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Spectrum Optimization for Satellite Communication Systems with Heterogeneous User Preferences

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***Abstract*—Owing to the proliferation of sophisticated satellite applications and rapid growth in data-consuming satellite services, refining spectrum efficiency remains a critical issue for satellite systems and has been promoted by the research community mainly from the perspectives of spectrum reuse and dynamic spectrum access. In this paper, we propose a new approach to spectrum optimization for multibeam satellite systems — introducing a market-based pricing mechanism. In this work, a key point to be highlighted is challenge is to build a market-inspired model that takes into consideration of satellite communication characteristics, not only simply migrating spectrum pricing of terrestrial networks into satellite systems. In this connection, we propose a differential pricing scheme which formulates the optimization problem based on the Hotelling model. The differential pricing scheme is capable of addressing the heterogeneous and tremendous effects of long and rigorous satellite links on its spectrum. Numerical results are given to show the effectiveness of the proposed method in enhancing spectrum efficiency.**

***Index Terms*—Multibeam satellite systems, satellite communications, spectrum allocation, Hotelling model**

I. Introduction

SATELLITE communication networks have successfully served the traditional needs of the telecommunication market, i.e. telephony and broadcasting. In recent years, owing to the rapid development of high-throughput satellites systems, they are increasingly relied upon as a broadband access solution in geographic areas where terrestrial links are impractical to deploy [1]-[5].

Many techniques including multiple spot beams, multi-protocol label switching, stochastic networks and dynamic spectrum access have been developed to exploit satellite system's potentials in order to support broadband or data-consuming satellite applications [6][7]. During the course of designing a proper resource optimization strategy in communication systems, a key point required to be fixed is how to balance the benefits of every parts involving in the bargaining. Especially in terrestrial communication networks, market-inspired technique including pricing-based or auction-based method is often under consideration to search the optimal solution or attract potential participants. Nevertheless, to the best of our knowledge, related marketed-oriented research work for satellite communication systems is still few, only several pricing-based resource optimization proposals have been devised [8][9].

As satellite bands have extensive span ranging from several hundreds of MHz to dozens of GHz, and satellite links always suffer from long and unstable paths, different satellite applications could experience hugely different levels of channel fading. When satellite networks accumulate sufficient idle spectrum for uniform selling, it requires a sophisticated and well-formulated mechanism to maximize the utilization of the heterogeneous and possibly unstable spectrum. To address this issue, we introduce a differential pricing model, the Hotelling model which is suitable for pricing scenarios with heterogeneous products. Through this dynamic pricing method for satellite systems, the proposed market mechanism incentivize different users to participate and optimize utilization efficiency autonomously. This way, the main concerns of satellite users can be addressed, while their stochastic preferences on heterogeneous spectrum will be modeled on the basis of this spectrum pricing. An iterative pricing algorithm is achieved after establishing the Nash equilibrium. The rest of this paper is organized as follows. In Section II, a system model with regard to multibeam satellite systems is given. Then, the spectrum optimization algorithm applying Hotelling game model is developed in Section III to maximize satellite systems' benefits. Also, numerical results are provided to testify the proposal's performances in Section IV. We conclude this paper in Section V.

II. System Model

A multibeam satellite system which stays in geostationary track and adopts spectrum reuse technique to enhance spectrum utilization is considered in this paper. To be specific, a practical four-color spectrum reuse pattern is applied in the scenario as shown in Fig. 1. The satellite systems are supposed to utilize flexible resource optimization methods. And, only uplink transmission of satellite users is considered in this case. Besides, oblique-projection-based multibeam system is taken

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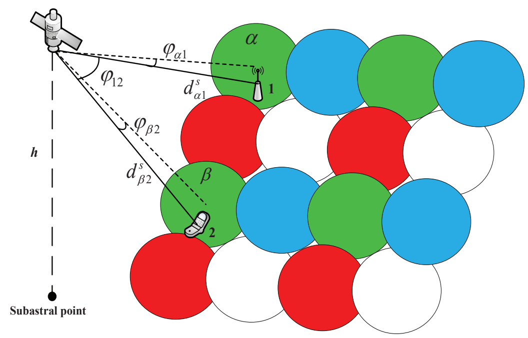

