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# Spectrum Allocation With Asymmetric Monopoly Model for Multibeam-Based Cognitive Satellite Networks

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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 user population and available bandwidth. Efficient spectrum management is required in order to meet the ever-increasing demand for broadband spectrum. In this paper, a spectrum allocation scheme for cognitive satellite networks is proposed to improve spectrum efficiency by addressing the situation that scarce spectrum resource is under-utilized while the overall demands of cognitive satellite users are not satisfied. The proposed scheme is devised to optimize bandwidth efficiency by achieving the Bayesian equilibrium through spectrum competition among cognitive satellite users. Due to the scarcity of spectrum resource, satellite systems have to eliminate some of the cognitive users' transmission information types in order to fulfill the spectrum needs of priority users. After declining one or several kinds of modulation modes, cognitive users can update their spectrum lists. With the increase in number of cognitive users and their corresponding transmission information types, the complexity of the optimization problem increases significantly and becomes a computation burden to cognitive satellite systems. Therefore, in this paper, we propose a simplified solution for spectrum resource optimization in a computation-efficient manner. Through rounds of eliminating operations, the satellite systems can identify the final Bayesian equilibrium as an optimal spectrum allocation strategy. We also provide proofs for the existence of Bayesian equilibrium. Numerical results are given to evaluate the performance of our proposed method from diverse perspectives.

**INDEX TERMS** Cognitive satellite communications, spectrum allocation, Bayesian equilibrium, monopoly market.

## I. INTRODUCTION

SATELLITE communication networks have been successful in serving traditional needs of telecommunication market, including telephony and broadcasting [1], [2]. While today's satellite broadband is able to support more than 30Gbps, the explosive adoption of productivity mobile applications such as vehicle navigation, IoT sensing, etc, are driving demands for wireless bandwidth to an unprecedented level [3]–[6]. Hence it is always desirable to look for means and mechanisms to make efficient uses of the available satellite bandwidth. More efficient spectrum management schemes deserve deep and full investigation in order to meet the ever-increasing demand for broadband spectrum in satellite networks.

To meet the growing demands for scarce satellite spectrum, the challenge of improving efficiency of spectrum utilization has attracted great attentions of communications researchers and practitioners [7]–[10]. Cognitive satellite communications, which allow terrestrial users or different satellite systems to dynamically access idle satellite spectrum, can enhance spectrum efficiency, combat with fast fading channels and even benefit satellite band owners through certain market-driven spectrum allocation mechanisms [11]–[14].

More recently, thanks to the rapid development of high throughput satellites systems, satellites are increasingly used as a broadband access solution in areas where terrestrial links are impractical to provide. Traditional satellite internet services have been the privileges of government users and established business organizations such as mining, offshore oil field and homeland security surveillance. With the worldwide effort in cyber inclusion by extending internet access to remote and isolated rural areas, demands for broadband satellite services have been growing at an unprecedented rate. As such, the licensed spectrum of 500 MHz for exclusive use, both for uplink and downlink, even in the Ka band has been shown to be insufficient to meet the current demands [15]–[17].

For recent years, various communication techniques, for instance multiple spot beams, spectrum reuse, OFDM, dynamic spectrum access and cognitive satellite communications, have been widely investigated or adopted in satellite communication systems to enhance spectrum efficiency and transmission capacity in deep [18]–[23]. To be specific, different emphases should be focused on for diverse application scenarios. For multibeam cases, since each beam intends to compete with others for wireless resources, such as bandwidth and power to achieve satisfactory communication, wherein elastic resource allocation between various beams plays a key role. Besides, during the process of spatial diversity and spectrum reuse in satellite communication networks, the interferences among different cells or beams become inevitable and attract more attention. For dynamic spectrum access or cognitive satellite communications, smart and rapid spectrum detecting, switching, accessing along with reasonable resource allocation also deserve deep investigations for researchers.

The techniques of resource allocation or energy efficiency for cognitive satellite networks have reaped growing research interests these years. Researchers involved in the investigations are always inspired by new emerging approaches of resource allocation in terrestrial cognitive radio networks. In fact, the rapid development of various technologies for dynamic spectrum access and cognitive radio networks in terrestrial wireless networks provide quantities of reference sources [24]–[29].

As the resource optimization in cognitive satellite networks usually needs to balance the benefits of different participants, numbers of mathematical solutions such as convex optimization, graph theory, intelligent algorithm and game theory are applied to solve the difficulties during the course [11]–[34]. In [11], Periola and Falowo proposed a model called cognitive earth observation network model which contains hybrid meteorological ground station and fractionated small satellites in the ground and space segment, respectively. The ground station is hybrid and functions in primary mode using TV white space channels and may bond channels of other satellite systems. In [30], a novel satellite-based wireless sensor networks was proposed which integrate the sensor networks with cognitive satellite terrestrial network. By providing seamless network access and alleviating spectrum scarcity, the proposed cognitive satellite terrestrial networks were considered as a promising candidate for future wireless networks with emerging demands of ubiquitous broadband applications. In [31], the emerging spectrum sensing and awareness techniques and approaches in cognitive satellite networks were studied, described and developed. Besides, how to use database and spectrum exploitation methods to improve resource optimization was investigated. In [32], to acquire robust transmission opportunity of dynamic spectrum access and preserve primary satellite users, the authors raised unequal power allocation scheme over the symbols of multi-rate modulation according to data sensitivity to channel errors and spectrum availability. Besides, [13] proposed a novel low-complexity solution of blind automatic modulation classification and parameter estimation in cognitive satellite communication networks based on the analytical study of Mth-power nonlinear transformation of co-channel mixture and inter-cell interferences.

