S = 0$. Meanwhile, if the participants cannot realize the benefits at the first round, we introduce a parameter φ ($\varphi \in (0, 1]$) as the time discount which means the opportunity cost for the terrestrial networks to decline current trading price. As a result, after i round of bargaining, the terrestrial networks' benefits become to be $\varphi_t^{i-1} T_i = \varphi_t^{i-1} (\omega U_A - \pi_i)$, and the satellite networks' benefits $\varphi_s^{i-1} S_i = \varphi_s^{i-1} (\pi_i - \sigma B)$. In this case, we assume that the terrestrial networks' benefits will suffer a potential loss with the increase of bargaining rounds. In this paper, our proposed method is to optimize the spectrum allocation from the perspective of satellite systems. Therefore, the discount parameter φ is given by the satellite systems to estimate terrestrial networks' profits with the ultimate intention of devising a rational spectrum pricing strategy.

Remark 1: In case of i th round of bargaining, if the satellite networks propose a price of π_i , the terrestrial networks achieve the benefits of $T_i = \varphi_t^{i-1} (\omega U_A - \pi_i)$ in precondition of agreeing the deal. Otherwise, if the terrestrial networks resist π_i and accept π_{i+1} , their benefits could be $T_{i+1} = \varphi_t^i (\omega U_A - \pi_{i+1}) = \varphi_t T_i$. Besides, if they decline $\pi_i, \pi_{i+1}, \dots, \pi_{M-1}$ until π_M , the benefits are $T_M = \varphi_t^{M-1} (\omega U_A - \pi_M) = \varphi_t^{M-i} T_i$. To maximize its profits, the cluster head of the terrestrial networks will try to select the price which can best improve its utility function. To accomplish this goal, a precondition is assumed that the cluster head can communicate with terrestrial terminals and acquire the actual profit values denoted by transmission capacity instantaneously. In fact, a terminal's transmission capacity obtained from this spectrum bargaining is ascertained by (5). The terrestrial users are supposed to be capable of detecting precise external interference and background noise, then send the latest QoS to the cluster head to update U_A . When the cluster head decides to accept the pricing of π_i , we conclude

$$\omega U_A - \pi_i \geq \varphi_t^i (\omega U_A - \pi_{i+j}), j \in [1, M-i]. \quad (8)$$

We also have

$$U_A \geq \max \left\{ \frac{\pi_i - \varphi_t \pi_{i+1}}{\omega(1 - \varphi_t)}, \frac{\pi_i - \varphi_t^2 \pi_{i+2}}{\omega(1 - \varphi_t^2)}, \dots, \frac{\pi_M - \varphi_t^{M-i} \pi_{i+1}}{\omega(1 - \varphi_t^{M-i})}, \pi_i \right\}. \quad (9)$$

On the other hand, to guarantee the pricing at the i th round will benefit the terrestrial networks most, we obtain $T_i \geq T_{i-k}, (k = 1, 2, \dots, i-1)$. Then, we have

$$U_A \leq \frac{\pi_{i-k} - \varphi_t^k \pi_i}{\omega(1 - \varphi_t^k)}, k = 1, 2, \dots, i-1. \quad (10)$$

Thus, there is

$$U_A \leq \min \left\{ \frac{\pi_{i-1} - \varphi_t \pi_i}{\omega(1 - \varphi_t)}, \frac{\pi_{i-2} - \varphi_t^2 \pi_i}{\omega(1 - \varphi_t^2)}, \dots, \frac{\pi_1 - \varphi_t^{i-1} \pi_i}{\omega(1 - \varphi_t^{i-1})} \right\}. \quad (11)$$

Due to $U_A \leq U_i$, in order to approach the actual utility and maximize the satellite networks' benefits, we obtain the upper threshold of the actual utility as

$$U_i = \frac{\pi_{i-1} - \varphi_t \pi_i}{\omega(1 - \varphi_t)}. \quad (12)$$

Remark 2: For the terrestrial networks, their actual utility denotes the transmission capacity they receive from this band trading, thus there is $U_A = C$ where C has been given in (5). Besides, aiming to ensure the utility functions positive, we have $\omega \geq \pi_i / U_A$ and $\sigma \leq \pi_i / B$, which means proper selections of monetary coefficients are essential.

For the terrestrial cluster head, even if it knows the spectrum price proposed by the satellite networks will go down at the next bargaining round, it still requires to make a balance between the reduction in band price and the increase in time discount along with opportunity cost. In the following subsection, we investigate the optimal pricing for satellite networks at every round.

Theorem 1: For this satellite band trading with maximal M round bargaining, when U_A distributes uniformly in region $[0, U_M]$, the optimal pricing at last round of bargaining is $\pi_M^* = (U_M + \sigma B) / 2$.

