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<td><strong>Author(s)</strong></td>
<td>Wang, Li; Li, Feng; Liu, Xin; Lam, Kwok-Yan; Na, Zhenyu; Peng, Hong</td>
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SPECTRAL OPTIMIZATION FOR COGNITIVE SATELLITE COMMUNICATIONS WITH COURNOT GAME MODEL

LI WANG\textsuperscript{1,5}, FENG LI\textsuperscript{2}, (Member, IEEE), XIN LIU\textsuperscript{3}, (Member, IEEE), KWOK-YAN LAM\textsuperscript{1}, (Senior Member, IEEE), ZHENYU NA\textsuperscript{4}, (Member, IEEE), AND HONG PENG\textsuperscript{5}

\textsuperscript{1}School of Computer Science and Engineering, Nanyang Technological University, Singapore 639798
\textsuperscript{2}School of Electronic Science and Engineering, Nanjing University, Nanjing, 210093, China
\textsuperscript{3}School of Information and Communication Engineering, Dalian University of Technology, Dalian 116024, China
\textsuperscript{4}School of Information Science and Technology, Dalian Maritime University, Dalian 116026, China
\textsuperscript{5}College of Information Engineering, Zhejiang University of Technology, Hangzhou 310023, China

Corresponding authors: Feng Li (fenglzj@zjut.edu.cn) and Xin Liu (liruxinstar1984@dlut.edu.cn)

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ABSTRACT With the availability of high-throughput satellite services at affordable cost, terrestrial network providers make use of satellite links to extend their coverage to areas, where land-based communication infrastructures are prohibitively costly to implement. Due to the ever-increasing demand for bandwidth resulted from the rapid development of data-intensive services in recent years, one of the fundamental challenges for satellite communications is to continuously improve utilization efficiency of the scarce satellite spectrum. Cognitive satellite communications address the problem by providing mechanisms for terrestrial and satellite users to dynamically access idle bands of licensed satellite networks, hence enabling spectrum sharing between two satellite systems or between satellite and terrestrial systems. In this paper, we investigate a distributed technique of spectrum sharing for cognitive satellite networks. In order to cater for situations with incomplete decision information, the proposed scheme is based on the Bayesian equilibrium theory. We first develop a spectrum allocation scheme by studying the action strategy of terrestrial cognitive terminals in a distributed competition. A feasible spectrum allocation scheme that caters for cases of incomplete user information is then developed as an extension of the basic scheme by formulating the problem as a Cournot game model. By identifying the unique equilibrium in this model, optimal spectrum allocation for cognitive satellite networks can be achieved. Essential discussions and proofs for the rationality of this method and uniqueness of the equilibrium are provided. Numerical results are given to justify the claimed advantages.

INDEX TERMS Cognitive satellite communications, spectrum allocation, Bayesian bargaining, incomplete information.

I. INTRODUCTION Satellite communication systems play an important role 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 recent years, due to explosive growth for broadband, multimedia and interactive services, high-quality satellite spectrum is more and more scarce. In order to meet the growing demands for the scarce satellite spectrum, the challenge of improving efficiency of spectrum utilization has attracted great attentions of communications researchers and practitioners. 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 some market-driven spectrum allocation mechanisms [5]–[9].

Cognitive satellite communications enable sublicensed satellite or terrestrial networks to use authorized bands for uplink and downlink transmission when they are otherwise idle, wherein a precondition should be noted is that the licensed communications performed by the original satellite users cannot be interfered. The flexible and adaptive spectrum sharing mechanism of cognitive satellite communications encourages the participation of more satellite users, thus improving ROI of satellite systems and communication capacity. On the other hand, when channel fading is very severe caused by harsh natural environment, dynamic satellite
spectrum switch can reduce channel loss to a large extent [10]–[12]. Besides, the ability to intelligently select and allocate reliable spectrum resource allows cognitive satellite networks to support critical operations such as disaster and rescue missions, which require users at ground operations to rapidly fit into the complex, mutable and harsh environment [13]–[16].