Compared to the study of resource allocation on terrestrial networks, the research work on satellite systems is not investigated very well. Since market-based resource allocation method can more efficiently redeploy the scarce spectrum, balance user demands and even incur potential participants, this technique has been widely dug in the area of terrestrial wireless networks. However, to the best of our knowledge, few related works are available for satellite communication networks yet.

In this paper, we investigate the problem of spectrum optimization for cognitive satellite networks in case when no enough spectrum is available for cognitive satellite users which leads to a monopoly market. We introduce a game theoretical method to address the problem and acquire the final solution by solving Bayesian equilibrium. In actual spectrum access market, the band requirement of cognitive users is usually very high which lets the spectrum optimization problem convert to how to benefit the primary system's profits caused by monopolistic resource. We firstly give the utility function of satellite systems according to the transmission characteristics of multibeam satellite communications. Then, in condition of incomplete information, the satellite systems need to obtain their optimal spectrum allocation scheme through forming an opportunistic selection strategy. By arbitrarily deleting improper cognitive users' information types, satellite systems can satisfy part of users' spectrum demands without competing operations. In every round of information elimination, satellite systems should evaluate the overall optimal spectrum allocation solution in time. Besides, we further provide proof for the rational existence of Bayesian equilibrium. Furthermore, numerical results are also supplied to testify the performance of our proposal from various aspects.

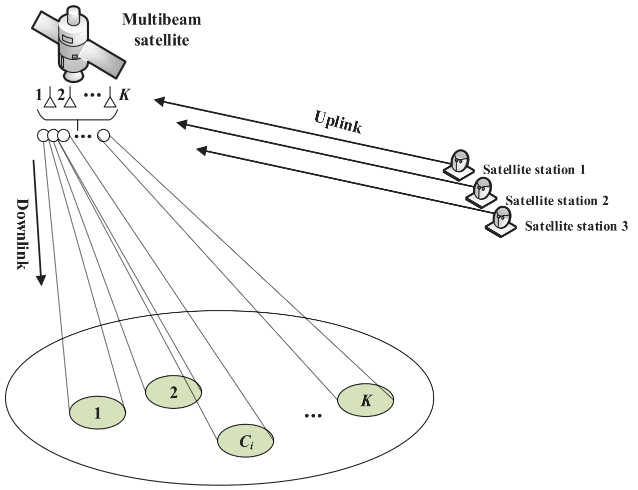


FIGURE 1. System model of multibeam satellite systems.

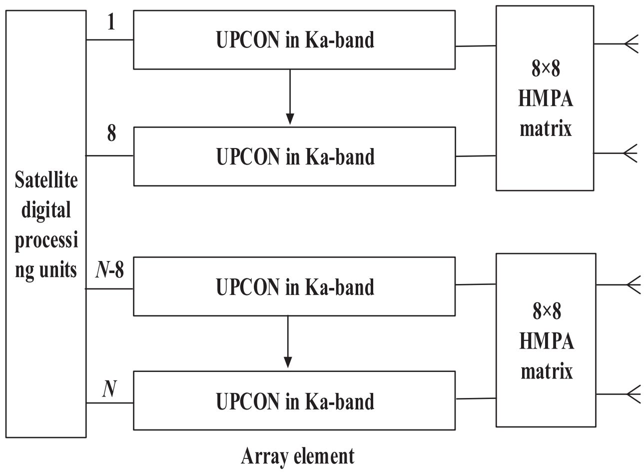


FIGURE 2. Payload structure of forward links.

The contributions of this paper can be highlighted as follows.

- A new game theoretical method for spectrum allocation in cognitive satellite networks is proposed, by introducing a bargaining-based algorithm to fix the problem of limited resource competition.
- In a monopoly spectrum market, we use optimal elimination strategy to seek the final Bayesian equilibrium which acts the optimal spectrum allocation scheme with the goal of maximizing satellite system's profits.
- With the increase of terrestrial cognitive user number, our proposed method is a simplified solution by reducing algorithm's computation cost and enhancing computing robustness.
- We further provide the proof and rationality explanations of Bayesian equilibrium and algorithm's implementation. Satellite system's profits and optimal strategy are testified by numbers of numerical simulation tests.

The rest of this paper is organized as follows. We give the system model of spectrum allocation scheme for cognitive satellite networks in Section II. Then, the spectrum allocation algorithm according to multibeam satellite transmission scenario is proposed in Section III. In Section IV, numerical results are supplied to evaluate the performance of our proposed algorithm. At last, we conclude this paper in Section V.

## II. SYSTEM MODEL

### A. INTERFERENCE MODEL

In this paper, a system model of multibeam satellite systems is considered in which a geostationary satellite network is supposed to adopt a transparent architecture and work in the Ka-band. Furthermore, in order to enhance satellite spectrum efficiency and system capacity, as shown in Fig. 1, a multibem-based satellite system is assumed to be applied whose spectrum reuse in various beams may cause inter-cell interference to certain content.

For the sake of optimally allocating limited satellite resource, the forward links of multibeam satellite systems are required to have flexible payload structure so as to elastically allocate power and bandwidth to each beam. As shown in Fig. 2, the payload structure should contain the following subsystem.

(1) Array fed reflector used to produce uniform beam network matrix.

(2) Satellite digital processing units containing digital beam forming network for digital synthesis of users' beams and digital channeling units for flexible spectrum channeling.

