One-Shot Games for Spectrum Sharing among Co-Located Radio Access Networks

Sofonias Hailu[1], Alexis A. Dowhuszko[1], Olav Tirkkonen[1] and Lu Wei[2]
[1] Department of Communications and Networking, Aalto University, P.O. Box 13000, FI-00076 Aalto, Finland
[2] Department of Mathematics and Statistics, University of Helsinki, P.O. Box 68, FIN-00014, Finland
E-mail: {sofonias.hailu, alexis.dowhuszko, olav.tirkkonen}@aalto.fi, lu.wei@helsinki.fi

***Abstract*—We consider an adaptive co-primary spectrum sharing scheme based on playing one-shot games between co-located distributed Radio Access Networks (RANs). Spectrum is divided into private and shared parts, and each RAN internally applies coordinated multi-point transmissions. Zero-forcing precoding is used in the private part, while unitary precoding is applied in the non-orthogonally shared part. A one-shot game is played such that each operator proposes a spectrum partition which maximizes its own sum utility, and the actual spectrum partition is resolved based on *a priori* decision rules that reflect the regulatory framework. Thus, adaptive spectrum sharing can be implemented with a minimal exchange of signaling information among operators. The existence of a unique Nash-equilibrium is shown for the game. Simulation results show that adaptive spectrum sharing is able to bridge between the baseline performance of orthogonal and full (non-orthogonal) spectrum in different signal-to-noise power ratio regions.**

I. INTRODUCTION

In order to cope with the forecast demand of mobile data traffic in future wireless networks, operators need to significantly increase their operational bandwidth [1]. Inter-operator spectrum sharing is one of the approaches that has been envisioned to increase the operational bandwidth of an operator. The conventional cognitive radio network approach that is used to share spectrum between operators assumes a pre-defined primary—secondary hierarchy. In an alternative co-primary spectrum sharing model, multiple operators are willing to jointly use a part (or the whole) of their licensed spectrum [2], [3]. Operators may have individual licenses to access exclusive frequency bands, or a group authorization to use a common pool of spectral resources. Joint use of the licensed spectrum of operators can be realized by sharing the frequency resources either orthogonally or non-orthogonally. Orthogonal sharing of common spectral resources could be achieved in time domain [4], frequency & power domain [5], [6], and/or space domain [7]. In the case of non-orthogonal spectrum sharing, operators simultaneously use common block of spectral resources, creating inter-operator interference. The operators might implement inter-operator interference mitigation schemes, see e.g. [8], [9].

Most of the works on co-primary spectrum sharing rely on operator specific information which in some cases needs to be exchanged. In [8], [9], operator specific information such as full inter-operator Channel State Information (CSI) is assumed to be available for all operators, in order to apply inter-operator interference mitigation schemes. However, the exchange of inter-operator CSI generally requires a dedicated link between the operators or to a central entity. In [5], [6], game theoretic approaches including one-shot games are discussed for unlicensed spectrum sharing, where the games depend on the power applied on all carriers by the operators. With these approaches, the rate that an operator could achieve on a given carrier or portion of the spectrum pool is unpredictable, as the inter-operator interference depends on the power applied on the carrier by other operators. In addition, both [5] and [6] considered systems comprised of single transmitter-receiver pairs leaving no room for multi-user diversity gain. On the other hand, in [10], a static co-primary spectrum sharing scheme is proposed, which restricts the gain from flexibly sharing the spectrum though it might be easier to implement.

In this paper, a one-shot game approach is considered for co-primary spectrum sharing among co-located distributed Radio Access Networks (RANs) of different operators. The operators do not exchange CSI, only preferences of partitioning the spectrum into private and non-orthogonally shared portions are exchanges. The decision to determine the actual spectrum partition is made based on *a priori* decision rule, taking into account the regulatory framework. The proposed one-shot game is shown to have a unique Nash equilibrium. Thus, the game could be played once per interval of time in which the channel realization of all the users remain constant. Simulation results indicate that the proposed one-shot game leads to better and more fair data rate allocations to the users, when compared to conventional schemes that share the whole communication bandwidth non-orthogonally among operators, or allocate an exclusive frequency band to each of the operator.

The rest of the paper is organized as follows: Section II explains the system model and presents the spectrum access schemes. Section III discusses the Coordinated Multi-Point Transmission (CoMP) techniques applied in the private and non-orthogonally shared portions of the spectrum, and describes the computation of the sum utility of the operators. Section IV presents the proposed one-shot game and proves the existence of a unique Nash-equilibrium solution. Section V discusses the characteristics of the simulation scenario and carries out performance analysis. Finally, conclusions are drawn in Section VI.

