Abstract—In this paper, we consider power control for a code-division-multiple-access (CDMA)-based satellite cognitive radio network where the satellite acts as the common transmitter of primary users and secondary users. Specially, we assume that primary users are willing to share resource with secondary users by means of leasing spectrum, while secondary users have to pay for the shared spectrum. In addition, secondary users are allowed to transmit on any sub-channel provided that the resulting interference to any primary users is below a critical threshold. We focus on the downlink. The objective is to maximize the throughput in the licensed frequency band of the satellite network. We formulate the problem as a game theoretic problem with all users as the players. We propose a two-phase control scheme that can be accepted willingly by both types of users and can maximize the throughput of the satellite network. In the first phase, the Nash Equilibrium point is calculated with an iterative method, the existence of the Nash Equilibrium point is also proved. In the second phase, Payoff Dominance Selection is used to choose the optimal power allocation under the constraints including quality of service protections of all users and maximum transmission power of the onboard power amplifier. Simulation is performed to study the parameters of the system and of each user. By simulation, we find that the throughput is greatly increased by the proposed scheme compared with traditional satellite networks where fixed power is allocated to only primary users. Onboard complexity is also analyzed.

Index Terms—Satellite Cognitive Communication; Power Control; Dynamic Spectrum Access; Downlink; Nash Equilibrium

I. INTRODUCTION

As reported by the Federal Communications Commission (FCC), spectrum utilization in many bands is very low [1]. For satellite communications, especially, spectrum resource is more precious than any other ingredients. However, satellites perform service to different area with dissimilar work states. Furthermore, traditional approaches of fixed spectrum allocation to licensed networks lead to spectrum underutilization. Actually, the fact that only a few licensed users access the satellite network does underutilizes the licensed spectrum. This motivates the concept of spectrum sharing that allows secondary cognitive radio networks [2]-[4] to exploit the under-utilized spectrum. More importantly, the profound significance for a satellite network to support both primary communications and secondary cognitive radios should be appreciated.

In this paper, we consider a downlink power control (PC) problem for a point-to-multipoint cognitive satellite network. Specifically, we consider a code-division-multiple-access (CDMA)-based cognitive network with one satellite as the common transmitter and multiple primary and secondary users as the downlink receivers that communicate with the satellite in a single hop.

The spread spectrum CDMA system consists of orthogonal pseudo-codes, where a pseudo-code can be thought of as an orthogonal sub-channel though this is not explicitly assumed. The secondary system may transmit on any of the orthogonal sub-channels provided that the interference created to a primary user (PU) is below a predefined threshold to guarantee the Quality of Service (QoS) of the PU.

We assume that perfect information of PU and secondary user (SU) is gathered by satellite at the beginning of every frame. We also assume that instantaneous fading gains are perfectly known at the satellite since each user can estimate channel gains and report to the common transmitter. As a result, for each user, a transmission power is decided at the satellite that ensures that both types of users receive signals without harmful interference created to any user by the satellite transmitting power on the downlink.

More precisely, we are interested in the idea of Dynamical Spectrum Leasing (DSL) [5] that allows PU and SU communicate cooperatively by means of payment from SUs to PUs. On one hand, an SU has to pay a certain cost for receiving signals from the satellite. On the other hand, a PU is willing to reap additional benefit from SUs by leasing spectrum.

We then propose a game model with all users as the players and define utility functions of both types of users. Naturally, the utility functions imply that every SU pursues maximum throughput at low cost while every PU obtains maximum benefit by sharing spectrum with SUs. A power allocation scheme that maximizes both the utilities can be obtained by calculating Nash Equilibrium
The rest of this paper is organized as follows: In section II, we review work that is related to this paper. In section III, the system model is described and the power allocation problem is formulated. The game model and the solution of optimal scheme are presented in section IV. In section V, numerical results are presented and complexity is analyzed. We state conclusion in section VI.