(3) Up Conversion subsystem which asks for the UPCON number in Ka-band matches the unit number of array fed reflectors.

(4) Dispersed radio frequency amplifier based on hybrid matrix power amplifier (HMPA) in which the number of traveling-wave tube equals to that of antenna array fed reflector.

The channel fading of satellite communications is mainly caused by signal band, elevation, receiver's altitude, transmit path fading, atmosphere attenuation, etc. Thus, the attenuation range matrix $A \in C^{K\times K}$ can be defined by the channels' transmission fading parameters as

$$A = diag\{\alpha_1, \alpha_2, \cdots, \alpha_k\} \tag{1}$$

where $\alpha_i$ denotes the attenuation factor during channel transmission.

In antenna systems with array fed reflector equipped beam forming technique, since the transmit power and bandwidth of every beam can be adjusted by arranging antenna array, the multibeam satellite systems are capable of providing elastic power allocation through controlling satellite processing units. The antenna gain powered by array antenna mainly depends on the antenna's unit number and array's spatial distribution. Therefore, antenna gain can be improved by increasing hardware complexity. In this case, the antenna gain matrix $G \in C^{K \times K}$ can be defined as

$$G = \begin{pmatrix} g_{11} & g_{12} & \cdots & g_{1k} \\ g_{21} & g_{22} & \cdots & g_{2k} \\ \vdots & \vdots & \ddots & \vdots \\ g_{K1} & g_{K2} & \cdots & g_{KK} \end{pmatrix} \quad (2)$$

where $g_{ij}$ denotes the gain value between the $i$ antenna unit and $j$ beam. Besides, after identifying the attenuation factor and antenna gain for every channel, we have the fading channel matrix $H$ where $H = GA$. In practical systems, $H$ can be actually estimated from feedback channel. In following simulation tests, the satellite channel model is supposed to be known. Suppose the signal as $x_k$ transmitted by the satellite to beam $k$, there is $x_k = [x_{k1}, x_{k2}, \cdots, x_{kQ}]^T \in C^{Q \times 1}$. The sub-band allocation vector for beam $k$ is $w_k \in R^{Q \times 1}$ used to denote the allocated bandwidth of beam $k$. The allocation matrix of system's band denoted as $W \in R^{Q \times K}$ can be defined to be $W = [w_1, w_2, \cdots, w_k]$ where vector $w_k \in R^{Q \times 1}$ of $k$ column can be given $w_k = [w_{k1}, w_{k2}, \cdots, w_{KQ}]^T$ which denotes the sub-band and transmit power in beam $k$.

Let $W_k = diag\{w_k\}$, the signal $y_k \in C^{Q \times 1}$ received by beam $k$ can denote the signal and interference in receiver as

$$y_k = h_{kk}\tilde{x}_k + \sum_k h_{ki}\tilde{x}_i + n_k \quad (3)$$

where $\tilde{x}_k = W_k\tilde{x}_k$ and $h_{kk}\tilde{x}_k$ denotes the received signal which should be transmitted to beam $k$. $\sum_k h_{ki}\tilde{x}_i$ denotes the sum of other beams' signal and interference signal on satellite, $n_k \in C^{Q \times 1}$ is the Gaussian noise with average 0 and variance $\sigma^2$.

Band allocation matrix $W$ can identically be denoted as $W = [\tilde{w}_1^T, \tilde{w}_2^T, \cdots, \tilde{w}_Q^T]$ whose every row vector $\tilde{w}_j = [w_{1j}, w_{2j}, \cdots, w_{kj}]$ presents the beam allocated with sub-band $j$. Row $k$ of matrix $H$ can be defined by $h_k = [h_{k1}, h_{k2}, \cdots, h_{kk}]$. Normalizing transmission signal amplitude, we have $|x_{ij}|^2 = 1, \forall i = 1, 2, \cdots, k, \forall j = 1, 2, \cdots, Q$. Thus, the transmit signal power in beam $k$ can be expressed by the diagonal elements of matrix $U_k \in R^{Q \times Q}$ as

$$U_k = |h_{kk}|^2 W_K W_K^H \quad (4)$$

In beam $k$, the co-channel interference caused by other beam signals can be given by the diagonal elements of matrix $R_k^{int} \in R^{Q \times Q}$ as

$$R_k^{int} = diag\{[g_k \tilde{w}_j^H \tilde{w}_j g_j^H]\}, j = 1, 2, \cdots, Q \quad (5)$$

Therefore, the interference added with noise can be given as

$$\begin{aligned} R_k &= R_k^{int} + \sigma^2 I \\ &= diag\{[g_k \tilde{w}_j^H \tilde{w}_j g_k^H + \sigma^2]\} + \sigma^2 I, j = 1, 2, \cdots, Q \end{aligned} \quad (6)$$

Define signal interference noise ratio (SINR) for beam $k$ as $\Gamma_k \in R^{Q \times Q}$, we have $\Gamma_k = U_k R_k^{-1}$. Diagonal element $j$ in $\Gamma_k$ presents the SINR of sub-band $j$ in beam $k$. Suppose the transmitter works in the status of optimal transmission, thus $\Gamma_k$, $U_k$ and $R_k$ are the functions of $W$. Thus, we optimize $W$ to obtain optimal strategy for power and band allocation.