Proof: At M th round of spectrum bargaining, for the terrestrial networks, an essential condition to accept the price offered by the satellite network is $U_A > \pi_M$. To maximize their utilities, the satellite networks should consider the following equation as their optimal strategy

$$\kappa_M = \max \{ (\pi_M - \sigma B) \times Pr(\text{accept } \pi_M) + 0 \times Pr(\text{reject } \pi_M) \} \quad (13)$$

Since U_A distributes uniformly in $[0, U_M]$, we have $Pr(\text{accept } \pi_M) = (U_M - \pi_M) / U_M$ and $Pr(\text{reject } \pi_M) = \pi_M / U_M$. After several deductions based on (13), we can obtain $\pi_M^* = (U_M + \sigma B) / 2$. ■

In fact, due to $U_M = \frac{\pi_{M-1} - \varphi_t \pi_M}{\omega(1 - \varphi_t)}$ and $\pi_M = (U_M + \sigma B) / 2$, we have $U_M = \frac{\pi_{M-1} - \varphi_t \sigma B / 2}{\omega - \omega \varphi_t + \varphi_t / 2}$ and $\pi_M = \frac{\pi_{M-1} - \varphi_t \sigma B / 2}{2\omega - 2\omega \varphi_t + \varphi_t}$.

After identifying the optimal pricing at the last round, we further investigate the optimal π_{M-1} at the $M-1$ th round.

At this point, in order to guarantee the maximal benefits, the satellite networks need to fix the following equation

$$\begin{aligned} \kappa_{M-1} = & \max\{(\pi_{M-1} - \sigma B) \times \Pr(\text{accept } \pi_{M-1}) + \\ & \varphi_t(\pi_M - \sigma B) \times \Pr(\text{reject } \pi_{M-1}, \text{accept } \pi_M) + \\ & 0 \times \Pr(\text{reject } \pi_{M-1}, \pi_M)\} \end{aligned} \quad (14)$$

Due to $U_{M-1} > U_M$, when the actual utility of the terrestrial networks lies in $[U_M, U_{M-1}]$, there is $\Pr(\text{accept } \pi_{M-1}) = (U_{M-1} - \pi_{M-1})/U_{M-1}$. Meanwhile, it can be concluded that the terrestrial networks will decline π_{M-1} and accept π_M if $U_A \in [\pi_M, U_M]$ holds. Hence, we have

$$\begin{aligned} & \Pr(\text{reject } \pi_{M-1}, \text{accept } \pi_M) \\ &= \Pr(\text{accept } \pi_M \mid \text{reject } \pi_{M-1}) \times \Pr(\text{reject } \pi_{M-1}) \\ &= \frac{U_M - \pi_M}{U_M} \frac{U_M}{U_{M-1}} = \frac{U_M - \pi_M}{U_{M-1}} \end{aligned} \quad (15)$$

Then, (14) can be rewritten as follows

$$\begin{aligned} \kappa_{M-1} = & \frac{(\pi_{M-1} - \sigma B)(U_{M-1} - \pi_{M-1})}{U_{M-1}} + \\ & \frac{\varphi_t(\pi_M - \sigma B)(U_M - \pi_M)}{U_{M-1}} \end{aligned} \quad (16)$$

Taking the derivation of κ_{M-1} and substituting U_M, π_M by $U_M = \frac{\pi_{M-1} - \varphi_t \sigma B/2}{\omega - \omega \varphi_t + \varphi_t/2}, \pi_M = \frac{\pi_{M-1} - \varphi_t \sigma B/2}{2\omega - 2\omega \varphi_t + \varphi_t}$, we have the optimal pricing for the satellite networks at the $M-1$ round as

$$\pi_{M-1}^* = \frac{U_{M-1} + \sigma B - \frac{\varphi_t B + \varphi_t \sigma A B}{2A^2}}{2 - \frac{\varphi_t}{2A^2}} \quad (17)$$

where $A = \omega - \omega \varphi_t + \varphi_t/2$ and $B = \varphi_t \sigma B/2$.

