Efficient Dynamic Spectrum Sharing in Cognitive Radio Networks: Centralized Dynamic Spectrum Leasing (C-DSL)

Kamrul Hakim, *Student Member, IEEE*, Sudharman K. Jayaweera, *Senior Member, IEEE*, Georges El-howayek, *Student Member, IEEE*, and Carlos Mosquera, *Member, IEEE*

***Abstract*—In this paper, we propose the concept of *centralized dynamic spectrum leasing* (C-DSL), in which multiple primary users belonging to the same primary system participate in the spectrum leasing process with secondary users (potential bidder for spectrum) under centralized control. We develop a new game-theoretic user interaction model suitable for C-DSL in a cognitive radio network. Dynamic Spectrum Leasing (DSL), proposed in [1]–[3] allows active participation of both primary and secondary users in the spectrum sharing process. Motivated by network spectrum utilization considerations, we propose generalizations to the primary system utility function defined in [2], [3] and a new utility function for the secondary users. We also generalize the proposed non-cooperative C-DSL game to allow for linear multiuser detectors at the secondary base stations. We formulate the conditions on the primary system and the secondary user utility functions so that the proposed C-DSL game has desired equilibrium properties. We prove that the proposed C-DSL game has unique Nash equilibria (NE) under both matched filter (MF) and linear minimum mean-squared error (LMMSE) receivers. Equilibrium performance of the system and robustness of the proposed game theoretic adaptive implementation are investigated through simulations.**

***Index Terms*—Cognitive radios, dynamic spectrum sharing, dynamic spectrum leasing, DSL, centralized dynamic spectrum leasing, C-DSL, Nash equilibrium, game theory.**

I. Introduction

As wireless applications are becoming more widely used, demand for bandwidth is also expected to increase in future years. Under the long-adhered regulatory framework, spectrum appears to be a scarce resource. On the other hand, it has been observed that the perceived scarcity of radio spectrum is mainly due to the inefficiency of traditional spectrum allocation policies [4], [5]. This led the FCC to recommend three broad solutions to improve the spectrum utilization in its 2002 Spectrum Policy Task Force Report: a) spectrum reallocation, b) spectrum leasing, and c) spectrum sharing. The first of these was meant to be a long-term solution. Perhaps, the best example is the opening of the 700MHz TV band for cognitive radio operation. Spectrum leasing in [4] was mostly interpreted to be a static, or off-line, solution, at least according to the current literature. As an alternative to the traditional static spectrum management policy, the *dynamic spectrum sharing* (DSS) in [6]–[10] is considered as an effective way to improve inefficient static spectrum utilization by allowing secondary users to dynamically access the so-called white spaces in spectrum already licensed to the primary users. Some of these spectrum sharing proposals can be identified as being hierarchical-access methods, in that there is usually a primary system that owns the spectrum rights and a secondary system that is interested in accessing this spectrum whenever possible [11], [12]. In almost all existing hierarchical spectrum sharing proposals, the burden of interference management and coexistence is squarely placed on the secondary system. As in [3], we term these proposals as *dynamic spectrum access* (DSA). Cognitive radios, which can be defined as smart radios with built in cognition [13], are especially suited for realizing such dynamic spectrum sharing due to their ability to assess, learn from and orient to the observed RF environment.

Recently [1]–[3], [14], [15] introduced the concept of *dynamic spectrum leasing* (DSL) as a new paradigm for spectrum sharing in cognitive radio networks. The authors identified that the passive primary systems/users that are oblivious to the existence of secondary users is incomplete at the best, and inefficient at the worst, if the objective is to achieve efficient spectrum utilization via DSS. In [1], [2], the primary users were allowed to dynamically manage the interference they experience from the secondary transmissions by adapting their interference cap (IC) according to the observed RF environment and required Quality-of-Service (QoS). Simultaneously, the secondary users aim to achieve energy efficient transmissions, while not causing excessive interference to the primary users. In this paper, we extend the DSL framework for spectrum sharing by introducing the *centralized dynamic spectrum leasing* (C-DSL) as a new game theoretic model for dynamic spectrum sharing in cognitive radio networks. In particular, we allow for multiple primary users to be simultaneously present in the primary frequency

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K. Hakim, S. K. Jayaweera, and G. El-howayek are with the Department of Electrical and Computer Engineering, University of New Mexico, Albuquerque, NM 87131-0001, USA (e-mail: {khakim, jayaweera, ghowayek}@ece.unm.edu).

C. Mosquera is with the Departamento de Teoría de la Señal y Comunicaciones, Universidad de Vigo, 36310 Vigo, Spain (e-mail: mosquera@gts.tsc.uvigo.es).

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band of interest. In the proposed C-DSL based DSS networks all primary users participate in the spectrum sharing process as a single system under a central control. We develop an alternative game-theoretic framework for C-DSL based spectrum sharing by identifying new payoff functions for both primary system and secondary users that are motivated by network spectrum utilization considerations. We introduce a general structure for a suitable class of utility functions for the primary system that reflects the demand for spectrum access from the secondary users, the primary system QoS requirements, and analyze the conditions for reaching a desired equilibrium under greedy adaptations. We also generalize the proposed non-cooperative C-DSL game to allow for linear multiuser detectors, in particular the matched filter (MF) and the linear minimum mean squared error (LMMSE) receivers, at the secondary base stations, and establish the existence of an equilibrium in this primary-secondary spectrum-leasing game. Several DSS radio networks based on the proposed C-DSL framework are investigated via simulations to analyze the equilibrium behavior and to identify design guidelines. As in previous work on DSL, we emphasize the need to minimize the need for conscious effort by the primary system to exchange inter-system control information. Indeed, as we will show later, the proposed C-DSL can be implemented with the same two broadcast parameters from the primary system assumed in [2], [3]. The robustness of the C-DSL based spectrum sharing to time-varying fading is also investigated.

Contributions of this paper that distinguishes it from previous literature are as follows: (i) a novel game-theoretic approach *centralized dynamic spectrum leasing* (C-DSL) is proposed for dynamic spectrum sharing in the presence of multiple primary users extending the model in [2], (ii) we generalize the primary system utility function defined in [2], [3] and introduce a new utility function for the secondary users that leads to efficient utilization of the network spectrum, (iii) the proposed non-cooperative C-DSL game is generalized to allow for linear multiuser detectors, such as the linear minimum mean squared error (LMMSE) receivers at the secondary receivers, and (iv) the robustness of the proposed C-DSL framework is investigated in the presence of slow time varying fading.

The remainder of this paper is organized as follows: Section II describes the C-DSL based spectrum leasing cognitive radio network model. Section III presents the proposed game-theoretic model for C-DSL in a DSS based cognitive radio network. Sections IV and V discuss the existence of unique Nash equilibria under MF and LMMSE receivers, respectively. Section VI evaluates the performance of a spectrum sharing network based on the proposed C-DSL under various conditions and discusses the performance trends and design guidelines. Finally, Section VII concludes the paper by summarizing our results.

II. C-DSL-Based Spectrum Sharing Cognitive Radio Network Model

We assume there is one primary wireless communication system that owns the exclusive rights to use the spectrum band of interest. In a bid to improve the spectrum usage efficiency while earning extra revenue, the primary system is willing to allow a secondary system to access this spectrum band whenever it can tolerate and to the maximum possible extent. It is further assumed that there are K_p primary users in the primary system and there are K_s secondary links of interest. For simplicity of exposition, all these secondary links are assumed to belong to the same secondary system. We will refer to j-th transmitter or j-th receiver to mean the transmitter and receiver of the j-th link. The channel gain between the j-th transmitter and the k-th receiver, either primary or secondary, is denoted by h_{jk}. We use p_j to represent transmission power of the j-th user. Note that, depending on the type of wireless networks assumed, the receivers of each link may or may not be physically distinct. For simplicity we will assume that all primary users communicate with the same primary receiver (for example, a base station) although this assumption can easily be dropped at the expense of notational complexity.

In a C-DSL network, the primary system is assumed to adapt its interference cap (IC), denoted by Q_0, which is the maximum interference the *primary system* is willing to tolerate from all secondary transmissions at a given time, and thus its reward can be an increasing function of the interference cap. However, in reality, the primary user should maintain a target signal-to-interference-plus-noise ratio (SINR) to ensure its required QoS. Moreover, an unnecessarily large interference cap by the primary user could hinder the performance of both systems due to resulting high primary interference. The goal of the secondary system, on the other hand, is to fully utilize the spectrum activity allowed by the primary user. Each secondary user may be assumed to act in its own interest to maximize its own utility. However, their transmission powers must be carefully self-regulated in order to ensure low interference to the primary user (within the IC) as well as to other secondary users.

The signal received at the primary receiver can be written as $r^{(p)}(t) = \sum_{i\in\mathcal{K}_p} A_{p,i}b_i s_i(t) + \sum_{j\in\mathcal{K}_s} A_{p,j}b_j s_j(t) + \sigma_p n(t)$, where $A_{p,l} = h_{pl}\sqrt{p_l}$ for $l \in \mathcal{K}_p \bigcup \mathcal{K}_s$, $n(t)$ is AWGN with unit spectral height and σ_p^2 is the variance of the zero-mean, additive noise at the primary receiver. Assuming M discrete-time projections $r_m^{(p)} = \langle r^{(p)}(t), \psi_m^{(p)}(t)\rangle$, for $m = 1, \cdots, M$, of the continuous time signal on to a set of M orthonormal directions specified by $\left\{\psi_1^{(p)}(t), \cdots, \psi_M^{(p)}(t)\right\}$, called the primary basis, and letting $\mathbf{r}^{(p)} = \left(r_1^{(p)}, \cdots, r_M^{(p)}\right)^T$, we may obtain the following discrete-time representation of the received signal at the primary receiver: $\mathbf{r}^{(p)} = \sum_{i\in\mathcal{K}_p} A_{p,i}b_i\mathbf{s}_i^{(p)} + \sum_{j\in\mathcal{K}_s} A_{p,j}b_j\mathbf{s}_j^{(p)} + \sigma_p\mathbf{n}^{(p)}$, where $\mathbf{s}_k^{(p)} = \left(s_{k1}^{(p)}, \cdots, s_{kM}^{(p)}\right)$, for $k \in \mathcal{K}_p$, is the M-vector representation of the k-th secondary user signalling waveform $s_k(t)$ w.r.t. the M-dimensional basis employed by the primary system, where $s_{km}^{(p)} = \langle s_k(t), \psi_m^{(p)}(t)\rangle$, and $\mathbf{n}^{(p)} \sim \mathcal{N}(\mathbf{0}, \mathbf{I}_M)$. With the conventional matched-filter (MF) detector at the primary receiver, and assuming that primary modulation is BPSK so that $b_i \in \{+1, -1\}$, the i-th primary user symbols are detected as $\hat{b}_i = sgn\left(y_i^{(p)}\right)$ where $y_i^{(p)} = \left(\mathbf{s}_i^{(p)}\right)^T\mathbf{r}^{(p)} = A_{p,i}b_i + \sum_{l\in\mathcal{K}_p\setminus\{i\}} \rho_{il}^{(p)} A_{p,l}b_l + \sum_{j\in\mathcal{K}_s} \rho_{ij}^{(p)} A_{p,j}b_j + \sigma_p\eta_i^{(p)}$, with $\rho_{kl}^{(p)} = \left(\mathbf{s}_k^{(p)}\right)^T\mathbf{s}_l^{(p)}$ for $k, l \in \mathcal{K}_s \bigcup \mathcal{K}_s$ and $\eta_i^{(p)} \sim$