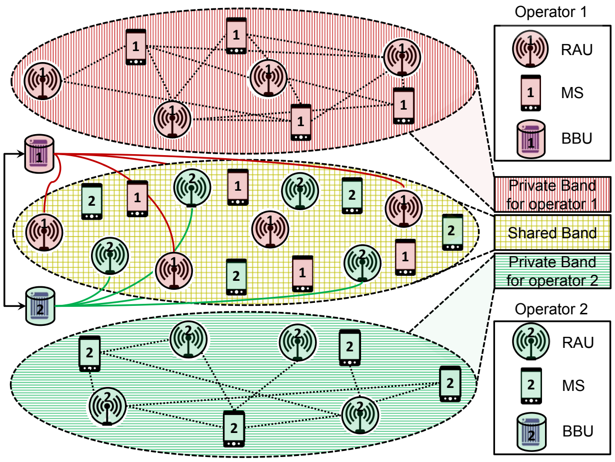

Fig. 1. Multi-operator downlink communication scenario with $|\mathcal{I}| = 2$ distributed RANs, covering an overlapping hot-spot area. Total communication spectrum is divided into three parts: a private band for each operator and a non-orthogonally shared band. The spectrum partitioning between operators is coordinated using control signaling between both BBUs of the operators.

II. System Model

A. Multi-operator downlink scenario

A multi-operator downlink communication scenario is considered which consists of co-located multiple operators belonging to the set $\mathcal{I}$, see illustration for $|\mathcal{I}| = 2$ in Fig. 1. The operators own independent distributed Radio Access Networks (RANs), their coverage area are overlapping, and they are willing to share their licensed spectrum to improve the performance of their Mobile Stations (MSs). The distributed RAN of operator $i \in \mathcal{I}$ consists of M_i Remote Antenna Units (RAUs) with wired connections to a centralized Baseband Unit (BBU). The centralized BBU of operator i performs scheduling decisions and carries out the multi-antenna signal processing operations that are required to serve K_i randomly deployed single-antenna MSs in the coverage area. For sake of simplicity, we assume that the number of RAUs and MSs per operator are equal, i.e., $M_i = K_i \ \forall i \in \mathcal{I}$. It is assume that the users are relatively static.

According to spectrum access model used, operator i may propose to share non-orthogonally part of its dedicated individual spectrum B_i^{ind}, or may request to have exclusive access to a portion of the common group spectrum B^{grp}. Negotiations dealing with the most convenient spectrum partition are carried out among operators in a time scale longer than scheduling interval, but shorter than the coherence time of channels and the traffic needs of the users. The results of a negotiation holds for one sharing period. The negotiation are based on a minimal exchange of control information. Operators do not share local information like scheduling decisions and transmit beamforming vectors, the only control information that is shared is the most convenient spectrum partition from the perspective of each individual operator. The decision on the spectrum partition used for the next sharing period is carried out by each operator in a decentralized way, following an *a priori* decision rule that all operators are forced to follow. According to the reached decision, for the duration of the next sharing period, shared sub-band $B^{(\text{s})}$ is used for non-orthogonal spectrum access among all operators, while private sub-band $B_i^{(\text{p})}$ is used for orthogonal spectrum access of operator i. Then, the total communication bandwidth for the multi-operator scenario is $B = B^{(\text{s})} + \sum_{i\in\mathcal{I}} B_i^{(\text{p})}$, and the aggregate communication bandwidth that operator i uses to serve its K_i MSs is $B_i = B_i^{(\text{p})} + B^{(\text{s})}$.

The transmit power spectral density of each operator is assumed to be constant across its aggregate bandwidth B_i. Thus, $P_{\text{tx},i}/B_i = P_{\text{tx},i}^{(\text{s})}/B^{(\text{s})} = P_{\text{tx},i}^{(\text{p})}/B_i^{(\text{p})}$, where $P_{\text{tx},i} = P_{\text{tx},i}^{(\text{p})} + P_{\text{tx},i}^{(\text{s})}$ is the total transmit power that operator i uses for communication, while $P_{\text{tx},i}^{(\text{p})}$ and $P_{\text{tx},i}^{(\text{s})}$ are the corresponding transmit power portions in the private and shared sub-bands, respectively. Note that based on this assumption, transmit power $P_{\text{tx},i}$ is a linear function of bandwidth B_i.