Theorem 2: In i th ($1 \leq i < M$) round of price bargaining, when the optimal pricing can be given as $\pi_i = c_i U_i$, we obtain the optimal utility of the satellite networks is

$$\begin{aligned} \kappa_i(U_i) = & [(mU_i + l)/n + d - \sigma B] \times \\ & \frac{[U_i - a[(mU_i + l)/n + d - \sigma B] + \varphi_t d]}{U_i} + \\ & \frac{\varphi_s [(mU_i + l)/n + d - \sigma B] + d - \sigma B}{U_i} \end{aligned} \quad (18)$$

where $a = \omega(1 - \varphi_t) + \varphi_t c$, $m = [\omega(1 - \varphi_t) + \varphi_t c]$, $l = [\omega(1 - \varphi_t) + \varphi_t c] \times (\varphi_t d - d + \sigma B + d\varphi_s - \sigma B\varphi_s)$, $n = 2[\omega(1 - \varphi_t) + \varphi_t c]^2 - 2c\varphi_s$, $c = (\sqrt{\Phi^2 - 8\Upsilon\varphi_t^2} - \Phi/4\varphi_t^2)$, $d = (2\omega c - \varphi_s)/(\varphi_s - 4\sigma)$, $\Phi = 2\omega\varphi_t - 2\omega\varphi_t^2 - \varphi_t + \varphi_s$ and $\Upsilon = 2\omega^2(1 - \varphi_t)^2 + \omega\varphi_t - \omega$, and there is

$$U_{i+1} = \frac{cU_i + d - \varphi_t d}{\omega - \omega \varphi_t + \varphi_t c} \quad (19)$$

Proof: According to the results of **Theorem 1**, we obtain $\pi_M^* = (U_M + \sigma B)/2$. Thus, we suppose there is the following linear equation between π_i and U_i

$$\pi_i = cU_i + d \quad (20)$$

The expected utility for satellite networks at i th round of bargaining can be expressed as

$$\kappa_i(U_i) = \max\{(\pi_i - \sigma B) \times \frac{U_j - \pi_i}{U_i} + \varphi_s \frac{U_{i+1}}{U_i} \kappa_{i+1}(U_{i+1})\} \quad (21)$$

According to (12), we have

$$\pi_i = \omega(1 - \varphi_t)U_{i+1} + \varphi_t \pi_{i+1} \quad (22)$$

On the basis of (20), (22) can be deduced to be

$$\pi_i = \omega(1 - \varphi_t)U_{i+1} + \varphi_t(cU_{i+1} + d) \quad (23)$$

As $\pi_i = cU_i + d$, we can obtain

$$U_{i+1} = \frac{cU_i + d - \varphi_t d}{\omega - \omega \varphi_t + \varphi_t c} \quad (24)$$

Substituting π_i in satellite networks' utility function, we have

$$\begin{aligned} \kappa_i(U_j, U_{i+1}) = & \{[\omega(1 - \varphi_t) + \varphi_t c]U_{i+1} + d - \sigma B\} \times \\ & \frac{U_i - \omega(1 - \varphi_t)U_{i+1} - \varphi_t(cU_{i+1} + d)}{U_i} + \\ & \frac{\varphi_s U_{i+1}(cU_{i+1} + d - \sigma B)}{U_i} \end{aligned} \quad (25)$$

Let $U_i = x$, $U_{i+1} = y$ and $\omega(1 - \varphi_t) + \varphi_t c = a$, (25) can be converted to

$$\begin{aligned} \kappa_i(x, y) = & \frac{(ay + d - \sigma B)(x - ay + \varphi_t d)}{x} + \\ & \frac{\varphi_s y(cy + d - \sigma B)}{x} \end{aligned} \quad (26)$$

Taking the derivation, we obtain the optimal U^* as

$$U_{i+1}^* = \frac{[\omega(1 - \varphi_t) + \varphi_t c](U_i + \varphi_t d - d + \sigma B) + d\varphi_s - \sigma B\varphi_s}{2[\omega(1 - \varphi_t) + \varphi_t c]^2 - 2c\varphi_s} \quad (27)$$

Then, the optimal pricing π_i^* at this round can be expressed as

$$\begin{aligned} \pi_i^* = & \omega(1 - \varphi_t) \times \frac{a(U_i + \varphi_t d - d + \sigma B) + d\varphi_s - \sigma B\varphi_s}{2a^2 - 2c\varphi_s} \\ & + \varphi_t(c \times \frac{a(U_i + \varphi_t d - d + \sigma B) + d\varphi_s - \sigma B\varphi_s}{2a^2 - 2c\varphi_s} + d) \end{aligned} \quad (28)$$

where $a = \omega(1 - \varphi_t) + \varphi_t c$.