With the growing adoption and rapid development of broadband satellite services, the requirement for improving bandwidth efficiency for satellite communication systems has become significant and attracted great attention from researchers and industry practitioners [12], [17]–[19]. In recent years, many techniques including multiple spot beams, OFDM, spectrum reuse and cognitive satellite communications, have been widely explored in order to achieve this objective [20]–[22], wherein efficient resource allocation plays a central role and requires continuous 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 systems need a high degree of flexibility in allocating its wireless resource in order to efficiently handle the dynamic nature of the requested traffic [23]. For spectrum reuse in satellite cells, it is essential to manage inter-cell interference in order to enhance effective resource allocation and system performance [24]. Besides, traditional satellite architectures are 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 [25]. The downlink satellite transmission architecture must make efficient use of satellite networks’ resource, including dynamically adapting to non-uniform demands and time-varying demands and weather-induced signal attenuation.

In recent years, researchers have proposed plenty of schemes for various application scenarios of cognitive satellite communications to address the challenges of resource allocation involving rapid spectrum detection, spectrum access and resource allocation [26]–[30]. Many of these techniques have been studied in the areas of terrestrial cognitive radio networks [31]–[37]. Tarchi et al. [26] defined several satellite communications scenarios, where cognitive radio techniques promise to introduce significant benefits, and discussed the major enablers with the associated challenges. Maleki et al. [27] designed a cognitive zone around incumbent broadcasting satellite service feeder links, it considered the situation that cognitive fixed service terminals beyond the feeder links can freely utilize the same frequency band. Reference [28] presented the concept of cognitive terrestrial radio systems for hybrid satellite-terrestrial systems. Furthermore, the concept of 3D-Spatial reuse of the spectrum was also presented by adopting the cognitive satellite communications considering low elevated the satellite ground stations. In [29], a spectrum sharing technique was proposed to offer unprecedented opportunities to increase capacity and reduce costs, hence allowing SatCom to meet the objectives of the digital agenda of Europe. Maleki et al. [30] investigated the potential of applying cognitive radio techniques in satellite communications in order to increase the spectrum opportunities for future generations of satellite networks without interfering with the operation of incumbent services.

In this paper, we propose a distributed solution for spectrum resource sharing in cognitive satellite communication networks. In this paper, we formulate the problem of spectrum allocation for cognitive satellite networks as a Cournot game model which can cater for complete information and incomplete information cases. For the cases of complete information, cognitive users obtain the relevant information about information about the transmission conditions of other users by communicating with each other in order to form their own spectrum sharing schemes. In this case, we use the Cournot game model to formulate this problem and achieve Bayesian equilibrium as the final solution for spectrum sharing. The proposed algorithm proves that terrestrial cognitive users can obtain more transmission benefits over cryptic transmit information types, meanwhile benefits to the secondary users will rise with the increase of distribution probability of the transmit information types.

The main contribution of this paper is to address the spectrum allocation problem in realistic situations where cognitive satellite users do not have complete information about the transmission conditions of other users. In this case, a heuristic sharing optimization solution is devised to solve the problem and a simplified scheme is obtained to reduce the system complexity. The proposed solution extends the basic Cournot game model by estimating the essential parameters according to historical experience information. By identifying the unique equilibrium in this model, optimal spectrum allocation for cognitive satellite networks can be achieved. Numerical results are provided to justify the proposed method’s performances and illustrate the impacts of corresponding parameters on terrestrial cognitive users’ benefits.

The rest of this paper is organized as follows. We give the system model of spectrum sharing solution for cognitive satellite communications in Section II. Then, the spectrum allocation algorithm based on Cournot game model is proposed in Section III. In Section IV, numerical results are provided to elucidate the performance of our proposal. Finally, we summarize this paper in Section V.

### II. SYSTEM MODEL

#### A. COGNITIVE SATELLITE NETWORKS WITH SPECTRUM SHARING

In this paper, we consider the geostationary satellite networks which employ 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. Furthermore, we suppose our spectrum optimization scheme
is applied in multibeam satellite systems. The reason why we adopt this scenario is that multibeam antenna technology can help enhancing frequency reuse and increasing communication capacity, wherein the problems of spectrum and power allocation in multibeam satellite systems are very significant especially in the face of spatial diversity as well as interference increase caused by band reuse.

Fig. 1 illustrates the application scenario proposed in this paper, where one satellite system and multiple terrestrial cognitive users coexist. The cognitive satellite networks carry out the satellite spectrum sharing by exchanging some useful information with the terrestrial cluster head, which performs the band operate on behalf of a group of end users. We assume the satellite system provides a continued band of idle spectrum as the spectrum to be used by terrestrial cognitive users.

