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Improving Spectrum Management for Satellite Communication Systems with Hunger Marketing

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Abstract—Efficient spectrum management is an important issue in satellite communications due to the pervasive growth in wireless communications and the ever-increasing demand by bandwidth-hungry mobile applications. While various kinds of static and dynamic spectrum allocation schemes have been studied by satellite researchers, the issue of unpredictable user behavior, hence demand for bandwidth, remains one of the key challenges faced by the research community. In this article, we introduce the hunger marketing strategy in satellite spectrum management in order to address the unpredictable user demands. When adopting hunger marketing, the system always maintain a certain level of spectrum supply shortage, thus stimulating the desire of users to plan and commit their bandwidth requirements in advance, hence making their behavior more predictable and benefiting satellite systems. Besides, in circumstances of multi-beam satellite systems, when allocating bands to new satellite users, the issue of increase in inter-cell interference is also considered in this article. Thus a two-stage dynamic game model based on hunger marketing is proposed which aims to achieve an optimal balance between spectrum utilization and inter-cell interference. Numerical results are presented to show the effectiveness of the proposed method.

Index Terms—Satellite communications, multibeam satellite systems, spectrum optimization, hunger marketing

I. INTRODUCTION

SATELLITE communication networks have successfully served the traditional needs of the telecommunication market, i.e. telephony and broadcasting, especially in geographic areas where terrestrial links are impractical to deploy [1][2]. In recent years, owing to the rapid development of data-consuming mobile services, there has been a phenomenal growth in demand for broadband satellite access.

Many techniques including multiple spot beams, multi-protocol label switching, stochastic networks and dynamic spectrum access have been developed to exploit satellite systems to support broadband applications by achieving higher

spectrum efficiency [3][4]. In [3], a non-orthogonal multiple access method was proposed. In [4], a cooperative transmission strategy between satellite systems and terrestrial networks was designed to guarantee lower performance degradation for both systems during sharing spectrum. In addition, dynamic allocation schemes were proposed to cater for various critical factors including hot zones, user priority, signal diversity, service types and even unstable weather. More system resources are often allocated to hot beams in order to meet user demands or to address adverse channels [5][6]. In recent years, dynamic spectrum sharing and market-based techniques have been introduced to enhance energy efficiency in satellite systems [7].

Spectrum management for broadband satellite systems, unlike their terrestrial counterparts, is an emerging area that attracts substantial on-going research. In general, satellite users adopt a subscription model by committing a fixed bandwidth for meeting their anticipated communication needs. Wholesale subscribers typically commit bulk purchase of spectrum resources and then resell the spectrum to retail subscribers. Recently, spectrum management schemes have been designed to utilize the idle bandwidth of wholesale subscriber users by allowing dynamic spectrum allocation to other users on an ad hoc basis [8][9]. However, due to the unpredictable behavior of retail subscriber users, it remains a challenge to design efficient spectrum management scheme that can achieve an optimal balance between spectrum utilization and increase in inter-cell interference.

In this article, we propose an efficient spectrum pricing framework to address the issue of unpredictable demands of common satellite users on satellite spectrum. Our design is based on the assumption that when there is ample supply of satellite bandwidth, retail subscriber users tend to be less motivated to plan and commit their bandwidth requirements early, hence resulting in highly unpredictable user demands on the satellite system. In this regard, we introduce the hunger marketing strategy to spectrum management so as to influence users' behavior in bandwidth planning and benefit satellite system meanwhile, thus allowing a more efficient dynamic spectrum management. A two-stage game model is adopted to formulate the optimization problem. The rest of this paper is organized as follows. In Section II, a system model with regard to multibeam satellite systems is given. Then, a spectrum optimization scheme based on hunger marketing is developed in Section III. Numerical results are presented in Section IV to justify the performance of the proposed scheme. This letter is concluded in Section V.

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Fig. 1. System model of multibeam satellite systems

II. SYSTEM MODEL

In this paper, we consider multibeam satellite systems which stay in geostationary tracks and adopt spectrum reuse techniques to enhance spectrum efficiency. To be specific, a practical four-color spectrum reuse pattern is applied in this scenario as shown in Fig. 1. The satellite systems are supposed to utilize flexible resource optimization methods. Oblique-projection-based multibeam system is taken into account to make the system model approaching to actual applications. As shown in Fig. 1, the cells with same color shares the same band wherein inter-cell interference interference unavoidably occurs.