II. RELATED WORKS

Downlink resource allocation of femto-cell aims at increasing the utilization of the available macro-cell bandwidth for users located indoors. In [7], time slot is treated as the resource to be allocated as the time division duplex (TDD) operation is proposed. The sensing is performed on the uplink channel and the transmission is carried out in the corresponding slot of the downlink channel. The outage probabilities of both PU and SU are discussed in [8]. In [9], mixed primal and dual decomposition methods are employed to solve the downlink spectrum sharing problem with the aim of maximizing throughput. The optimization question is divided into two subproblems including a channel allocation problem and a power control problem on each channel. In [10], OFDMA is operated in both maro- and femto-cells, and the optimal power allocation on downlink is obtained according to Karush-Kuhn-Tucker (KKT) condition. And in [11], downlink power control is accomplished in a game model with sum throughput of maro- and femto-cells as the utility function.

Resource allocation in OFDM-based wireless networks has been an active research topic. In [12], the optimal power control problem that aims at maximizing throughput is divided into four subproblems including: throughput computation, transmission power allocation, channel allocation and Lagrange multipliers calculation. In [13], a downlink channel/power allocation scheme that maximizes the number of supported fixed-location wireless subscriber with opportunistic spectrum access is obtained by solving a mixed-integer linear programming. A suboptimal scheme that can be obtained at a lower complexity based on local knowledge is also introduced in [13]. In [14], a joint cross-layer scheduling and spectrum sensing design framework that adapts the power allocation and subcarrier assignment across the secondary users is proposed to optimize a system utility. A distributed implementation for the cross-layer sensing and scheduling design using primal-dual decomposition is also introduced in [14]. An optimal and two suboptimal algorithms are proposed in [15]. The optimal one at a higher complexity is to find a power profile that holds KKT conditions so that the maximum throughput can be achieved. To reduce complexity, one of the suboptimal algorithms is to allocate power for a particular CR user by considering the effect only on the PU band where the CR user causes the most amount of interference. The other takes the step size of the ladder to be inversely proportional to the primary signal energy in the licensed spectrum. In [16], a primary radio network willingness-based framework for coexistence and sub-channel sharing is designed, where PU determines its interference margin and broadcasts to CR users while CR users optimize their sum data rate by implementing water-filling.

Game theory is a useful tool to study the strategic behavior of network participants in cognitive radios. In [17], a game theoretic approach for downlink power control to solve the resource allocation problem from a set of base stations (BSs) to a number of CR users. In the game model, BSs and users act as the players and the pricing mechanism motivates the BS to provide service to users. As forementioned, a game model is established in [11].

Finding a power vector/matrix which holds KKT condition is another available approach to deal with the resource allocation problem. In [18], a solution to uplink and downlink power allocations according to KKT conditions is presented in a CR system including a BS and multi-users with perfect channel state information. In [19], the problem which takes into account the uncertainty of the primary users’ location is modeled as a mixed integer nonlinear programming problem. KKT condition is applied to find the optimal assignment of channel and power to each user to maximize the downlink average throughput by means of decomposition of the dual optimization problem into a number of subproblems. As mentioned earlier, KKT condition is used in OFDMA case in [10].

There are also several other methods to allocate downlink power/channel. In [20], a fair spectrum allocation approach to maximize throughput is introduced. However, the study object is fixed device, not cognitive users. The fairness is also discussed in [21]. Besides, an optimal solution for jointly controlling data rate, transmission power, and sub-band allocation to optimize the sum throughput in a relay-assisted cognitive cellular downlink system accessing a spectrum licensed to a primary network is presented in [21]. An optimal resource allocation for multi-BSS working in identical frequency band is proposed in [22]. In [23], a compressed sensing (CS) –based algorithm is presented according to the sparsity of difference between fore-and-aft power allocation vectors of PU and SU, i.e. $P_{\text{prior}} - P_{\text{next}}$, and $P_{\text{prior}} - P_{\text{prior}} - P_{\text{next}}$ , and the power control procedure is completed by announcing sensed results to BS. An integration-based model to contain the correlation in shadow fading is modified and the definition of coverage area and protection area are also introduced in [24]. In [25], device-to-device communication as a potential resource reuse technique underlaying the cellular network is addressed. In [26], a power allocation scheme that
maximizes the throughput in scene including a CR BS and multi fixed-location CR user is presented. The contribution of this paper is that transmission power should be calculated at first. After that power/channel allocations of both uplink and downlink are achieved by broadcasting the channel information to all users. In [27], a max-min problem based downlink resource allocation in a fair and efficient fashion is formulated for an OFDMA-based cognitive radio point-to-multipoint network with fixed users according to the backlog of each user. A model to compute the allowed maximum transmission power for CR is introduced in [28].