As shown in Fig. 1, we consider the cases in which one satellite system and \( N \) pairs of terrestrial cognitive users coexist. We suppose that each of cognitive terminals communicate with another fixed terminal as a pair. For simplicity, we refer to the pair of cognitive users \( i \) as the cognitive user \( i \). Also in Fig. 1, there are a total of \( Q_N \) band of idle spectrum for sharing with cognitive users. The band resource set obtained by all the cognitive users is supposed to be \( Q = \{Q_1, Q_2, \ldots, Q_i, \ldots, Q_N\} \), and the spectrum price for each unit charged by the satellite system is \( P(Q) \).

According to the market-driven theoretical method, the pricing per unit of the idle spectrum can be expressed as

\[
P(Q) = X + Y \left( \sum_{j=1}^{N} Q_j \right)^\tau
\]

where \( X, Y, \tau \) are all positive and \( \tau \geq 1 \). After the satellite system completes spectrum allocation, cognitive users will use the spectrum allocated to perform the communications within two terminals.

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 spectrum reuse pattern is employed which is a practical scheme to avoid coverage conflict and to improve spectrum efficiency as shown in Fig. 2. We can observe from this figure that inter-cell interference within one multibeam satellite systems is mainly caused by spectrum reuse.

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 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, it should also be noted that the cell’s shape will change with the angle between the central line and the bottom.

**B. INTERFERENCE MODEL**

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 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 follows 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 $\phi$ describing the deviation angle between user ($\beta, 2$) and cell center $o$ can be expressed as

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

$$\times \left(2d_o^s d_{\beta 2}^s\right)^{-1}$$  \hspace{1cm} (2)

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

$$C = \frac{P_{u 1 \beta} g_{\alpha 1}(\varepsilon_{\alpha 1}) G_{\alpha}(\phi_{\alpha 1}^a)}{(4\pi d_{\alpha 1}/\lambda)^2 f_{u 1}(\varepsilon_{\alpha 1})}$$

where $P_{u 1 \beta}$ denotes the transmit power of satellite terminal ($\alpha, 1$), $g_{\alpha 1}(\varepsilon_{\alpha 1})$ denotes the elevation angle from user ($\alpha, 1$) to the satellite system, $G_{\alpha}(\phi_{\alpha 1}^a)$ denotes the antenna gain of terminal user ($\alpha, 1$) at the direction $\phi_{\alpha 1}^a$, $d_{\alpha 1}$ is the straight-line distance between the user ($\alpha, 1$) and the satellite system, $\lambda$ denotes the wavelength, and $f_{u 1}(\varepsilon_{\alpha 1})$ denotes the channel fading of user ($\alpha, 1$) at the direction $\varepsilon_{\alpha 1}$.

Thus, interference among the terrestrial cells can be given as

$$I = \sum_{\beta=1}^{k} \frac{p_{\beta 2} g_{\beta 2}(\varepsilon_{\beta 2}) G_{\beta}(\phi_{\beta 2}^a)}{(4\pi d_{\beta 2}/\lambda)^2 f_{\beta 2}(\varepsilon_{\beta 2})} + N_0(\varepsilon_{\alpha 1})$$

where $k$ denotes the number of the cells sharing the same frequency with cell $\alpha$, $p_{\beta 2}$ denotes the transmit power of satellite terminal ($\beta, 2$), $G_{\beta}(\phi_{\beta 2}^a)$ is the satellite antenna gain of cell $\beta$ at the direction $\phi_{\beta 2}^a$, $d_{\beta 2}$ is the straight-line distance between the user ($\beta, 2$) and the satellite system, $\lambda$ 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. $\rho_{\beta}^a$ is the polarization isolation factor between cell $\alpha$ and $\beta$. Then, the uplink SINR can be expressed as

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

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 $\alpha$.