For a lossless optimal receiver, the capacity for beam $k$ can be expressed as

$$R_k(W) = B_c \log_2(1 + \Gamma_k) \quad (7)$$

Supposing SINR of sub-band $j$ in beam $k$ to be $\gamma_{kj}$, in practical application scenario, such as DVB-S2 system, the capacity under spectrum bandwidth $B_c$ can be given as

$$R_k(W) = B_c \sum_{j=1}^{Q} \eta(\gamma_{kj}) \quad (8)$$

where $\eta(\cdot)$ is the spectrum efficiency function which can be expressed by $\eta(\cdot) = \log_2(1 + \gamma_{i,j})$. In standard of DVB-S2, the function is a quasi-linear function related with SINR.

### B. OPTIMIZATION OBJECTIVE

In general, when we investigate the issue of spectrum allocation in cognitive satellite networks, we assume that the idle spectrum resource owned by the satellite systems can satisfy the overall demands of terrestrial cognitive terminals. In another word, it is supposed that the cognitive users can obtain the final equilibrium solutions which mean the Nash equilibrium under complete information or Bayesian equilibrium under incomplete information, by sufficient competitions. In fact, Bayesian equilibrium is also a Nash equilibrium, but in general, the equilibrium of the complete information static game is Nash equilibrium. The equilibrium of static game with incomplete information is Bayesian equilibrium. Compared with Nash equilibrium, Bayesian equilibrium is a complex equilibrium. Nash equilibrium, which is suitable for simple game, is not necessarily applicable to Bayesian equilibrium. The explanations have been added just before the Theorem 1 in Section III. Thanks for your comments. However, in practical networks, satellite system's idle spectrum resource may be unable to meet the requirements of all the cognitive users, which leads the cognitive users cannot attain the two kinds of equilibriums above mentioned. At this moment, how to efficiently share the limited spectrum band in the monopoly market deserves more investigations.

To analyze the spectrum sharing problem in cases of limited network resource, we suppose the idle spectrum provided by the satellite systems cannot meet the spectrum resource allocation scheme under incomplete information. In this case, the cognitive satellite networks conduct as a monopoly market. In practical networks, as terrestrial cognitive users have high demands to the spectrum resource, the key point involved in the spectrum resource allocation is how to optimize satellite system's profits rather than cognitive users' profits. In this paper, we propose a spectrum allocation scheme for the cases of limited spectrum resource in cognitive satellite networks from the perspective of satellite systems.

As shown in Fig. 3, the idle bands to be allocated to terrestrial cognitive users are labeled by $Q_1, Q_2, Q_3, \cdots, Q_{N-1}, Q_N$

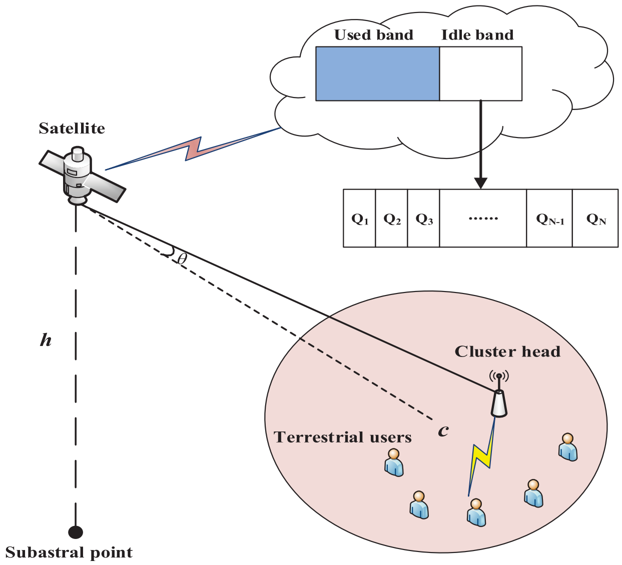


**FIGURE 3.** Spectrum allocation.

with different band units, then the corresponding capacities can be given as $R_1, R_2, R_3, \cdots, R_{N-1}, R_N$. Then, the satellite system can price the spectrum resource to be

$$P(R) = X + Y(\sum_{j=1}^{N} R_j)^{\tau} \tag{9}$$

where $X, Y, \tau$ are supposed to be positive, and $\tau \geq 1$. After allocating the satellite spectrum, terrestrial cognitive users can utilize the band allocated to carry out transmission. Then, the overall profits of the satellite systems can be expressed as

$$U_P(R) = P(R) \times \sum_{j=1}^{N} R_j = [X + Y(\sum_{j=1}^{N} R_j)^{\tau}] \times \sum_{j=1}^{N} Q_j \tag{10}$$

As the satellite system will maximize its own profits, the spectrum optimization problem for the whole terrestrial cognitive users can be converted to be

$$R_i(\theta_i) \in \arg\max_{R_i} \{X(\sum_{j=1}^{N} R_j) + Y(\sum_{j=1}^{N} R_j)^{\tau+1}\}$$
$$s.t. \sum_{j=1}^{N} R_j \leq R_P \tag{11}$$

where $R_P$ is the upper threshold of the idle spectrum band provided by the satellite system.

In cases of incomplete information which means the cognitive users cannot obtain the transmission information of each other in time, the satellite system has to optimize its own profits by opportunistic spectrum allocation method. Actually, the satellite system is also unknown of the transmission information of all the cognitive users participating in the spectrum sharing if they do not broadcast the information actively. Therefore, satellite systems and terrestrial cognitive users need to estimate other users' expected transmission information by historical experience or distribution pattern to optimize the resource allocation.

