INTERVENTION FRAMEWORK FOR COUNTERACTING COLLUSION IN SPECTRUM LEASING SYSTEMS

*Juan J. Alcaraz**

Universidad Politecnica de Cartagena
TIC Department
Plaza del Hospital, 1, Cartagena, Spain

Mihaela van der Schaar

University of California, Los Angeles
EE Department
420 Westwood Plaza, Los Angeles, CA, USA

ABSTRACT

We consider a spectrum leasing system in which secondary networks offer offload services to a primary network (PN) in exchange of temporary access to the PN's spectrum. When the SANs collude and coordinate their prices, forming a cartel, the PN experiences cartel overcharge, which in our scenario implies lower transmission rates for the serviced PUs. To protect the spectrum owner's interests and possibly enforce market regulation, we propose an intervention framework in which an intervention device or manager (possibly with the authorization and/or supervision of an external regulatory agency) counteracts cartel formation. This framework exploits the specific features that make wireless systems different from conventional markets, enabling the manager to modify the set of achievable outcomes. The intervention capability is limited, so the objective is to design an intervention rule which is maximizes the PN transmission rate within the given constraints.

Index Terms— Spectrum leasing, cooperative secondary spectrum access, coalitional game theory, intervention game.

1. INTRODUCTION

We consider infrastructure-based secondary networks (SNs) comprising a secondary access node (SAN) and some secondary users (SUs). As in [2] and [3], each SAN can provide high-quality wireless links to nearby PUs, and connect them to the core of the PN by means of the SAN's backhaul connection. In return to these offloading services, each serving SN is granted access to part of the wireless bandwidth of the served PU. As in many other trading scenarios, the outcome of the system can change significantly if competing agents reach cooperative agreements and collude instead of competing. For example, a set of SANs with overlapping coverage areas may agree to make coordinated offers to the PUs. When all the competing SANs collude, they form a *cartel*, allowing them to offer their offload services in exchange of more bandwidth. Compared to a fully competitive situation, the service provided by the cartel of SANs is more *costly* to the PN in terms of spectrum. This is known as *cartel overcharge*, and has been widely reported both in theory and practice in the economic and legal literature [4].

In this paper, we extend the game theoretic framework of *intervention* [5][6] to coalitional games with the goal of minimizing cartel overcharge in a spectrum leasing system.

2. RELATED WORK AND CONTRIBUTIONS

The specific spectrum trading scenario that we consider is similar to [2][3], where infrastructure-based SNs offer offload services to PUs in exchange of spectrum. In other works [8][9][10][11], the SUs act as wireless relays for PU transmissions, generally using *amplify-and-forward* or cooperative ARQ schemes. In all these works, the spectral resources of the served PU are split between the PU and the serving SN. In [8][10][11] it is the PN (either the PU or the primary base station) who determines the amount of resources allocated to the SN's own transmissions, i.e. the SNs are non-strategic with respect to resource allocation, which is an important difference with our work.

When the SNs are strategic and negotiation can be done between the PN and each SN individually, this allocation can be the result of a bargaining process [7], but this approach is not applicable in our system, in which multiple self-interested SNs compete in several overlapped coverage areas, each area having a different set of competitors (multiple coupled oligopolies). Cooperative (not collusive) behavior of the SNs was studied in [1], but requiring monetary transfers among the agents (like in [3][9]). Our scenario does not involve payments or any type of payoff transfers. Table 1 summarizes the features of the related works, compared to ours.

What makes spectrum leasing different from conventional trading scenarios is that it is performed among wireless agents, which allows us to use intervention mechanisms to

*Juan J. Alcaraz performed the work while at UCLA, Electrical Engineering department, as a visiting scholar supported by personal grant Fulbright/Jose Castillejo CAS12/00101. He also acknowledges MINECO/FEDER project grant *CALM TEC2010-21405-C02-02*, as well as "Programa de Ayudas a Grupos de Excelencia de la Region de Murcia, Fundacion Seneca".