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 QoS during satellite communications, it can be concluded that the terrestrial user $1$ is required to achieve the transmission capacity as

$$C_1 = B_1 \times \log_2$$

$$\times \left(1 + \frac{p_{u 1 \beta} g_{\beta 1}(\varepsilon_{\beta 1}) G_{\beta}(\phi_{\beta 1}^a) d_{\beta 1}^2 f_{u 1}(\varepsilon_{\alpha 1})}{\sum_{\beta=1}^{k} \frac{p_{\beta 2} g_{\beta 2}(\varepsilon_{\beta 2}) G_{\beta}(\phi_{\beta 2}^a) \mu_{\beta 2} \rho_{\beta}^a}{(4\pi d_{\beta 2}/\lambda)^2 f_{\beta 2}(\varepsilon_{\beta 2})} + N_0(\varepsilon_{\alpha 1}) B_1} \right)$$

For terrestrial cognitive 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 cognitive users involved in this work share the spectrum honestly and cooperatively.

In our proposal, the cognitive 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. SPECTRUM SHARING IN COGNITIVE SATELLITE COMMUNICATIONS

A. DISTRIBUTED SPECTRUM ALLOCATION SCHEME

Through the definitions of cognitive users’ transmission benefits and introduction of various communication factors, we can achieve the difference between the total transmission benefits and costs for cognitive user i as

\[ U_i(Q) = \theta_i Q_i - P(Q) Q_i = r_i k_i Q_i - P(Q) Q_i \]  

where \( \theta_i = r_i k_i \). We define \( \theta_i \) as the actual benefits on per unit band for cognitive terminals, and it is directly proportional to the transmission rate for per unit band. Put (1) into (7), we can obtain the transmission benefits for cognitive user i as

\[ U_i(Q) = r_i k_i Q_i - [X + Y(\sum_{j=1}^{N} Q_j)^T]Q_i \]  

Taking the derivation of (8), we have

\[ \frac{\partial U_i(Q)}{\partial Q_i} = r_i k_i Q_i - [X + Y(\sum_{j=1}^{N} Q_j)^T] - YQ_i(\sum_{j=1}^{N} Q_j)^{T-1} = 0 \]  

where \( i = 1, 2, \ldots, N \). By substituting cognitive user’s various parameters including \( \theta_i = r_i k_i \), we obtain a linear equation with \( N \) unknowns \( Q = \{Q_1, Q_2, \ldots, Q_N\} \).

By fixing these equations, we have the Nash equilibrium of \( Q^* = \{Q_1^*, Q_2^*, \ldots, Q_N^*\} \). When the game involved in the cognitive users is non-cooperative, this equilibrium is the optimal solution. Once the equilibrium is attained, every rational users participating this game do not deviate from this equilibrium. Otherwise, its benefit will be damaged.

The aforementioned distributed spectrum allocation models based on two ideal hypotheses:

1) The terrestrial cognitive users will be informed by each other about the benefit information, while the transmission information of the whole networks is supposed to be reliable.

2) The total number of the idle spectrum owned by the satellite system can satisfy the resource demands of cognitive users.

However, these two hypotheses cannot be met for some complex situations. Firstly, cognitive users involved in this spectrum sharing are usually non-cooperative, thus one user may prefer to hide certain key information of the transmission benefits when it can receive more profit by this action. Secondly, when the spectrum demands of the terrestrial cognitive users are very huge and to the extent that it exceeds the total number of the currently available idle band resource, the results reached by the competition of cognitive terminals will not be the Nash equilibrium due to the mismatch between the number of Nash equilibrium solutions and the number of idle spectrum resource.

Therefore, when actual terrestrial cognitive networks cannot satisfy the two conditions above, we should analyze and solve the resource allocation strategy in the cases of incomplete information and limited resource.

B. SPECTRUM ALLOCATION WITH INCOMPLETE INFORMATION

In this subsection, we propose a distributed spectrum allocation method for the cases of incomplete information by using Cournot competition model. We also focus on the resource allocation strategy under limited number of total resource in cognitive satellite networks. The incomplete information raised in this paper means that the cognitive user participating in this resource sharing will not broadcast its transmission benefit \( \theta_i = r_i k_i \) to other users. Thus, for the transmission benefit information \( \theta_i = r_i k_i \) of user i, other users can only obtain it by statistical analysis and learning of the historical interaction information. When most of these information are unavailable, the Bayesian role can be adopt to analyze this situation. In this paper, we assume that cognitive users have this capability.

