Optimal Pricing for Service Provisioning in the Secondary Spectrum Market

Fan Gu[1], Xianwei Li[2,a], Liang Zhao[3], Haiyang Zhang[4], and Xiaoying Yang[5]

[1]*School of Continuing Education, Anhui Institute of International Business, Hefei, China*
[2]*School of Information Engineering, Suzhou University, Suzhou, China*
[3]*School of School of Computer Science, Shenyang Aerospace University, Shenyang, China*
[4]*School of Environment and Geomatics Engineering, Suzhou University, Suzhou, China*
[5]*School of Information Engineering, Suzhou University, Suzhou, China*

Abstract. In this paper, we investigate the problem of spectrum sharing in a secondary spectrum market where one secondary operator provisions network access services to a number of secondary users (SUs) by leasing spectrum from spectrum holder. For the system model under consideration, the spectrum allocated to the secondary operator can be shared by SUs. We model the interaction between the secondary operator and SUs as a two-stage Stackelberg game, where the secondary operator network price decisions in the first stage, and SUs make their spectrum demands decisions in the second stage. We use the backward induction method to solve this game. The numerical results show that the proposed solution method can capture the main factors of the secondary spectrum market, and provide a promising framework for the design of future secondary CR systems.

1 Introduction

Radio spectrum is recognized as one of the most scare and precious resources in the wireless networks, which is conventionally controlled by government via static license-based allocations. However, according to some recent works, many spectrum bands are not fully utilized even in densely populated urban areas, such Chicago [1]–[3]. Besides, users' demands for wireless data service have increased rapidly in the past few years. According to a recent report from by Cisco, the monthly global mobile data traffic will reach 49 exabytes by 2021 [4]. The paradox between the rapidly growing demand for wireless data services and low utilization of spectrum allocation suggests that there are some shortcomings for current static spectrum allocation policy.

Cognitive Radio (CR), also known as dynamic spectrum access (DSA), has been proposed as a novel approach to improve the efficiency utilization of spectrum. In Cognitive Radio Networks (CRNs), unlicensed secondary users (SUs) can dynamically access unused part of legacy spectrum bands owned by primary (licensed) users (PUs).

Today, secondary operators, also called mobile virtual network operators (MVNOs), have received significant success worldwide, which is one of the main motivations of our study. MVNOs do not own the physical infrastructure and lease spectrum from spectrum holders to provide services to SUs. For example, IIJmio and LINE MOBILE are two MVNOs in Japan, and Karma is a MVNO in USA.

Although a lot of efforts have been devoted to spectrum allocation in CRNs, most of them focus on the technical aspects of spectrum sharing (e.g., designing power control method), in this paper we study from the economic aspect. Moreover, different from previous works that simply analyse homogeneous SUs, which means that all SUs have homogeneous valuation for the spectrum service, we divide SUs into different types based on their preferences for the spectrum quality. For example, some SUs who are watching videos may have higher valuations
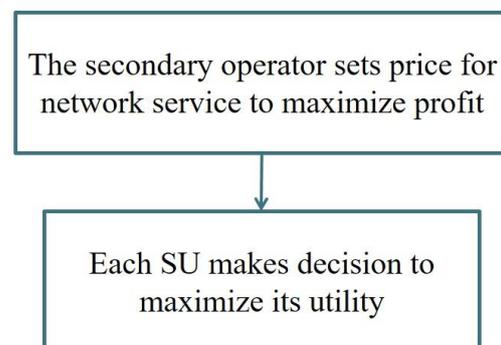

Figure 1. Two-level structure between operators and secondary users.

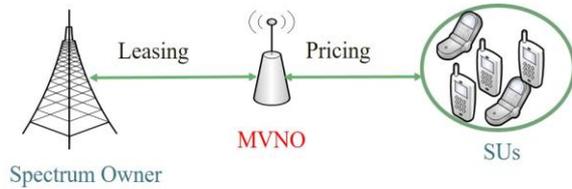[a] Corresponding author: lixianwei163@163.com

Figure 2. System Model.

of the spectrum while some other SUs who are just phoning have lower valuations on the spectrum [5].