$\mathcal{N}(0,1)$. It is straightforward to observe that the total secondary interference (SI) from all secondary transmissions to the i-th primary user decisions is given by

$$I_i = \sum_{j\in\mathcal{K}_s} \left(\rho_{ij}^{(p)}\right)^2 h_{pj}^2 p_j = \sum_{j\in\mathcal{K}_s} \tilde{A}_{i,j}^2 p_j, \qquad (1)$$

where $\tilde{A}_{i,j} = \rho_{ij}^{(p)} h_{pj}$. We denote the maximum of these interference at any given time over all primary users as I_0, so that $I_0 = \max_{i\in\mathcal{K}_p} I_i = \sum_{j\in\mathcal{K}_s} \tilde{A}_j^2 p_j$ where $\tilde{A}_j = \tilde{A}_{i*j}$, for some $i* \in \mathcal{K}_p$. This total interference parameter I_0 plays a key role in the C-DSL based DSS systems, as we will see below.

Similarly, the received signal at the j-th secondary-system receiver can be written as $r_j^{(s)}(t) = \sum_{k\in\mathcal{K}_s} B_{j,k} b_k s_k(t) + \sum_{i\in\mathcal{K}_p} B_{j,i} b_i s_i(t) + \sigma_s n_j(t)$, where $B_{j,k} = h_{jk}\sqrt{p_k}$, for $k \in \mathcal{K}_s$, $B_{j,i} = h_{ji}\sqrt{p_i}$, for $i \in \mathcal{K}_p$ and σ_s^2 is the variance of secondary receiver noise. A discrete-time representation of $r_j^{(s)}(t)$ with respect to an N-dimensional orthonormal basis $\left\{\psi_1^{(s)}(t), \cdots, \psi_N^{(s)}(t)\right\}$ used by the secondary system, termed the secondary basis, can be written as $\mathbf{r}_j^{(s)} = \sum_{k\in\mathcal{K}_s} B_{j,k} b_k \mathbf{s}_k^{(s)} + \sum_{i\in\mathcal{K}_p} B_{j,i} b_i \mathbf{s}_i^{(s)} + \sigma_s \mathbf{n}_j^{(s)}$, where $\mathbf{r}_j^{(s)} = \left(r_{j1}^{(s)}, \cdots, r_{jN}^{(s)}\right)^T$, $r_{jn}^{(s)} = \langle r_j(t), \psi_n^{(s)}(t)\rangle$, for $n = 1, \cdots, N$, is the projection of the received signal at the secondary receiver j on the the n-th orthonormal basis function, $\mathbf{s}_l^{(s)} = \left(s_{l1}^{(s)}, \cdots, s_{lN}^{(s)}\right)$, for $l \in \mathcal{K}_p \bigcup \mathcal{K}_s$, is the N-vector representation of $s_l(t)$ with respect to the N-dimensional basis employed by the secondary system with $s_{ln}^{(s)} = \langle s_l(t), \psi_n^{(s)}(t)\rangle$, and $\mathbf{n}_j^{(s)} \sim \mathcal{N}(\mathbf{0}, \mathbf{I}_N)$.

III. C-DSL Game Model for Dynamic Spectrum Sharing

In the proposed C-DSL-based DSS networks, the primary system and secondary users interact with each other by adjusting their interference cap and transmit power levels, respectively, in order to maximize their own gains. The primary system action is to set the interference cap Q_0 which specifies the maximum interference it is willing to tolerate from all secondary users. We model the above system as in the following noncooperative C-DSL game $(\mathcal{K}, \mathcal{A}_k, u_k(.))$:

1) Players: $\mathcal{K} = \{0, 1, 2, \cdots, K_s\}$, where we assume that the 0-th user is the primary system consisting of multiple primary users and $k \in \mathcal{K}_s$ represents the k-th secondary user.
2) Action space: $\mathcal{P} = \mathcal{A}_0 \times \mathcal{A}_1 \times \mathcal{A}_2 \cdots \times \mathcal{A}_{K_s}$, where $\mathcal{A}_0 = \mathcal{Q} = [0, \bar{Q}_0]$ represents the primary system's action set and $\mathcal{A}_k = \mathcal{P}_k = [0, \bar{P}_k]$, for $k \in \mathcal{K}_s$, represents the k-th secondary user's action set. Note that $\bar{Q}_0$ and $\bar{P}_k$ represent, respectively, the maximum IC of the primary system and the maximum transmission power of the k-th secondary user. We denote the action vector of all players in the noncooperative C-DSL game by $\mathbf{a} = [Q_0, p_1, \cdots, p_{K_s}]^T$, where $Q_0 \in \mathcal{Q}$ and $p_k \in \mathcal{P}_k$. The action vector excluding that of the k-th user is denoted as $\mathbf{a}_{-k}$.
3) Utility function: We denote by $u_0(Q_0, \mathbf{a}_{-0})$ the primary system's utility function and by $u_k(p_k, \mathbf{a}_{-k})$, for $k \in \mathcal{K}_s$, the k-th secondary user's utility function.

At any given time the target SINR of the i-th primary link is defined in terms of its assumed worst-case secondary interference $\bar{\gamma}_i = \frac{h_{pi}^2 p_i}{Q_0 + MAI(i) + \sigma_p^2}$, where $MAI(i) = \sum_{l\in\mathcal{K}_p\setminus\{i\}} \left(\rho_{il}^{(p)}\right)^2 h_{pl}^2 p_l = \sum_{l\in\mathcal{K}_p\setminus\{i\}} \left(\rho_{il}^{(p)}\right)^2 A_{p,l}^2$ is the *multiple access interference* (MAI) from all other primary transmissions to the i-th primary-user. Our proposed model allows primary users to adapt their actions so as to control their throughput. We could allow $\bar{\gamma}_i$ to be time-varying. In that case $Q_0(t)$ would have to be chosen in such a way so that $\gamma_i(t) \geq \bar{\gamma}_i(t)$ and secondary interference $I_0(t)$ would change according to $I_0(t) \leq Q_0(t)$. On the other hand, the i-th primary user's actual instantaneous SINR is given by

$$\gamma_i = \frac{h_{pi}^2 p_i}{\sum_{l\in\mathcal{K}_p\setminus\{i\}} \left(\rho_{il}^{(p)}\right)^2 h_{pl}^2 p_l + \sum_{j\in\mathcal{K}_s} \left(\rho_{ij}^{(p)}\right)^2 h_{pj}^2 p_j + \sigma_p^2}$$
$$\geq \bar{\gamma}_i \left(1 + \frac{Q_0 - I_0}{I_0 + MAI(i) + \sigma_p^2}\right). \qquad (2)$$

Thus, as seen from (2), each primary user's instantaneous SINR will be above the least acceptable SINR threshold as long as the primary system's interference cap $Q_0 \geq I_0$. It is to be noted that each primary user under the primary system choose its transmit power from least acceptable SINR threshold as $p_i = \bar{\gamma}_i \left(\frac{Q_0 + MAI(i) + \sigma_p^2}{h_{pi}^2}\right)$. Since $I_0 \leq Q_0$, instantaneous SINR of i-th primary user would be, in general, greater than the least acceptable SINR as seen from (2). If sharing is not enabled, i.e., $Q_0 = 0$ and $I_0 = 0$, i-th primary user's power would be $p_i = \bar{\gamma}_i \left(\frac{MAI(i) + \sigma_p^2}{h_{pi}^2}\right)$, which is less than the power, the i-th primary user had to transmit if sharing were enabled. According to (2), the instantaneous SINR would be exactly equal to the least acceptable SINR in this case. On the other hand, if sharing is enabled, i.e. $Q_0 \neq 0$ and $I_0 \neq 0$, rate achieved by i-th primary user is $W_i \log(1 + \gamma_i)$, which is at least greater than least acceptable data rate $W_i \log(1 + \bar{\gamma}_i)$. Hence, if sharing is enabled, as long as $I_0 \leq Q_0$, data rate of i-th primary user is guaranteed to be above the minimum required threshold, but of course at the expense of transmitting at a higher power.

By generalizing the approach proposed in [2], [3], we propose the following utility function for the primary system:

$$u_0(Q_0, \mathbf{a}_{-0}) = u_0(Q_0, I_0)$$
$$= \left(\bar{Q}_0 - (Q_0 - I_0(\mathbf{a}_{-0}))\right) F(Q_0), \qquad (3)$$

where $F(.)$ is a suitable continuous reward function for the primary system. For example, in [2] the authors proposed a linear reward function $F(Q_0) = Q_0$ assuming that the reward for the primary system is directly proportional to the interference cap it chooses. In this paper, we establish conditions on $F(.)$ so that the proposed C-DSL game has desired equilibrium properties. Note that, (3) also assumes that the utility of the primary system is proportional to the *demand* in addition to the reward function $F(.)$. The demand is taken to be decreasing when extra interference margin $Q_0 - I_0$ increases. This discourages the primary system from swamping all other transmissions by setting too large an interference cap that will lead to higher transmission powers according to (2). As a special case of (3), we choose

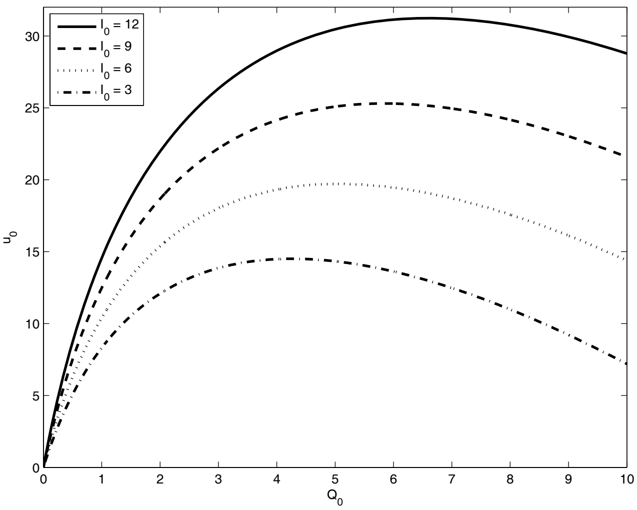


Fig. 1. Primary utility u_0 for a fixed secondary interference I_0 with $\overline{Q}_0 = Q_0^{max} = 10$, $h_{p1} = 1$, $\rho_{01}^{(p)} = \rho_{10}^{(s)} = 1$ and $\lambda = 1$.

