Interference-Aware Power Control for Cognitive Radio Networks

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***Abstract*— The deployment of cognitive radio networks is a means of allowing for efficient spectrum sharing and opportunistic spectrum access. It presents new challenges to the classical problem of interference management in wireless networks. Dynamic power allocation is an essential feature in cognitive radio that has been under-explored in comparison to power control in cellular networks. We first develop a framework based on four goals of power allocation in cognitive radio: QoS protection to primary users, opportunism to secondary users, admissibility to secondary users, and autonomous operation by individual users. Through theoretical analysis and simulation, we show that an autonomous interference-aware power control algorithm can address these goals.**

I. Introduction

THE notion that spectrum is a scarce and diminishing commodity has been derived from static frequency allocations that are being increasingly labeled as outdated. The under-utilization of spectrum is continuously being documented in works on cognitive radio. This is the driving force behind research on efficient techniques for spectrum management. The deployment of cognitive radios to combat the under-utilization of spectrum brings forth interesting issues in radio resource management. The cognitive radio concept relies upon users deploying intelligent protocols so as to be aware of their environment and adapt to its variations. It's certainly conceivable that the continuous advances in software-defined radios will make such user agility a reality. An insightful survey of the taxonomy of spectrum access models for cognitive radio networks is given in [1]. Under the shared-use of primary licensed spectrum taxonomy, licensed devices deemed primary users share the spectrum with non-license holders referred to as secondary users. The spectrum sharing is contingent upon the transmissions of secondary users having minimal impact on the operating conditions for which primary user devices are designed. Ideally a secondary network should operate in the background of the primary network, with the primary network users' QoS being oblivious to the presence of the secondary users.

The majority of established power control works have focused on devising policies for users in cellular networks were the fulfillment of a QoS constraint is a premium. Thus, transmitters shall increase power to cope with channel impairments and interference. Within the spectrum sharing framework, a network will strongly oppose of secondary users transmitting with arbitrarily high power and interfering with the QoS of the primary users. Such intrusion clearly violates the sense of the primary users' QoS being oblivious to the presence of the secondary users. In [2] Haykin introduces and advocates the notion of interference temperature as being critical in decision making within a cognitive radio network. It appears natural that power allocation decisions should rely on interference levels. What is not as obvious is the differing dynamics of primary network users and secondary network users in response to their respective perceived interference levels. In this work we shall discuss the applicability of an interference-aware power control policy for users in a cognitive network paradigm.

Due to the existence of two classes of users, primary and secondary, the traditional problem of interference management through power control is different than that of cellular systems or ad hoc networks. This paper discusses four attributes that are deemed as being necessary for a power control policy deployed in a cognitive radio network: QoS protection to primary users, opportunism to secondary users, admissibility to secondary users, and autonomous operation by individual users.

Subsequently, we investigate the use of an Autonomous Interference-aware Power Control (AIPC) algorithm in addressing all four attributes for a cognitive radio network. We show that the AIPC algorithm can protect primary users from the entrance of secondary users, provide opportunism to secondary users, and prevent the most adverse types of admission errors. Both theoretical analysis and simulation results are presented. The remainder of this paper is organized as follows. In Section II a system model of wireless users in a cognitive radio network is considered. A discussion of several attributes which we deem as being essential of any power control policy deployed by users in a cognitive radio network is provided in Section III. This is followed by a description of the AIPC policy. Section IV includes the main results on how the AIPC policy allows for etiquette to be imposed among autonomous users in a cognitive radio network. Simulation results illustrating the dynamics of AIPC when deployed for primary and secondary users are provided in Section V.

II. System Model

We model a cognitive radio network consisting of primary and secondary users as a multiple access wireless system with a collection of transmitters and receivers. Depending on the deployed architecture the transmitters or the receivers can be

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co-located. Alternatively, the network may consist of a collection of radio links with neither the transmitters or receivers being co-located. In such a scenario the network is a collection of separate radio links in space. The dispersive nature of the wireless channel is modeled by the multiplicative link gains $\{G_{ij}(k)\}$, with $G_{ij}(k)$ denoting the attenuation from the jth user's transmitted signal to the ith user's intended receiver. In effect, $G_{ij}(k)$ determines the interference contributed by the jth user's presence to the signal of user i at time k. Although not crucial for our formulation, the link gains will be assumed as being fixed for the duration of the convergence of the power control algorithm. This indicates that the fading rate of the channel is slow in comparison to the rate at which power updates are performed.