We then introduce the basic model for distributed spectrum allocation under incomplete information. In this case, there are \( N \) terrestrial cognitive users having different transmission information types. When a cognitive user i adjusts its modulation mode for better fitting in various channels, other cognitive users can only obtain this modulation information of user i by historical experience estimation and computing the occurrence probability of various kinds of transmission benefits. Basically, it is concluded that the terrestrial cognitive users can be classified into two types as follows:

I. \( \theta_i = r_i k_i \) of cognitive user i is public benefit information which means all the other users will also use this information during the competition of resource allocation.

II. \( \theta_i = r_i k_i \) of cognitive user i is non-public benefit information which means the transmission types adopted by the cognitive user i will not be informed during the spectrum sharing. The only information that other users can obtain is supposed to be the distribution probability of the benefit types.

We suppose the number of cognitive users in type I is \( N_1 \), and every user is labeled by \( 1, 2, \ldots, N_1 \). The number of cognitive users in type II is \( N_2 \) which is labeled by \( N_1 + 1, N_1 + 2, \ldots, N_1 + N_2 \). From the definition of (1) and (8), the actual transmission benefits for a cognitive user i in type I can be expressed as

\[ U_i(Q) = \theta_i Q_i - [X + Y(Q_i + \sum_{j=1}^{N} Q_j^T)Q_i \]  

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Similarly, cognitive users in this satellite network can learn from historical information to obtain the distribution probability of transmission benefit types of cognitive users in type II. In this case, we suppose the cognitive user \( j \) belonging to type II has \( M_j \) kinds of transmission benefit types as \( \theta_{j1}, \theta_{j2}, \ldots, \theta_{jM} \). Then, the corresponding distribution probabilities are \( p_{j1}, p_{j2}, \ldots, p_{jM} \) where \( p_{j1} + p_{j2} + \cdots + p_{jM} = 1 \). Thus, we can obtain the expected benefit \( \theta_j \) of cognitive user \( j \) as

\[
E(\theta_j) = \sum_{k=1}^{M_j} \theta_{jk} p_{jk} \tag{11}
\]

The expectation of the available spectrum bandwidth for cognitive \( j \) of type II can be expressed as

\[
E(Q_j) = \sum_{k=1}^{M_j} Q_{jk} p_{jk} \tag{12}
\]

Hence, when the available bandwidth for cognitive user \( i \) of type I is \( Q_i \), the optimal spectrum bandwidth strategy can satisfy the following equation

\[
Q_i(\theta_i) \in \arg \max_{Q_i} \theta_i Q_i - [X + Y(Q_i + \sum_{k=1}^{N} Q_k)^{\tau-1}]Q_i \tag{13}
\]

As the cognitive users of type I do not now the actual bandwidth \( Q_k \) obtained by cognitive user \( k (N_1 + 1 \leq k \leq N) \) of type II, cognitive user \( i \) has to detect user \( k \)'s expected bandwidth \( E(Q_k) \) by past experience and historical information. Then, we achieve the following equation by first-order derivation

\[
\theta_i - \{X + Y(Q_i + \sum_{k=1}^{N_1} Q_k + \sum_{k=N_1+1}^{N} E[q_k])\}
- \tau YQ_i(Q_i + \sum_{k=1}^{N_1} Q_k + \sum_{k=N_1+1}^{N} E(Q_k))^{\tau-1} = 0 \tag{14}
\]

Similarly, when the cognitive user \( j (N_1 + 1 \leq j \leq N) \) can obtain spectrum bandwidth \( Q_j \), its optimal resource strategy meets

\[
Q_j(\theta_j) \in \arg \max_{Q_j} \theta_j Q_j - [X + Y(Q_j + \sum_{k=1,j
\neq k}^{N} Q_k)^{\tau}]Q_j \tag{15}
\]

Also, the cognitive user \( j \) of type II does not know the available bandwidth \( Q_k \) of the other user \( k \) of type II, thus the cognitive user \( j \) needs to estimate the expected bandwidth \( E(Q_k) \). By first-order derivation, we have

\[
\theta_j - \{X + Y(Q_j + \sum_{k=1}^{N_1} Q_k + \sum_{k=N_1+1}^{N} E[q_k])^{\tau}\}
- \tau YQ_j(Q_j + \sum_{k=1}^{N_1} Q_k + \sum_{k=N_1+1,k
\neq j}^{N} E(Q_k))^{\tau-1} = 0 \tag{16}
\]