$F(Q_0) = \log(1+Q_0)$ so that the primary utility is proportional to the capacity attained by the secondary system with respect to the primary receiver. We believe this model for the primary system utility is more sensible in a dynamic spectrum leasing cognitive radio network, compared to [2], when the secondary system is concerned about the rate its users achieve rather than their transmission powers. By choosing a reasonable revenue/utility rate based on the market value, the revenue earned by the primary system could be increased, and the revenue achieved in that case would reflect actual capacity achieved by the secondary system more compared to that in [2]. Figure 1 shows the above primary utility as a function of the interference cap Q_0 for a fixed total secondary interference I_0. Observe from Fig. 1 that the primary system utility u_0 is quasi-concave in interference cap Q_0.

As can be seen from (2) as long as the secondary user interference $I_0 \leq Q_0$, the primary system quality of service will be guaranteed for all its users. To ensure this the utilities of secondary users must be fast decaying functions of $I_0 - Q_0$ when this difference is positive. Thus, if $f(p_k)$ is the reward achieved by the k-th secondary user by transmitting at a power p_k, then a suitable utility function for it would be $f(p_k)q(Q_0 - I_0)$ where $q(.)$ is the unit step function. Motivated by these arguments, and in an attempt to avoid the discontinuity of the step function, in this paper we propose the following utility function for the k-th secondary user, for $k \in \mathcal{K}_s$:

$$u_k\left(p_k, \mathbf{a}_{-k}\right) = \frac{f(p_k)}{1 + e^{\lambda(I_0 - Q_0)}} = \frac{f(p_k)}{1 + e^{\lambda(I_{0,-k}(\mathbf{a}_{-k}) - Q_0)} e^{c_k p_k}}, \quad (4)$$

where $f(.)$ is a suitable reward function chosen by the secondary system and the weighting term $\frac{1}{1+e^{\lambda(I_0-Q_0)}}$ in (4) is a sigmoidal function used to approximate the unit step with the property that it goes to either $+1$ or 0, as $I_0 - Q_0$ tends to either negative or positive infinity, respectively, while the parameter λ can be used to adjust the steepness of the transition region. Note that $I_{0,-k} = I_0 - \tilde{A}_k^2 p_k$ is the interference from all secondary transmissions to the worst-hit primary user excluding that from the k-th secondary user and that we have defined $c_k = \lambda \tilde{A}_k^2 \geq 0$ in (4).

In a dynamic spectrum leasing system, a suitable objective for the secondary system would be to maximize the sum capacity of all its users in the shared primary spectrum. However, from the perspective of a particular secondary user, it would be interested in gaining the maximum possible rate it can achieve. As a result, we will use $f(p_k) = W_k \log\left(1 + \gamma_k^{(s)}\right)$ throughout this paper as a special case of (4) where $\gamma_k^{(s)}$ is the received SINR of the k-th *secondary link* for $k \in \mathcal{K}_s$ and $W_k > 0$ can be taken as proportional to the bandwidth. Hence, in the remainder of this paper we will limit ourselves to investigating equilibrium strategies of the game $G = (\mathcal{K}, \mathcal{A}_k, u_k)$ where users are interested in maximizing the utility functions defined in (3) and (4) with $F(Q_0) = \log(1 + Q_0)$ and $f(p_k) = W_k \log\left(1 + \gamma_k^{(s)}\right)$ respectively.

Definition 1: A strategy vector $\mathbf{p} = (a_0, a_1, \cdots, a_k)$ is a Nash equilibrium of the primary-secondary user power control game $G = (\mathcal{K}, \mathcal{A}_k, u_k)$ if, for every $k \in \mathcal{K}$, $u_k\left(a_k, \mathbf{a}_{-k}\right) \geq u_k\left(a_k', \mathbf{a}_{-k}\right)$ for all $a_k' \in \mathcal{A}_k$.

The best response correspondence of a user in a game is the best reaction strategy a rational user would choose in order to maximize its own utility, in response to the actions chosen by other players.

Definition 2: The user k's best response $r_k : \mathcal{A}_{-k} \longrightarrow \mathcal{A}_k$ is the set

$$r_k\left(\mathbf{a}_{-k}\right) = \left\{a_k \in \mathcal{A}_k : u_k\left(a_k, \mathbf{a}_{-k}\right) \geq u_k\left(a_k', \mathbf{a}_{-k}\right) \text{ for all } a_k' \in \mathcal{A}_k\right\}. \quad (5)$$

Clearly both the primary system and secondary user action sets are both compact and convex being closed and bounded intervals on the real line. Further, according to our construction, both $u_0(\mathbf{a})$ and $u_k(\mathbf{a})$ are continuous in the action vector $\mathbf{a}$. The usefulness of the best-response strategies come handy in establishing the uniqueness of the Nash equilibrium of a C-DSL game, as we will see later. Indeed, it has been shown that if the best response correspondences $r_k(\mathbf{a}_{-k})$ of a game are so-called *standard functions* for every $k \in \mathcal{K}$, then the game has a unique Nash equilibrium [16], where

Definition 3: A function $\mathbf{r}(\mathbf{a})$ is said to be a standard function if it satisfies the following three properties [16]: (i) *Positivity* : $\mathbf{r}(\mathbf{a}) > 0$, (ii) *Monotonicity* : If $\mathbf{a} \geq \mathbf{a}'$, then $\mathbf{r}(\mathbf{a}) \geq \mathbf{r}(\mathbf{a}')$, (iii) *Scalability* : For all $\mu > 1$, $\mu\mathbf{r}(\mathbf{a}) \geq \mathbf{r}(\mu\mathbf{a})$.

IV. Analysis of the Proposed C-DSL Game with the MF Secondary Receiver

We assume that all secondary transmissions are BPSK and all secondary detectors are based on the MF. Then, the j-th secondary link receiver detects the corresponding j-th secondary transmitter's symbols as $\hat{b}_j = sgn\left(y_j^{(s)}\right)$ where, for $j \in \mathcal{K}_s$, $y_j^{(s)} = \left(\mathbf{s}_j^{(s)}\right)^T \mathbf{r}_j^{(s)} = B_{j,j}b_j + \sum_{l \in \mathcal{K}_s \setminus \{j\}} \rho_{jl}^{(s)} B_{j,l} b_l + \sum_{i \in \mathcal{K}_p} \rho_{ji}^{(s)} B_{j,i} b_i + \sigma_s \eta_j^{(s,j)}$ with $\rho_{kl}^{(s)} = \left(\mathbf{s}_k^{(s)}\right)^T \mathbf{s}_l^{(s)}$ and $\eta_k^{(s,j)} = \left(\mathbf{s}_k^{(s)}\right)^T \mathbf{n}_j^{(s)} \sim \mathcal{N}(0,1)$.

Hence, the j-th secondary link's SINR is given by

$$\gamma_j^{MF} = \frac{|h_{jj}|^2 p_j}{\sum_{l\in\mathcal{K}_s\setminus\{j\}} \left(\rho_{jl}^{(s)}\right)^2 |h_{jl}|^2 p_l + \sum_{i\in\mathcal{K}_p} \left(\rho_{ji}^{(s)}\right)^2 |h_{ji}|^2 p_i + \sigma_s^2} = \frac{|h_{jj}|^2 p_j}{i_j^{(j)} + \tilde{\sigma}_{s,j}^2} = \frac{p_j}{N_j}, \quad (6)$$

where $i_k^{(j)} = \sum_{l\in\mathcal{K}_s\setminus\{k\}} \left(\rho_{kl}^{(s)}\right)^2 h_{jl}^2 p_l$ is the total interference from all other secondary users to the k-th secondary link signal at the j-th secondary receiver, $\tilde{\sigma}_{s,j}^2 = \sum_{i\in\mathcal{K}_p} \left(\rho_{ji}^{(s)}\right)^2 |h_{ji}|^2 p_i + \sigma_s^2$ is the effective primary interference plus noise seen by the j-th link and $N_j = \frac{i_j^{(j)} + \tilde{\sigma}_{s,j}^2}{|h_{jj}|^2}$. It can be easily seen that $\frac{\partial \gamma_j^{MF}}{\partial p_j} = \frac{\gamma_j^{MF}}{p_j}$ when the secondary system employs the MF receiver.

Assuming single-user primary and secondary systems, the proposed secondary user utility in (4) with $\gamma_j^{(s)} = \gamma_j^{MF}$ is shown in Fig. 2(a) parameterized by the primary interference cap, while Fig. 2(b) shows the effect of parameter λ on the utility function. It can be seen from Fig. 2(a) that the proposed secondary user utility function u_j is quasi-concave in p_j, and the unique maximum of u_j is an increasing function of primary interference cap Q_0. Hence pushing the primary interference cap to a higher value encourages the secondary users to transmit at higher powers and thus allow the primary user to achieve higher leasing gains. From Fig. 2(b), it can be seen that the parameter λ can be used to adjust the steepness of the transition region of the secondary utility function. The higher the value of λ, the steeper the transition, and indicates that the primary system expects the secondary users to strictly adhere to the $I_0 \leq Q_0$ requirement. The following proposition guarantees the existence of a Nash equilibrium in the proposed centralized DSL game under certain conditions on the primary reward function $F(Q_0)$:

Proposition 1: With $\mathcal{A}_k$'s and u_k's as defined above, the centralized dynamic spectrum leasing (C-DSL) game $G = (\mathcal{K}, \mathcal{A}_k, u_k)$ has a Nash Equilibrium when $\gamma_k^{(s)} = \gamma_k^{MF}$ if $F(Q_0)$ satisfies the following conditions:

1. $F(Q_0)$ is continuous and strictly monotonic for $Q_0 > 0$
2. $F(0) = 0, F'(0) > 0$ and $\lim_{Q_0\to\infty} \frac{F(Q_0)}{F'(Q_0)} > -\infty$
3. $\frac{F(Q_0)F''(Q_0)}{(F'(Q_0))^2} < 2$ for $Q_0 > 0$
4. $0 \leq Q_0 + I_0(\mathbf{a}_{-0}) < \infty$.