Compared to all these related works, our paper focuses on the satellite cognitive radio network downlink which has never been mentioned so far. As stated earlier, indeed, the insufficiency of spectrum utilization of traditional satellite communication is an imperative. We believe that the spectrum efficiency can be improved by introducing secondary users into the traditional satellite networks. By considering spectrum leasing from PU to SU, the proposed scheme in this paper can greatly increase the throughput in licensed frequency band.

III. PROBLEM DEFINITION

A. System Model

In this section, we propose a dynamic spectrum leasing CDMA satellite cognitive network architecture in which the primary network which has the license of the available spectrum is co-located with the secondary network and is willing to share its spectrum with secondary systems. We assume that the satellite works as a common transmitter of both networks. Let $L$ and $K$ denote the numbers of PUs and SUs respectively. Obviously leasing would mean that the secondary system will have to pay certain compensation to the primary system for this spectrum access. An SU could receive data from downlink only if the QoS of primary system has been protected. The primary system has an incentive to allow SUs to access the licensed spectrum in order to maximize the possible compensation from SUs. Meanwhile, the SUs are interested in maximum throughput under certain payment.

Let $h_{lq}$ be the channel gain between satellite and SU $k$ and $h_{lp}$ be the channel gain between satellite and PU $l$. The primary user can adapt its interference cap denoted by $Q_{l}$, which is the maximum tolerable interference from all secondary transmissions. Let $P_{l}$ and $P_{k}$ respectively denote the transmission power from satellite to PU $l$ and SU $k$.

B. Operational Requirements

We assume that both types of users in the satellite networks have same communication conditions and spreading code length. In other words, each user has equal CDMA gain $G$, and $h_{lq} = h_{lp} = h$. There are many phenomena that lead to signal loss on transmission through the earth’s atmosphere. $h$ changes in different weather conditions and so does $Q_{l}$. Under a specific weather condition, $Q_{l}$ is determined by $P_{l}$ while QoS is unchanged. In our model, satellite lease licensed spectrum by adjusting $P_{l}$ and QoS of PU must be protected at the same time.

For the PU system, the SINR of $l$ th downlink can be calculated as:

$$\gamma^{(p)}_{l} = \frac{Gh_{lq}^{2}P_{l}}{\sum_{k \neq l} h_{lp} + \sum_{i \neq l} h_{lp} + N} = \frac{Gh_{lq}^{2}P_{l}}{I_{l}^{p} + N} \tag{1}$$

where $I_{l}^{p}$ is the total interference suffered by PU $l$. $I_{l}^{p} = \sum_{i \neq l} h_{lp} + \sum_{k} h_{lp}$, and $N$ is the noise. For a PU to protect its QoS, the target SINR is defined as $\gamma_{l}$, and the interference gap $Q_{l}$ on the $l$ th downlink with $P_{l}$ as the transmission power can be calculated as:

$$Q_{l} = \frac{Gh_{lq}P_{l}}{\gamma_{l}} - N \tag{2}$$

For the SU system, the received SINR of $k$ th downlink can be calculated as:

$$\gamma^{(s)}_{k} = \frac{Gh_{lp}}{\sum_{i \neq k} h_{lp} + \sum_{i \neq k} h_{lp} + N} = \frac{Gh_{lp}}{I_{k}^{s} + N} \tag{3}$$