The wireless channel gain between RAU m of operator i and MS k is given by

$$h_{(m,i),k} = \widetilde{h}_{(m,i),k} / \sqrt{L_{(m,i),k}} \qquad i \in \mathcal{I}, k \in \mathcal{K}, \quad (1)$$

where $L_{(m,i),k}$ is the distance dependent pathloss attenuation and $\widetilde{h}_{(m,i),k}$ are the complex fast fading components of the wireless channel model. In case of rich scattering and flat fading, $\widetilde{h}_{(m,i),k}$ is described by a zero-mean circularly symmetric complex Gaussian Random Variable (RV) with unit variance. All fast fading components of the wireless channel are assumed to be uncorrelated. Finally, the noise powers that MS k experiences in private and shared sub-bands are modeled as a zero-mean Gaussian complex RVs with power $P_{\text{N}}^{(\text{s})} = N_0 \, B^{(\text{s})}$ and $P_{\text{N},k}^{(\text{p})} = N_0 \, B_i^{(\text{p})}$, with N_0 the thermal spectral density.

B. Spectrum sharing models

The negotiations to determine the spectrum partition for the whole multi-operator scenario are performed in a decentralized manner between peers. In this process, each operator first informs to the other operators its preferred spectrum partition. Next, the actual spectrum partition is resolved locally by each operator, based on pre-defined rules that take into account the type of license that operators have to access spectrum. Based on the spectrum license of the operators, two co-primary sharing models are considered [2].

1) Mutual renting: Each operator i owns a license for exclusive access to a frequency band of bandwidth B_i^{ind}. For simplicity, we assume equal amounts of licensed spectrum, i.e, $B_i^{\text{ind}} = B^{\text{ind}} \ \forall i \in \mathcal{I}$. Operator i determines its preferred fraction $0 \le \alpha_i^{\text{ind}} \le 1$ that it is willing to share and informs this to the other operators. If proposal α_i^{ind} is accepted by all operators, the total bandwidth of the shared sub-band becomes $B^{(\text{s})} = |\mathcal{I}| \, \alpha_i^{\text{ind}} \, B^{\text{ind}}$, while the bandwidth of the private sub-band is reduced to $B_i^{(\text{p})} = B^{\text{ind}} - B^{(\text{s})}/|\mathcal{I}| \ \forall i \in \mathcal{I}$.

2) Limited spectrum pool: In this case, the $|\mathcal{I}|$ operators have a license to access a pool of common frequency resources with total bandwidth B^{grp}, which is assumed to be non-orthogonally shared among all operators. Then, operator i determines its preferred fraction $0 \leq \alpha_i^{\mathrm{grp}} \leq 1/|\mathcal{I}|$ that it prefers to use privately. If proposal α_i^{grp} is accepted by all operators, the bandwidth of the private sub-band becomes $B_i^{(\mathrm{p})} = \alpha_i^{\mathrm{grp}} B^{\mathrm{grp}} \; \forall i \in \mathcal{I}$, while the total bandwidth of the shared sub-band is reduced to $B^{(\mathrm{s})} = B^{\mathrm{grp}} - |\mathcal{I}| \, B_i^{(\mathrm{p})}$.

III. Utility function and multi-antenna transmission schemes

For a given spectrum partition $\{B_i^{(\mathrm{p})}, B^{(\mathrm{s})}\}$, operator i has the opportunity to schedule its associated MSs either in the private, shared, or both private and shared frequency sub-bands. In the shared frequency sub-band $B^{(\mathrm{s})}$, full-rank Unitary Precoding (UP) is used to make the instantaneous inter-operator interference power remain constant, independently of the local scheduling decisions that operators make. In the private frequency sub-band $B_i^{(\mathrm{p})}$, on the other hand, Zero-Forcing Precoding (ZF) is employed to cancel completely the intra-operator interference that is created among the data streams intended to the different scheduled users. Let $\mathcal{K}_i$ be the set of MSs associated to operator i. Then, the indexes of those MSs that are scheduled in the private and shared frequency sub-bands are contained in sets $\mathcal{S}_i^{(\mathrm{p})} \subseteq \mathcal{K}_i$ and $\mathcal{S}_i^{(\mathrm{s})} \subseteq \mathcal{K}_i$, respectively. In this paper, $\mathcal{S}_i^{(\mathrm{p})} \cup \mathcal{S}_i^{(\mathrm{s})} = \mathcal{K}_i$ is always verified.