	[8][10][11]	[3]	[9]	[1]	[7]	[2]	our work
Infrastructure-based SNs	no	yes	no	no	no	yes	yes
Spectrum owners	1	N	1	N	1	N	1
Payment transfer	no	yes	yes	yes	no	no	no
SN strategic in resource alloc.	no	yes	yes	yes	yes	no	yes
SN-PN cooperative game	no	no	no	yes	no	yes	no
SN-SN strategic game	no	no	yes	no	no	no	yes
SN-SN cooperative game	no	no	no	yes	no	no	yes
SN collusion	no	no	no	no	no	no	yes

Table 1. Comparison of existing works on spectrum in exchange of service.

mitigate cartel effects. The main challenges to be faced are: to design an intervention rule that is effective as a threat and to efficiently exploit the limited intervention capabilities. The contribution of this work is to develop a game intervention framework to reduce cartel overcharge that efficiently exploits the intervention capabilities of the system.

3. SYSTEM MODEL

The system involves two main types of entities, a *primary base station* (PBS), managed by a wireless operator which has the license to use a certain spectrum band, and a set $\mathcal{N} = \{1, \ldots, N\}$ of secondary access nodes (SANs), or *agents*. The SANs cover a small part of the area covered by the PBS. They are completely independent from the operator, and their objective is to provide wireless access to a different type of terminals, the SUs. The SANs have a high bandwidth connection to a wired network, but very limited wireless spectrum. Providing offload services to the PUs allows the SANs to obtain additional spectral resources. In particular, when an SAN connects a PU to the PN core network, the serving SAN is granted the right to use part of the served PU channel resources. Part of the PU channel will be used for the SAN-PU wireless link, and the remaining part will be used by the SAN for their own transmissions. Because of the short link distance, the quality of the SAN-PU link can provide higher transmission rate than the PBS-PU link, even if only a fraction of the PU channel is used. Figure 1 illustrates a simple system with 2 SANs.

The area covered by $\mathcal{N}$ is divided into a set of sub-areas $\mathcal{C} = \{1, \ldots, C\}$. For a SAN $i \in \mathcal{N}$, a_i is the fraction of the PU channel that the i-th SAN is willing to devote to PU's data transmission over the SAN-PU link, so that the remaining fraction $(1 - a_i)$ will be occupied by SAN-SU transmissions as long as the SAN-PU link remains active. The offer a_i made by the i-th SAN belongs to a discrete set of values $\mathcal{A}_S = \{a_{\min}, a_{\min} + \delta_a, a_{\min} + 2\delta_a \ldots, a_{\max}\}$, where δ_a is a fixed increment, the minimum value $a_{\min} > 0$ guarantees that the PU always obtains a positive rate increment with the service, and the maximum value $a_{\max} < 1$ assures that it is worth for the SAN to service the PU.

Let $\gamma(d)$ denote the average SNR of a SAN-PU link of length d. We assume that all the SANs are equal, and

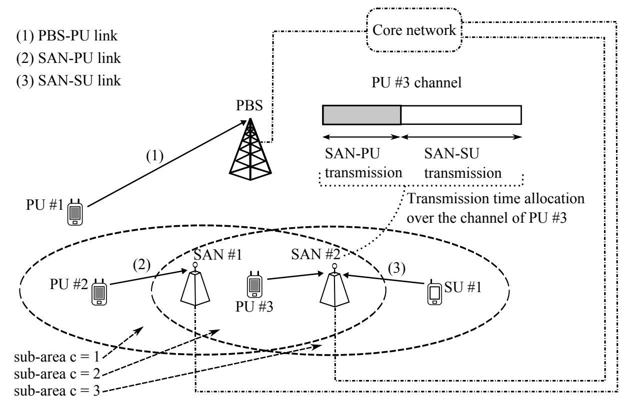

Fig. 1. System with $\mathcal{N} = \{1, 2\}$, covering three sub-areas.