where $I_{k}^{s}$ is the total interference suffered by SU $k$, $I_{k}^{s} = \sum_{i \neq k} h_{lp} + \sum_{i \neq k} h_{lp}$ . To receive data from satellite, SU which consume transmission power should be charged. Cost factor $\lambda_{k}$ is defined as the amount charged by satellite when the satellite transmits per unit power on $k$ th downlink to SU $k$. In other words, SU $k$ should pay $\lambda_{k}P_{k}$ to receive data from satellite on $k$ th downlink, and the payment can be seen as the compensation (benefit) of PU system. The total benefit of PU can be calculated as:

$$B = \sum_{k = 1}^{K} \lambda_{k}P_{k} \tag{4}$$

We assume that, for appropriate performance of the primary network, the received SINR at each PU receiver must be above a predefined value of $\gamma_{l}$. For the same reason, SU receiver also requires the received SINR to be above a predefined threshold $\gamma_{min}$. Both of the assumptions can be expressed as:

$$\gamma^{(p)}_{l} \geq \gamma_{l} \tag{5}$$

$$\gamma^{(s)}_{k} \geq \gamma_{min} \tag{6}$$
C. Users’ Utility

For the whole satellite communication system, developing a scheme that maximizes spectrum efficiency is the aim. It means maximum system throughput that includes both PU’s and SU’s throughput. As the license holder, PU system aims at maximizing $B$, that means the satellite transmit lowest power to each PU with the confines of PU’s target SINR. For a specific PU, PU could be satisfied only if $Q_l \geq I'_l$. Meanwhile, as tenants, SUs are seeking to receive maximum data after a certain payment. Thus, the utility functions of PU $l$ and SU $k$ are given respectively by:

$$U^l_l(Q_l, P^s_h) = Q_l - \mu_2 \left( (Q_l - I'_l)^2 \varepsilon(Q_l - I'_l) \right) -$$

$$\mu_2 \left( e^{((Q_l - I'_l) - 1) (Q_l - I'_l)} \right)$$

$$U_k(p_k, P^s_h) = \ln \left( 1 + \gamma^{(s)}_k \right) - \lambda_k p_k$$

$$= \ln \left( 1 + \frac{G p_k}{I'_k + N} \right) - \lambda_k p_k$$

where the transmit power vector of all SUs except SU $k$ is denoted by $P^s_h$ and the transmit power vector of all PUs except PU $l$ is denoted by $P^s_h$. $\varepsilon(\cdot)$ is the step function with $\varepsilon(x) = 1$ for $x > 0$ and $\varepsilon(x) = 0$ for $x \leq 0$ and $\mu_1$ and $\mu_2$ are positive punishment coefficients. Note that the second and third terms in (7) are introduced to ensure that QoS required by PU $l$ is satisfied. If a PU downlink instantaneous SINR is less than the target SINR, i.e. if $Q_l < I'_l$, the PU downlink should be strictly punished because it can not satisfy PU’s reception. On the contrary, if a PU downlink instantaneous SINR is greater than the target SINR, i.e. if $Q_l > I'_l$, the PU downlink should also be penalized because it is unnecessary for the satellite to transmit higher power when PU’s reception is satisfied. Higher transmit power means greater interference to other users and lower benefit, and especially, for satellite communication it makes energy wasted. We also note that the first term in (8) is the Shannon capacity for secondary user, where $\ln$ replaces $\log_2$ for the sake of expedite computation. The second term in (8) is the total amount charged on SU $k$ for receiving data. It is easy to see that the goal of secondary user is to achieve the most energy efficient transmission from the utility function in (8).

