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An optimal pricing scheme to improve transmission opportunities for a mobile virtual network operator

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ABSTRACT

Selling spectrum resources to mobile virtual network operators (MVNOs) is popular among primary network operators (POs) for increasing licensed spectrum utilization. An MVNO seeks *transmission opportunities* (TXOPs) on the PO's licensed spectrum channel(s) by spectrum sensing. Since licensed primary users (PUs) often have higher transmission priority, TXOPs available to the MVNO are directly determined by PUs' transmission behaviors. In this paper, we present the first study that uses a pricing scheme to regulate PUs' transmission behaviors so that TXOPs for an MVNO are improved, meanwhile quality-of-service (QoS) of PUs can be guaranteed as well. Our idea is to design a non-uniform pricing scheme that regulates PUs to transmit based on a time-varying non-uniform transmission cost. We model the optimal pricing problem as a hierarchical game where the interaction between the PO and PUs is modeled as a Stackelberg game and the spectrum random access among PUs is modeled as a non-cooperative game. We first solve the non-cooperative game among PUs, as a building block, then we embed its outcome to a Markov Chain Monte Carlo (MCMC) framework to solve the whole optimal pricing problem. We strictly shows that there could be multiple optimal pricing schemes for a PO. Comprehensive simulations confirm the theoretical analysis, and valid the effectiveness of our proposed scheme.

1. Introduction

Due to spectrum scarcity, free spectrum bands, which can be allocated to new mobile service operators as licensed spectrum resources, are becoming limited. In order to satisfy increasing demands on spectrum resources, radio management authorities such as FCC open the spectrum market thus allows licensed spectrum resources owned by licensed operators, often called primary operators (POs), to be sold to emerging operators who have no statically allocated spectrum bands. For example, in US, AT&T hosts 420 Wireless, AirVoice Wireless and Black Wireless as its secondary operators. Similar strategies are also used by Verizon, T-Mobile and Sprint, so as in UK like Vodafone and O2 as well. Those secondary operators are often called mobile virtual network operators (MVNOs) where "virtual" is in the sense that those MVNOs do not really own any spectrum bands. In this way, spectrum scarcity issue is mitigated and market demands is relatively fulfilled.

Not only aiming to satisfy the demands of emerging MVNOs who are unable to have any licensed bands

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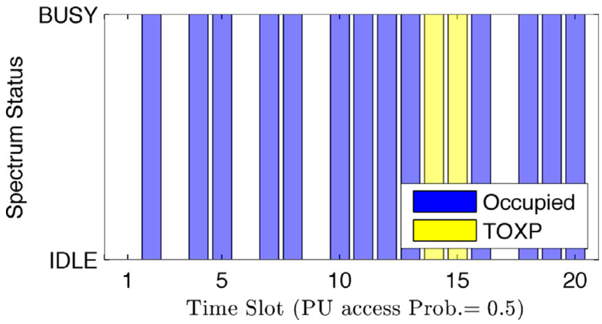

Fig. 1. A motivating example.

anymore, but also because of potential improvement on spectrum utilization of POs, renting licensed spectrum resources to MVNOs becomes popular among POs nowadays. One motivation behind is that POs wish, in future with cognitive radio technology [1], an MVNO will be able to access the spectrum resources cognitively so as to efficiently utilize the idle spectrum left by primary users (PUs). More importantly, POs also expect to gain extra revenues by charging transmissions from MVNOs. Driven by these, one rich line of research works done was to study how well an MVNO can exploit transmission opportunities (TXOPs) [2], and how a PO should charge an MVNO so that to gain maximum revenues [3–7]. In nutshell, existing works focused more on the subjects of TXOP exploitation and TXOP selling.

We observe that those works have an explicit prerequisite that idle spectrum already exist ahead, of which we think such a reason makes existing works less considered the influence of PUs' transmission behaviors to the availability of idle spectrum (i.e., TXOPs). A few prior investigations such as in [8,9] have, nevertheless, shown that PUs' behaviors can largely affect the availability of TXOPs. Clearly, due to unmanaged transmissions from PUs, TXOPs for MVNOs would be unstable and unpredictable. More importantly, as an MVNO will often sign *service-level-agreements* (SLAs) with a PO in reality, if the stability of TXOPs (e.g., a minimum available length) cannot be reached, those idle spectrum cannot be used by the MVNO. Consequently, some idle spectrum resources will be wasted since neither PUs nor the MVNO utilize them eventually.