In this paper, we investigate the problem of network services in a secondary spectrum market where a MVNO leases spectrum from the spectrum holder and provides network services to a pool of SUs. The goal of the MVNO is to maximize its own profit. We model the interaction between the MVNO and SUs as a Stakelberg (leader-follower) game, where the MVNO first sets service access prices for the network services to maximize its profits, and then each SU will decide whether to subscribe to network services based on prices and qualities of the services, as illustrated in Fig.1. We use backward induction method to solve the game.

2 Related Works

We review and discuss some notable related works that cantered around price-based spectrum service access control in CRNs in this part.

Game theory has been widely used for resource allocation and management in wireless networks in the past few years. Focusing on a duopoly femtocell communications market, Ren et al. studied the problem of long-term entry and spectrum sharing scheme decision from the perspective of an entrant network service provider [9]. Due to users have different preferences for different time slots, Zhang et al. studied time-dependent price competition in a duopoly wireless networks market [10]. But these works did not consider the costs of network service providers.

Spectrum trading and sharing in CRNs have been extensively studied by using game theory. Some works related works analysed the interaction between the primary and secondary operators. The authors in [7] jointly addressed the problem of pricing and network selection in CRNs, where the primary operator who can provide higher guaranteed service and the secondary operator who provides cheaper best-effort secondary network service compete to serve a common pool of users. The problem under consideration is formulated as a a Stackelberg game, where the two operators first set the prices of network services to maximize their revenues. Then, users decide which operator to select. Kinoshita et al. proposed a spectrum sharing method aiming to achieve both users' higher throughput and operators' profit by setting appropriate pricing strategy [11]. However, these previous works have limitations in ignoring users' heterogeneous types or without considering the channel information. Apart from the existing works, we take both users' heterogeneous types and channel information into consideration.

3 System Model

In this section, we introduce the system model where one secondary operator, denoted by MVNO, lease spectrum from spectrum owner and provide network service to a number of SUs, as illustrated in Fig.2. The system model that we use is mainly inspired by the works of Li [8] and Zhao [16] but with different objective functions. As the radio spectrum allocated to spectrum holder remains largely unused even in densely populated urban areas [1], the unused spectrum can form a spectrum pool where the total available bands are divided into a lot of unit channels.

These channels have different qualities due to interference levels, as shown in Fig.3. We assume that SUs purchase network service from the MVNO and have their own preferences for channel quality.

We assume that the channels with quality q are leased to MVNO. The channel quality q can be expressed as [8] [16]

$$q = B\log_2(1 + \frac{\rho}{I_i}) \tag{1}$$

where B is bandwidth, ρ is the power received by the SU, and I_i is the interference of the channel.

3.1 SUs' Model

In order to capture SUs' heterogeneous valuations of the spectrum service, we divide SUs into different types based on their different preferences for the spectrum quality. We assume that SUs have different types and the type of SU k is characterized by a parameter θ_k which reflects SU's preference for spectrum quality, and a higher value of θ_k means this user has a higher preference for spectrum quality. For the θ_k SU, its utility function can be expressed as [17] [8] [16]

$$U_k = \theta_k q - \pi(q) \tag{2}$$

where q denotes the spectrum quality of this MVNO, and $\pi(q)$ is the channel price.

3.2 Secondary Operator's Model

From the perspective of the secondary operator MVNO, its profit function is denoted as

$$R_k = \pi(q) - C(q) \tag{3}$$

where $C(q)$ is the channel cost with quality q, which is denoted as [18]

$$C(q) = C_0 + T(q) = C_0 + aq^b \qquad (4)$$

where, C_0 is the fixed cost which includes the infrastructure cost, and a and b reflect the impact of channel quality on operating costs and users' sensitivity to price, respectively.

The objective of the MVNO is to maximize its profit. It is obvious that this MVNO would like to sell network service if and only if $\pi(q) \geq C(q)$.

For convenience of analysis, the notations used throughout this paper are summarized in Table 1.

4 Single Pricing Scheme under Incomplete Information

In this section, we analyse a secondary spectrum market where one secondary operator sets single price of its service to maximize profit. We consider incomplete information case in this section, that is the secondary operator MVNO does not know the type of each SU, but knows the distribution of user types. We assume that the types of SUs is uniformly distributed [0, 1] with probability distribution function (PDF) $f(\cdot)$ and cumulative distribution function (CDF) $F(\cdot)$. The relationship between the secondary operator and SUs is modelled as a two-stage Stakelberg game, which can be solved by employing the backward induction method [14], [15]. We first analyse the utility maximization of SUs in Stage II based on the price of network service. Then, we investigate how the secondary operator sets network service prices in Stage I.