D. Objective

We are interested in finding a downlink power allocation schemes that maximize the spectrum efficiency in a satellite DSL Cognitive network. In other words, the aim of this paper is to maximize the satellite network throughput in its licensed frequency band. As mentioned above, the throughput of the satellite network including both PUs’ and SUs’ throughput is calculated as:

$$T(P_l, p_k) = \sum_{l=1}^{L} \ln \left( 1 + \frac{\gamma^{(p)}_l}{} \right) + \sum_{k=1}^{K} \ln \left( 1 + \frac{\gamma^{(s)}_k}{} \right)$$

subject to

1. $0 \leq \sum_{k=1}^{K} p_k + \sum_{l=1}^{L} P_l \leq P_{max}$
2. $I'_l = I''_l + P'' \leq Q_l$
3. $\gamma^{(s)}_l \geq \Gamma_{min}$

Where $P_{max}$ is the maximum power that the on board power amplifier (PA) could transmit.

IV. GAME MODEL AND OPTIMAL POWER ALLOCATION

A. The Proposed Game Model

In practice, the satellite parameters, such as: $G$, $h$, $\lambda_k$, $\Gamma_{min}$, $I'_l$ and $N$, are known. Thus, the game model is as follows:

Players: Let $\Pi$ be the closet of players which include $L$ PUs and $K$ SUs, and each player is rational and has common knowledge. All players are waiting to receive data from satellite.

Action set: $A = \Pi_1 \times \Pi_2 \times \ldots \times \Pi_L \times \Pi_h \times \Pi_2 \times \ldots \times \Pi_K$, where $\Pi_l = [0, P_{max}]$ is the action set of PU $l$ and $P_l \in \Pi_l$ is the power that the satellite transmit to PU $l$, $\Pi_h = [0, P_{max}]$ is the action set of SU $k$ and $p_k \in \Pi_h$ is the power that the satellite transmit to SU $k$. An action vector can be expressed as: $p = [P_1, P_2, \ldots, P_L, p_1, \ldots, p_K]$, where $p \in A$.

The utility functions of PU and SU are (7) and (8) respectively. The outcome of the game is that each user could receive data with required QoS and that the satellite network achieves maximum throughput.

B. Nash Equilibrium

Existence of Nash Equilibrium: We note that the constrain 2. in (10) is $I''_l \leq Q_l$ which makes the third term in (7) be zero. Thus, equations (7) and (8) are continuous functions of $p$ and strictly quasi-concave with respect to $P_l$ and $p_k$. Furthermore, since the set of admissible power allocation strategies of each player is nonempty, convex and compact, we can conclude that this game
model has a pure Nash Equilibrium by using Kakutani Fixed Point Theory[29][30].

Calculating Nash Equilibrium: Recall the utility of each PU, as mentioned in (7). In the Nash point of the game model, each PU tries to maximize its utility. For PUI, we can achieve its optimal interference gap $Q_{l}^{\omega}$ by setting the derivative of (7) to zero. The equivalent consequence is that the satellite transmits power $P_{l}^{\omega}$ to PUI. Both of $Q_{l}^{\omega}$ and $P_{l}^{\omega}$ can be calculated as:

$$Q_{l}^{\omega} = I_{l}^{\omega} + \frac{1}{2\mu_{l}}$$  \hspace{1cm} (11)

$$P_{l}^{\omega} = \frac{\gamma_{l}}{G} \left( \frac{Q_{l}^{\omega} + N}{Gh} \right)$$  \hspace{1cm} (12)

Similarly, each SU tries to achieve its maximum utility. However, the QoS of PU should be perfectly protected and SUs will acquire their optimal power allocations under that condition. As mentioned above, the utility of each SU will be maximum when the derivative of (8) equals to zero. For a given SU $k$, the optimal power allocation $p_{k}^{\omega}$ can maximize its utility and $p_{k}^{\omega}$ can be calculated as:

$$p_{k}^{\omega} = 1 - \frac{1}{\lambda_{k}} \left[ \frac{\gamma_{k}}{G} \left( \sum_{i \neq k} p_{i} + \sum_{i \neq k} P_{i} + \frac{N}{h} \right) \right]$$  \hspace{1cm} (13)

When an action vector $p^{\omega}$ satisfies (11) and (13), the action of each PU or each SU is best-response to others’ actions. Therefore, the power allocation vector $p^{\omega}$ is an equilibrium strategy. To maximize the satellite network throughput, finding the equilibrium strategy $p^{\omega}$ which satisfies (10) is the goal of this paper. Let (10) be the utility function of the satellite communication system, then we can achieve the unique power allocation strategy by using PDS [6].