Substituting π_i in (26) by this result, we have

$$\begin{aligned} \kappa_i(U_i) = & [(mU_i + l)/n + d - \sigma B] \times \\ & \frac{[U_i - a[(mU_i + l)/n + d - \sigma B] + \varphi_t d]}{U_i} + \\ & \frac{\varphi_s [(mU_i + l)/n + d - \sigma B] + d - \sigma B}{U_i} \end{aligned} \quad (29)$$

where $a = \omega(1 - \varphi_t) + \varphi_t c$, $m = [\omega(1 - \varphi_t) + \varphi_t c]$, $l = [\omega(1 - \varphi_t) + \varphi_t c] \times (\varphi_t d - d + \sigma B + d\varphi_s - \sigma B\varphi_s)$ and $n = 2[\omega(1 - \varphi_t) + \varphi_t c]^2 - 2c\varphi_s$. Furthermore, comparing (24) and (27), we also can achieve $c = (\sqrt{\Phi^2 - 8\Upsilon\varphi_t^2} - \Phi/4\varphi_t^2)$, $d = (2\omega c - \varphi_s)/(\varphi_s - 4\sigma)$, $\Phi = 2\omega\varphi_t - 2\omega\varphi_t^2 - \varphi_t + \varphi_s$ and $\Upsilon = 2\omega^2(1 - \varphi_t)^2 + \omega\varphi_t - \omega$. ■

Theorem 3. For given utility function $f_i = \kappa_i$ and strategy function $s_i = \pi_i$, a pure Nash equilibrium for the proposed pricing game algorithm exists.

Proof: Based on the theorem of Debreu's equilibrium existence [26], for the functions s_i and f_i given above, a pure strategy Nash equilibrium exists, once the following two

sufficient conditions can be satisfied: (1) In limited Euclidean space, strategy function s_i is a non-empty and compact subset. (2) For a strategy combination S based on s_i , f_i is continuous and concave.

First of all, we define $S : \Sigma \rightarrow \Sigma$ to be a Cartesian direct product for s_i and Σ_i is a simplex in dimension $|s_i|$. s_i can be a compact subset in limited Euclidean space only in the condition that s_i are symmetrically bounded and continuous functions is met. In order to prove s_i are symmetrically bounded, thus $\forall \varepsilon_1$, it requires certifying that $\exists \delta = \delta(\varepsilon_1)$ can make $\forall \psi \in F$ workable which can be

$$|\psi(x_1) - \psi(x_2)| < \varepsilon_1 \quad (\text{when } \rho(x_1, x_2) < \delta), \quad (30)$$

where $\rho(x, y) \triangleq \max_{a \leq t \leq b} |x(t) - y(t)|$ and $\psi(x_i) \Rightarrow s_i$. As the subset $\varepsilon_1/3$ is finite $\bar{N}(\varepsilon_1/3) = \{\psi_1, \psi_2, \dots, \psi_n\}$, then based on the characteristic of continuity, $\exists \delta = \delta(\varepsilon/3)$. Therefore, in condition of $\rho(x_1, x_2)$, we have

$$|\psi_i(x_1) - \psi_i(x_2)| < \varepsilon_1/3 \quad (i = 1, 2, \dots, n), \quad (31)$$

Because of $\forall \psi \in F, \psi_i \in N(\varepsilon/3)$ enabling $d(\psi, \psi_i) < \varepsilon/3$, we can obtain

$$\begin{aligned} & |\psi(x) - \psi(x')| \\ & \leq |\psi(x) - \psi_i(x)| + |\psi_i(x) - \psi_i(x')| + |\psi_i(x) - \psi(x')| \\ & \leq 2d(\psi, \psi_i) + |\psi_i(x) - \psi_i(x')| < \varepsilon_1 \quad (\text{when } \rho(x, x') < \delta), \end{aligned} \quad (32)$$

where $d(u, v) = \max |u(x) - v(x)|$. Besides, it is apparent that s_i can be continuous and differentiable, and we concluded s_i is a nonempty and compact subset in the limited Euclidean space.

Furthermore, since the requirement for concave function is that $f(tx + (1-t)y) \geq tf(x) + (1-t)f(y)$, and f_i is concave, we thus needs the following equation for the high-quality channels

$$\pi_i'' < 0, \quad (33)$$

Hence, obviously, proper parameter settings can satisfy the condition. Hence, the existence of a pure Nash equilibrium for our proposed algorithm has been proved in this case which is also unique [27]. ■

B. Solution of Sharing Satellite Band

Prior to the spectrum trading with satellite networks, the terrestrial cluster head should devise a proper solution of spectrum sharing for multiple satellite users to make full use of the spectrum they buy. The cluster head can evaluate the overall benefits of the terrestrial networks according to (5). Unlike non-cooperative pricing game between the networks, satellite users within the terrestrial networks are capable of cooperating with each other to enhance the usage efficiency of scarce spectrum. Thus, the cluster head can serve as the leader of this cooperative game and propose a feasible solution to share the spectrum. To accomplish this target, the cluster head needs to gather essential information of the terrestrial users involved in this spectrum bargaining. Therefore, the terrestrial networks are considered to work in the centralized mode and the header will act as a spectrum agent serving for both sides.