In multibeam satellite systems, the inter-beam interference takes effect 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 paper, the mixed projection is as shown in Fig. 1. Wherein, θ denotes the deviation angle between satellite terminal $(\beta, 2)$ and the cell center. We have

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

where d_o^s is the distance between spatial satellite and the cell center. $d_{\beta 2}^s$ and $d_{\beta 2}^o$ are the distances from terrestrial user $(\beta, 2)$ to satellite and subaerial point, respectively. R denotes earth radius.

In this paper, we focus on uplink resource management and a point-to-multipoint satellite networks is considered. In uplink satellite transmission, the carrier power can be given as

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

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

Then, for satellite user $(\alpha, 1)$ shown in Fig. 1, the transmission capacity with unit bandwidth can be expressed as

$$C_{\alpha 1} = \log_2 \left(1 + \frac{\rho_{\alpha 1} g_{\alpha 1}(\varepsilon_{\alpha 1}) G_{\alpha}(\varphi_{\alpha 1})}{d_{\alpha 1}^2 f_{\alpha 1}(\varepsilon_{\alpha 1}) \sum_{\beta=1}^l \frac{\rho_{\beta 2} g_{\beta 2}(\varepsilon_{\beta 2}) G_{\beta}(\varphi_{\beta 2}) \mu_{\beta 2} \rho_{\beta}^{\alpha}}{(4\pi d_{\beta 2}/\lambda)^2 f_{\beta 2}(\varepsilon_{\beta 2})} + N_0(\varepsilon_{\alpha 1}) \right). \quad (3)$$

III. SATELLITE SPECTRUM MANAGEMENT WITH HUNGER MARKETING

The proposed satellite spectrum scheme is expected to be deployed in a traditional scenario where satellite users need to purchase bands from satellite systems, and the satellite band resource is assumed to be relatively sufficient. It can be envisioned, if satellite systems release all available spectrum to market, an ideal price or profit would hardly be attained. Besides, to respond to unpredictable demands of satellite users, hunger marketing means that the number of available spectrum resource will remain limited and certain degree of shortage or spectrum scarcity is allowed. Only when the spectrum shortage attains a maximal threshold, more satellite spectrum can be further released to market.

The proposed hunger marketing scheme requires that several important factors to be taken into account: i) The spectrum demand of satellite user is continuous and stochastic; ii) The number of available satellite bands is relatively sufficient; iii) Spectrum shortage is allowed until settled maximal threshold is reached; iv) Periodic checking on spectrum dealing will be performed by satellite systems.

In this scenario, the spectrum demand variable X is stochastic which likely leads to the randomness of satellite spectrum's supplement. Besides, spectrum bandwidth will be checked by satellite systems in period of T . When available spectrum drops to the given level of r or below, supplying behavior initiates. In hunger marketing, r can be negative. In formulation of this satellite spectrum management, we aim to analyze every cost of satellite systems and achieve an optimal spectrum level in spectrum pool on the basis of satellite user's stochastic demand. In every detecting period T , spectrum supplement will be proceeded from clock $t = 0, t \in [0, T]$ before the number of available spectrum $I_X(t) < 0$ in spectrum pool. It means the spectrum supplement triggers only when the market drops into hungry condition. With the increase of trading time, we have

$$I_X(t) = -Xt + Q - B, \quad t \in [0, T] \quad (4)$$

where Q denotes the spectrum increment for every round, B denotes the maximal shortage threshold. The expectation of spectrum demand in every period is

$$\int_0^T \int_0^{\infty} x f(x) dx dt = T\mu \quad (5)$$

The spectrum shortage does not occur when available spectrum in market is non-negative, i. e., $I_X(T) > 0$. Bringing $t = T$ into formula $I_X(t)$, we have $X < \frac{Q-B}{T}$. That means, in condition of $0 < X < \frac{Q-B}{T}$, supplement shortage of satellite

spectrum will not happen. Then, the overall expected holding cost can be expressed as

$$\begin{aligned}
 HC &= \int_0^\infty \left(\int_0^T h I_x(t) dt \right) f(x) dx \\
 &= \int_0^{\frac{Q-B}{T}} \left(\int_0^T h(-xt + Q - B) dt \right) f(x) dx \\
 &\quad + \int_{\frac{Q-B}{T}}^\infty \left(\int_0^{\frac{Q-B}{x}} h(-xt + Q - B) dt \right) f(x) dx \\
 &= \int_0^\infty \frac{h(Q-B)^2 f(x)}{2x} dx - \int_0^{\frac{Q-B}{T}} \frac{h(Tx - Q + B)^2 f(x)}{2x} dx
 \end{aligned} \tag{6}$$

where h denotes the index of spectrum holding cost.