therefore, for a given SAN-PU link distance, γ is equal for every $i \in \mathcal{N}$. The expected achievable transmission rate of a SAN-PU link on a given area c is $R_{PU}(c) = E\left[\kappa W \log_2(1 + \gamma(d))\right]$ where the expectation is obtained over the PU location in c, and $\kappa < 1$ is a proportionality factor respect the AWGN Shannon capacity. Similarly, the expected achievable rate in the PBS-PU link in c is defined as $R_0(c) = E\left[\kappa W \log_2(1 + \gamma_0(d_0))\right]$, where $\gamma_0(d_0)$ is the SNR of the PBS-PU link for a d_0 PBS-PU distance. Because the coverage area of the SANs is assumed to be very small compared to the PBS coverage area, we can consider that d_0 is approximately constant in $\mathcal{C}$ and therefore $R_0(c) \approx R_0$ for every c. Given a_i, the expected transmission rate of the SAN-PU link provided by $i \in \mathcal{N}_c$ is $a_i R_{PU}(c)$.

Let $D_i(\mathbf{a}, c) = P(\text{select } i | \mathbf{a}, c)$ denote the probability of the PN selecting SAN i in subarea c given $\mathbf{a} = (a_i)_{i \in \mathcal{N}}$. The PN selects, with equal probability, one of the best offers at each subarea c. For each PU incoming service request, the location of the PU is distributed over $\mathcal{C}$ according to a probability distribution denoted by $\mathbf{p} = (p_1, \ldots, p_C)$. It is assumed that $p_c > 0$ for all $c \in \mathcal{C}$, i.e. PUs can be located at every subarea. Therefore, given $\mathbf{a}$, the payoff obtained by the PN from the offload services of $\mathcal{N}$ is defined as the expected increment,

δ_R, on the overall transmission rate:

$$\begin{aligned} E_{\mathbf{a},p}\left[\delta_R\right] &= \sum_{c\in\mathcal{C}}\sum_{i\in\mathcal{N}_c}\left(a_i R_{PU}(c)-R_0\right)D_i(\mathbf{a},c)p_c \\ &= \sum_{c\in\mathcal{C}}\left(a_c^* R_{PU}(c)-R_0\right)p_c \end{aligned} \quad (1)$$

As in previous works [8][9][10][11], the SAN can only use the spectral resources of a PU while the SAN-PU link is active. The payoff of each agent $i \in \mathcal{N}$ is given by a function $u_i : A \to \mathbb{R}$ defined as $u_i(\mathbf{a}) = (1-a_i)R_{SU}\sum_{c\in\mathcal{C}} p_c D_i(\mathbf{a},c)$, where R_{SU} is the expected transmission rate achievable by a SAN-SU link using the PU channel resources. The function $u_i(\mathbf{a})$ characterizes the expected additional transmission rate obtained by agent i from each PU service request. For a given $\mathbf{a}$, the outcome vector for the set of agents $\mathcal{N}$ is defined as $\mathbf{u}(\mathbf{a}) = (u_1(\mathbf{a}), \ldots, u_N(\mathbf{a}))$. The finite strategic game played by the agents is denoted by $\Gamma = \langle \mathcal{N}, \mathcal{A}, (u_i)_{i\in\mathcal{N}}\rangle$. Let $\mathcal{U}$ denote the set of outcomes of Γ, and $\mathcal{U}^+$ denote the set of *efficient* (non-dominated) points in $\mathcal{U}$.

If the agents agree to avoid price competition by forming a grand coalition or cartel, they can obtain an efficient outcome. Let us consider the action profile where all the agents select the smallest channel fraction for the PU, $\underline{\mathbf{a}} = (a_{\min})_{i\in\mathcal{N}}$. It is straightforward to check that this action would maximize the aggregate utility of the SANs and minimize the payoff for the PN, i.e. $\underline{\mathbf{a}}$ maximizes the cartel overcharge for the PN. A coalitional analysis shows that cartels are stable, in the sense that no agent would benefit when deviating from the grand coalition. Considering that this practice is against market regulations, the following section presents a framework to counteract cartel effects.