Proof: See Appendix A. ■

In a non-cooperative game if all users are allowed to adapt their actions sequentially according to their best-response correspondences, then they are guaranteed to converge to a Nash equilibrium of the game. The unique interior best response of primary system is given by the solution to $Q_0^*(I_0) = \left(\bar{Q}_0 + I_0\right) - \frac{F(Q_0^*)}{F'(Q_0^*)}$. Since $u_0(Q_0)$ is monotonic increasing for $Q_0 < Q_0^*$, if the maximum interference cap is such that $\bar{Q}_0 < Q_0^*$, then the primary system best response is given by $r_0(\mathbf{a}_{-0}) = \min\{\bar{Q}_0, Q_0^*(I_0)\}$. In order to determine this best response $r_0(\mathbf{a}_{-0})$ for a chosen power vector by the secondary links, the only quantity the primary system needs to know is the maximum total secondary interference experienced by any user at the primary receiver, denoted by $I_0 = \max_{i\in\mathcal{K}_p} I_i$. This total interference can easily be estimated at the primary receiver without much difficulty. It is to be noted that the simplification $I_0 = \max_i I_i$ may lead to not fully capitalizing on different channel conditions on different primary users, as different primary users may experience different interference from secondary users in general[1]. However, the context to which the proposed C-DSL applies is when a set of primary users share the same frequency band (e.g. CDMA) and communicate to a single receiver. In that case, the receiver needs to be able to work with the worst-hit primary user conditions.

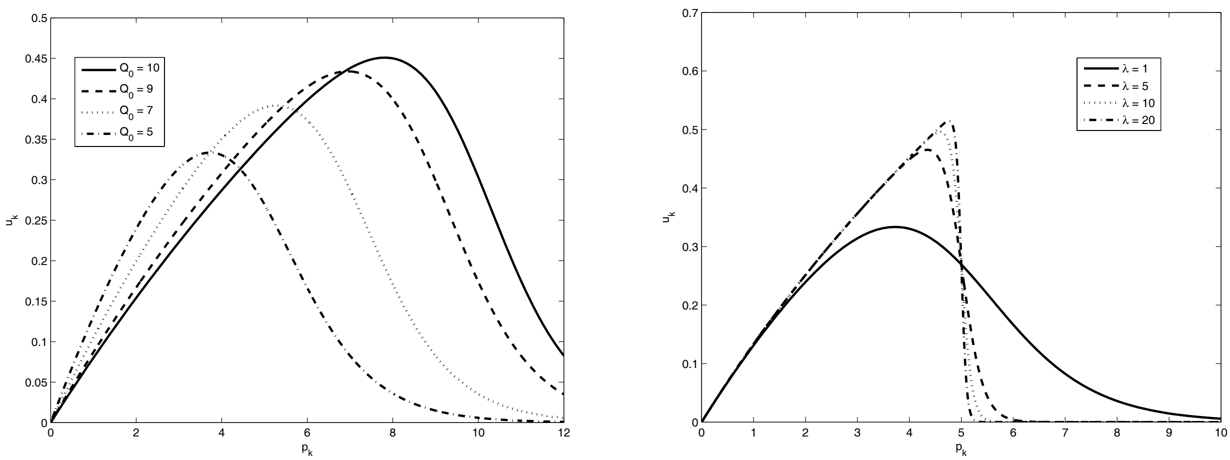
On the other hand, the best response of the j-th secondary link to the transmit powers of other secondary users as well as IC set by the primary user is given by the (unique) solution $p_j = p_j^*\left(Q_0, I_{0,-j}, i_j^{(j)}\right)$ to the equation $g_j^{MF}(p_j) = 0$ defined in Appendix A. Again, since u_j is quasi-concave in p_j, if $p_j^*\left(Q_0, I_{0,-j}, i_j^{(j)}\right) > \bar{P}_j$, then its best response is to set its transmit power to $p_j = \bar{P}_j$. Hence, we have the best response of the j-th secondary link, for $j \in \mathcal{K}_s$: $r_j(\mathbf{a}_{-j}) = \min\{\bar{P}_j, p_j^*\left(Q_0, I_{0,-j}, i_j^{(j)}\right)\}$.

Observe that in general the best response of the j-th secondary link is a function of the residual interference $Q_0 - I_{0,-j}$ of all other secondary users at the primary receiver and the total interference from all secondary and primary users to the j-th link at its receiver. The j-th secondary link receiver can easily estimate the latter quantity. However, to obtain the residual interference $Q_0 - I_{0,-j}$ the secondary receiver needs to know the current interference cap Q_0 as well as the secondary interference $I_{0,-j}$ at the primary receiver. In this work, we assume that the primary base station broadcasts both Q_0 and I_0 whenever it adjusts its interference cap to a new value. This is the only conscious interaction the primary system is assumed to be having with the secondary system if decentralized optimization is considered. Observe that knowing I_0, each secondary user can compute the residual interference $I_{0,-j} = I_0 - \tilde{A}_j^2 p_j$ since it knows its own transmit power and it may estimate the channel state information $\tilde{A}_j$ if the reverse link signals are available on the same frequency band. On the other hand, if the optimization were to be centralized, then the central system had to be aware of the channel state information and powers of all the secondary users. In addition to that it had to inform each individual secondary user about its new transmit power p_k, which would cost sufficient amount of bandwidth dedicated to control signals.

V. Analysis of the Proposed C-DSL Game with the LMMSE Secondary Receiver

In this section we assume that the secondary system is equipped with so-called LMMSE receivers. Note that, to make fair comparisons with the case of MF-based secondary receivers as discussed in the previous section, we hold the primary receiver to be still based on the MF. Of course it is also possible for the primary system to be equipped with an LMMSE (or any other MUD) detector. The effect of that

[1]Exploiting the channel variations over different primary channels/frequency bands is considered in our follow-up paper [17].



(a) (b)

Fig. 2. Secondary-link utility u_k for (a) fixed interference cap Q_0 and (b) fixed λ with $Q_0 = 5$. Other parameters used are: $W_k = W = 1$, $h_{p1}^2 = h_{11}^2 = 1$, $\sigma_p^2 = \sigma_s^2 = 1$ and all the cross-correlations are assumed to be unity.

would be for the primary system to be able to tolerate higher I_0 values, for the same primary transmission powers.

For detecting signals of the j-th secondary link, the j-th secondary link receiver employs the LMMSE filter defined by $\min_{\mathbf{w_{j,j}}} \mathbb{E}\left[\left(b_j - \mathbf{w}_{j,j}\mathbf{r}_j^{(s)}\right)^2\right]$, where $\mathbf{w}_{j,j} \in \mathbb{R}^N$ is the vector of LMMSE filter coefficients at the j-th receiver that achieves minimum mean-squared error in estimating j-th link symbols. It is well-known that the solution to the above optimization problem is given straightforwardly by $\mathbf{w}_{j,j} = \mathbb{E}\left[\mathbf{r}_j^{(s)}\left(\mathbf{r}_j^{(s)}\right)^T\right]^{-1}\mathbb{E}\left[b_j\mathbf{r}_j^{(s)}\right]$. It can be verified that $\mathbb{E}\left[\mathbf{r}_j^{(s)}\left(\mathbf{r}_j^{(s)}\right)^T\right] = \sum_{l\in\mathcal{K}_s} B_{j,l}^2\mathbf{s}_l^{(s)}\mathbf{s}_l^{(s)^T} + \sum_{i\in\mathcal{K}_p} B_{j,i}^2\mathbf{s}_i^{(s)}\mathbf{s}_i^{(s)^T} + \sigma_s^2\mathbf{I}$ and $\mathbb{E}\left[b_j\mathbf{r}_j^{(s)}\right] = B_{j,j}\mathbf{s}_j^{(s)}$, resulting in the following LMMSE filter coefficient vector for the j-th link: $\mathbf{w}_{j,j} = \frac{B_{j,j}}{1+B_{j,j}^2\mathbf{s}_j^{(s)^T}\Sigma_{j,j}^{-1}\mathbf{s}_j^{(s)}}\Sigma_{j,j}^{-1}\mathbf{s}_j^{(s)}$, where $\Sigma_{j,j} = \sigma^2\mathbf{I} + \sum_{i\in\mathcal{K}_p} B_{j,i}^2\mathbf{s}_i^{(s)}\mathbf{s}_i^{(s)^T} + \sum_{l\in\mathcal{K}_s\setminus\{j\}} B_{j,l}^2\mathbf{s}_l^{(s)}\mathbf{s}_l^{(s)^T}$. Note that although we omit details due to space constraints, the above LMMSE filter coefficient vector can easily be adapted without explicit knowledge of primary or the other secondary signaling waveforms. We refer the interested readers to [18]. The received output SINR of the j-th secondary link can be written as:

$$\begin{aligned}\gamma_j^{MMSE} &= B_{j,j}^2\left(\mathbf{s}_j^{(s)}\right)^T\Sigma_{j,j}^{-1}\mathbf{s}_k^{(s)}\\ &= h_{jj}^2 p_j\left(\mathbf{s}_j^{(s)}\right)^T\Sigma_{j,j}^{-1}\mathbf{s}_j^{(s)}. \qquad (7)\end{aligned}$$

Due to the LMMSE detector's well known property of maximizing the output SINR, the linear MMSE receiver may require secondary radios to transmit at a lower power than that with the MF receiver to achieve the same QoS. Note that, since $\mathbf{s}_j^{(s)}$, $\Sigma_{j,j}^{-1}$ and h_{jj} are independent of p_j, it follows that $\frac{\partial\gamma_j^{MMSE}}{\partial p_j} = \frac{\gamma_j^{MMSE}}{p_j}$ as in the case of MF based receivers. In fact, it should be pointed out that the only difference between the C-DSL game with the LMMSE receiver and that with the MF receiver is in the above SINR expression of secondary users. As a result we have the following proposition, whose proof has been deferred to the Appendix B, that establishes the existence and uniqueness properties of the equilibrium of the C-DSL game when secondary receivers are equipped with LMMSE detectors:

Proposition 2: With $\mathcal{A}_k$'s and u_k's as defined before, the centralized dynamic spectrum leasing (C-DSL) game $G = (\mathcal{K}, \mathcal{A}_k, u_k)$ still has a *unique* Nash Equilibrium when $\gamma_k^{(s)} = \gamma_k^{MMSE}$, if conditions $(1)-(4)$ in *Proposition 1* are satisfied.