Fig. 4. User's satisfaction degree

Overhead cost should be undertaken by the cluster header to accomplish the satellite spectrum trading.

In this case, we raise a satisfaction-based spectrum sharing method to reallocate the purchased band. With rapid development of modern multimedia applications, wireless terminals should carry out multiple types of information transmission, such as voice, picture and data, etc. However, in fact, the time delay, QoS demand and service types are various which will eventually lead to the users satisfactory diversity even on same band, thus we aim to design an efficient resource sharing solution base on the satellite networks' characteristics to address this issue.

For a satellite user j , its transmission satisfaction degree USF_j at time t can be given as

$$USF_j^k = \sum_{t=t_0}^{\infty} \vartheta_j(t) f_j^k(R_{j,t}), \quad (34)$$

where $R_{j,t}$ denotes the transmission rate of user j at time t , $f_j^k(R_{j,t})$ denotes the satisfaction degree of user j for service type k with capacity $R_{j,t}$. k denotes the service type where $k = \{1, 2, 3\}$ presents the voice, picture and video services, respectively. t_0 denotes the initial times and $\vartheta_j(t)$ is the transmission weight where $\vartheta_j(t = t_0 + i) = \alpha^{\sqrt{i}}$ and $\alpha \in (0, 1)$. We have $\alpha \rightarrow 0, \vartheta_j(t) \rightarrow 0$ for the application with strict limitation on time delay, such as voice information. Otherwise, when the demand on time delay looses, there is $\vartheta_j(t = t_0 + i) = \alpha^{\sqrt{i}} \in (0, 1)$. Furthermore, in condition of no limitation on time delay, $\alpha \rightarrow 1$ and $\vartheta_j(t = t_0 + i) \rightarrow 1$.

As shown in Fig. 4, three application types have differential satisfaction curves where the video transmission needs large capacities, and the voice service works in very low rate. A variation of t is introduced to the definition of USF denoted in (34) to describe the service types performed by satellite users.

By introducing the definition of user's satisfaction degree, we can evaluate the overall service index for different kinds

of applications during satellite band usages. Wherein, if every satellite user involved in the spectrum sharing wants maximal USF defined in (34), it can be foreseen the network capacity will suffer damage, even impacting the band efficiency. In order to improve the network performance and take full advantage of cooperative bargaining within terrestrial networks, we devise a spectrum allocation solution based on the centralized Nash bargaining model to enhance the satellite users' satisfaction degree. We assume the band allocated to the satellite users are $Q = \{Q_1, Q_2, \dots, Q_N\}$, then the objective function of spectrum sharing can be expressed as

$$\begin{aligned} \max_{Q_1, Q_2, \dots, Q_N} \{ & \prod (Q) = [USF_1(Q_1)^{\tau_1}] [USF_2(Q_2)^{\tau_2}] \dots \\ & [USF_{N-1}(Q_{N-1})^{\tau_{N-1}}] [USF_N(Q_N)^{1-\tau_1-\tau_2-\dots-\tau_{N-1}}] \} \\ \text{s.t. } & \sum_{i=1}^N Q_i \leq Q^T \text{ and } Q_i \geq 0 \text{ for } 1 \leq i \leq N \end{aligned} \quad (35)$$

where $\tau_i (\tau_1 + \tau_2 + \dots + \tau_N = 1, 1 \leq i \leq N)$ denotes the weight information for user i involving in the resource allocation, Q^T denotes the band number. This optimization problem is a kind of constrained optimization which is subject to the convexity of the objective function. If every user's USF_j is convex, the problem can be solved by usual linear optimization. Otherwise, it should be converted to a sub-optimal problem to be fixed.

C. Spectrum Optimization with Heterogeneous Terrestrial User Selections

In the spectrum optimization proposal above-mentioned, we suppose a cluster head as the trading agent for terrestrial terminals to make bargaining with the satellite systems. Thus, a one-to-one trading model is designed and unfolded for attaining the optimal spectrum allocation strategy. In this subsection, we extend our research to the case of one-to-many bargaining where the cluster head is abandoned and terrestrial users obtain the satellite spectrum directly from the satellite systems. During the course, satellite systems need to predict heterogeneous purchasing needs of various users, then apply an optimal dealing strategy to optimize their profits.

In satellite communications, due to the apparent difference on fading characteristics and external interference for various satellite spectrum, the satellite spectrum qualities with different band positions are inhomogeneous. In our model, we classify the satellite spectrum into three types with high, medium and low qualities, respectively. Different kinds of satellite spectrum under same band means differential capacities for the terrestrial users. It can be expected that the high-quality spectrum deserves higher price or profit. In order to facilitate the satellite spectrum dealing, all the available spectrum is centralized and divided into uniform channels for selling.