If the transmission information of cognitive user $j$ can be expressed as $\theta_j$ with mathematical expectation of $E(\theta_j)$, its expectation to obtain spectrum band is $E(R_j)$. Due to $X > 0, Y > 0$, (11) can be converted to the following optimization problem

$$R_j(\theta_j) \in \arg\max_{R_j}\{\sum_{j=1}^{N} E(R_j)\}$$
$$s.t. \sum_{j=1}^{N} R_{j,max} \leq R_P \tag{12}$$

where $R_{j,max}$ denotes the maximal spectrum bandwidth which may be achieved by cognitive user $j$.

## III. HEURISTIC SPECTRUM ALLOCATION ALGORITHM

In this section, a heuristic spectrum optimization algorithm will be given to address resource allocation issue for cognitive satellite monopoly market. Suppose terrestrial cognitive user $j$ will achieve spectrum band $Q_{j,k}$ allocated by satellite systems where $1 \leq j \leq N, 1 \leq k \leq M_j$ and $\sum_{k=1}^{M_j} p_{j,k} = 1$. To be general, we consider that, for cognitive user $j$ in cognitive satellite networks, the band number it may obtain can be sequenced by $Q^*_{j,1} < Q^*_{j,2} < \cdots < Q^*_{j,M_j}$, thus the constraint condition that cognitive users should satisfy under incomplete information case can be given as

$$Q_P \geq \sum_{j=1}^{N} Q_{j,M_1^*} \tag{13}$$

In this case, satellite systems should figure out the Bayesian equilibrium which is attained by the competition between the cognitive users. By identifying the equilibrium, satellite systems can estimate the potential spectrum allocation solution cognitive users want to pursue. To meet the condition $Q_P \geq \sum_{j=1}^{N} Q_{j,M_1^*}$ above mentioned, satellite systems need to compulsively decline part of transmission information types of cognitive user $j$ in conditions of relatively large profit information $m_j$. Thus, the satellite systems will enforce cognitive users do not adopt the following transmission information as $\theta_{j,M_j-m_j+1}, \theta_{j,M_j-m_j+2}, \cdots, \theta_{j,M_j}$ where $0 \leq m_j \leq M_j$. When the satellite systems has declined one kind or multi-kinds of modulation types, the maximal spectrum bandwidth cognitive user $j$ can obtain should be updated to be $Q_{j,max} = Q_{j,M_j-m_j}$.

### A. BASIC HYPOTHESES FOR INFORMATION PROBABILITY DISTRIBUTION OF COGNITIVE USERS' PROFITS

Actually, if cognitive user $j(1 \leq j \leq N)$ has various kinds of transmission information, the other cognitive users in this cognitive satellite networks should estimate the corresponding distribution probabilities of transmission information.

Hence, when the satellite systems compulsively eliminate one kind or multi-kinds of profit information of cognitive user $j(1 \le j \le N)$, the other cognitive terminals in networks will unavoidably update new possible transmission information's distribution probability of $j(1 \le j \le N)$ according to historical information.

In summary, for every user $j(1 \le j \le N)$, $\theta_{j,k}$ corresponds to probability $p_{j,k}$. Then, the probability sum of transmission information types in the eliminated modulation mode for cognitive user $j(1 \le j \le N)$ can be expressed as

$$p_{j,reject} = p_{j,M_j-m_j+1} + p_{j,M_j-m_j+2} + \cdots + p_{j,M_j} \quad (14)$$

In this paper, we do not discuss the details of estimation method of probability distribution for cognitive user $j(1 \le j \le N)$. When one kind or multi-kinds of modulation modes of cognitive user $j(1 \le j \le N)$ are deleted by the satellite systems, the cognitive user has the following three kinds of adjustment strategies of modulation method as

*Rule 1:* For every single cognitive user $j(1 \le j \le N)$, the probability of $\theta_{j,k}(1 \le k \le M_j - m_j)$ is: $p_{j,k} + p_{j,reject}/(M_j - m_j)$;

*Rule 2:* For every single cognitive user $j(1 \le j \le N)$, the probability of $\theta_{j,k}(1 \le k \le M_j)$ is: $p_{j,k}/(1 - p_{j,reject})$;

*Rule 3:* For every single cognitive user $j(1 \le j \le N)$, the probability of $\theta_{j,k}(1 \le k \le M_j - m_j - 1)$ is: $\theta_{j,k}(k = M_j - m_j) \Rightarrow p_{j,k} + p_{j,reject})$;

Due to $m_j \in [0, M_j]$, for $N$ terrestrial cognitive users, the collocation of transmission types that the satellite system can decline is $(M_1 + 1)(M_2 + 1) \cdots (M_N + 1)$. In order to make satellite systems to obtain optimal elimination scheme, we suppose the optimal elimination scheme in this case of cognitive satellite networks can be expressed as $\{m_1^*, m_2^*, \cdots, m_N^*\}$. Even kinds of information transmission types of cognitive user $j(1 \le j \le N)$ are deleted, no conflict is shown to the premise of incomplete information scenario. Therefore, when satellite systems strike out some transmission information types of cognitive users in cognitive satellite communications, the cognitive terminals are still capable of attaining optimal spectrum sharing solution by mutual competition. Thus, in this case, the cognitive satellite networks can also achieve an equilibrium, one kind of Bayesian equilibrium.

### B. HEURISTIC SPECTRUM ALLOCATION STRATEGY UNDER CONSTRAINTS OF AVAILABLE BANDWIDTH

In order to identify optimal elimination collocation of cognitive users, satellite systems need, firstly, to figure out the equilibrium spectrum allocation solutions–Bayesian equilibrium for all kinds of cognitive combinations. Secondly, when satellite systems have detected the final equilibrium solutions of cognitive satellite networks, to maximize their profits, they require to fix the optimization problem raised in (12).