4. INTERVENTION FRAMEWORK

The idea of intervention, introduced in [5] and [6] for strategic and repeated games respectively, relies on the existence of a manager or intervention device capable of observing the action profiles and modifying, to some extent, the agents' payoffs. Let $\mathcal{A}_0$ denote the set of all possible intervention actions. The strategy for the manager under perfect information is defined as a mapping $f : \mathcal{A} \to \mathcal{A}_0$. The set of all possible intervention rules is denoted by $\mathcal{F}$. With intervention, the payoff function is redefined as $u_i : \mathcal{A}_0 \times \mathcal{A} \to \mathbb{R}$. The payoff vector for action $\mathbf{a}$ and intervention rule f, is given by $\mathbf{u}_f = (u_i(f,\mathbf{a}))_{i\in\mathcal{N}}$. Let $\tilde{f}$ denote the absence of intervention. Therefore, $u_i(\tilde{f},\sigma) = u_i(\sigma)$, and $\mathbf{u}_{\tilde{f}}(\sigma) = \mathbf{u}(\sigma)$. The strategic finite game induced by the manager is $\Gamma_f = \left\langle \mathcal{N}, \mathcal{A}, (u_i(f,\cdot))_{i\in\mathcal{N}}\right\rangle$. The manager is also associated to a payoff function which, in our scenario, corresponds to the expected rate increment, δ_R, of the PN. Therefore, let us define $u_0 : \mathcal{A} \to \mathbb{R}$ as the payoff function for the manager, also referred to as agent 0, and given by $u_0(\mathbf{a}) = E_{\mathbf{a},p}\left[\delta_R\right]$.

The intervention action consists of reducing the throughput of SAN transmissions by interfering them with jamming signals from the PUs. These jamming signals are subject to several constraints that are implicit in $\mathcal{A}_0$. First, the jamming power should be constrained to the hardware limitations of the PU terminals. Second, it should be assured that, even with interference, every SAN obtains a throughput that is above the minimum that justifies cooperation with the PN. Figure 2 illustrates the intervention operation. The intervention device associated to the i-th SAN generates a jamming signal only during a fraction $\alpha_i \in (0,1)$ of the time that the SAN devotes to SU communication. The SAN achievable rate under the reduced SINR caused by jamming is $R'_{SU} < R_{SU}$. Therefore, for the i-th SAN we have that $\epsilon_i R_{SU} = \alpha_i R'_{SU} + (1-\alpha_i)R_{SU}$. Defining $\epsilon_{\min}$ as the minimum reduction factor technically achievable, the intervention device determines the reduction factor $\epsilon_i \in [\epsilon_{\min}, 1]$ by changing the fraction of time in which the jamming signal is transmitted. Moreover, for a SAN selecting action $a_i \in \mathcal{A}_i$, the reduction factor should satisfy $\epsilon_i(1-a_i) \geq 1 - a_{\max}$, to assure that the SAN obtains the minimum throughput increment to justify cooperation with the operator. For each action $a_i \in \mathcal{A}_i$, the intervention capability is defined by the set $\mathcal{E}(a_i) = \left\{\epsilon \middle| \max\left\{\epsilon_{\min}, \frac{1-a_{\max}}{1-a_i}\right\} \leq \epsilon \leq 1\right\}$. We can now define the set of feasible intervention actions for each $\mathbf{a} \in \mathcal{A}$ as $\mathcal{A}_0(\mathbf{a}) = \mathcal{E}(a_1) \times \ldots \times \mathcal{E}(a_N)$. The intervention rule is given by $f(\mathbf{a}) = (\epsilon_i)_{i\in\mathcal{N}}$, where $\epsilon_i \in \mathcal{E}(a_i)$, for each $i \in \mathcal{N}$, and the payoff function for each i under intervention is $u_i(f,\mathbf{a}) = \epsilon_i u_i(\mathbf{a})$.