Table 1. Notations Summary.

Notation	Description
k	subscript of a SU
π	single price of network service
π_k	price of network service for SU k
R_k	the profit of MVNO for selling network service to user k
R_i^*	optimal profit of MVNO in incomplete information case
R_c^*	optimal profit of MVNO in complete information case
q	spectrum capacity of the MVNO
θ_k	SU k's preference for spectrum quality
$f(\cdot)$	probability density function (PDF) of SUs' preferences parameter
$F(\cdot)$	cumulative density function (CDF) of SUs' preferences parameter
Ω	the number of users that subscribe to network services in incomplete information case
θ^*	the marginal point where SUs switch from negative utility to positive in incomplete information case
U_k	the utility that type θ_k SU gets from MVNO

4.1 User's Utility Maximization Problem in Stage II

For the SU θ_k, it will subscribe to network services if and only if

$$U_k = \theta_k q - \pi(q) \geq 0 \qquad (5)$$

From which, we know that only the types of SUs whose values meet the following requirement subscribe to network services:

$$\theta_k \geq \frac{\pi(q)}{q} \qquad (6)$$

Denote

$$\theta_k^* = \frac{\pi(q)}{q} \qquad (7)$$

The number of users that subscribe to network services can be expressed as

$$\Omega = 1 - F(\theta_k^*) = 1 - \frac{\pi(q)}{q} \qquad (8)$$

4.2 MVNO's Profit Maximization Problem in Stage I

From the perspective of the MVNO, its objective is to maximize profit, which is the difference between its revenue and cost,
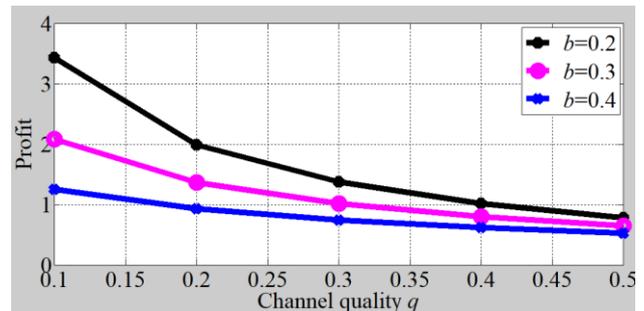

Figure 4. The optimal profit of MVNO versus its channel quality.

$$R = \int_{\theta^*}^{1} [\pi(q) - C(q)] f(\theta) d(\theta)$$
$$= (1 - \frac{\pi(q)}{q})[\pi(q) - aq^b] \qquad (9)$$

It is obvious that the above objective function is a concave function, therefore, by taking the derivative of R with respective to π, and setting the equality to zero, we have

$$\frac{\partial R}{\partial \pi(q)} = \frac{C_0 + aq^b - 2\pi(q) + q}{q} = 0 \qquad (10)$$

From which we get

$$\pi(q) = \frac{C_0 + aq^b + q}{2} \qquad (11)$$

By substituting Eq.(11) in to Eq.(9), we get the optimal profit of the MVNO,

$$R^* = \pi(q) = \frac{[q - (C_0 + aq^b)]^2}{4q} \qquad (12)$$

5 Numerical Results

In this section, we present numerical results to validate the performance of our analysis. Based on [18], the default parameters are set as follows unless otherwise stated: $C_0 = 0.01$, $q = 0.4$, $a = 2$ and $b = 3$.

Fig.4 shows how the optimal profit of MVNO varies with its channel quality in the incomplete information case. This figure suggests that the profit of the MVNO firstly decreases with channel quality increasing due to the reason that the MVNO sets single price for the SUs in the incomplete information case. This figure also shows that if cost parameter b increases, the profit of the MVNO decreases, which means that as the increment of cost for a unit quality increase, the MVNO will get less profit.

6 Conclusions

In this paper, we studied price differentiation in a secondary spectrum market, where the idle spectrums with different qualities are leased to a secondary operator who provide service access to SUs with the objective of maximizing its profits. Our numerical results show that the MVNO can improve the channel quality to improve its profits in the two information cases, and the MVNO gets less profit if its operating costs increases. In the incomplete information case, the profit of the MVNO first increases as the channel quality increases, then decreases with the channel quality increasing.

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