Proof: See Appendix B. ■

VI. Performance Analysis of a Centralized Dynamic Spectrum Leasing System

In this section, our goal is to investigate the behavior of the primary and secondary systems at the equilibrium and delineate the key characteristics emerging from our framework for spectrum leasing. We will compare performance of our proposed framework for both MF and LMMSE secondary receivers. The performance of the system is considered as its performance at the Nash equilibrium. For simplicity of exposition, we assume that both primary and secondary systems are equipped with only one receiver each in the uplink.

A. Identical links: AWGN Channels

To illustrate the characteristics of the Nash equilibrium in this primary-secondary user C-DSL game, it is interesting to look at perhaps the most simple situation in which there are identical secondary links ($K_s > 1$) and a single primary user ($K_p = 1$). We assume that all secondary links' have the same cross-correlation coefficients $\rho_{0k}^{(p)} = \rho_0^{(p)}, \rho_{k0}^{(s)} = \rho_0^{(s)}, \rho_{kj}^{(s)} = \rho^{(s)}$, for all $k, j \in \mathcal{K}_s$ and all channels are additive white Gaussian noise (AWGN): $h_{sk} = h_{pk} = 1$ for all $k \in \mathcal{K}_s$ so that $\tilde{A}_k = \tilde{A}$ for all k. By symmetry, in this case all secondary users must have the same power $p_k = p^*$ at the Nash equilibrium (equivalently, the same SINR $\gamma_k = \gamma^*$). Thus when the secondary system employs MF receiver, with

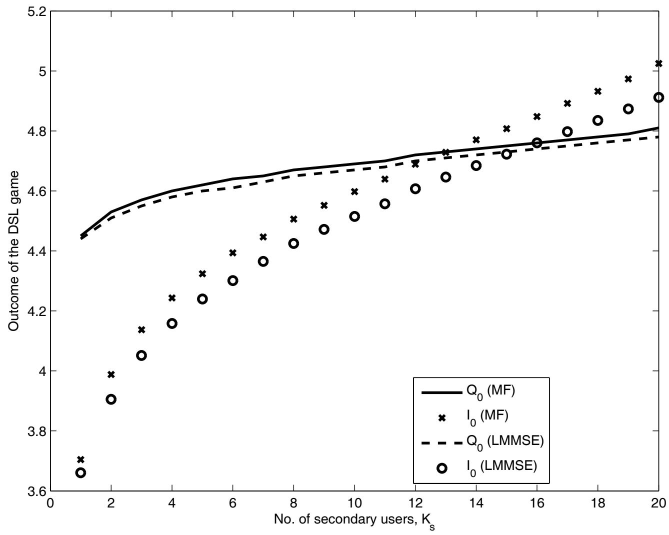


Fig. 3. Outcome of the C-DSL game at the system NE, with MF and LMMSE receiver, as a function of secondary system size K_s assuming identical secondary links, when $\lambda = 5$.

$F(Q_0) = \log(1 + Q_0)$, the Nash equilibrium is characterized by the intersection (Q_0^*, p^*) of the following two curves:

$$Q_0 = r_0(p) = (\text{solution to equation } \psi_{Q_0}(p) = 0), \tag{8}$$

$$p = r_s(Q_0) = \left(\text{solution to equation } g^{MF}(p) = 0\right), \tag{9}$$

where $\psi_{Q_0}(p) = Q_0 + (1 + Q_0)\log(1 + Q_0) - \bar{Q}_0 - K\tilde{A}^2 p$ and $g^{MF}(p) = \frac{1}{N}e^{-cp} + \frac{1}{N}e^{-\lambda Q_0}e^{(K-1)cp} - c\left(1 + \frac{p}{N}\right)\log\left(1 + \frac{p}{N}\right)e^{-\lambda Q_0}e^{(K-1)cp}$. In the case of a secondary system with the LMMSE receiver, the Nash equilibrium is given by the intersection (Q_0^*, p^*) of (8) and the curve: $p = r_s(Q_0) = \left(\text{solution to equation } g^{MMSE}(p) = 0\right)$, where $g^{MMSE}(.)$ is defined in Appendix B for identical secondary links.

Figure 3 shows the C-DSL game outcomes when the secondary system is equipped with the MF as well as the LMMSE receiver. Note that we have set $W_k = W = 1$, $\bar{Q}_0 = 10$, $\bar{P}_k = 20$, $\bar{\gamma}_0 = 1$, $h_{pk}^2 = h_{sk}^2 = 1$, for all $k \in \mathcal{K}_s$, $\sigma_s^2 = \sigma_p^2 = 1$, and all cross-correlations being 0.5. While the system shows similar performance trends with both receivers, the effect of having LMMSE receiver is that the safety margin $Q_0 - I_0$ is slightly larger compared to that with the MF receiver. As can be seen from Fig. 3, with the MF-based secondary receiver, the primary system can support only up to $K_s \leq 13$ secondary users before the secondary system violates the primary interference cap. On the other hand, with an LMMSE-based secondary receiver, the primary system can support up to $K_s \leq 15$ secondary users due to the superior interference suppression capability of the LMMSE receiver [18].

Figure 4 shows the primary and secondary utilities at the Nash equilibrium of the system as a function of the secondary system size K_s. It is observed from Fig. 4(a) that the equilibrium utility of the primary system is decreased when the secondary system is equipped with the LMMSE receiver. This is because, with the LMMSE receiver, the secondary system can better manage its transmit power and thus total secondary interference to the primary system is reduced, which in turn reduces the primary utility. If one were to interpret the primary utility as proportional to a leasing payment the secondary system needs to make to the primary system, this shows how the secondary system can benefit by employing better receiver techniques.

Figure 4(b) shows both the sum-rate $\sum_{k=1}^{K_s} \log\left(1 + \gamma_k^{(s)}\right)$ as well as the per-user rate $\frac{1}{K_s}\sum_{k=1}^{K_s} \log\left(1 + \gamma_k^{(s)}\right)$ achieved by the secondary system at the Nash equilibrium. As we observe from Fig. 4(b), the secondary sum-utility and per-user utility with the LMMSE receiver are higher compared to those achieved with the MF receiver. It can also be seen that the sum-utility of all the secondary users with LMMSE receiver has a unique maximum at $K_s = 6$. As the secondary system attempts to include more users into the system, the sum-utility of the secondary system starts to monotonically decrease. This is because, as the number of secondary users increases, users in both primary and secondary system experience additional interference. In response to that, each secondary user attempts to transmit at a higher power to achieve their target SINR's, thereby causing an overall degradation of both sum- and per-user rate. Note that, from a system point of view the secondary system would prefer to maximize the sum-rate. Thus from the secondary system's perspective, it may prefer to operate at $K_s = 6$ with the LMMSE receiver. As we see from Fig. 4(b), the sum-rate first increases and then decreases with K_s for LMMSE-based receiver, but stays almost the same for MF-based receiver. Thus, at a first glance, allowing more secondary users to operate simultaneously seems to be the preferred solution with the MF-based receiver. However, Figure 4(b) also shows that the per-user rate is monotonically decreasing in K_s for both MF and LMMSE-based secondary system, leading to decreasing incremental gains in sum-rate (with the MF receiver) as additional secondary users are added to the system. Depending on the application and the QoS requirement of the secondary system, each secondary user may have a minimum required rate (in bits per transmission) below which the transmissions would be useless. Thus we note that this QoS requirement will determine the maximum number of secondary users, the system would want to support at any given time. For example, with the LMMSE-based secondary system, if the minimum per-user rate required is 2 bps, the optimal K_s would be $K_s^* = 8$. If, on the other hand, the rate threshold was reduced to 1 bps, the secondary system might allow up to $K_s^* = 12$ secondary users to operate simultaneously. Note that on the other hand, if maximizing the sum-rate were to be the objective, then as noted above the optimum K_s would be $K_s^* = 6$.

B. Non-identical links: Fading Channels

In the presence of wireless channel fading, the Nash equilibrium power profile of the C-DSL based dynamic spectrum sharing system will depend on the observed channel state realizations as well as on the type of receivers used in the secondary system. It is expected that in this case the Nash equilibrium transmit powers of individual secondary users will be different for each user. We assume that all channel gains follow Rayleigh distributions with all channel coefficients

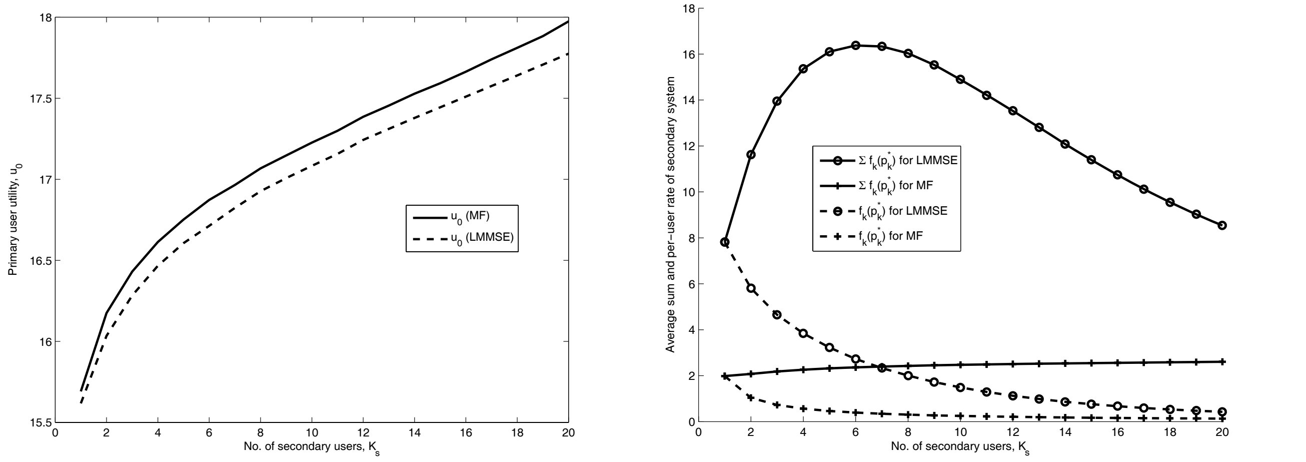


Fig. 4. Primary and secondary utilities at the system NE as a function of secondary system size K_s for $\lambda = 5$ and assuming identical secondary user. (a) Primary system utility, (b) Sum-rate and the per-user rate achieved by the secondary system at the NE.