A wireless user's signal-to-interference ratio (SIR) constitutes the user's QoS. At time k, the SIR of the ith network user is defined as

$$\mathrm{SIR}_i(k) = \frac{P_i(k)G_{ii}}{\sum_{j\neq i} P_j(k)G_{ij} + \eta_i} = \frac{P_i(k)G_{ii}}{I_{-i}(k)} \tag{1}$$

with η_i denoting the thermal noise power at the ith user's intended receiver. The ith user's perceived interference, and aggregate interference are defined as

$$I_{-i}(k) = \sum_{j\neq i} P_j(k)G_{ij} + \eta_i \tag{2}$$

and

$$I_i(k) = \sum_{j} P_j(k)G_{ij} \; + \; \eta_i = I_{-i}(k) + P_i(k)G_{ii}, \tag{3}$$

respectively. The subscript "$-i$" denotes the absence of the ith user's signal. The ith user has a desired QoS as characterized by a target SIR value of SIR_i^{tar}. The ith user's instantaneous SIR error

$$E_i(k) = \mathrm{SIR}_i^{tar} - \mathrm{SIR}_i(k) \tag{4}$$

is viewed as a QoS measure, since it indicates the deviation between a user's attained performance and desired (i.e. target) performance.

We shall restrict attention to the cognitive network model of Fig. 1, which effectively represents the network as a collection of transmitter and receiver pairs. This model is applicable to the scenario of the primary users comprising the downlink (respectively, uplink) of a cellular system in which case the primary users' transmitters (receivers) would be co-located. Figure 1 would also apply to the scenario of the primary users' and secondary users' receivers (transmitters) being co-located. An example of this would be if both the secondary and primary users are doing a file upload (download) through a common sink (source). Note that even for geographically co-located transmitters or receivers, different link gains will be seen if the transmission or reception is achieved via distinct antenna elements. We shall restrict attention to all users using the same piece of spectrum at a given time instant.

Thus far we have not distinguished between primary users and secondary users. We seek a power control algorithm that will enable the network the flexibility to decide whether a user has a primary or a secondary application, and adopt the concept of a local spectrum server (LSS) as a mediating entity among autonomous secondary network users. The incorporation of such an entity as a means of regulating the admission of and priority level of secondary users has been motivated by works such as [5] [6] [7] [8]. We adhere to the LSS concept here and acknowledge that it is most applicable to a licensed spectrum system. Although the LSS will essentially mediate the sharing of spectrum among the secondary users; the LSS will not have the capability to control the actions of the individual users. The users shall thus operate in an autonomous manner.

III. Power Control for Cognitive Radio

A. Framework

Spectrum sharing can lead to vast improvements in spectral efficiency over exclusive access where the spectrum may be idle for long durations due to two primary phenomenons:

- The dormancy of primary users.
- The relative immunity of primary users to secondary user interference due to the close proximity of the primary users to their respective receivers.

It is challenging to devise a power control technique which allows primary users' to satisfy strict QoS requirements, and yet is flexible enough to accommodate secondary users' opportunistic communication. We list several essential attributes for a power control technique for cognitive radio:

- <u>QoS Protection</u>: Primary users will maintain a target SIR irrespective of how many secondary users enter the network and transmit in the same spectrum. The secondary users' interference level must be sufficiently low so as to not disrupt the primary users' applications.
- <u>Opportunism</u>: If a primary user leaves the network, the secondary users will witness an improvement in QoS while the remaining primary users still maintain their target QoS.

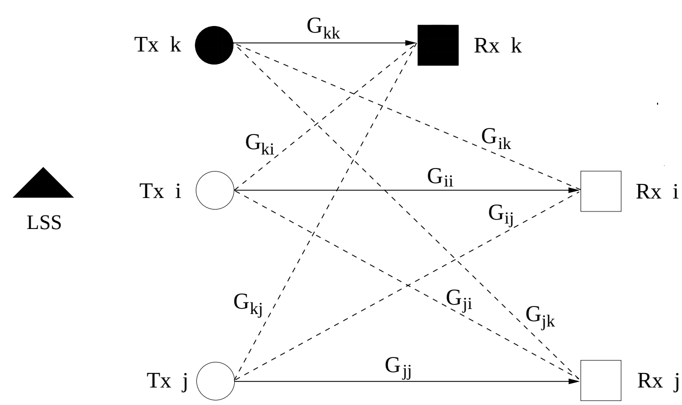

Fig. 1. Model of a cognitive network with transmitter and receiver pairs i and j constituting two primary users, and transmitter and receiver pair k constituting a secondary user. Each link gain is written above the corresponding link with the solid lines denoting intended transmissions and the dashed lines denoting unintended interference among a set of users accessing the same spectrum.