Application to satellite cognitive communication: In satellite cognitive networks, the licensed users play the role of primary users which are willing to lease their downlink spectrum to cognitive users which are considered as secondary users. All users are regarded as players. Utility function of each type of users is given by (7) and (8) respectively. To achieve the outcome that throughput of the satellite network is maximized, the optimal power allocation should be searched from action set.

In a single game, the numbers of both PUs and SUs are constant. Equilibrium strategies can be gained after iteratively calculating (11), (12) and (13). If the result is unique, the equilibrium strategy is the optimal power allocation vector $p^{\omega}$. Otherwise, the optimal power allocation $p^{\omega}$ can be achieved by using PDS with (10) as the utility function. Since the PU and SU may enter or quit the network, the number of players will be variable and the power control scheme should be updated whenever any user enters or exits the satellite network. To keep the network stable, the information of users’ entrance and exit should be refreshed periodically. In practice, the satellite collects all the users’ information and on board processor builds the game model and calculates the optimal power allocation vector. After that, the satellite transmits data to all users at the optimal power level.

V. PERFORMANCE EVALUATION

In this section, we discuss the performance of the proposed scheme in DSL game model by simulation. Firstly, the maximum numbers of PUs and SUs that the satellite network could afford should be considered. Secondly, individual action of each user is modeled and the optimal action strategy of each user is selected after iteration and optimization. Thirdly, the maximum throughput that the network could achieve is analyzed and results in normal situation and in the proposed scheme are also compared. Finally, the utility of each user is shown. Furthermore, computing complexity of the scheme which is substantial since the algorithm is completed on board is given in this section.

A. Simulation Model

The satellite is assumed to work in geostationary earth orbit and carry a C-band transmitter with a bandwidth of 100MHz. To simplify the simulation process, both types of users are considered to be uniformly configured respectively. In other words, all PUs have the same configuration parameters and all SUs are identical. Other parameter assumptions are shown as follows:

<table>
<thead>
<tr>
<th>Simulation parameters</th>
<th>$G_{s} = 30$(dB)</th>
<th>Tx-Rx antenna gain= 70(dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_{min} = 20$(dBW)</td>
<td>Path loss = –196.5(dB)</td>
<td>$\lambda_{d} = 2$</td>
</tr>
<tr>
<td>$\gamma_{s} = 12$(dB)</td>
<td>Noise temperature = 75(K)</td>
<td>$\Gamma_{s} = 10$(dB)</td>
</tr>
<tr>
<td>$\mu_{1} = 10/k^{2}$</td>
<td>$h = 126.5$(dB)</td>
<td>$N = 129.8$(dBW)</td>
</tr>
<tr>
<td>$\mu_{2} = 100/k^{2}$</td>
<td>$\Gamma_{env} = 10$(dB)</td>
<td></td>
</tr>
</tbody>
</table>

B. System Capacity to Accept SUs

In a scenario with $N$ as the noise power, relation between SUs’ and PUs’ number is shown in Fig.1. In particular, in view of the interference to PUs produced by SUs’ transmission, Fig.1 depicts the maximum number of SUs that the satellite CDMA network can afford with existence of PUs when both types of users achieve their required SINR. Each curve in the picture denotes a different ratio between satellite transmission power to each PU and that to each SU. On one hand, it can be observed intuitiontially from this picture that the largest numbers of SUs in different power ratio are equal to 100,
and the numbers are decreasing with the increase of PUs’ number. On the other hand, the less power ratio is, in other words, the lower power the satellite transmits to each SU, the larger number of SUs the network can afford. When the power ratio is 0.5, the system could admit over 80 SUs even that 10 PUs are active at the same place and same time and the difference between situations of 0 and 1 PU existing in the network is approximately ignorable. However, if the power ratio is 1.5, the number of admitted SUs is less than 40 while 10 PUs exist and the system capacity to accept SUs will reduce acutely while PU number changes from 0 to 1. As illustrated in Fig.1, the numbers of admitted SUs are different under diverse power condition that the satellite transmits to each SU. It is suggested that both the numbers of PUs and SUs be considered. Otherwise, a destructive influence on satellite network will be exerted if superabundant SUs exist actively in the satellite cognitive networks.