To fulfill the optimization mode above mentioned, satellite systems should pursue the optimal spectrum allocation scheme under every possible cognitive users' Bayesian equilibrium after deleting part of information types. In this case, suppose satellite system's computation cost is $o(M_1 M_2 \cdots M_N)$. With the increase of cognitive terminal number and the transmission information types owning by the cognitive users, the complexity of spectrum allocation optimization aggravates satellite network's burden. To simplify the optimization issue for the cognitive satellite networks, we propose a spectrum optimization solution for this case as following.

**Step 1:** Before eliminating any transmission information type of cognitive users, satellite systems should firstly evaluate the optimal spectrum allocation strategy–Bayesian equilibrium for the whole cognitive satellite networks. Meanwhile, we set the stage parameter $i = 1$, and define the potential available spectrum band number of cognitive user $j(j \in [1, N])$ under different transmission information types to be $Q_{j,1}^{(1)}, Q_{j,2}^{(1)}, \cdots, Q_{j,M_j}^{(1)}$.

**Step 2:** If the terrestrial cognitive users involved in the **Step 1** can obtain the overall spectrum band in the spectrum optimization strategy to be $\sum_{j=1, j\neq k}^{N} Q_{j,M_j-m_j^{(i)}}^{i} \le Q_p$ where $Q_{k,M_k-m_k^{(i)}+1}^{(i)} + \sum_{j=1,j\neq k}^{N} Q_{j,M_j-m_j^{(i)}}^{i} > Q_p$ where $k \in [1, N]$. Furthermore, all the potential combination under the constraints above mentioned can be given as $\{m_1^{(i)}, m_2^{(i)}, \cdots, m_N^{(i)}\}$.

**Step 3:** For every combination $\{m_1^{(i)}, m_2^{(i)}, \cdots, m_N^{(i)}\}$ recorded in **Step 2**, conduct the following sub-steps:

**Sub-Step 3.1:** In the recorded combination, delete the transmission information types belonging to relatively large $Q_j$; Recompute Bayesian equilibrium to complete spectrum allocation to obtain $Q_{j,1}^{(i+1)}, Q_{j,2}^{(i+1)}, \cdots, Q_{j,M_j-m_j^{i+1}}^{(i+1)}$.

**Sub-Step 3.2:** For any $j \in [1, N]$, if the obtained spectrum resource allocation scheme satisfies $\sum_{j=1,j\neq k}^{N} Q_{j,M_j-m_j^{(i)}}^{i+1} > Q_p$, then update information $M_j = M_j - m_j^{(i)}$ and $i = i+1$ and step back to **Step 2** thus making $m_j = \sum_{k=1}^{i} m_j^{(k)}$ and storing $\sum_{j=1}^{N} E(Q_j)$.

**Step 4:** Comparing the record of $\sum_{j=1}^{N} E(Q_j)$ in **Step 3**, choose combination $\{m_1, m_2, \cdots, m_N\}$ to maximize $\sum_{j=1}^{N} E(Q_j)$, and define an optimal elimination combination $\{m_1^*, m_2^*, \cdots, m_N^*\}$.

In summary, the combination $\{m_1^*, m_2^*, \cdots, m_N^*\}$ obtained in Step 2 can maximize $\sum_{j=1}^{N} E(Q_j)$ and satisfy the conditions $\sum_{j=1}^{N} Q_{j,max} \le Q_p$ for spectrum resource. Then, testify whether the combination can meet the constraints through **Step 3** as: If the combination has been identified to mismatch the conditions above mentioned, thus go back to **Step 2**. If the conditions can be met, back to **Step 4**. Then, the combination $\{m_1^*, m_2^*, \cdots, m_N^*\}$ obtained from the above steps is the final spectrum optimization scheme for the cognitive satellite networks in conditions of incomplete information.

Through the heuristic elimination strategy of spectrum optimization, satellite systems can compulsively delete part of cognitive users' transmission information types in cognitive satellite communications and achieve the final optimal spectrum allocation solution under incomplete information cases. In this case, the computation cost of elimination operation depends on the number of idle spectrum bands, thus more spectrum resource available to be allocated incurs more computation intensity.

## IV. EXISTENCE OF BAYESIAN EQUILIBRIUM

After identifying the spectrum optimization algorithm from the perspective of satellite systems in cognitive satellite communications, we further give the analyses of equilibrium existence along with its sufficient conditions. In this case, the Kakutani's Fixed Point Theorem is adopted to prove a Bayesian equilibrium in respond to the satellite system's utility function given in (12) is a pure and fixed equilibrium in this game [35]. Based on Kakutani's Fixed Point Theorem, when giving response function also named utility function as $U_s$ and argument $R$ defined above, a fixed point exists if the following essential conditions are met: (1) Based on $U_s$, space set $\sum$ is a compact convex subset in given limited Euclidean space. It should be noted that $U_s : \sum \rightarrow \sum$ denotes Cartesian direct product for $U_s$. (2) $\forall R$, $U_s(R)$ should be nonempty. (3) $\forall R$, $U_s(R)$ should be convex. (4) A closed mappings subset exists in $U_s$ given above.