- <u>Admissibility</u>: The power allocation policy allows for a means of dictating the admission of a secondary user into

the network. An arbitrarily number of secondary users should be allowed access to the spectrum so long as their entrance solely deters the QoS of other secondary users.
- Autonomous Operation: The power control technique allows for asynchronous operation with transmitters having access to only local information consisting of the link gain to an intended receiver and the perceived interference. A transmitter would obtain the local information via feedback from its intended receiver.

We list two attributes which we deem as being more elegant than critical:

- Licensing: Forcing a user to transmit with power level of zero is a means of essentially denying a user network access. It would be desirable if the power control policy deployed by a user would autonomously know when that user should be dormant. In essence, we would like a policy in which a LSS can exercise control in assigning priorities to the applications of various users.
- Versatility: The policy should be flexible enough so as to be deployed by all users in the network, whether primary or secondary.

These attributes will be discussed further in Section IV within the context of the AIPC algorithm.

B. *Overview of the AIPC Policy*

The AIPC policy was presented[1] in [9] within the context of a multiple access wireless network. We shall provide an overview of the AIPC algorithm in prelude to a discussion on how the AIPC attempts to address the above attributes.

In correspondence to an interference-based power control ideology, the ith user will dynamically adapt power in response to its perceived interference via

$$P_i(k+1) = P_i(k) + \alpha_i(k) I_{-i}(k), \tag{5}$$

with the gain $\alpha_i(k)$ parameterizing the increase/decrease in transmit power. With AIPC the optimal gain is given by

$$\begin{aligned}\alpha_i^*(k) &= \left[\frac{1}{I_{-i}(k)G_{ii}(1+\rho_i I_{-i}^2(k+1))}\right]\left[\rho_i I_{-i}^2(k+1)\right.\\ &\times \quad (-P_i(k)G_{ii} - I_{-i}(k+1)) + \mathrm{SIR}_i^{tar} I_{-i}(k+1)\\ &- \quad \left.\mathrm{SIR}_i(k) I_{-i}(k)\right]\end{aligned} \tag{6}$$

so as to minimize the convex cost function

$$J_i(k) = \rho_{i1}E_i^2(k+1) + \rho_{i2}I_i^2(k+1) \tag{7}$$

with $\rho_i \triangleq \rho_{i2}/\rho_{i1}$ in (6) and (7). The motivation behind (7) stems from an autonomous user adapting power so as to minimize cost. The SIR deviation alone is a cost which may be minimized by not transmitting with more power than that necessary for meeting the target SIR. The interference term constitutes an additional cost, or penalty, meant to inhibit the user from achieving a desired QoS with arbitrarily high energy expenditure. The positive weights ρ_{i1} and ρ_{i2} dictate the priority given to the fulfillment of a QoS requirement and controlling the level of network interference, respectively. The optimal power update $P_i^*(k+1) = P_i(k) + \alpha_i^*(k)I_{-i}(k)$ with $\alpha_i^*(k) = \arg\min_{\alpha_i(k)}\{J_i(k)\}$ can be performed in a distributive manner since a transmitter only requires local information pertaining to its perceived interference and the link gain to its intended receiver.

The computation of $\alpha_i^*(k)$ requires knowledge of the current (estimated), and the next-step (predicted) values for the perceived interference. In general a user may devise any estimator to autonomously calculate such quantities when provided with feedback from it's intended receiver. Within the context of power control, the benefits of predictive policies in providing improved robustness and convergence speed were initially motivated by [11] [12].

Let k^{ss} denote the time instant at which the power control algorithm has converged with the powers having reached their steady-state values. At the convergence of the AIPC algorithm the ith user will have attained a modified target SIR of $\widetilde{\mathrm{SIR}}_i^{tar} \triangleq \beta_i \mathrm{SIR}_i^{tar}$, with

$$\beta_i = \max\left\{0, \frac{\mathrm{SIR}_i^{tar} - \rho_i I_{-i}^2(k^{ss})}{\mathrm{SIR}_i^{tar}(1+\rho_i I_{-i}^2(k^{ss}))}\right\} \in [0,1]. \tag{8}$$

Note that $\widetilde{\mathrm{SIR}}_i^{tar} \leq \mathrm{SIR}_i^{tar}$ with equality holding for $\rho_i = 0$ (in which case $\beta_i = 1$). For the remainder of this presentation we shall suppress the time index k on dynamic parameters such as power and interference when referring to steady-state values obtained upon the convergence of the power control policy (i.e. when $k = k^{ss}$).