At first, to specifically describe the benefits of terrestrial users involving in the one-to-many spectrum dealing, we give the utility function of terrestrial user k as

$$U_k = \varpi \theta_k C_i - \varrho p_i + \varsigma B_k, \quad (36)$$

Fig. 5. Terrestrial user's spectrum preference in various distributions

where C_i denotes the transmission capacity expressed in (5). Note that $C_{\{1,2,3\}}$ corresponds to low, medium and high quality of satellite spectrum. p_i denotes the pricing for spectrum $i (i = 1, 2, 3)$ with unfixed qualities, B_k denotes the fund budget of user k . ϖ, ς are monetary coefficient transforming the variables to uniform unit, and ϱ is a weighted coefficient. In this circumstance, due to the diversity of satellite spectrum quality, terrestrial users' spectrum selection cannot be same. We introduce spectrum preference parameter θ_k to depict the disparity related to various C_i where θ_k locates in $[\theta_1, \theta_3]$ and a terrestrial user l will select low-quality satellite spectrum C_1 when its preference parameter θ_l approaches to θ_1 . Furthermore, we define a non-preference parameter θ'_b to describe the balancing state that the terrestrial user does not have preference for both low-quality spectrum C_1 and medium-quality spectrum C_2 . Thus, there is $\varpi \theta_k C_1 - \varrho p_1 + \varsigma B_k = \varpi \theta_k C_2 - \varrho p_2 + \varsigma B_k \Rightarrow \theta'_b = \frac{\varrho(p_1 - p_2)}{\varpi(C_1 - C_2)}$. Similarly, θ''_b denotes the balancing point between C_2 and C_3 .

When satellite terminals' preferences are changing with different distribution characteristics in given region, the satellite systems require differential spectrum pricing schemes to maximize their profits. In this paper, we study the spectrum allocation schemes when terrestrial users' spectrum preferences are subject to normal or linear distribution. In fact, normal distribution match the real situation well since it can be adopted to model the stochastic scenario with massive statistical experiments. Fig. 5 presents the terrestrial user's preference distribution.

Then, based on the terrestrial user's preference characteristics, the profit function of the satellite systems can be expressed as

$$\begin{aligned} \xi = (p - M)D = & N_1(p_1 - M_1) \int_{\theta_1}^{\theta'_b} g(\theta) d\theta + \\ & N_2(p_2 - M_2) \int_{\theta'_b}^{\theta''_b} g(\theta) d\theta + N_3(p_3 - M_3) \int_{\theta''_b}^{\theta_3} g(\theta) d\theta, \end{aligned} \quad (37)$$

where $N = N_1 + N_2 + N_3$ is the total number of terrestrial users, M_i denotes the marginal cost of spectrum i

which can be given by $M_i = \mu C_i$, D denotes the demand function. Then, for the case of normal distribution, there is $F(\theta) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\theta} \exp[-\frac{1}{2}(\frac{\theta-\nu}{\sigma})^2] d\theta$. The first item of (37) can be deducted to be

$$\begin{aligned} \xi_1 &= N_1(p_1 - M_1) \int_{\theta_1}^{\theta'_b} g(\theta) d\theta \\ &= N(p_1 - \mu C_1) \int_{\theta_1}^{\theta'_b} \frac{1}{\sqrt{2\pi}} \exp[-\frac{1}{2}(\frac{\theta - \nu}{\sigma})^2] d\theta \\ &= \frac{N(p_1 - \mu C_1)}{\sqrt{2\pi}} \int_{\frac{\theta_1 - \nu}{\sigma}}^{\frac{\theta'_b - \nu}{\sigma}} \exp(-\frac{t^2}{2}) dt \\ &= \frac{N(p_1 - \mu C_1)}{\sqrt{2\pi}} \times [\int_{-\infty}^{\frac{\theta'_b - \nu}{\sigma}} \exp(-\frac{t^2}{2}) dt \\ &\quad - \int_{-\infty}^{\frac{\theta_1 - \nu}{\sigma}} \exp(-\frac{t^2}{2}) dt] = F \end{aligned} \quad (38)$$

In this case, we define $\alpha = \frac{N(p_1 - \mu C_1)}{\sqrt{2\pi}}$. Using circle area to approach integral domain and introducing polar coordinate form, we can convert (38) into

$$F^2 \approx \alpha \int_0^{2\pi} \int_0^R \exp(-\frac{\rho^2}{2}) \rho d\rho d\varphi = 1 - \exp(-\frac{R^2}{2}) \quad (39)$$