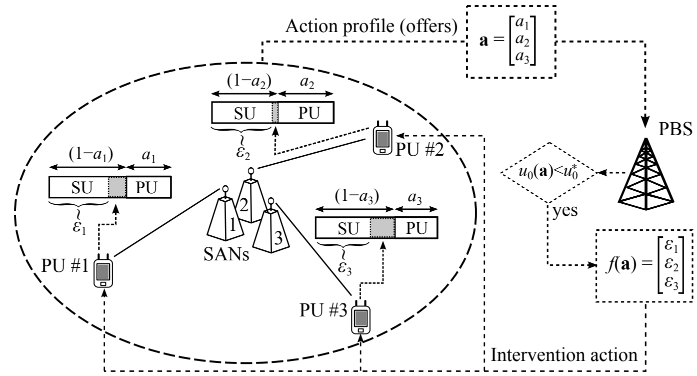

Fig. 2. Example of an intervention execution sequence.

Let us define the ordered set $\mathcal{A}_{u_0} = \left\{\mathbf{a}^1, \mathbf{a}^2, \ldots, \mathbf{a}^{|\mathcal{A}|}\right\}$, with $\mathbf{a}^j \in \mathcal{A}$, and $u_0(\mathbf{a}^j) \leq u_0(\mathbf{a}^{j+1})$, for $j = 1, \ldots |\mathcal{A}| - 1$. The notation $g <_{u_0} h$ denotes a pair of indexes $g < h$ in $\mathcal{A}_{u_0}$. We will use $A = \{1, 2, \ldots, |\mathcal{A}|\}$ to refer to the set of indexes in $\mathcal{A}_{u_0}$, and the notation a_i^j to refer to the i-th element of $\mathbf{a}^j$. We say that an intervention rule is effective if it is not executed at any efficient outcome for the agents (that is, if $\mathbf{u}_f(\mathbf{a}) \in \mathcal{U}^+$ then $\mathbf{u}_f(\mathbf{a}) = \mathbf{u}(\mathbf{a})$). The effective intervention rule providing the maximum lower bound of the manager's utility u_0^*, is given by the solution of the following optimization problem, the Intervention Rule Design Problem, IRDP (the proof is omitted for space limitations):

$$
\begin{aligned}
&\max_{j\in A} u_0(\mathbf{a}^j)\\
&\text{s.t.}\\
&\tfrac{u_i(\mathbf{a}^{\underline{g}(j,k)})}{u_i(\mathbf{a}^k)} - \delta \geq \max\left\{\epsilon_{\min}, \tfrac{1-a_{\max}}{1-a_i^k}\right\}, \\
&\text{for } i \in \mathcal{N},\ k <_{u_0} j, \text{ and}\\
&\underline{g}(j,k) = \arg\min_{h \geq_{u_0} j} \left\|\mathbf{u}(\mathbf{a}^k) - \mathbf{u}(\mathbf{a}^h)\right\|_\infty,
\end{aligned}
\tag{2}
$$

where δ determines the distance of the intervened outcomes with respect to the efficient ones. If $j \in A$ solves the above problem, the resulting intervention rule $f(\mathbf{a}^k) = (\epsilon_i^k)_{i\in\mathcal{N}}$ is given by

$$
\begin{aligned}
&\epsilon_i^k = 1 \text{ (no intervention)}, && \text{for } i \in \mathcal{N}, \text{ and } k \geq_{u_0} j\\
&\epsilon_i^k = \min\left\{\frac{u_i(\mathbf{a}^{\underline{g}(j,k)})}{u_i(\mathbf{a}^k)} - \delta, 1\right\}, && \text{for } i \in \mathcal{N}, \text{ and } k <_{u_0} j
\end{aligned}
\tag{3}
$$

Note that the intervention actions are defined over action profiles, not individual actions, since the objective is to act upon collusive behaviors of the SANs.