Here we give a motivating example in Fig. 1 to illustrate the consequence. We define a TXOP to an MVNO as a window containing 2 continuously available time slots. During a time frame with 20 time slots, if a PU accesses the spectrum channel with probability 0.5, randomly there is only 1 TXOP (yellow bars), though there are total 5 idle time slots. This means that $\frac{3}{5} = 60\%$ idle slots are wasted (white bars). The root reason here is the PU's arbitrary transmissions producing many idle spectrum fragments that cannot be used by the MVNO either. Instead, if we can regulate the PU to transmit more regular (e.g. more compactly or more periodically), more continuously available time slots (i.e., TXOPs) may appear. Hence, in addition to TXOP exploitation and TXOP selling issues, we believe that it is equally important to study another line of issues, that may be more critical: how a PO can improve TXOPs for an MVNO, while such a study is still missing.

Our study will be positioned in a typical cellular base-station (BS) scenario as follows. A PO manages a cellular network and in one cell covered by a BS tower, there is a set of PUs, each of which contends to access the spectrum channel like TDMA. Meanwhile, with coexisting to the primary network (i.e., the PO + PUs), an MVNO seeks TXOPs cognitively and pays the PO for any successful occupations of TXOPs. Based on this scenario, our goal is to maximize the total utilization/revenues of the spectrum channel, subject to (1) the *quality-of-service* (QoS) of PUs and (2) the SLAs of the MVNO signed with the PO. The objective accounts for two parts of revenues where the first is the revenues generated by PUs' transmissions whose behaviors directly determine the TXOPs to the MVNO, who only generates the second part of revenues to the PO when the idle spectrum fulfill the SLAs requirement.

It is not a trivial task to generate more TXOPs fulfilling the SLAs requirement as well as to guarantee meanwhile the QoS of PUs because of the following reasons. First of all, PUs' transmissions are hardly to be controlled directly as they are distributed and selfish endpoints. In addition, it is even more difficult to predict their influence to the TXOPs to the MVNO because outcomes of PUs' random access are complex. In order to solve the problem, we use a pricing mechanism, namely *an invisible hand*, to stimulate PUs transmitting more regular. We formulate the pricing problem as a *Stackelberg game* modeling the interactions between the PO and PUs. For PUs, their spectrum random access are further formulated as a *non-cooperative game*. In the hierarchical game, the PO first prescribes an incentive pricing scheme to the PUs, then the PO observes the responses from PUs (i.e., the outcomes of the spectrum random access game among PUs) and measures how the TXOPs for the MVNO will be affected. Through optimization, the PO tries to derive optimal pricing scheme(s) subject to the constraints mentioned above.

To solve the hierarchical game, technically, such a problem is known as *a bilevel programming with equilibrium constraint* (BPEC) problem [10] (The equilibrium constraint here refers to the spectrum random access game among PUs). Theoretical results have shown that a BPEC problem is difficult because in most of cases the response from the followers (i.e., the PUs) is implicit. Consequently, traditional optimization techniques cannot be applied directly to find the optimal solutions for the leader (i.e., the PO). In addition to the inherited challenge as a typical BPEC problem, as to be shown later, our problem has a unique challenge in that the objective function of the leader is a "black-box", because it is impossible to know how many TXOPs can be generated given a pricing scheme analytically. This unique challenge further renders our problem to be a black-box BPEC problem [11], and thus hampers us to design an exact algorithm like gradient-based or approximation-based methods. Hence, we first design an efficient solver for the non-cooperative game among PUs at the lower level, and then use it as a building block to embed in a *Markov Chain Monte Carlo* (MCMC) framework, which holds promise for non-convex and black-box problems, to ultimately solve the optimal pricing problem. Our contributions are summarized as follows.