normalized so that $\mathbb{E}\left\{h^2\right\} = 1$. Other parameters used for simulations are: $W_k = W = 1$, $\bar{Q}_0 = 10$, $\bar{P}_k = 20$, $\lambda = 5$, $\bar{\gamma}_0 = 1$, $\sigma_p^2 = \sigma_s^2 = 1$ and all cross-correlations being 0.5. We investigate the performance with both quasi-static (QS) fading (channel state information is constant for the duration of a block) and slow time varying fading. For slow time varying (TV) fading, the temporal correlation is modeled as a first order Gauss-Markov process [19], and is described via $h_{(.,.)}(i) = \sqrt{1-\epsilon^2}h_{(.,.)}(i-1) + \epsilon w_{(.,.)}(i)$, where the driving noise $w_{(.,.)}(i)$ are iid $\mathcal{CN}(0, \sigma^2_{h_{(.,.)}})$ and ϵ is the channel variation rate. We assume that the channel state information (CSI) is not instantaneously available to the receivers, and each receiver updates the CSI periodically every L samples. The detectors' decisions will use the estimated CSI defined as: $\hat{h}_{(.,.)}(i) = h_{(.,.)}\left(\lfloor i/L \rfloor L\right)$. For our simulations, we used $L = 10$ and $\epsilon = 0.1$. All simulation results are obtained by averaging over 2000 fading realizations.

In Fig. 5(a), we have shown the C-DSL game outcome at the Nash equilibrium as a function of number of secondary users K_s in the presence of both time-varying and quasi-static channels. It can be seen from Fig. 5(a) that for quasi-static channel and with secondary MF receiver, the primary system can support up to $K_s \leq 13$ secondary users before the secondary system violates the primary interference cap. With the secondary LMMSE receiver, the primary system can support up to $K_s \leq 16$ secondary users in this channel scenario. On the other hand, for time-varying channel, the primary system can support up to $K_s \leq 12$ and $K_s \leq 15$ with the secondary MF and LMMSE receivers respectively. Note also that in the time-varying fading scenario, the safety margin $Q_0 - I_0$ decreases as secondary system size increases. In the time-varying case, values of Q_0 and I_0 are slightly higher than those for the quasi-static system. Figure 5(b) shows that the secondary link utility is decreased in time varying channels compared to that with quasi-static channels. This is because of the incomplete channel information forcing the system to deviate from the actual Nash equilibrium. It also shows that the secondary sum-utility as well as the per-user utility with the LMMSE receiver are also much better compared to those achieved with the MF receiver. Note that, the monotonic reduction in per-user utility with K_s is common to both LMMSE and MF-based receivers. However, with the LMMSE receiver, this monotonic reduction is more than offset by the increased number of users in the secondary system.

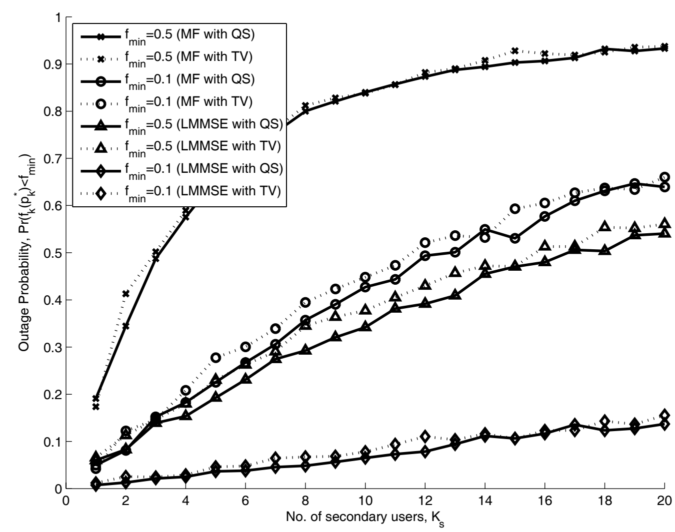
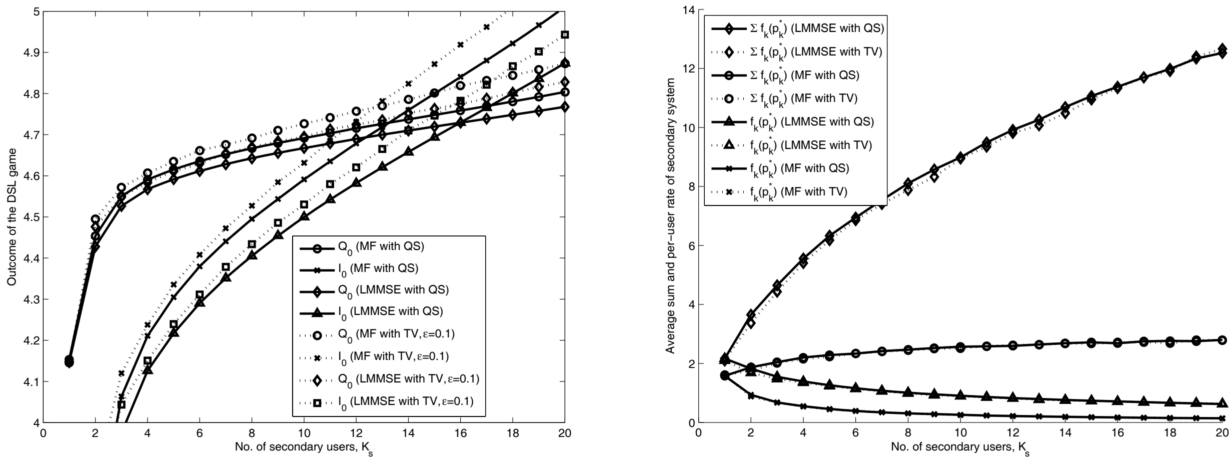


Fig. 6. Outage probability $Pr\left(f_k\left(p_k^*\right) < f_{min}\right)$ of a typical secondary user at the NE of the C-DSL game in fading channels as a function of secondary system size K_s for a required QoS requirement f_{min}.

When $f\left(p_k\right) = \log\left(1 + \gamma_k^{(s)}\right)$ the reward for a secondary link is the rate (in bps) it can achieve assuming all other transmissions (both primary and secondary) are purely noise. The minimum transmission quality for the secondary system is defined as the average (over fading) minimum reward achieved by a link at the equilibrium. We denote this minimum required QoS for secondary link k as $f_{min,k}$ and in all simulation results below assume that $f_{min,k} = f_{min}$ for all secondary links. Figure 6 shows the outage probability $Pr\left(f_k\left(p_k^*\right) < f_{min}\right)$ of a typical secondary link as a function of K_s. It can be seen from Fig. 6 that the outage probability increases with



(a) (b)

Fig. 5. (a) Outcome of the C-DSL game at the system NE, with MF and LMMSE secondary receiver, as a function of secondary system size K_s in the presence of channel fading, (b) Average sum-rate and the per-user rate achieved by the secondary system at the NE.

K_s as well as with the minimum QoS requirement. Note also that in general outage probability increases for both secondary MF and LMMSE receivers. Here also the LMMSE-based system ensures a higher QoS due to efficient management of secondary links' transmit powers. The maximum secondary system size that can be supported according to Fig. 5(b) thus needs to be interpreted in conjunction with the outage probabilities shown in Fig. 6. For example, in quasi-static channels with a MF-based secondary system, Fig. 5(b) shows that about 4 secondary links can (on average) meet the $f_{min} = 0.5$ bps QoS requirement with $\lambda = 5$. However, according to Fig. 6 each of the these users may be in outage about 60% of time. On the other hand, for the LMMSE-based secondary system, about 20 secondary links can (on average) meet $f_{min} = 0.5$ bps QoS in Fig. 5(b), while also having an outage probability of about 50% according to Fig. 6. This, of course, is the price of operating as the secondary system. However, outage probabilities with the model proposed in this paper are better than that in [2]. The improvement in the outage probability $f_{min} = 0.1$ bps with secondary MF receiver, is almost 8 times for $K_s = 1$ and 1.5 times for $K_s = 20$. On the other hand for the same f_{min}, improvement in the outage probability with the secondary LMMSE receiver, is almost 20 times for $K_s = 1$ and 7 times for $K_s = 20$. This is because of the difference in the secondary utility functions u_k's in our paper and in [2]. Since we approximate the unit step function with a sigmoidal function, with a suitably chosen value of the parameter λ and higher value of positive $Q_0 - I_0$, the secondary utility function u_k converges to the reward function $f(p_k)$. Thus unlike the secondary utility function u_k in [2], the maximum of our proposed secondary utility function u_k also approximately corresponds to maximum of $f(p_k)$. As a result, outage probability in our paper is better than that in [2].

Figure 7 shows the primary and secondary rates achieved at the NE in a quasi-static channel as a function of secondary system size K_s when the primary system has $K_p = 3$ users. It can be seen from Fig. 7(a), the primary user data rate is above the minimum required threshold as long as $I_0 \leq Q_0$ and it decreases as more secondary users are added into the system. For $K_s \geq 13$ (MF) and $K_s \geq 15$ (LMMSE), $I_0 \geq Q_0$ and the primary user rate drops below minimum required threshold. Hence, operation beyond this points is not desirable. As one would expect, in Fig. 7(b), the secondary sum and per-user rates are decreased with both the MF and LMMSE detector for $K_p = 3$. This is because of the increase in the total interference due to additional primary users in the system. As a result, the secondary system with the MF detector suffers more than that with the LMMSE detector when additional primary users are accommodated in the primary system. In Fig. 8, due to the same reason given above, the QoS of the secondary system in terms of outage worsens with both the LMMSE and MF detectors for $K_p = 3$.