Fig. 1. System model of multibeam satellite systems

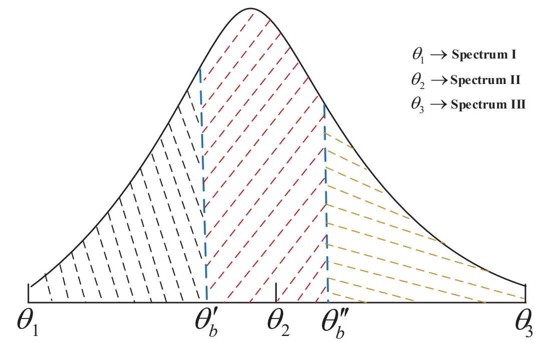

Fig. 2. Terrestrial user's spectrum preference

into account to make the system model closer to the actual applications. As shown in Fig. 1, the cells with same color share the same band wherein interference will occur.

In multibeam satellite systems, inter-beam interference can have impacts on system performance. In the coverage area of multibeam satellite, oblique projection is mixed with ellipse projection which leads to the difference between multibeam satellite systems and traditional cellular distribution. In this case, we take into account the effects of this mixed projection as shown in Fig. 1. Wherein, φ denotes the deviation angle between satellite terminal $(\beta, 2)$ and the cell center. We have

$$\begin{aligned}\varphi = &\arccos\left(\{(d_o^s)^2 + (d_{\beta 2}^s)^2 - 2R^2[1-\cos(d_{\beta 2}^o/R)]\},\right.\\ &\left.\times\,(2d_o^s d_{\beta 2}^s)^{-1}\right)\end{aligned} \tag{1}$$

where d_o^s is the distance between spatial satellite and the cell center. $d_{\beta 2}^s$ and $d_{\beta 2}^s$ are the distances from terrestrial user $(\beta, 2)$ to satellite and subastral point, respectively. R denotes earth radius. In uplink transmission, the inter-beam interference can be given as

$$I = \sum_{\beta=1}^{l} \frac{\rho_{\beta 2} g_{\beta 2}(\alpha_{\beta 2}) G_\beta(\xi_{\beta 2}^{\beta})}{(4\pi d_{\beta 2}/\lambda)^2 f_{\beta 2}(\alpha_{\beta 2})} \mu_{\beta 2} \varrho_\beta^\alpha, \tag{2}$$

where $\rho_{\beta 2}$ is the transmit power of satellite user $(\beta, 2)$. $g_{\beta 2}(\varepsilon_{\beta 2})$ denotes the antenna gain of terminal user $(\beta, 2)$ at direction ε_{Mn}, $G_\beta(\xi_{\beta 2}^{\beta})$ is the satellite antenna gain of cell β at direction $\xi_{\beta 2}^{M}$ and $f_{\beta 2}(\varepsilon_{\beta 2})$ denotes the channel fading of user $(\beta, 2)$ at direction $\varepsilon_{\beta 2}$. ϱ_β^α is the polarization isolation factor between cell β and α. Then, for satellite user $(\alpha, 1)$ shown in Fig. 1, the transmission capacity with unit bandwidth can be expressed as

$$\begin{aligned}C_{\alpha 1} = &\log_2(1+\\ &\frac{\rho_{\alpha 1} g_{\alpha 1}(\varepsilon_{\alpha 1}) G_\alpha(\varphi_{\alpha 1})}{d_{\alpha 1}^2 f_{\alpha 1}(\varepsilon_{\alpha 1}) \sum\limits_{\beta=1}^{l} \frac{\rho_{\beta 2} g_{\beta 2}(\varepsilon_{\beta 2}) G_\beta(\varphi_{\beta 2}) \mu_{\beta 2} \rho_\beta^\alpha}{(4\pi d_{\beta 2}/\lambda)^2 f_{\beta 2}(\varepsilon_{\beta 2})} + N_0(\varepsilon_{\alpha 1})}).\end{aligned} \tag{3}$$

where $\rho_{\alpha 1}$ is the transmit power of user $(\alpha, 1)$, $N_0(\varepsilon_{\alpha 1})$ denotes the noise, $g_{\alpha 1}$ and G_α denote the antenna gain and $d_{\beta 2}$ denotes the straight-line distance from user $\beta 2$ to the satellite system.