Thus, substituting \( \theta_j \) in (15) and (16) and introducing (13), we can obtain the final optimal spectrum allocation scheme for the whole cognitive satellite networks. By solving the equations above, we define \( Q_i^* \) as the spectrum bandwidth \( i \) for the cognitive users of type I, and \( Q_{jk}^* \) as the bandwidth value of \( j \in (N_1 + 1 \leq j \leq N), k \in (1 \leq k \leq M_j) \) for the cognitive users of type II. The optimal spectrum allocation solution in cases of incomplete information can be noted as

1. The cognitive user \( i \in (1 \leq i \leq N_1) \) of type I can achieve the bandwidth number \( Q_i^* \) from the satellite system.
2. The cognitive user \( j \in (N_1 + 1 \leq j \leq N) \) of type II attains the spectrum of bandwidth \( Q_{jk}^* \) with the probability of \( p_{jk} \).

This solution is the Bayesian equilibrium we can obtain. The meaning of Bayesian equilibrium solution lies in that the cognitive users in this cognitive satellite networks can optimize their expected benefits in the networks through 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.

Then, we give the proof for the unique existence of the Bayesian equilibrium. Thus, if we suppose there are \( X \geq 0, Y \geq 0 \) and \( \tau \geq 1 \), for any \( E[Q_k], k \neq i \), an unique solution exists for (10). At the moment, any terrestrial cognitive user will not discard this equilibrium solution, since the deviation from the Bayesian equilibrium easily leads to a loss of higher expected profits.

Theorem 1: For the cognitive user \( i \) of type I and user \( j \) of type II, if \( Q_i = E(Q_j) \) and \( \theta_j = E(\theta_j) \) hold, we have \( E(U_j) \geq E(U_i) \).

Proof: Rewrite (16) as

\[
\theta_j = (\tau + 1)YQ_j^\tau + o(Q_j^\tau) \tag{17}
\]

where \( o(Q_j^\tau) \) denotes the high-order polynomial of \( Q_j \) and its highest order is less than \( \tau \). Furthermore, there is \( j \in (N_1 + 1 \leq j \leq N) \).

Therefore, the expected transmission benefits for cognitive user \( j \) is as follows

\[
E(U_j) = \sum_{k=1}^{M_j} p_{jk} U_{jk}(Q_{jk}) = \sum_{k=1}^{M_j} p_{jk}[Q_{jk}\theta_{jk} - Q_{jk}P(Q)] \tag{18}
\]

where the cognitive user's benefit \( U_{jk}(Q_{jk}) \) corresponds information type of \( \theta_{jk} \), and the spectrum band allocated is \( Q_{jk} \).
By arranging (18), we can obtain
\[
E(U_i) = \sum_{k=1}^{M_i} p_{jk} [(\tau + 1) Y Q_{jk}^{r+1} + o(Q_{jk}^{r+1})]
\]
\[
= (\tau + 1) Y E[Q_{jk}^{r+1}] + o(E[Q_{jk}^{r+1}])
\]
(19)

Due to \( \tau \geq 1 \), the order of function \( E[Q_{jk}^{r+1}] \) is larger than \( E(Q_i) \). Meanwhile, as we suppose \( Q_i = E(Q_i) \), we can obtain the following inequality as
\[
E[Q_{jk}^{r+1}] > (E(Q_i))^{r+1} = Q_i^{r+1}
\]
(20)

Similarly, (19) can be inducted as the information function of the cognitive users of type I to be \( \theta_i = (\tau + 1) Y Q_i^{\tau+1} + o(Q_i^{\tau+1}) \). Also, \( o(Q_i^{\tau+1}) \) is the high-order polynomial of \( Q_i (1 \leq i \leq N_i) \) whose highest order is less than \( \tau \). Then, we have
\[
U_i(Q_i) = \theta_i Q_i - Q_i P(Q) = (\tau + 1) Y Q_i^{\tau+1} + o(Q_i^{\tau+1})
\]
(21)

We suppose \( Q_i \) as the solution under Bayesian equilibrium which is a constant. The final expected transmission benefits of the cognitive user in type I are \( E(U_i) = U_i(Q_i) \). Substituting (21) into (20), we obtain
\[
E(U_i) = (\tau + 1) Y E[Q_i^{\tau+1}] + o(E[Q_i^{\tau+1}])
\]
\[
> (\tau + 1) Y Q_i^{\tau+1} + o(Q_i^{\tau+1}) = E(U_i) = U_i
\]
(22)

Thus, we have the conclusion of this theorem that cognitive users in the cognitive satellite communications can improve their benefits by hiding their own transmission information types.