We firstly define $S$ as the strategy combination for satellite systems. Thus, due to $\sum$ being the simplex in dimension $S-1$, the condition (1) holds. Then, in given compact subset of $U_s$ who also has a maximum in the region, $U_s$ can be linear and continuous. Besides, due to $U_s$ ought to be nonempty in the cognitive satellite networks, condition (2) should also be satisfied. At last, we prove the condition (4) by contradiction. It is apparent that when $U_s$ is not a convex function, we have $R' \in U_s(R)$, $R'' \in U_s(R)$ and $\lambda \in (0, 1)$ which let $\lambda R' + (1-\lambda)R'' \notin U_s(R)$. Besides, for cognitive user $j$, we thus have

$$U_j^s(\lambda R_j' + (1-\lambda)R_j'', R_{-j}) = \lambda U_j^s(R_j', R_{-j}) + (1-\lambda)U_j^s(R_j'', R_{-j}) \quad (15)$$

If $R_j'$ and $R_j''$ can be the optimization strategies for $R_{-j}$, corresponding weighted mean should also be the optimal solution. Thus, this conclusion contradicts the hypothesis that $U_s(R)$ is not convex. Therefore, $U_s(R)$ should be convex. In addition, we further prove (4) by the method of contradiction. If condition (4) is not met, a conclusion exists as $(R^n, \hat{R}^n) \rightarrow (R, \hat{R})$, $\hat{R}^n \in U_s(R^n)$. As $\hat{R} \notin U_s(R)$, there exists $\hat{R}_j \notin U_j^s(R)$. Thus, there is $\varepsilon > 0$ and $R_j'$ which enable $U_j^s(R_j', R_{-j}) > U_j^s(\hat{R}_j, R_{-j}) + 3\varepsilon$. Besides, as function $U_j^s$ is continuous along with $(R^n, \hat{R}^n) \rightarrow (R, \hat{R})$, giving a large $n$, we have

$$U_j^s(R'^n, R_{-j}^n) > U_j^s(R'^j, R_{-j}) - \varepsilon > U_j^s(\hat{R}_j, R_{-j}) + 2\varepsilon > U_j^s(\hat{R}_j^n, \hat{R}_{-j}^n) + \varepsilon \quad (16)$$

For a given $R_{-j}^n$, $R_j'$ will be prior to $\hat{R}_j^n$ which has been contradict the premise above mentioned. Thus, condition (4) should be met. We can obtain the conclusion that a pure Bayesian equilibrium exists in this case. Besides, according to Reference [36], we can also conclude that the equilibrium is unique in this case.

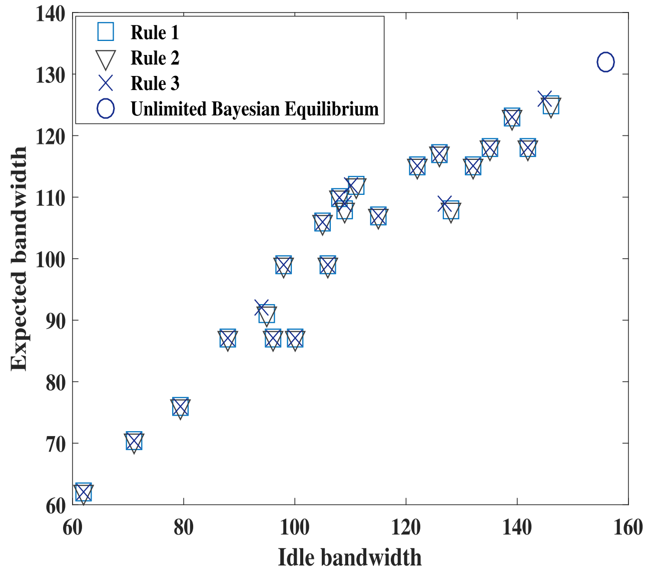


**FIGURE 4.** Effective spectrum allocation combination for the cognitive satellite networks.

## V. NUMERICAL RESULTS

In this simulation scenario, we consider there is a single satellite with consecutive idle spectrum band serving the terrestrial cognitive users in cognitive satellite networks. In the following simulated tests, the basic unit for spectrum bandwidth is MHz. The number of terrestrial cognitive users is 3. For every cognitive user $i(1 \leq i \leq 3)$, we suppose the SINR threshold at receiver to be $\gamma_i = 12dB$ corresponding to $BER_i^{tar} = 10^{-4}$, and the transmission between cognitive users is carried out in Gaussian channels. For the given parameters in satellite system's utility function, there are $X = 0, Y = 1$.

In our proposal, we consider the case in which terrestrial cognitive users' spectrum demands cannot be satisfied by satellite systems due to limited spectrum resource. Thus, a seller's market or monopoly market is an apparent sign for this spectrum sharing situation. At this time, satellite systems perform the optimal spectrum allocation strategy raised above by eliminating cognitive users' redundant information types $M_i, 1 \leq i \leq 3$ to seek the final solutions. Due to $M_1 = 1, M_2 = 2, M_3 = 3$, we obtain that the combination number for three cognitive users' elimination operating should be $(M_1+1)(M_2+1)(M_3+1) = 24$.