III. Spectrum Optimization Pricing

In this paper, the satellite spectrum allocation is carried out in the mode of spectrum trading where satellite systems offer price on the satellite spectrum with differential transmission qualities to potential satellite users. All the available satellite bands are divided into uniform channels for centralized selling. Besides, since the fading characteristics and external interference of various satellite bands vary apparently, in the system model, we classify the satellite spectrum into three types with high, medium and low qualities. Various spectrum qualities means different transmission capacities for the satellite users. Hence, it can be envisioned that high-quality spectrum is worthy of higher price.

Based on the transmission capacity given above, for spectrum i, the utility function of a satellite user involving in this spectrum trading can be given as

$$U_t = \varpi \theta C_i B - \varepsilon p_i, \tag{4}$$

where C_i denotes the transmission capacity or spectrum quality depicted in (3), B denotes the bandwidth, p_i denotes the spectrum price, ϖ is monetary coefficient which transforms capacity to uniform unit. Besides, ε denotes weighted coefficient. In this paper, we define a preference parameter θ locating in $[\theta_1, \theta_3]$ to describe terrestrial user's preference on three kinds of satellite spectrum, as shown in Fig. 2. To be specific, if a user j would like to pick up a high-quality spectrum, its θ_j approaches to θ_3.

To further formulate the pricing problem, we further introduce a non-preference coefficient θ_b to depict a balancing preference state which means the satellite terminal has no preference for adjacent spectrum. As shown in Fig. 2, θ_b' is achieved by $U_t^{C_1} = U_t^{C_2} \Rightarrow k\theta_b' C_1 B - \varepsilon p_1 = k\theta_b' C_2 B - \varepsilon p_2$. Thus, we have $\theta_b' = \frac{\varepsilon(p_1 - p_2)}{\varpi B(C_1 - C_2)}$. Similarly, we obtain $\theta_b'' = \frac{\varepsilon(p_2 - p_3)}{\varpi B(C_2 - C_3)}$.

After interpreting user's preference characteristics, the profit function of the satellite systems on spectrum $i (i \in [1, 3])$ can be expressed as

$$\pi_i = (p_i - M_i) D_i = N(p_i - M_i) \int g(\theta) d\theta, \tag{5}$$

where D_i denotes the demand function, N denotes the user number, M_i denotes the marginal cost for the satellite systems and $g(\theta)$ is the PDF of preference parameter. Then, we give the detailed expressions of profit function and corresponding optimal pricing for spectrum I. Similar conclusions are applicable to spectrum II and III. Therefore, for spectrum I, based on (5), we have

$$\pi_1 = (p_1 - M_1)D_1 = N(p_1 - \mu C_1 B)\int_{\theta_1}^{\theta_b'} g(\theta)d\theta, \quad (6)$$

Apparently, we have to identify the PDF of user preference parameter so as to solve (6) and achieve the specific satellite system's function on spectrum I eventually. Due to the randomicity of user preference, a normal distribution characteristics can be assumed in condition of massive data.

Proposition 1: When terrestrial user's preference parameter θ is subject to stochastic normal distribution, satellite systems can reap profits on spectrum I as

$$\pi_1 = \frac{N(p_1 - \mu C_1 B)}{2} \times (\sqrt{1 - \exp[-\frac{2}{\pi}(\frac{\theta_1 - \nu}{\sigma})^2]} - \sqrt{1 - \exp[-\frac{2}{\pi}(\frac{\frac{\varepsilon(p_1-p_2)}{\varpi B(C_1-C_2)} - \nu}{\sigma})^2]}). \quad (7)$$

Proof: To identify satellite system's profit, we deduct (6) as follows

$$\begin{aligned} & N(p_1 - \mu C_1 B)\int_{\theta_1}^{\theta_b'} g(\theta)d\theta \\ &= N(p_1 - \mu C_1 B)\int_{\theta_1}^{\theta_b'} \frac{1}{\sqrt{2\pi}}\exp[-\frac{1}{2}(\frac{\theta-\nu}{\sigma})^2]d\theta \\ &= \frac{N(p_1 - \mu C_1 B)}{\sqrt{2\pi}}\int_{\frac{\theta_1-\nu}{\sigma}}^{\frac{\theta_b'-\nu}{\sigma}} \exp(-\frac{t^2}{2})dt \\ &= \frac{N(p_1 - \mu C_1 B)}{\sqrt{2\pi}} \times [\int_{-\infty}^{\frac{\theta_b'-\nu}{\sigma}} \exp(-\frac{t^2}{2})dt \\ & - \int_{-\infty}^{\frac{\theta_1-\nu}{\sigma}} \exp(-\frac{t^2}{2})dt] = F \end{aligned} \quad (8)$$