A. Received SINR in private and shared frequency sub-bands

The data rate that a MS $k \in \mathcal{K}_i$ is able to achieve depends on both the spectrum partition $\{B_i^{(\mathrm{p})}, B^{(\mathrm{s})}\}$ and the scheduling decisions $\{\mathcal{S}_i^{(\mathrm{p})}, \mathcal{S}_i^{(\mathrm{s})}\}$, where the latter affects the Signal-to-Interference plus Noise power Ratio (SINR) that the MS observes in reception. Then, the SINR that MS $k \in \mathcal{K}_i$ experiences in the shared frequency sub-band is

$$\gamma_k^{(\mathrm{s})} = \frac{P_{\mathrm{tx},i}^{(\mathrm{s})} |\mathbf{h}_{i,k}^{\mathrm{T}} \mathbf{w}_{i,k}^{(\mathrm{s})}|^2}{\underbrace{\sum_{l \in \mathcal{S}_i^{(\mathrm{s})}, l \neq k} P_{\mathrm{tx},i}^{(\mathrm{s})} |\mathbf{h}_{i,k}^{\mathrm{T}} \mathbf{w}_{i,l}^{(\mathrm{s})}|^2}_{\text{Intra-operator interference}} + \underbrace{\sum_{l \in \mathcal{S}_j^{(\mathrm{s})}, j \neq i} P_{\mathrm{tx},j}^{(\mathrm{s})} |\mathbf{h}_{j,k}^{\mathrm{T}} \mathbf{w}_{j,l}^{(\mathrm{s})}|^2}_{\text{Inter-operator interference}} + \underbrace{P_{\mathrm{N}}^{(\mathrm{s})}}_{\text{Noise}}}, \tag{2}$$

where $\mathbf{h}_{i,k}^{\mathrm{T}}$ is a row vector that contains all channel gains from RAUs of operator i to MS k, $\mathbf{w}_{i,k}^{(\mathrm{s})}$ is the transmit beamforming vector that operator i uses to serve MS k in the shared frequency sub-band, and $P_{\mathrm{N}}^{(\mathrm{s})}$ is the noise power in the shared frequency sub-band. Note that when MS $k \notin \mathcal{S}_i^{(\mathrm{s})}$, beamforming vector $\mathbf{w}_{i,k}^{(\mathrm{s})}$ is a null vector of the proper dimension.

Similarly, the SINR that MS $k \in \mathcal{K}_i$ experiences in reception in the private frequency sub-band is obtained from (2) when the superscripts '(s)' are replaced with '(p)', and when the inter-operator interference term of the denominator is removed. Note that if ZF is used to serve MSs in the private frequency sub-band, the intra-operator interference term that appears in the denominator of (2) vanishes as well.

Algorithm 1 Unitary precoder for shared frequency sub-band

Initialization: Set $\mathcal{U}_1 = \mathcal{S}_i^{(s)}$ and $\mathcal{D}_0 = \emptyset$
for $m = 1$ to $|\mathcal{S}_i^{(s)}|$ **do**
  for $n = 1$ to $|\mathcal{U}_m|$ **do**
    $\mathbf{v}_n^{(m)} \leftarrow \mathbf{h}_{i,n}^{\mathrm{H}} / \|\mathbf{h}_{i,n}\| - \sum_{d \in D_{i-1}} \mathbf{u}_d^{\mathrm{T}} (\mathbf{h}_{i,n}^{\mathrm{H}} / \|\mathbf{h}_{i,n}\|) \mathbf{u}_d$
    $\mathbf{v}_n^{(m)} \leftarrow \mathbf{v}_n^{(m)} / (\sqrt{|\mathcal{S}_i^{(s)}|} \|\mathbf{v}_n^{(m)}\|)$
    $I_n^{(m)} = \sum_{d \in D_{i-1}} P_{\mathrm{tx},i}^{(\mathrm{s})} |\mathbf{h}_{i,n}^{\mathrm{T}} \mathbf{u}_d|^2$
    $\gamma_n^{(m)} = \frac{P_{\mathrm{tx},i}^{(\mathrm{s})} |\mathbf{h}_{i,n}^{\mathrm{T}} \mathbf{v}_n^{(m)}|^2}{I_n^{(m)} + \sum_{l \in \mathcal{S}_j^{(s)}, j \neq i} P_{\mathrm{tx},j}^{(\mathrm{s})} |\mathbf{h}_{j,n}^{\mathrm{T}} \mathbf{w}_{j,l}^{(s)}|^2 + P_{\mathrm{N}}^{(\mathrm{s})}}$
  end for
  $\pi_m = \arg\min_{n \in \mathcal{U}_m} \gamma_n^{(m)}$
  $\mathcal{D}_m = \mathcal{D}_{m-1} \cup \{\pi_m\}$
  $\mathcal{U}_{m+1} = \mathcal{U}_m - \{\pi_m\}$
  $\mathbf{u}_m = \mathbf{v}_{\pi_m}^{(m)}$
end for
Output: $\mathbf{W}_i^{(\mathrm{s})} = [\mathbf{u}_1 \cdots \mathbf{u}_{|\mathcal{S}_i^{(s)}|}]$ and $\mathcal{D}_i^{(\mathrm{s})} = \mathcal{D}_{|\mathcal{S}_i^{(s)}|}$