The overall expected cost of spectrum shortage is

$$\begin{aligned}
 SC &= \int_{\frac{Q-B}{T}}^\infty \left\{ \int_{\frac{Q-B}{x}}^T [-p(-xt + Q - B)] dt \right\} f(x) dx \\
 &= \int_{\frac{Q-B}{T}}^\infty \frac{p(Tx - Q + B)^2}{2x} f(x) dx
 \end{aligned} \tag{7}$$

where p denotes the cost index of spectrum shortage.

Then, the satellite system's overall cost per unit time is

$$\begin{aligned}
 TC(B, Q) &= \frac{1}{T} \{ K + cQ + HC + SC \} = \frac{1}{T} \left\{ \int_0^\infty h \left[T(Q - B) - \frac{T^2 x}{2} \right] \right. \\
 &\quad \times f(x) dx + K + cQ + \int_{\frac{Q-B}{T}}^\infty \frac{(p+h)(Tx - Q + B)^2}{2x} f(x) dx \Big\} \\
 &= \frac{\mu}{Q} \left\{ K + cQ + \frac{hQ^2}{2\mu} - \frac{hQB}{\mu} + \int_{\frac{(Q-B)\mu}{Q}}^\infty \frac{(p+h)[Qx - (Q-B)\mu]^2}{2x\mu^2} f(x) dx \right\}
 \end{aligned} \tag{8}$$

Our target is to find optimal Q and B , making the overall expected cost $TC(B, Q)$ minimal, i. e., the optimization objective can be depicted as $\min_{Q>B>0} TC(B, Q)$. Taking derivative of $TC(B, Q)$, we have

$$\begin{aligned}
 \frac{\partial TC(B, Q)}{\partial Q} &= -\frac{TC(B, Q)}{Q} + \frac{\mu}{Q} \left\{ c + \frac{hQ}{\mu} - \frac{hB}{\mu} \right. \\
 &\quad \left. + \int_{\frac{(Q-B)\mu}{Q}}^\infty \frac{(p+h)[Qx - (Q-B)\mu]}{x\mu} \left(\frac{x}{\mu} - 1 \right) f(x) dx \right\}
 \end{aligned} \tag{9}$$

$$\begin{aligned}
 \frac{\partial TC(B, Q)}{\partial B} &= \frac{\mu}{Q} \left\{ -\frac{hQ}{\mu} + \int_{\frac{(Q-B)\mu}{Q}}^\infty \frac{(p+h)[Qx - (Q-B)\mu]}{x\mu} f(x) dx \right\}
 \end{aligned} \tag{10}$$

Let $H(Q, B) = \frac{Q}{\mu} \frac{\partial TC(B, Q)}{\partial B}$ and $G(Q, B) = \frac{Q}{\mu} \frac{\partial TC(B, Q)}{\partial Q}$. Taking second derivatives, we have $\frac{\partial^2 TC(B, Q)}{\partial B^2} > 0$, $\frac{\partial^2 TC(B, Q)}{\partial Q^2} > 0$, $\frac{\partial^2 TC(B, Q)}{\partial B \partial Q} < 0$. Given K, h, p, μ , for $\forall(Q, B)$, $GH(Q, B) \equiv 0$ does not hold, i. e., no constant k can make $G(Q, B) = kH(Q, B)$ for $\forall(Q, B)$. Hence, the

solution (Q^*, B^*) exists to make $H(Q, B) = 0$, $G(Q, B) = 0$ tenable in same time. According to the extreme value theorem of multivariate function, (Q^*, B^*) is the optimal point we are searching.

IV. SATELLITE SPECTRUM PRICING

After analyzing satellite system's costs during the hunger marketing, we head to achieve the optimal spectrum pricing scheme subsequently. In this case, we introduce a two-stage pricing model — Stackelberg game model to formulate this problem. Furthermore, the effects of inter-cell interference when new satellite users purchase the band and join in the networks, are taken into account. Amidst applying Stackelberg model, in Stage I, the leader (satellite system) moves first to offer the spectrum and interference pricing. Then, the satellite user (as the follower) choose a strategy to maximize its benefit in respond to the satellite system's action. In another hand, the satellite system needs to predict the response of the follower and proposes an reasonable price.