Then, define $\alpha = \frac{N(p_1-\mu C_1 B)}{\sqrt{2\pi}}$. By utilizing circle to approximate to the integral area and adopting polar coordinate format, (12) can be converted into

$$F^2 \approx \alpha \int_0^{2\pi}\int_0^R \exp(-\frac{\rho^2}{2})\rho d\rho d\varphi = 1 - \exp(-\frac{R^2}{2}) \quad (9)$$

Therefore, we obtain the satellite system's profit on spectrum I as

$$\begin{aligned} \pi_1 &= N(p_1 - \mu C_1 B)\int_{\theta_1}^{\theta_b'} g(\theta)d\theta \\ &= \frac{N(p_1 - \mu C_1 B)}{2} \times (\sqrt{1 - \exp[-\frac{2}{\pi}(\frac{\theta_1 - \nu}{\sigma})^2]} \\ & - \sqrt{1 - \exp[-\frac{2}{\pi}(\frac{\theta_b' - \nu}{\sigma})^2]}) \end{aligned} \quad (10)$$

■

Similarly, the satellite system's utility function for spectrum II and spectrum III can be expressed as

$$\pi_2 = N(p_2 - \mu C_2 B)\int_{\theta_b'}^{\theta_b''} g(\theta)d\theta. \quad (11)$$

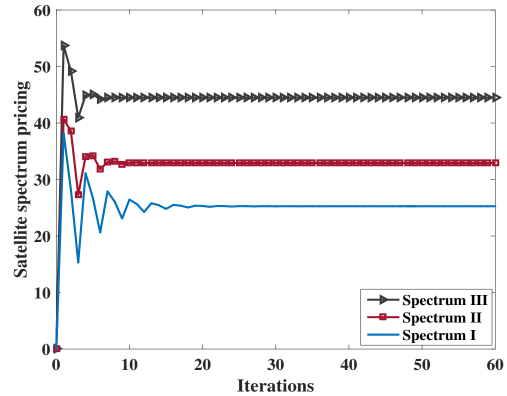

Fig. 3. Satellite spectrum pricing

$$\pi_3 = N(p_3 - \mu C_3 B)\int_{\theta_b''}^{\theta_3} g(\theta)d\theta. \quad (12)$$

In the light of essential conditions of pure Nash equilibrium, by taking the derivations of profit functions above, we acquire the iterative optimal spectrum pricing at step $k+1$ as

$$p_i^{k+1} = p_i^k + \frac{\partial \pi_i}{\partial p_i}. \quad (13)$$

For this optimal pricing solution, the following two points should be noted.

Remark 1: On the basis of Debreu's equilibrium existence theory [10], for optimization strategy $s_i = p_i^*$ along with utility function $f_i = \pi_i$, Nash equilibrium's existence can be ensured since the following sufficient conditions are met: (1) In limited Eucidean space, given strategy function s_i can be concluded to be a nonempty and compact subset; (2) For the strategy combination S, utility function f_i is continuous and concave.

Remark 2: To make sure the pricing method for satellite spectrum meaningful, the iterative algorithm we proposed above should be convergent. Based on the pricing solution given in (10), the equations can be rewritten in the following Jacobi matrix form

$$P^{k+1} = U^{-1}WP^k + U^{-1}b, \quad k = 0, 1, 2, \cdots \quad (14)$$

When $\rho(U^{-1}W) < 1$ holds, spectrum pricing p_i^k converges to a fixed point. Back to the proposed algorithm, we can easily derive the Jacobi matrix and corresponding maximal eigenvalue. By properly arranging pricing algorithm's parameter, we can make sure $\rho(U^{-1}W) < 1$. Furthermore, the oscillating point of the iterative curve appears when $\rho(U^{-1}W) = 1$.