The satellite system's profit on spectrum I can be obtained as

$$\begin{aligned} \xi_1 &= N(p_1 - \mu C_1) \int_{\theta_1}^{\theta'_b} g(\theta) d\theta \\ &= \frac{N(p_1 - \mu C_1)}{2} \times (\sqrt{1 - \exp[-\frac{2}{\pi}(\frac{\theta_1 - \nu}{\sigma})^2]} \\ &\quad - \sqrt{1 - \exp[-\frac{2}{\pi}(\frac{\theta'_b - \nu}{\sigma})^2]}) \end{aligned} \quad (40)$$

where $\theta'_b = \frac{\varrho(p_1 - p_2)}{\varpi(C_1 - C_2)}$. With similar deduction process, we can also acquire ξ_2 and ξ_3 . Then, the satellite systems' profits in conditions of normal distribution of terrestrial users' spectrum preference can be identified. Besides, when the users' preferences comply with linear distribution, we have

$$\begin{aligned} \xi_1 &= N_1(p_1 - M_1) \int_{\theta_1}^{\theta'_b} g(\theta) d\theta \\ &= N(p_1 - \mu C_1) \int_{\theta_1}^{\theta'_b} \kappa \theta d\theta \\ &= \frac{1}{2} \kappa N(p_1 - \mu C_1) ([\frac{\varrho(p_1 - p_2)}{\varpi(C_1 - C_2)}]^2 - \theta_1^2) \end{aligned} \quad (41)$$

Similarly, we acquire $\xi = \xi_1 + \xi_2 + \xi_3$. Then, we can further achieve the optimal spectrum pricing p_1^*, p_2^*, p_3^* for spectrum I, II and III by taking the derivations of profit functions ξ_i .

Fig. 6 and Fig. 7 give the optimal pricing for satellite spectrum with different qualities. As shown in Fig. 6, the optimal pricing of spectrum III is relatively high due to its higher marginal cost. Besides, the optimal pricing in linear distribution is expensive as the terrestrial users prefer high-quality spectrum.

Fig. 6. Optimal pricing for satellite spectrum

Fig. 7. Optimal pricing for spectrum I in various distribution types

IV. NUMERICAL RESULTS

In this section, we testify the performances of our proposed utility functions and spectrum pricing scheme. In the following tests, we first fix several relevant parameters as $SINR^{tar} = 10\text{dB}$, $N_0(\varepsilon_{\alpha 1}) = 0.004$, $f_{\beta 2} = 0.15$, $\mu_{\beta 2} = 0.2$, $\rho_{\beta}^{\alpha} = 0.03$, $p_{max} = 10W$, $t_0 = 1$, $Q_p = 10\text{kHz}$, $g_{\alpha 1} = 15\text{dB}$, $G_{\alpha 1} = 47\text{dB}$. The beams of satellite systems are 36, and clonal proportion is set to be 4. In this case, we consider that inter-cell interferences are mainly caused by spectrum reuse within the satellite systems' multibeam cells, and assume no further interferences from other satellite networks or terrestrial networks take effect.

As shown in Fig. 8, the performances of optimal pricing obtained with different monetary coefficients $\omega(USD/bps/Hz)$ are given, where the abscissa value means the actual utility of

Fig. 8. Optimal pricing with different monetary coefficients ω

Fig. 9. Optimal pricing with different monetary coefficients σ

terrestrial networks. In this case, we fix $\sigma = 0.6(USD/Hz)$. The unit of spectrum price can be as USD. The expression of the optimal pricing can be achieved by (28). In this figure, it is apparent the spectrum prices rise with upgrading actual utility of terrestrial networks denoted by U_A and increasing ω . The actual utility U_A which can be predicted and estimated by U_j , has been expressed in (5). When U_A increases, terrestrial networks receive more benefits from the spectrum trading which make it possible for the terrestrial cluster head to accept higher band price. Thus, as a result, satellite networks incline to offer higher price for reaping more profits in respond. In fact, larger actual utility U_A corresponds to a larger U_j . We substitute U_j into (28), then achieve a higher optimal pricing for the satellite systems. On the other hand, we can obtain from Fig. 8, the spectrum pricing also increases with upgrading ω .

It is understandable that larger monetary coefficient ω in (6) leads to more system utilities for terrestrial networks. Similar to the effects of U_A , the terrestrial cluster head is willing to agree with an expensive band price only when a better income based on the leased spectrum is expectable. When the terrestrial users are running demanding applications (with respect to data rate), the cluster head should be prepared to pay a higher price for the leased satellite spectrum, as compared to the one reached when the users are only running non data-hungry applications. Also, for a fixed value of U_A (i.e., the same average data rate demands by the terrestrial users), the terrestrial operator will lease the spectrum at a higher price, when the offered services are more expensive.