C. Performance Analysis under Variable SU Number

Licensed user could be steady in a period of time in satellite communication network. In this segment, let 10 PUs be active and the number of SUs increase in size by 5 each time. Fig. 2 illustrates the individual action of each user. As we can see, each PU requires lowest transmission power and receives constant SINR when 5 SUs exist in the network. At the same time, every SU could ask for highest transmission power and achieve highest SINR because of the minimum interference from SUs to PUs and the maximum throughput leased from PUs to SUs. As the number of SUs grows, the interference to PUs goes up even if each SU reduces its claimed power. Thus, PUs require the satellite to transmit higher power in order to keep QoS at a certain level. Because of the simultaneity of decreasing claimed power and increasing interference from both types of users, the received SINR of each SU will reduce rapidly with the increase of SUs. We note that the received SINR of SU is lower than the required boundary that equals 10 when 85 active SUs are present. It is straightforward to see that more SUs will destroy cognitive communication when the number of SUs exceeds the system capacity. Several SUs will quit and send quit message to the satellite since they can not receive information from the common transmitter. The satellite will not reuse our scheme to allocate transmission power to all users until SUs number reaches a certain level.

Comparison Fig.1 with Fig.2 shows the relationship among transmission power, SUs number and system capacity of SUs. On one hand, PUs need lower transmission power from the satellite while fewer SUs exist in the network, and each SU receives a higher power at the same time. Thus, the lower power PUs receive, the fewer SUs network could accommodate, and vice versa. On the other hand, throughput of each SU that is in direct proportion to SINR decreases as the number of SUs is increased till cognitive communication has been destroyed.

A single Sub-game Perfect Nash Equilibrium (SPNE) could be obtained by iterative calculations while both numbers of PUs and SUs are confirmed. After that, we could achieve the optimal power allocation in (10) by PDS. Fig.3 illustrates the relation between SUs number and throughput in condition that 10 PUs maintain activity. For each PU, QoS has been protected and SINR and throughput remains constant. Nevertheless, for each SU, throughput decreases unlinearly with the number of SUs because the interference caused by SUs becomes larger. Actually, the total throughput of SU system increases monotonically, but unlinearly, with the number of SUs. Similarly, throughput of each SU becomes 0 when the number of SUs exceeds the system capacity, and so does throughput of the SU system. From the aspect of system, throughput is the summation of throughputs of both types of users. Since throughput of each PU keeps invariable over time, system throughput has the same trend as total throughput of SUs.

For a certain SU, utility which can be calculated by (8) is unique in condition that the satellite applies the optimal power allocation to SUs and PUs which are foresighted. Fig.4 shows the utilities and the benefit of PUs from SUs in situations with different numbers of SUs. Obviously, utility curve of each SU trends descending monotonically in condition that the satellite applies the optimal power allocation to SUs and PUs which are foresighted. For a certain SU, utility which can be calculated by (8) is unique in condition that the satellite applies the optimal power allocation to SUs and PUs which are foresighted. For a certain SU, utility which can be calculated by (8) is unique in condition that the satellite applies the optimal power allocation to SUs and PUs which are foresighted. For a certain SU, utility which can be calculated by (8) is unique in condition that the satellite applies the optimal power allocation to SUs and PUs which are foresighted. For a certain SU, utility which can be calculated by (8) is unique in condition that the satellite applies the optimal power allocation to SUs and PUs which are foresighted.
from SUs to PUs, namely \( B = \sum_{i=1}^{K} \lambda_i P_i \), will be on the rise as the number of SUs is increased. And this is the prime motive for PUs to lease spectrum to SUs.