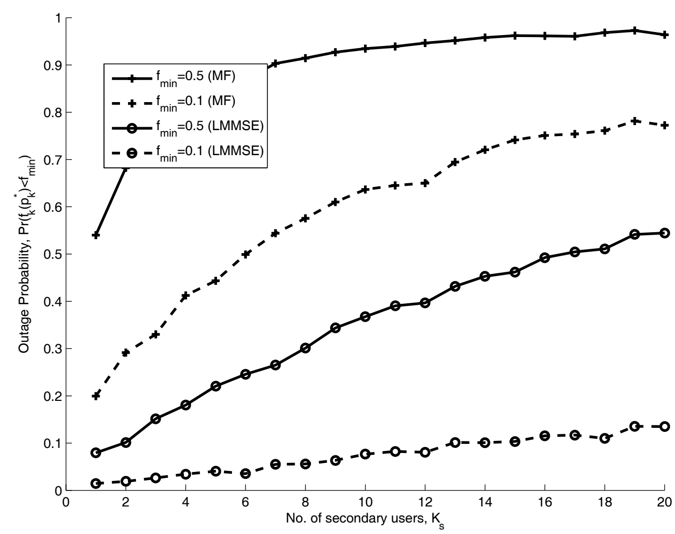
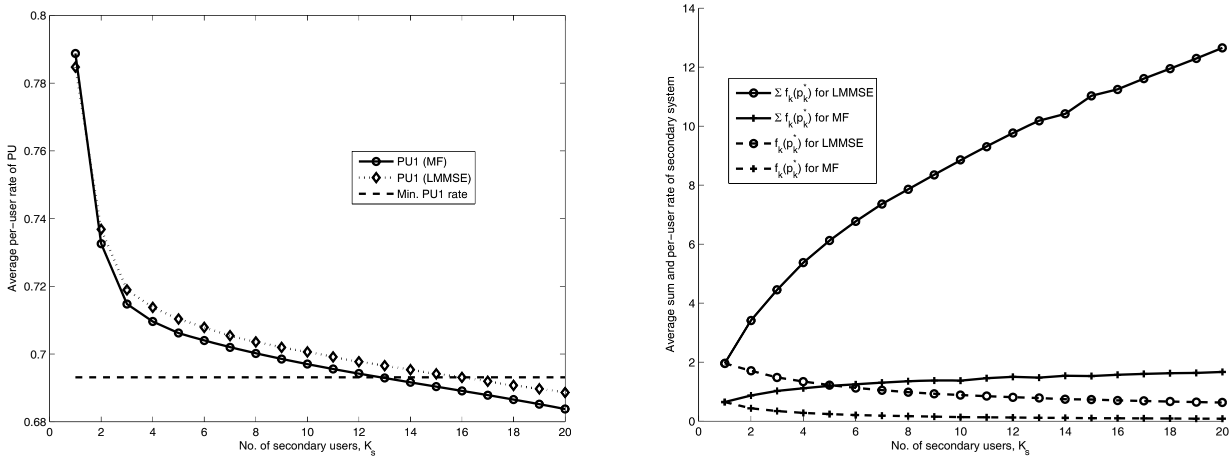


Fig. 8. Outage probability $Pr\left(f_k\left(p_k^*\right) < f_{min}\right)$ of a typical secondary user at the NE of the C-DSL game in fading channels with $K_p = 3$ for a required QoS requirement f_{min}.



(a) (b)

Fig. 7. Primary and secondary rates at the system NE as a function of secondary system size K_s in the presence of channel fading with $K_p = 3$ (a) Average data rate of primary user 1, (b) Average sum-rate and the per-user rate achieved by the secondary system at the NE.

VII. Conclusion

In this paper, we developed a new game-theoretic framework for dynamic spectrum sharing in cognitive radio networks. In contrast to previously proposed hierarchical dynamic spectrum access networks, the proposed *centralized dynamic spectrum leasing* (C-DSL) networks provide an incentive for the primary system (possibly containing multiple primary users) to proactively accommodate secondary spectrum access whenever feasible. In our proposed framework, motivated by the network utility considerations, we further generalized the primary system utility defined in [2], [3] and have introduced a new utility function for the secondary system. We generalized our proposed game to allow for linear multiuser detectors, such as MF and LMMSE receivers at the secondary system. We established the conditions on the existence and uniqueness of the Nash equilibrium. In particular, we have established the general conditions on the primary system reward functions $F(.)$ so as to ensure the existence of a unique Nash equilibrium. We analyzed several examples of C-DSL networks in detail to investigate the proposed system behavior at equilibrium. For such a system, we observed that the proposed C-DSL game leads to a design that determines the maximum number of secondary links based on the required minimum QoS along with the $I_0 \leq Q_0$ criteria. We showed that the secondary system with the LMMSE receiver outperforms that with the MF receiver in terms of both the allowed secondary system size and the outage probability. It is to be noted that the meaning of *best performance* of the proposed C-DSL game may depend on what performance aspect we are interested in. From the secondary system point of view, C-DSL with LMMSE secondary receiver is better since it maximizes the output SINR. However, the primary system utility decreases when the secondary receiver is equipped with the LMMSE detector, which leads to loss in revenue. Hence, from primary perspective LMMSE secondary receiver may not be preferred. We also investigated, through simulations, the robustness of the proposed C-DSL game to slow time-varying fading, and showed that the primary and secondary systems can still successfully coexist at the C-DSL Nash equilibrium. Finally we showed that the proposed C-DSL game performs well even when there are more than one primary users active in the spectrum band of interest.

Appendix A
Existence and Uniqueness of a NE with the Secondary MF Receiver

With the assumed form of action sets $\mathcal{A}_k$, the best response $r_k(\mathbf{a}_{-k})$ is both compact and convex for all $k \in \mathcal{K}_s$. Further, both $u_0(\mathbf{p})$ and $u_k(\mathbf{p})$ are continuous in the action vector $\mathbf{p}$. Let us define a function $\Phi(Q_0)$ as, $\Phi(Q_0) = \frac{F(Q_0)}{F'(Q_0)} + Q_0$. It can be seen that u_0 has a local maximum that is indeed a global maximum if $\Phi(Q_0) = \bar{Q}_0 + I_0(\mathbf{a}_{-0})$ has only one solution for $Q_0 \in \mathcal{Q}$. Clearly this equation has a solution if $\Phi(Q_0)$ is continuous and $\lim_{Q_0 \to 0} \Phi(Q_0) \leq \bar{Q}_0 + I_0(\mathbf{a}_{-0}) < \lim_{Q_0 \to \infty} \Phi(Q_0)$. This solution would be a global maximum if in addition $\Phi'(Q_0) > 0$ for $Q_0 > 0$. It can be easily verified that $\Phi'(Q_0) > 0$ will be true if $F(Q_0)$ is such that $\frac{F(Q_0)F''(Q_0)}{(F'(Q_0))^2} < 2$. Note also that $\lim_{Q_0 \to \infty} \Phi(Q_0) = \infty$ if $\lim_{Q_0 \to \infty} \frac{F(Q_0)}{F'(Q_0)} > -\infty$.

As can be seen from (4), clearly $u_k(\mathbf{a})$ is continuous in $\mathbf{a}$. Next, consider first order derivative of $u_k(p_k) = \frac{W_k \log\left(1+\gamma_k^{MF}\right)}{1+e^{\lambda(I_0-Q_0)}}$ w.r.t. p_k where γ_k^{MF} is given by (6): $\frac{\partial u_k(p_k)}{\partial p_k} = \frac{W e^{c_k p_k} g_k^{MF}(p_k)}{\left(1+\gamma_k^{MF}\right)\left(1+e^{\lambda\left(I_{0,-k}-Q_0\right)} e^{c_k p_k}\right)^2}$, where $c_k = \lambda \tilde{A}_k^2 \geq 0$ and $g_k^{MF}(p_k) = \frac{1}{N_k}\left(e^{-c_k p_k} + e^{\lambda(I_{0,-k}-Q_0)}\right) - c_k e^{\lambda(I_{0,-k}-Q_0)}\left(1+\gamma_k^{MF}\right)\log\left(1+\gamma_k^{MF}\right)$. At an interior local extremum point for $p_k \in [0,\infty)$, we should have $g_k^{MF}(p_k) = \frac{1}{N_k}e^{-c_k p_k} + \frac{1}{N_k}e^{\lambda(I_{p,-k}-Q_0)} - c_k e^{\lambda(I_{0,-k}-Q_0)}\left(1+\gamma_k^{MF}\right)\log\left(1+\gamma_k^{MF}\right) = 0$. Since $g_k^{MF}(0) = \frac{1}{N_k}\left(1+e^{\lambda(I_{0,-k}-Q_0)}\right) > 0$, $g_k^{MF}(\infty) \longrightarrow -\infty$ and $g_k^{MF}(p_k)$ is continuous in p_k, clearly $g_k^{MF}(.)$ must have at least one zero crossing. However, since $g_k^{'MF}(p_k) = -\frac{c_k}{N_k}\left[e^{-c_k p_k} + e^{\lambda(I_{0,-k}-Q_0)}\left(1+\log\left(1+\frac{p_k}{N_k}\right)\right)\right] < 0$ for $p_k \geq 0$, there is exactly one zero of $g_k^{MF}(p_k)$ on

$[0,\infty)$, implying that $u_k(p_k)$ only has one local extremum point on $p_k \in [0,\infty)$. It follows that the local extremum point $p_k = p^*$ is indeed a global maximum of $u_k(.)$ on $[0,\infty)$, implying that $u_k(p_k)$ is quasi-concave in p_k, for each $k \in \mathcal{K}_s$.