B. Sum utility function

The operator sum utility is defined as

$$U_i = \sum_{k \in \mathcal{K}_i} u_i(r_k) \qquad \forall i \in \mathcal{I}, \tag{3}$$

where $u_i(x) = \log_e(x)$ in case of a proportional fair log-rate utility, and

$$r_k = B_i^{(\mathrm{p})} \log_2(1 + \gamma_k^{(\mathrm{p})}) + B^{(\mathrm{s})} \log_2(1 + \gamma_k^{(\mathrm{s})}) \quad \forall k \in \mathcal{K}_i \tag{4}$$

is the aggregate rate that MS k is able to achieve. Note that Aggregate rate (4) depends on the bandwidth of spectral portions $B_i^{(\mathrm{p})}$ and $B^{(\mathrm{s})}$, as well as the received SINRs $\gamma_k^{(\mathrm{p})}$ and $\gamma_k^{(\mathrm{s})}$ that MS k experiences in both private and shared frequency sub-bands, respectively.

C. Unitary precoder in shared frequency sub-band

The columns of the unitary precoder matrix $\mathbf{W}_i^{(\mathrm{s})}$ that is used to serve MSs $k \in \mathcal{S}_i^{(\mathrm{s})}$ are determined by an orthogonalization process. The order of orthogonalization depends on the received SINR $\gamma_k^{(m)}$ that each MS experiences in reception at each iteration m of the process, and takes into account both intra-operator and inter-operator interference powers. The intra-operator interference power comes from the MSs that were orthogonalized in a previous iteration of the process, while the inter-operator interference power remains constant during the whole process because it is assumed that the other operators also use UP in the shared frequency sub-band. To increase the level of fairness among users, the MS with lowest SINR is selected for orthogonalization at each iteration. A summary of the procedure that is used to determine the unitary precoder for the shared frequency sub-band of operator i is presented as Algorithm 1.

D. Zero-forcing precoder in private frequency sub-band

The MSs scheduled in the private frequency sub-band are served using ZF with sum power constraint. The precoder matrix that operator i uses in the private frequency sub-band becomes

$$\mathbf{W}_i^{(\mathrm{p})} = \left[\mathbf{w}_{i,1}^{(\mathrm{p})} \cdots \mathbf{w}_{i,|\mathcal{S}_i^{(\mathrm{p})}|}^{(\mathrm{p})}\right] = \frac{\mathbf{H}^{+}_{i,\mathcal{S}_i^{(\mathrm{p})}}}{\|\mathbf{H}^{+}_{i,\mathcal{S}_i^{(\mathrm{p})}}\|_{\mathrm{F}}} \qquad \forall i \in \mathcal{I}, \quad (5)$$

where $\mathbf{H}^{+}_{i,\mathcal{S}_i^{(\mathrm{p})}}$ is the pseudoinverse of the channel matrix $\mathbf{H}_{i,\mathcal{S}_i^{(\mathrm{p})}}$, which is formed by the concatenation of row vectors $\mathbf{h}_{i,k}^{\mathrm{T}}$ $\forall k \in \mathcal{S}_i^{(\mathrm{p})}$, and $\|\cdot\|_{\mathrm{F}}$ is the Frobenius norm of a matrix. Note that the pseudoinverse of matrix $\mathbf{H}$ is defined as $\mathbf{H}^{+} = (\mathbf{H}^{\mathrm{H}}\mathbf{H})^{-1}\mathbf{H}^{\mathrm{H}}$ where $(\cdot)^{-1}$ and $(\cdot)^{\mathrm{H}}$ are the inverse and Hermitian transpose of a matrix, respectively.

IV. Proposed one-shot game

In this paper, we model the co-primary spectrum sharing problem as a one-shot game $\{\mathcal{I}, \{a_i\}_{i\in\mathcal{I}}, \{U_i\}_{i\in\mathcal{I}}\}$. In this definition, $\mathcal{I}$ denotes the set of players — the operators with serving the same hotspot area. The set $\{a_i\}_{i\in\mathcal{I}}$ denotes the instantaneous strategies of the players, and the set $\{U_i\}_{i\in\mathcal{I}}$ identifies their corresponding payoffs.