D. Performance Analysis under Variable SINR PU Required

In this segment, by varying PU required SINR from 2 to 20, we discuss the performance of the proposed scheme in a scene where numbers of PUs and SUs are regarded to be 10 and 30 respectively. Fig.5 illustrates the relation among allocated power, actual SINR and minimum SINR that PUs required. As can be verified, for an individual PU, to claim a higher transmission power is necessary in order to achieve a greater SINR. However, the claimed power is against constraint 1 in (10) when the required SINR is greater than 18dB. That is to say, in the same condition, the satellite can not afford the total transmission power even if no SU exists. At this point, communications of both types of users have been broken. And before this point, transmission power to PUs and actually received SINR of each PU ascends monotonically as the minimum required SINR increase. On the contrary, the same parameters of each SU descend monotonically under the same condition till the required SINR reaches 18dB.

Fig.6 shows the relationship between throughputs and the required SINR. As can be observed, average throughput of single PU ascends as the required SINR increases till it reaches 18dB, and so does the total throughput of PUs. For SU system, by contrast, the same parameters descend monotonically in the same situation. However, the total throughput of network is not a monotonic function. Before the required SINR reaches 14dB, network throughput ascends, and after that, it descends statically in the range from 14dB to 16dB. As the required SINR continues increasing, network throughput will decrease at large scale when PU required SINR exceeds 16dB. As can be concluded from this figure, the network will achieve maximum throughput if the minimum SINR required by PUs is within [12dB, 16dB].

The relation between utilities and the required SINR is illustrated by Fig.7. The utility of PU reaches vertex when the required SINR is 18dB. However, as aforementioned, it is impossible for the satellite to support such a power allocation. In addition, the utility of SU descends sharply and the benefit from SUs becomes less when PU required SINR is greater than 16dB. Furthermore, as we can deduce from this picture, SUs are unwilling to pay more cost for less communication capacity as PU required SINR increases.
E. Complexity Analysis

In practice, whenever the number of SUs varies or required SINR of PUs changes, the optimal power allocation has to be updated. Thus, complexity of single calculation circle is an important parameter which is restricted by onboard processor. Let us assume \( L \) PUs and \( K \) SUs be active in a calculation circle, simulation results show that Nash Equilibrium will be achieved after 6 iterative calculations. Thus, the complexity brought by (11), (12) and (13) is \( o(K+L) \) in a circle. Then, selection accomplished by (10) needs \( o(K+L) \) multiplications and \( o(K+L) \) additions. Therefore, computation complexity in an updating circle is bounded by \( o(K+L) \). Another important parameter for the onboard processor is the number of memory elements. When iterative calculation occurs, both series of variables before and after computation should be stored. In detail, variables such as \( 2KP_1, 2LP_2, 2LQ_3, K\lambda, L\tau_i \) and constants such as \( G, h, \Gamma_{\text{min}}, N, \mu_1, \mu_2, P_{\text{max}}, P_{\text{max}} \) have to be memorized. Therefore, onboard processor approximately needs \( 3(K+L) \) memory elements in total to complete an updating circle. Naturally, the size of memory element depends on the required precision of each variable. On account of the current technology level, it is sufficient for a satellite to accomplish the proposed scheme.

VI. CONCLUSION

In this paper, we introduce underlay cognitive radio into satellite CDMA communication network and consider the problem of downlink power allocation to maximize spectrum efficiency in a DSL scene where SUs pay PUs for transmission power from satellite. Using game theory, we propose a centralized power control scheme implemented by onboard processor to protect the communication of primary users while providing maximum possible throughput for secondary users. The simulation results have shown the performance of the proposed scheme. The complexity of the scheme has been also analyzed.
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