Stage I: The satellite system's utility function can be expressed as

$$\begin{aligned}
 U_s &= \pi p_n f_{ns} + \chi B_n - HC_n - SC_n - \kappa X_{loss} \\
 \max_{\substack{p_n^{max} \geq p_n \geq 0, \\ \pi \geq 0}} & \quad \text{subject to} \quad \gamma_o = \frac{p_o f_{os}}{p_n f_{ns} + N_0(\alpha_o) B_o} \geq \gamma^{tar}
 \end{aligned} \tag{11}$$

where $\pi p_n f_{ns}$ denotes the interference cost charged by the satellite system. π is interference pricing, p_n is the transmit power of the new satellite user, and f_{ns} is the corresponding path loss to the satellite system. HC_n and SC_n denote the holding cost and shortage cost described above. B_n denotes the bandwidth purchased and χ denotes the spectrum pricing coefficient transferring bandwidth to uniform benefit. Besides, $X_{loss} = p_o - p'_o$, where p'_o denotes the power required by the original satellite user sharing the same band with satellite user n in previous condition without such co-channel interference.

Stage II: The satellite user's utility function can be expressed as

$$\begin{aligned}
 U_n &= \omega \log_2 \left(1 + \frac{p_n f_{ns}}{p_o f_{os} + N_0(\alpha_n) B_n} \right) - \chi B_n - \pi p_n f_{ns} \\
 \max_{\substack{p_n^{max} \geq p_n \geq 0, \\ \pi \geq 0}} & \quad \text{subject to} \quad \gamma_n = \frac{p_n f_{ns}}{p_o f_{os} + N_0(\alpha_n) B_n} \geq \gamma^{tar}
 \end{aligned} \tag{12}$$

where $\log_2 \left(1 + \frac{p_n f_{ns}}{p_o f_{os} + N_0(\alpha_n) B_n} \right)$ denotes the transmission capacity received by the new satellite user as its benefit. ω denotes the monetary coefficient.

In the execution phase, having observed the spectrum and interference pricing of the satellite system, the satellite user's Nash equilibrium can be derived firstly. Then, combining optimal transmit power p_n^* and given SINR requirement $\frac{p_n f_{ns}}{p_o f_{os} + N_0(\alpha_n) B_n} = \gamma^{tar}$, we obtain $p_o(\pi)$. Substituting p_n and p_o , we can identify the equations to solve the optimal pricing of π and χ .

Fig. 2. Trading cost in spectrum hunger marketing

V. NUMERICAL RESULTS

In this part, simulation tests are performed to evaluate the effects of the proposed solution. In this case, the satellite systems are supposed to work in the mode of channelized TDM in which external interference incurred by other satellite networks are ignored. We further assume that the multibeam satellite system has 16 beams, and each beam's radius is 200km; and terrestrial users could be in any random location in each cell. We also consider the interference in each beam are mainly caused by spectrum reuse in the multibeam networks.

As shown in Fig. 2, we give the performances of trading cost with various cost index of spectrum shortage p and maximal spectrum shortage threshold B . In hunger marketing, satellite system's trading cost TC has been given in (8). Many parameters have impacts on the cost, and we present the effects of trading cost under two key indexes. Due to the risk of keeping the spectrum supplement in shortage condition which easily leads to the customer loss, we introduce a cost index of spectrum shortage. As shown from the Fig. 2 and equation (8), the cost index's rising will start a trend of increase for trading cost. Furthermore, we also give the presentation of trading cost with various maximal threshold of spectrum shortage in Fig. 2. In the initial stage, with the increase of shortage threshold which means more tolerable space for spectrum insufficiency, higher shortage cost is required yet lower holding cost is attained. However, excessive threshold for spectrum shortage instead aggravates trading cost as the satellite users may dynamically use spectrum in other modes.

Then, in Fig. 3, the satellite system's profits with changing monetary coefficient ω are given. When taking the inter-cell interferences into account, interference cost along with trading cost are both affecting the satellite system's profits and satellite users' actions. As shown from this figure, with the increase of interference price, system profit cannot be improved linearly. In this circumstance, satellite users can dynamically adjust their transmit power to respond system pricing. Thus, an appropriate interference price rather than a very high one will

Fig. 3. Satellite system's profits with various monetary coefficient ω

optimize satellite system's benefits in the end.

VI. CONCLUSIONS

In this article, we have introduced a marketing-based spectrum optimization strategy to enhance spectrum efficiency and satellite system's benefit. To be specific, we adopt hunger marketing and interference pricing to address satellite user's stochastic spectrum demand in multibeam satellite systems. Owing to the potential risk for satellite systems to adopt hunger marketing in which spectrum shortage often occurs, spectrum holding cost and shortage cost have been formulated in detail. Then, a two-stage dynamic game model has been utilized to depict the response between satellite system's interference pricing and satellite users' power control in the proposed dealing mode. Numerical results are provided to evaluate the proposal's effects on trading cost and system's utility.

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