The allowed strategy of a player is restricted to an interval $a_i \in [0, \alpha_{\max}]$ $\forall i \in \mathcal{I}$, and have different meaning depending on the co-primary spectrum sharing model. In the case of mutual renting, the strategy of a player represents the fraction of its licensed spectrum that the operator is willing to share with the other operators, and $\alpha_{\max} = 1$ if $B_i^{\mathrm{Ind}} = B_j^{\mathrm{Ind}}$ $\forall i, j \in \mathcal{I}$. In the case of limited spectrum pool, the strategy of a player denotes the fraction of common spectrum resource that the operator is requesting for private (exclusive) use, and $\alpha_{\max} = 1/|\mathcal{I}|$.

The payoff $U_i(a_i, a_{-i})$ of player i is defined as the sum of the utilities of its associated MSs after the proposals that different players proposed for partitioning the spectrum are resolved. According to this definition, the payoff of a player i depends not only on its own strategy a_i, but also on the strategy of the other players a_{-i} and the *a priori* rule that all players agree to follow in order to resolve their spectrum partition proposals.

Taking into account the spectrum regulatory framework, we propose an *a priori* rule to resolve the outcomes of the spectrum partitioning proposals by

$$a_{\min} = \min_{i\in\mathcal{I}} a_i, \quad (6)$$

and thus

$$U_i(a_i, a_{-i}) = U_i(a_{\min}), \qquad a_{\min} = \min_{i\in\mathcal{I}} a_i. \quad (7)$$

Therefore, in the case of mutual renting, an operator is guaranteed that it is not going to share more than the fraction of its licensed spectrum that it is willing to share. Similarly, in the case of limited spectrum pool, an operator is guaranteed that it will not be forced to non-orthogonally share less than the fraction of the common resource that it is willing to share.

A. Selecting the strategy of a player

For simplicity, we require that each user is always scheduled in both private and shared frequency sub-bands. Then, it is possible to show that the utility function of an operator is strict concave function of a_i if the log-rate utility function is used. This follows from the observation that, when scheduling decisions are fixed, the data rate of an MS is a linear function of a_i, and it is well-known that the sum of logarithms of linear functions is a strictly concave function [11].

A player chooses a strategy that maximizes its payoff function. However, the payoff function of a player depends on the instantaneous strategies of all the players, and a player cannot know in advance the strategies of other players. As the CSIs of the other players are not known, in a generic game, a player would have to apply a probability distribution of all the strategies of the other players to deduce its chosen strategy, so that the outcome of the game would be closest to the preferred one. The outcome decision rule considered here, however, together with concavity, simplifies the strategy selection process. We assume that player i selects its strategy without considering probability distributions of other player's strategies,

$$\begin{aligned} a_i^* = \arg\max_{a_i} \quad & U_i(a_i) \\ \text{subject to} \quad & 0 \le a_i \le \alpha_{\max} \quad , \\ & \mathcal{S}_i^{(\mathrm{p})} = \mathcal{S}_i^{(\mathrm{s})} = \mathcal{K}_i \end{aligned} \quad (8)$$

Note that in (8), the sum utility for a particular $a_i \in [0, \alpha_{\max}]$ is obtained computing the corresponding $B_i^{(\mathrm{p})}$ and $B^{(\mathrm{s})}$ first, and then plugging the obtained results in equation (4) and (3). Due to the concavity of $U_i(a_i)$, and the outcome decision rule (6), this is the optimal strategy choice for i, irrespectively of the other players actions. This will be seen below, and is the reason for the existence of a Nash equilibrium. The solution to (8) can be readily obtained using efficient convex optimization algorithms, like the ones presented in [11].

B. Existence and uniqueness of Nash-equilibrium

A unique Nash-equilibrium exists for the proposed one-shot game, when players are rational and try to selfishly maximize their own sum utility.

Proposition 1. *The proposed one-shot game has a unique Nash-equilibrium point* $a^* = \{a_1^*, \ldots, a_i^*, \ldots, a_{|\mathcal{I}|}^*\}$ *where* $a_i^*, \forall i \in \mathcal{I}$ *is chosen according to* (8)*, the payoff* $U_i(a_i^*, a_{-i}^*), \forall i \in \mathcal{I}$ *is given by* (7)*, and the sum utility* $U_i(a_i)$ *in* (8) *is a strict concave function of* a_i.