5. NUMERICAL EVALUATION

Let us evaluate the performance of the intervention scheme in a specific scenario with 2 SANs separated a by 50 m. The average signal to noise ratio for a given SAN-PU link length, d, is computed by means of a two ray model $\gamma(d) = \frac{p_{\text{tx}}K}{BN_0 d^4}$, where p_{tx} is the transmission power (which is set to 0.2 W), B is the channel bandwidth (set to 500 MHz), N_0 is the noise spectral density (set to 10^{-9} W/Hz), and K is a constant depending on the antenna gains and heights (set to 100). A PU requesting a service can be located at any of the three subareas with equal probability, and the SANs can select up to 10 actions between $a_{\min} = 0.2$, and $a_{\max} = 0.8$. The intervention capability allows $\epsilon_{\min} = 0.7$, which means that the punishment signal can reduce the SAN throughput to, at most, 70% of its nominal throughput. Applying the intervention rule solving the IRDP with $\delta = 0.01$, the attainable bound is $u_0 \approx 3 \times 10^4$ bit/s, while it is $u_0 \approx 0.3 \times 10^4$ in absence of intervention. Figure 3 shows the outcomes $\mathbf{u} \in \Gamma$, of the intervened action profiles (before intervention), and the outcomes, $\mathbf{u}_f \in \Gamma_f$, of these action profiles under intervention. The figure also shows the sets of payoffs corresponding to the coalitional representations of Γ *without* intervention, V, and *with* intervention, V_f, respectively. The intervention reduces the achievable outcomes such that no intervention is executed at any efficient outcome. Let us evaluate how the intervention capability, determined by $\epsilon_{\min}$, affects on the performance of the intervention. We compare the intervention rule obtained by solving the IRDP, with a simpler intervention scheme that is also *effective*. The simpler scheme consists of making all the intervened outcomes $\mathbf{u}_f$ be dominated by one outcome $\mathbf{u}(\mathbf{a})$ such that $a_i = a_j$ for every $i, j \in \mathcal{N}$. It can be shown that this scheme solves a simplified version of problem (2).

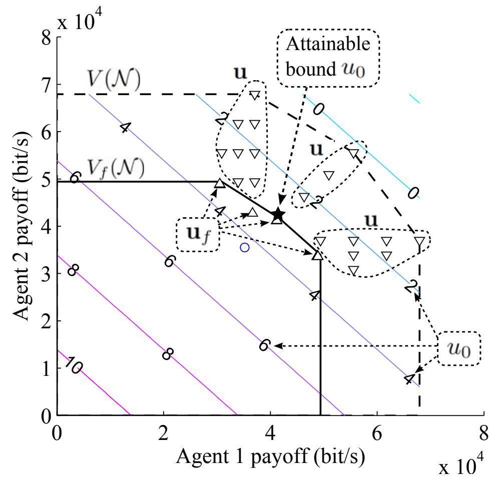

Fig. 3. Outcomes in a two SANs example with $\epsilon_{\min} = 0.7$.

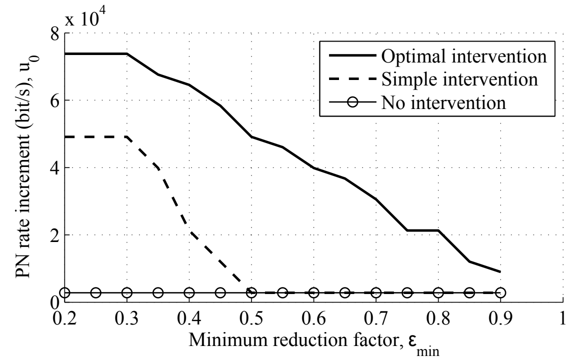

Fig. 4. Effect of $\epsilon_{\min}$ on the intervention performance.

Figure 4 shows the minimum transmission rate increment attainable by the PN (attainable bound of u_0) for different values of $\epsilon_{\min}$.

6. CONCLUSIONS

This paper presents an intervention framework for coalitional games to counteract cartel formation effects. The intervention device should be capable of observing the actions of the agents and modifying the payoff of these agents. The framework is applied to a spectrum leasing system in which several secondary access nodes offer offload services to a network operator, in exchange of bandwidth from the serviced PUs. If the SANs form a cartel, the PUs obtain lower increments of the transmission rate. In the design of an intervention rule, the objective is to maximize the minimum attainable bound for the manager's payoff with the premise that the intervention should be effective without needing to be exerted. Moreover, the intervention rule needs to make an efficient use of limited intervention capabilities. An exact rule fulfilling this characteristics can be found by solving an optimization problem.

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