Based on the three **Rules** mentioned in previous section, Fig. 4 gives satellite system's maximal expectations under all potential information combinations. Furthermore, Fig. 5 presents the performances of satellite system's elimination solution which seeks the optimal spectrum strategy for terrestrial cognitive users by deleting the transmission information types corresponding to relatively large $Q$. Through this method of eliminating information types, the computation complexity of our algorithm is under control. In Fig. 5, after 15 times of elimination operator, we obtain Bayesian equilibrium as final optimal solution. In this circumstance,

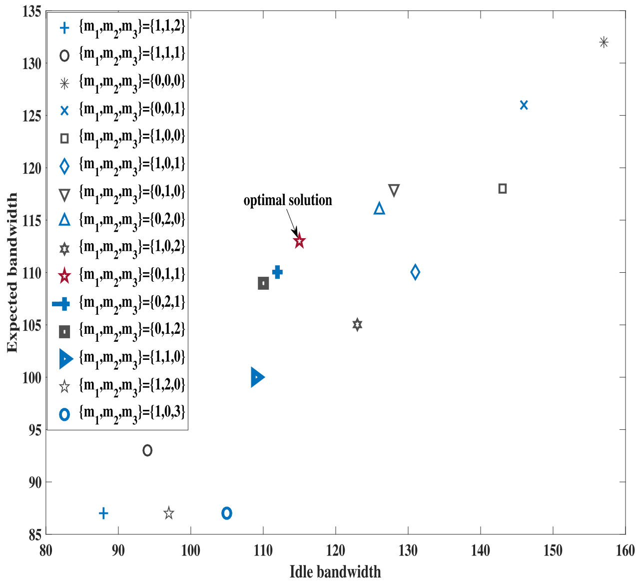


**FIGURE 5.** Elimination solutions of satellite systems.

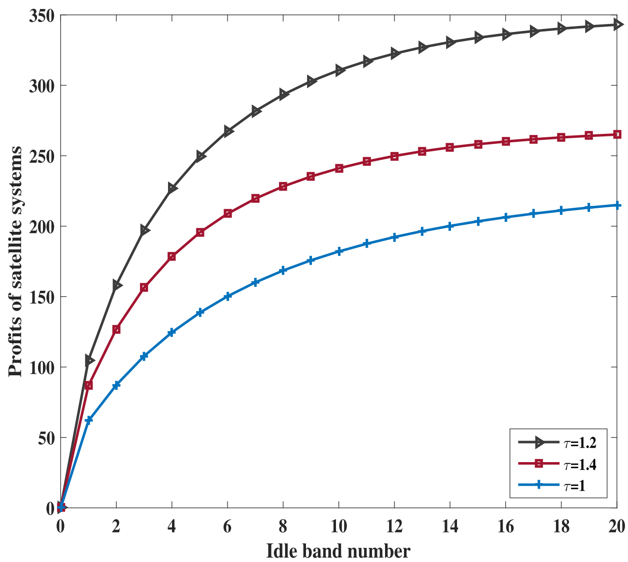


**FIGURE 6.** Satellite system's profits.

we suppose the overall bandwidth demand is 160, and $Q_p = 120$ which is below the spectrum requirement.

From Fig. 5, we can achieve that the optimal elimination strategy is $\{m_1, m_2, m_3\} = \{0, 1, 1\}$. It means that the satellite systems should delete the information types of cognitive users as: the information setting types belonging to $\theta_{2,2}$ of terminal 2 and $\theta_{3,3}$ of terminal 3. In this case, the probability update scheme adopted is **Rule 3** as shown in Fig. 5.

Thus, in this situation, cognitive user 1 can acquire band number $Q_1 = 62$, and the band number of cognitive user 2 is $Q_2 = 9$. For cognitive user 3, in conditions of probability allocation $p_{3,1} = 1/5, p_{3,1} = 4/5$, the corresponding band number is $Q_{3,1} = 34.3$ and $Q_{3,2} = 43.1$, respectively. Furthermore, as shown from Fig. 4 and Fig. 5, satellite system's profits under constraints will not outperform that without any constraints.

Besides, the profits of satellite systems are affected by the parameter settings such as $X, Y, \tau$ given in (9). In Fig. 6, we give the performances of satellite system's profits with different $\tau$. Apparently, higher $\tau$ means more profits obtained by the satellite communication systems with same spectrum bandwidth.

## VI. CONCLUSION

In this paper, we propose a novel spectrum allocation algorithm for cognitive satellite networks by using game theoretical method. The main contribution of this paper lies in that we adopt game theory model to formulate the spectrum optimization and raise a novel proposal according to the characteristics of spectrum monopoly market. In this work, we focus on the situation that the spectrum demands of cognitive satellite users exceed the resource number provided by satellite systems. The optimization objective of this work is to maximize the profits of satellite systems. During the course, satellite systems should balance and figure out which kind of transmission types can most benefit themselves. Due to the limitation of spectrum resource, satellite systems will arbitrarily eliminate part of cognitive users' information types to selectively satisfy the overall requirement. By deleting one or several kinds of modulation modes, cognitive satellite users should update spectrum list to match satellite system's spectrum allocation scheme. Through many rounds of eliminating operations, satellite systems obtain the optimal spectrum allocation scheme by fixing Bayesian equilibrium. We further prove the existence of Bayesian equilibrium. Numerical results are also provided to testify the performance of our proposal from various aspects.

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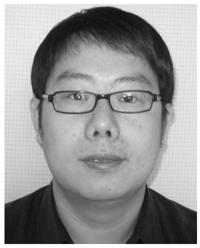

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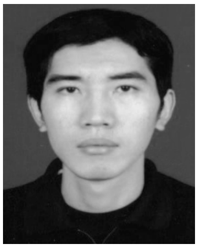

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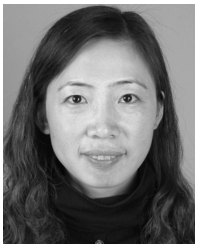

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