Proof. Consider a player unilaterally changing its strategy from a_i^* to a_i, and let $a_{-i,\min}^* = \min\{a_j^*\}_{j\neq i, j\in\mathcal{I}}$. We now analyze two complementary cases:

Case 1. Assume that $a_i^* >= a_{-i,\min}^*$

If $a_i \ge a_{-i,\min}^*$, $U(a_i, a_{-i}^*) = U(a_i^*, a_{-i}^*)$. If $a_i < a_{-i,\min}^*$, $U(a_i, a_{-i}^*) < U(a_i^*, a_{-i}^*)$ since $U(a_i, a_{-i}^*)$ is a strict concave function in $a_i \in [0, a_{-i,\min}^*)$.

Case 2. Assume that $a_i^* < a_{-i,\min}^*$

For $a_i \neq a_i^*$, $U(a_i, a_{-i}^*) < U(a_i^*, a_{-i}^*)$. Thus a Nash equilibrium exists.

The uniqueness of the Nash-equilibrium follows from the strict concavity of $U_i(a_i)$ in (8), since it is a sum of log functions. Thus, the action of a player which is selected by maximizing (8) is unique. □

It is worth to notice, that the game setting discussed here allows for a Nash equilibrium where each operators do not always use the full spectrum. This is in contrast to the spectrum sharing games in frequency/power domain [5], where the Nash equilibrium is to use the full frequency. The difference in outcomes is due to Rule (6) of the game considered here. In the game model here, (6) is outside the domain of the decision of the players, and enables non-trivial outcomes of the game.

V. Performance Results

To understand characteristics of the considered spectrum sharing game, we simulate it in a multi-operator downlink scenario.

A. Simulation Scenario

We consider $|\mathcal{I}| = 2$ co-located distributed RANs belonging to different operators. We use an evaluation scenario simulation similar to the small cell network deployments model of [12]. The network elements of both RANs are independently deployed to serve the same hotspot area. Each operator i uniformly deploys a total of $M_i = 4$ RAUs in an inner circle of radius R_1, and a total of $K_i = 4$ single-antenna MSs in an outer concentric circle of radius R_2. Minimum distances $d_{\min,\text{rau-rau}} = 10$ m and $d_{\min,\text{rau-ms}} = 3$ m are respected when the network elements are owned by the same operator. There is no minimum RAU-to-RAU or RAU-to-MS distance restriction when the network elements belong to different operators.

The distance dependent path loss attenuation is calculated using the Urban Micro (UMi) wireless channel model with a carrier frequency of 3.4 GHz [13]. For sake of simplicity, we assume that there is always a Non Line-of-Sight (NLOS) condition between each RAU and MS pair; therefore, the path loss attenuation is

$$L_{(m,i),k} = 36.7 \log_{10}(d_{(m,i),k}) + 22.7 + 26 \log_{10}(f_c), \quad (9)$$

where $d_{(m,i),k}$ is the distance in meters between RAU m of operator i and MS k, and f_c is the carrier frequency in GHz. The antenna gains are $G_{\text{rau}} = 5$ dBi and $G_{\text{ms}} = 0$ dBi for the RAUs and MSs, respectively. The noise figure of the MSs is set to $\text{NF}_{\text{ms}} = 9$ dB.

For the mutual renting regulatory model, both operators are assumed to have exclusive access to a frequency band of bandwidth $B_i^{\text{ind}} = 10$ MHz $\forall i \in \mathcal{I}$. Similarly, in the limited spectrum pool regulatory model, both operators are assumed to have authorization to access a common pool of frequency resources of bandwidth $B^{\text{grp}} = 20$ MHz. The transmit power spectral density is 20 dBm/MHz, and is kept constant independently on the aggregate communication bandwidth B_i.

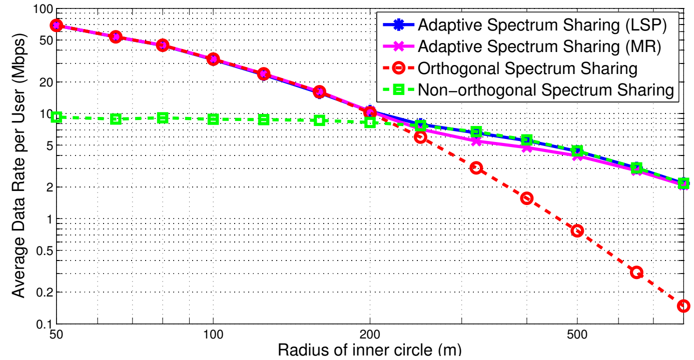

Fig. 2. Mean data rate per user for different spectrum sharing schemes as a function of inner circle radius R_1 (outer circle radius $R_2 = 1.4\,R_1$). Dashed lines: Fixed spectrum sharing schemes. Solid lines: Adaptive spectrum sharing schemes. MR: Mutual renting. LSP: Limited spectrum pool.