**Theorem 2:** For the cognitive users of type II, if \( E(Q_i) = E(Q_k) \) and \( \text{Var}(\theta_i) > \text{Var}(\theta_k) \), we have \( E(U_i) > E(U_k) \).

**Proof:** Due to \( \tau \geq 1 \), for the cognitive uses in type II, if its distribution variance of profit information \( \theta_i \) is relatively large, then \( E[Q_i^{\tau+1}] > (E(Q_i))^{\tau+1} \) will be larger. Thus, there exists \( E[Q_i^{\tau+1}] > (E(Q_i))^{\tau+1} > E[Q_i^{\tau+1}] > E(Q_i^{\tau+1}) \), which means there is \( E[Q_i^{\tau+1}] = E(Q_i^{\tau+1}) \) in condition of \( E(Q_i) = E(Q_k) \). From (19), we have
\[
E(U_i) = (\tau + 1) Y E[Q_i^{\tau+1}] + o(E[Q_i^{\tau+1}])
\]
\[
> (\tau + 1) Y E[Q_i^{\tau+1}] + o(E[Q_i^{\tau+1}]) = E(U_k)
\]
(23)

Thus, we achieve the conclusion given in Theorem 2 which also means that in condition of equal expectations of transmission information for the cognitive users in type II, they can receive more benefits through this spectrum sharing when the variances of distribution probabilities of transmission information types become larger.

**IV. NUMERICAL RESULTS**

In this section, we discuss the performances of our proposed spectrum sharing algorithm. In this simulation scenario, we suppose the cognitive satellite networks have only one satellite system which has a constant band of idle spectrum for sharing, there pairs of cognitive terminals labeled by 1, 2, 3, thus \( N = 3 \). The basic bandwidth is \( MHz \) in this simulation, then the simulation settings is as follows.

1) For every cognitive user \( i(1 \leq i \leq 3) \), the SINR threshold at the receiver is set to be \( \gamma_{\text{tar}}^{i} = 10 \text{dB} \). 
2) We suppose every cognitive user is working in Gaussian impulsive channels where the BER threshold is \( BER_{\text{tar}} = 10^{-4} \).
3) There are \( X = 0, Y = \tau = 1 \) in (1).

Firstly, we suppose the spectrum resource of the cognitive satellite system can meet terrestrial cognitive users’ demands and every cognitive user involving in this activity freely select their transmission information type. To compare the resource allocation schemes in cases of both complete information and incomplete information, we take the following two situations into account. Case 1: All the users work in the mode of complete information. Case 2: each of them works in the mode of incomplete information.

Then, we compute the equilibrium results of the different cases in the cognitive satellite networks and give the corresponding resource allocation solutions. Meanwhile, in order to more effectively compare the effects of our proposal in different cases, we suppose the cognitive users in the two cases have same expectations.

In Case 1, there is \( \theta_1 = \theta_2 = \theta_3 \). In Case 2, we define \( \theta_1 = E(\theta_2) = E(\theta_3) \). In Case 1, every cognitive user can obtain the distribution probabilities of the other users’ transmission information types. As shown in Fig. 4, we give the profits of the cognitive users with changing band number \( Q_i \). In Fig. 4, we set the parameter \( \theta_1 = \theta_2 = \theta_3 = 135 \) in conditions of complete information types. In case of complete information, the curves of there profits functions coincide. In this case, when every cognitive user \( i(1 \leq i \leq 3) \) acquires achieve spectrum band \( Q_i = 20 \), maximal overall profits is 149 as shown in Fig. 4.
In Fig. 5 and Fig. 6, the relations of Nash equilibrium and Bayesian equilibrium for cognitive users have been given. As shown in Fig. 5, in condition of complete information type, cognitive user’s equilibrium solutions can be attained at $Q_1 = 34$. Obviously, when user 2 and 3 choose to hide their transmission information types in incomplete information mode, the spectrum allocation scheme changes in respond. When the cognitive users work in the mode of Case 2, we suppose the distribution probability of the transmission information type for the users belongs to public knowledge which can be learned. The settings of the tests in Fig. 5 and Fig. 6 are as follows: $\theta_1 = 170, \theta_{21} = 120, \theta_{22} = 210, \theta_{31} = 140, \theta_{32} = 150, \theta_{33} = 190$. The corresponding probabilities are $p_{21} = 0.4, p_{22} = 0.6, p_{31} = 0.2, p_{32} = 0.2, p_{33} = 0.3$. All the parameters should meet the condition $r_{ki} > [X + Y(\sum_{j=1}^{N} Q_j)^\tau]$. As if the users’ transmission settings satisfy $r_{ki} \leq [X + Y(\sum_{j=1}^{N} Q_j)^\tau]$, we can obtain from (8) that terrestrial cognitive users will not receive any profits from this spectrum sharing.