Besides, in Fig. 9, we give the optimal pricing performances with different monetary coefficients σ . In this situation, we fix $\omega = 1$. As shown from the figure, when σ decreases, spectrum pricing gets down. We can obtain from the definition of satellite networks' utility function that larger σ means more potential trading cost for the satellite systems, thus a benefit balance is required which likely incurs a price rise as a result. Similarly, for a given value of actual utility U_A , the terrestrial operator will pay less, in case the price per Hz is lower, as compared to the case where satellite bandwidth is considered as a very precious resource.

In Fig. 10 and Fig. 11, we give the performances of the satellite networks' utilities with changing monetary coefficients ω and time discount φ_s . Satellite system's utility function has been given in (29). As shown in Fig. 10 and Fig. 11, in general, the system utility will rise with increasing U_A . Also, we can achieve from the expression of utility function that the utility is not changing linearly with U_A . To be specific, in the region of large U_A , the utility will edge up, but not by much. Thus, the marginal effect begins to take effect. On the other hand, when time discount index φ_s rises which means the satellite networks have to encounter a high loss with increasing rounds of pricing bargaining, then the cost pressure makes the satellite networks anxious to offer a more proper price to promote the deal. As a result, very high system utility is relatively uneasy to reach. In addition, many parameters all have apparent impacts on the system utility more or less, we do not provide more numerical results to present the facts due to limited amount of space.

Furthermore, the performances of optimal pricing with various time discount φ_s and φ_t are given in Fig. 12 and Fig. 13. For both satellite and terrestrial networks, different time discounts mean various marginal costs since there is an opportunity cost for the terrestrial cluster head to decline the spectrum price at the current round of bargaining for seeking a lower price in future. The cluster head needs to balance the potential benefit damage with more ideal price in the following rounds. Excessive anticipations on a lower band price offered by the satellite systems will cause a trading failure which will be harmful to terrestrial networks' benefit in the end. Due to the poor predictability of both the pricing of next round along with the cluster head's decision, every participant should not be too subtle to carry out the bargaining. It is wise for both of them to seek a quick deal which means the terrestrial cluster head would accept the offer once a proper spectrum price is

Fig. 10. Satellite networks' utilities with different monetary coefficients ω

Fig. 12. Optimal pricing with different time discount ϕ_t

Fig. 11. Satellite networks' utilities with different time discount ϕ_s

Fig. 13. Optimal pricing with different time discount ϕ_s

available.

At last, we further present the performances of optimal spectrum pricing at every bargaining round in Fig. 14. It is apparent that the optimal price goes down with the increase of bargaining rounds which accords with our basic assumption that the spectrum pricing made by satellite networks is degressive for every new round expressed by $\pi_i > \pi_{i+1}$. During the pricing bargaining, the number of bargaining round is not fixed or predictable to the terrestrial cluster head. When the time and opportunity costs increase, as a rational game player, the cluster head is also inclined to complete the trading early. On the other hand, we can obtain from the figure, the price decrease with rising rounds becomes shallowing with the increase of satellite systems' marginal cost and narrowing of the further bargaining. For the similar reason, too many

bargaining rounds will cause damage to both participants.

V. CONCLUSION

In this paper, the issue of efficient spectrum management of multi-beam satellite systems was discussed, and a market-driven approach for band allocation in satellite networks was proposed. This resource allocation technique was not extended from the perspectives of fixed band pricing, hot traffic distribution, user demand diversity or dynamic spectrum access. Our goal is to improve the utility of the scarce band resource by increasing the economic benefits to satellite systems and balancing the demands of terrestrial networks via price adjustment. The proposed solution of band pricing aimed to maximize the profits of satellite networks. After evaluating the actual benefits achieved by the terrestrial networks at every

Fig. 14. Optimal pricing at every round

round of bargaining, a non-cooperative game-based model was adopted to form the interaction between the satellite systems and the terrestrial cluster head who acts as a trading agent to make the deal. As the unattainability of accurate values of the terrestrial networks' benefits for each bidding round due to dynamic transmit powers or distribution of the satellite users, a sub-optimal estimating approach is devised to approach the actual values. Besides, the Nash equilibrium was identified to fix the optimal band price for every round of bidding. We further proved the rationality of the proposed pricing solution and the existence of a rational and unique Nash equilibrium in this game. Numerical results were further provided to evaluate the performance of our proposed pricing on the system's benefits. In the following research, we will investigate the pricing diversity of the different satellite bands to address the problem of resource allocation in satellite systems more detailedly.

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