From the above discussion it follows that the above game G then has at least one Nash equilibrium due to the well-known result that NE exists in game $G = (\mathcal{K}, \mathcal{A}_k, u_k)$, if for all $k = 0, 1, \cdots, K_s$ (i) $\mathcal{A}_k$ is a non-empty, convex and compact subset of some Euclidean space $\mathbb{R}^N$, (ii) $u_k(\mathbf{p})$ is continuous in action vector $\mathbf{p}$, and (iii) $u_0(Q_0, \mathbf{a}_{-0})$ and $u_k(p_k, \mathbf{a}_{-k})$ are quasi-concave in Q_0 and p_k respectively [20]. ■

APPENDIX B
EXISTENCE AND UNIQUENESS OF A NE WITH THE SECONDARY LMMSE RECEIVER

Since secondary receivers don't influence the behavior of the primary system utility function, the quasi-concavity of the primary system utility function with the LMMSE secondary receiver still holds. Thus for the existence of a NE, the only condition that we need to establish anew is the quasi-concavity of secondary-user utility as a function of its power p_k, when the receiver is based on an LMMSE detector. We consider the first order derivative of $u_k(p_k, \mathbf{a}_{-k}) = \frac{W \log\left(1+\gamma_k^{MMSE}\right)}{1+e^{\lambda(I_0 - Q_0)}}$ w.r.t. p_k, where γ_k^{MMSE} is given by (7): $\frac{\partial}{\partial p_k}\{u_k(p_k)\} = \frac{W e^{c_k p_k} g_k^{MMSE}(p_k)}{\left(1+\gamma_k^{MMSE}\right)\left(1+e^{\lambda(I_{0,-k}(\mathbf{p}_{-k})-Q_0)} e^{c_k p_k}\right)^2}$, where $c_k = \lambda \tilde{A}_k^2 \geq 0$ and $g_k^{MMSE}(p_k) = \frac{h_{kk}^2 \left(\mathbf{s}_k^{(s)}\right)^T \Sigma_{k,k}^{-1} \mathbf{s}_k^{(s)}}{e^{c_k p_k}} + h_{kk}^2 \left(\mathbf{s}_k^{(s)}\right)^T \Sigma_{k,k}^{-1} \mathbf{s}_k^{(s)} e^{\lambda(I_{0,-k}(\mathbf{p}_{-k})-Q_0)} - c_k e^{\lambda(I_{0,-k}(\mathbf{p}_{-k})-Q_0)} \left(1+\gamma_k^{MMSE}\right) \log\left(1+\gamma_k^{MMSE}\right)$. At an interior local extremum point for $p_k \in [0,\infty)$, we should have $g_k^{MMSE}(p_k) = 0$. Since $g_k^{MMSE}(0) = h_{kk}^2 \left(\mathbf{s}_k^{(s)}\right)^T \Sigma_{k,k}^{-1} \mathbf{s}_k^{(s)} \left(1 + e^{\lambda(I_{0,-k}(\mathbf{p}_{-k})-Q_0)}\right) > 0$, $g_k^{MMSE}(\infty) \longrightarrow -\infty$ and $g_k^{MMSE}(p_k)$ is continuous in p_k, function $g_k^{MMSE}(p_k)$ must have at least one zero crossing. However, since

$$g_k^{'MMSE}(p_k) = -c_k h_{kk}^2 \left(\mathbf{s}_k^{(s)}\right)^T \Sigma_{k,k}^{-1} \mathbf{s}_k^{(s)} \left[e^{-c_k p_k} + e^{\lambda(I_{0,-k}(\mathbf{p}_{-k})-Q_0)} \left(1+\gamma_{k,k}^{(s)}\right)\right] < 0$$

for $p_k \geq 0$), there is exactly one zero of $g_{j,k}(p_k)$ on $[0,\infty)$, implying that $u_k(p_k)$ only has one local extremum point on $p_k \in [0,\infty)$. Similar to the argument given in Appendix A, it follows that $u_k(p_k)$ is indeed quasi-concave in p_k, for each $k \in \mathcal{K}_s$. Hence the C-DSL game has at least one Nash equilibrium due to the well known result of Debreu, Glicksberg and Fan [20].

To establish the uniqueness of the NE of the proposed C-DSL game with secondary LMMSE receiver, we show that the best response correspondence $r_k(\mathbf{a}_{-k})$ is a *standard function* for $k = 0, 1, \cdots, K_s$ [16]. For simplicity of exposition, below we assume $\bar{Q}_0 \longrightarrow \infty$ and $\bar{p}_k \longrightarrow \infty$. We adopt the convention that all the vector inequalities are component-wise.

1) Primary system best response: For $F(Q_0) = \log(1 + Q_0)$, the unique interior maximum of u_0 is given by

$$Q_0^* + (1+Q_0^*)\log(1+Q_0^*) = \left(\bar{Q}_0 + I_0\right). \quad (10)$$

Since $u_0(Q_0)$ is monotonic increasing for $Q_0 < Q_0^*$, if the maximum interference cap is such that $\bar{Q}_0 < Q_0^*$, the best response is given by $r_0(\mathbf{a}_{-0}) = \min\{\bar{Q}_0, Q_0^*(I_0)\}$.

I. *Positivity*: From (10), for $\mathbf{a}_{-0} = \mathbf{0}$, $Q_{0min}^* > 0$. So $r_0(\mathbf{a}_{-0}) > 0$ for $\mathbf{a}_{-0} \geq \mathbf{0}$.

II. *Monotonicity*: Since the left and the right hand side of (10) are increasing functions of Q_0 and $\mathbf{a}_{-0}$, respectively, given $\mathbf{a}_{-0} \geq \mathbf{a}'_{-0}$, $r_0(\mathbf{a}_{-0}) \geq r_0(\mathbf{a}'_{-0})$.

III. *Scalability*: From (10), $Q_0^*(I_0)$ is concave in I_0 since $\frac{d^2 Q_0^*}{dI_0^2} = \frac{-1}{(1+Q_0^*)\left(2+\log(1+Q_0^*)\right)^3} < 0$ for $Q_0^* \geq 0$. It can be easily seen that positivity and concavity of $Q_0^*(I_0)$ together implies scalability. So for $\mu > 1$, we have $\mu r_0(\mathbf{a}_{-0}) > r_0(\mu \mathbf{a}_{-0})$.

Therefore, by Definition 3, the best response correspondence of the primary system is a standard function.

2) Secondary links' best response: The best response correspondence of the k-th secondary link is the transmit power which provides it with the optimum SINR γ^{MMSE^*} given by the solution p_k to the equation $g_k^{MMSE}(p_k) = 0$. Thus the best response correspondence of the k-th secondary link is $r_k(\mathbf{a}_{-k}) = \min\left\{\frac{\gamma^{MMSE^*} I_k^{(k)}}{h_{kk}^2}, \bar{p}_k\right\}$, where $I_k^{(k)} = \left[\left(\mathbf{s}_k^{(s)}\right)^T \Sigma_{k,k}^{-1} \mathbf{s}_k^{(s)}\right]^{-1}$. Since $\frac{\partial \gamma_k^{MMSE}(p_k)}{\partial p_k} = \frac{\gamma_k^{MMSE}}{p_k}$, maximizing the utility function for each user is equivalent to finding optimum SINR γ^{MMSE*}. Note also that γ^{MMSE^*} is independent of k as long as all secondary users have the same reward function.

I. *Positivity*: Since $\gamma^{MMSE^*} > 0$ and $I_k^{(k)} > 0$, the best response correspondence of the k-th secondary link $r_k(\mathbf{a}_{-k}) > 0$ for all $k \in \mathcal{K}_s$.

II. *Monotonicity*: By following a proof similar to [1], we have that for $\mathbf{a}_{-k} \geq \mathbf{a}'_{-k}$, $I_k^{(k)}(\mathbf{a}_{-k}) > I_k^{(k)}(\mathbf{a}'_{-k})$. Thus $r_k(\mathbf{a}_{-k}) = \frac{\gamma^{MMSE^*} I_k^{(k)}(\mathbf{a}_{-k})}{h_{kk}^2} \geq \frac{\gamma^{MMSE^*} I_k^{(k)}(\mathbf{a}'_{-k})}{h_{kk}^2} = r_k(\mathbf{a}'_{-k})$, for all $k \in \mathcal{K}_s$.

III. *Scalability*: For $\mu > 1$, $\mu r_k(\mathbf{a}_{-k}) = \frac{\mu \gamma^{MMSE^*} I_k^{(k)}(\mathbf{a}_{-k})}{h_{kk}^2}$ and $r_k(\mu \mathbf{a}_{-k}) = \frac{\gamma^{MMSE^*} I_k^{(k)}(\mu \mathbf{a}_{-k})}{h_{kk}^2}$. Similar to the proof given in [1], we have that $\mu I_k^{(k)}(\mathbf{a}_{-k}) > I_k^{(k)}(\mu \mathbf{a}_{-k})$. Hence, $\mu r_k(\mathbf{a}_{-k}) > r_k(\mu \mathbf{a}_{-k})$, for all $k \in \mathcal{K}_s$.

So, the noncooperative C-DSL game with secondary LMMSE receiver has a unique NE. ■

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Kamrul Hakim (S'06) received his B.Sc. degree in Electrical and Electronic Engineering from Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh in 2005 and M.Sc. degree in Electrical Engineering from The Pennsylvania State University - University Park, USA in 2008. He is currently working towards his Ph.D. degree at the Communication and Information Sciences Laboratory (CISL), Department of Electrical and Computer Engineering at the University of New Mexico, Albuquerque, NM, USA. His research interests focus on collaborative and distributed information processing in wireless sensor networks, cognitive radios, dynamic spectrum leasing and applications of game theory.

Sudharman K. Jayaweera (S'00, M'04, SM'09) received the B.E. degree in Electrical and Electronic Engineering with First Class Honors from the University of Melbourne, Australia, in 1997 and M.A. and PhD degrees in Electrical Engineering from Princeton University in 2001 and 2003, respectively. He is currently an assistant Professor in Electrical Engineering at the Department of Electrical and Computer Engineering at University of New Mexico, Albuquerque, NM. From 2003-2006 he was an assistant Professor in Electrical Engineering at the Department of Electrical and Computer Engineering at Wichita State University. Dr. Jayaweera is currently an associate editor of *EURASIP Journal on Advances in Signal Processing*. His current research interests include cooperative and cognitive communications, information theory of networked control systems, statistical signal processing and wireless sensor networks.

Georges El-howayek (S'06) received his B.E. degree in Electrical and Electronic Engineering with minor degree in Mathematics from Lebanese American University (LAU), Byblos, Lebanon in 2008 with distinction. He is currently working towards his Ph.D. degree at the Communication and Information Sciences Laboratory (CISL), Department of Electrical and Computer Engineering at the University of New Mexico, Albuquerque, NM, USA. His research interests focus on communication theory, wireless communications, information theory, cognitive radios, cooperative communications, dynamic spectrum leasing (DSL) and applications of game theory.

Carlos Mosquera (S'93-M'98) received the M.Sc. degree in electrical engineering from Stanford University, Stanford, CA, in 1994 and the Ph.D. degree in electrical engineering from the University of Vigo, Vigo, Spain, in 1998. He has been Associate Professor at the University of Vigo since 2000. He held visiting positions with the European Space Agency (1999) and the University of New Mexico (2007), respectively. He holds four patents in collaboration with industry, and has coauthored over 20 journal papers and two books. He has been the principal investigator of a number of national and European projects and research contracts, and has been member of several international technical program committees. He is currently the Research director of Gradiant (Galician Research and Development Center in Advanced Telecommunications) in digital communications.