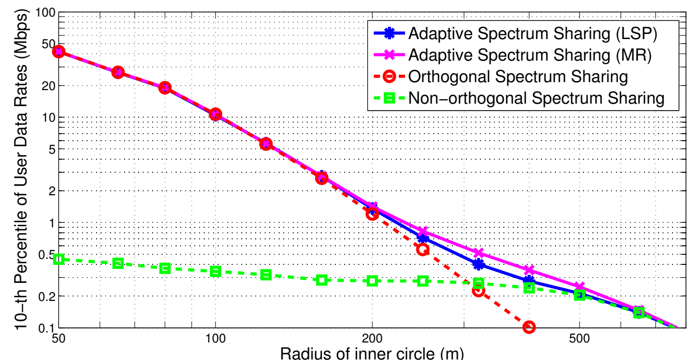

Fig. 3. 10-th percentile of user data rates for different spectrum sharing schemes as a function of inner circle radius R_1 (outer circle: $R_2 = 1.4\,R_1$). Dashed lines: Fixed spectrum sharing schemes. Solid lines: Adaptive spectrum sharing schemes. MR: Mutual renting. LSP: Limited spectrum pool.

B. Analysis of numerical results

In order to study the effect that the Signal-to-Noise power Ratio (SNR) has on the performance of the proposed spectrum sharing schemes, the radius of inner circle R_1 (i.e., the deployment area for RAUs) and the radius of the outer circle R_2 (i.e., the deployment area for MSs) are varied keeping the ratio $R_2/R_1 = 1.4$. This is in line with the baseline recommendation presented in [12], which defines $R_1 = 50$ m and $R_2 = 70$ m. For each value that R_1 takes, numerical simulations are run for 20 independent RAU deployments, each of them having 20 independent deployments of MSs. For each separate RAU and MS snapshot, 20 independent fast fading states are used when modeling the gains of the wireless channel. Orthogonal spectrum sharing is used as baseline scheme for performance evaluation for mutual renting scenario. When operators have a group license to access a spectrum pool, full non-orthogonal spectrum sharing is the baseline. Figure 2 shows the mean data rate per user (i.e., from an average rate performance perspective), and Figure 3 presents the 10-th percentile of user data rate, which reflects outage rate performance.

According to simulation results presented in Figure 2 and

Figure 3, orthogonal spectrum sharing works well in the high SNR region, while full spectrum sharing works better in the low SNR region, i.e., when R_1 grows and the multi-operator scenario becomes noise-limited. Adaptive spectrum sharing with one shot game protocols provides a performance that is *at least* as good as the one that is achieved with the fixed spectrum allocation schemes previously described. This observation is valid for both mean and 10-th percentile data rate curves. For mid-range SNR values, i.e. for R_1 in the range of 200-400 m, the gain of adaptive spectrum sharing is notable when compared to both baseline spectrum sharing schemes, particularly when the 10-th percentile data rate figure is analyzed in detail. Finally, for mid-range SNR values, adaptive spectrum sharing with group license and limited spectrum pool works slightly better in terms of mean user data rate, while adaptive spectrum sharing with individual license and mutual renting has a better performance in terms of the 10-th percentile of the user data rate.

VI. Conclusion

In this paper, a one-shot game was proposed to implement adaptive co-primary spectrum sharing among co-located distributed RANs of different operators. The game was considered in different forms for an individual licensing with mutual renting and group license model with limited spectrum pool, and can be implemented with a minimal exchange of control signaling. The game was shown to have a unique Nash equilibrium in all network states. The performance of the proposed adaptive spectrum sharing scheme was analyzed in terms of both mean user rate and 10-th percentile of user rate, assuming a dense small cell network scenario with multiple operators serving the same hotspot area. For low and high SNR regions, adaptive spectrum sharing scheme is able to choose the better of full spectrum sharing and orthogonal spectrum sharing. For mid-range SNR values, adaptive spectrum sharing scheme showed a notable gain with respect to both fixed spectrum sharing schemes. It can be concluded that adaptive spectrum sharing based on minimal information exchange between operators holds promise for guaranteeing more spectrum and corresponding better service for users served by future communication systems.

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