IV. Numerical Results

In this section, simulation tests are performed to testify the performances of the proposed solution. In this case, satellite systems work in the mode of channelized TDMA in which external interferences incurred by other satellite networks are assumed to be ignored. **Further suppose the multibeam satellite system has 16 beams, and each beam's radius is 200km. In each cell, 10 satellite users randomly locate**.

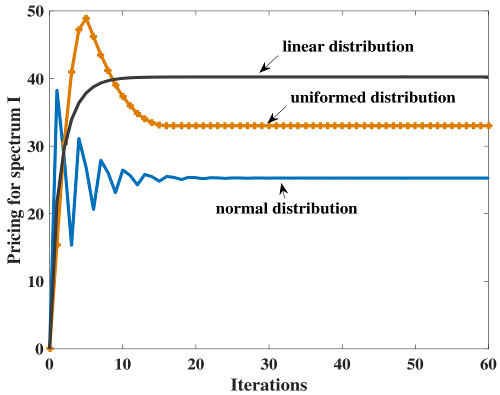

Fig. 4. Pricing for spectrum I in various distribution types

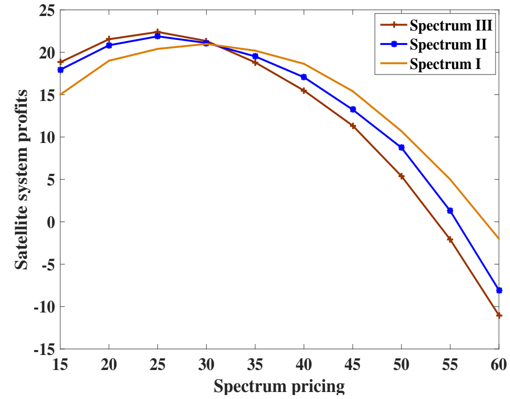

Fig. 5. Satellite systems' profits

We consider the interference in each beam are mainly caused by spectrum reuse in multibeam network. Furthermore, for the proposed iterative pricing algorithm, we set the initial spectrum pricing for three kinds of quality channels as $p_i^{(0)} = 0.01$. Other related parameters are set as $\theta_1 = 1$, $\theta_2 = 5$, $\theta_3 = 10$, $B = 1$, $\varpi = 2$, $\varepsilon = 1.2$, $N = 10$.

As shown in Fig. 3 and Fig. 4, the spectrum pricing of satellite systems are shown with different parameter settings. Since the proposed algorithm is iterative, the curves finally converge. In fact, a convergence coefficient can be added to the integral term in (10) to adjust convergent speed of the algorithm. The satellite spectrum price can be affected by many factors, such as spectrum quality, user preference, monetary coefficient, etc. Wherein, spectrum quality and user preference play a critical role. In Fig. 3, the spectrum pricing rises apparently with the increase of spectrum quality. For satellite systems, high-quality spectrum means high marginal cost and carries more profit expectation, thus relatively high pricing is reasonable. Besides, we can obtain from Fig. 4 that different preference distributions of terrestrial users influence spectrum pricing distinctly. In this circumstance, linear distribution implies the user's preference degree increases directly when the spectrum quality is going up. In the conditions of urgent spectrum demand or sufficient budget, terrestrial users will be more likely to pick a better channel. In our proposed scenario, we set the mean ν of the normal distribution less than θ_2, thus a relatively lower pricing is attained.

Furthermore, we give the satellite systems' profits under our spectrum pricing strategy in Fig. 5. In the figure, the system profit changes like a para-curve with the increase of spectrum pricing. It can be concluded that high price does not mean more profits generally. Thus, too high spectrum pricing will harm potential consumers' interest and purchasing desire. As a result, the profits of satellite systems will suffer damage eventually. In addition, we obtain from the figure that the high-pricing spectrum has faster profit decrease compared with other types of spectrum.

V. Conclusions

In this paper, we have investigated the spectrum optimization problem for satellite networks in cases of multibeam transmission with heterogenous user preferences. The main contribution of this paper lies in that we introduce a pricing-based method to carry out spectrum allocation in satellite networks so as to inspire participants and enhance spectrum efficiency within a market-driven mechanism. During the course, we depicted inhomogeneous user preferences on differential satellite spectrum and formulate the problem by using Hotelling mathematical model. Essential analysis and discussion on existence of Nash equilibrium and rationality of iterative convergency have been provided. Numerical results were given to testify the proposed method's performances.

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