As shown from Fig. 4 to Fig. 6, we have given the performances of cognitive users’ transmission benefits in both complete information mode and incomplete information mode. In fact, due to the difference of transmission information types, the curves of transmission benefits are changing according to the benefits per unit. The cognitive users with high transmission information type expect to reap more profits. At the same time, each cognitive user’s transmission benefit in incomplete information type is similar to that in complete mode, which rises with the increase of spectrum bandwidth. However, when the spectrum band number approaches a given threshold, the transmission benefits for cognitive users will go down with the increase of band number. Actually, this change matches basic principles of economic activities. From another aspect, satellite system wants to raise the price of per band unit when cognitive users’ demand on the spectrum resource increases. As a result, the increase of spectrum price will let cognitive users bear more costs during the spectrum sharing. Thus, when the demand exceeds the supply in this spectrum market, cognitive users’ transmission benefits will decrease. As shown from Fig. 5 and Fig. 6, it should be noted that the profits received by the cognitive users will be affected by each other, since they all participate in the spectrum sharing activities. Optimal spectrum pricing can be attained by choosing proper parameters given in the utility functions. Besides, despite we have proven that our utility function proposed above will have a equilibrium which means the
function at least has a solution to be found, unsuited parameters can also lead to unreasonable solutions for cognitive users’ profits.

Furthermore, we give the performances of user 2’s Nash equilibrium and Bayesian equilibrium with changing \( \theta \) in Fig. 7 and Fig. 8. A basic principle we can obtain from the figures is that the satellite systems need to raise their spectrum price if they tend to reap more profits by the spectrum sharing. The equilibrium described in the figures represents the optimal solution we can achieve from our proposal. Same tendency can be envisioned for the other pairs of cognitive users. Besides, in general, the value of Bayesian equilibrium is relatively lower than that of Nash equilibrium, thus optimal profits can be reached with more ideal spectrum price for terrestrial cognitive users.

V. CONCLUSION

In this paper, we investigated the spectrum sharing problem for cognitive satellite communications when taking into consideration the effects of multibeam satellite systems. The main contribution of this paper includes the introduction of a Cournot-based model to describe and formulate the transmission benefit changes of cognitive users in both complete and incomplete information modes. Discarding traditional fixed spectrum allocation method, we attempt to introduce more dynamic solution to solve the resource optimization problem in cognitive satellite communication systems. We first analyzed the interference model in multibeam satellite system where spectrum reuse and oblique projection between different beams should be carefully modeled. Then, for cases when cognitive users in these satellite networks can share their transmission information, a distributed spectrum sharing solution was proposed to maximize the cognitive users’ overall profits. We also investigated the problem of spectrum sharing in cases of incomplete transmission information. When the cognitive users cannot obtain the transmission information of other users in a timely manner, they need to estimate their information types and make their spectrum decisions based on user experiences and historical data. Thus, we proposed a heuristic sharing optimization method to solve the problem and a further simplified scheme to reduce the system complexity was presented. Numerical results were provided to justify the proposed method’s performances, and illustrate the impacts of various algorithm parameters on terrestrial cognitive users’ benefits in cases of cognitive satellite communications.

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ZHENYU NA received the B.S., M.S., and Ph.D. degrees from the Harbin Institute of Technology, Harbin, China, in 2004, 2007, and 2010, respectively. He is currently an Associate Professor with Dalian Maritime University. His research interests include IoT networks and satellite communication systems.

HONG PENG was born in Hubei, China. She is currently an Associate Professor with the College of Information Engineering, Zhejiang University of Technology. Her research interests include IoT networks and wireless sensor networks.