The following two propositions are critical in illustrating the utility of AIPC as far as the differentiation between a primary and a secondary user.

Proposition 1: In the case of $\rho_i = 0$ the AIPC policy reduces to that of the Foschini-Miljanic algorithm. Thus the ith user would have a hard target SIR constraint of SIR_i^{tar}. Such user will adapt power with the sole purpose of satisfying its SIR constraint irrespective of the amount of interference in the network.

Proof: From (5)-(7) it can be readily verified that in the case of $\rho_i = 0$ the AIPC power update and objective function reduce to $P_i^*(k+1) = \mathrm{SIR}_i^{tar} I_{-i}(k+1)/G_{ii}$ and $J_i(k) = \rho_{i1}E_i^2(k+1)$, respectively. We note that the objective function $J_i(k) = \rho_{i1}E_i^2(k+1)$ requires that the ith user satisfy it's target SIR with equality irrespective of perceived interference or transmit power. The Foschini-Miljanic policy also requires that a user satisfy it's target SIR with equality irrespective of perceived interference or transmit power. Furthermore, the power update with the Foschini-Miljanic algorithm is $P_i(k+1) = SIR_i^{tar} I_{-i}(k)/G_{ii}$. Thus we conclude that in the scenario of $\rho_i = 0$ the AIPC reduces to a predictive version of the Foschini-Miljanic algorithm. ■

Proposition 2: In the case of $\rho_i > 0$ the ith user will seek a soft target SIR constraint of $\widetilde{\mathrm{SIR}}_i^{tar}$. In effect, the user will attain a modified target QoS of $\widetilde{\mathrm{SIR}}_i^{tar} < \mathrm{SIR}_i^{tar}$ with $\widetilde{\mathrm{SIR}}_i^{tar}$ decreasing with interference.

Proof: We note from (8) that for $\rho_i > 0$ we shall have $\beta_i < 1$. A decrease in a secondary users target SIR with an increase in perceived interference is asserted via $\partial\beta_i/\partial I_{-i} = -2\rho_i I_{-i}(1+\mathrm{SIR}_i^{tar})/\mathrm{SIR}_i^{tar}(1+\rho_i I_{-i}^2)^2 < 0.$

[1] An earlier description of AIPC can be found in the conference paper [10].

■

The next result provides a game-theoretic interpretation of the power allocation attained with AIPC.

Theorem 1: Upon the convergence of the AIPC policy the transmit powers of the N network users will reach a unique Nash equilibrium. Furthermore, the network users will attain iterative convergence to the unique fixed point with asynchronous power updates and outdated information pertaining to the interference caused by other users.

Proof: The proof is presented in the appendix because it requires notation and definitions discussed in Section IV.A. ■

The fact that AIPC allows the network users to attain iterative convergence to the unique fixed point $\mathbf{p}^*$ in asynchronous fashion with outdated information on the interference caused by other users is essential. This is because within the cognitive network paradigm users will be autonomous with primary and secondary network users potentially operating on vastly different time scales.

The so-called *opt-out* scenario of the AIPC policy warrants attention as we shall refer to it within the context of a secondary user in the following sections. It was shown in Corollary 1 of [AIPC paper] that the ith user with $\rho_i > 0$ and $P_i^{min} < P_i(k)$ will transmit with a minimum allowable power level[2] of P_i^{min} at time $k+1$ if

$$I_{-i}(k) > \max\left\{ \frac{P_i^{min} - P_i(k)}{\alpha_i^*(k)},\ \frac{\mathrm{SIR}_i^{tar} I_{-i}(k+1)}{\mathrm{SIR}_i(k)} \right. \\ \left. - \frac{\rho_i I_{-i}^2(k+1)\,(P_i(k)\,G_{ii} + I_{-i}(k+1))}{\mathrm{SIR}_i(k)} \right\}. \tag{9}$$

This indicates that a (secondary) user whose perceived interference exceeds a certain threshold will autonomously *opt-out* and transmit with minimum power. Similarly, upon the convergence of the AIPC policy, a user with

$$I_{-i} \geq \sqrt{\frac{\mathrm{SIR}_i^{tar}}{\rho_i}} \tag{10}$$

would be transmitting with a minimal power level of P_i^{min}. Inspection of (9) and (10) reveals the threshold by which a bad channel is defined as being heavily dependent on the value of ρ_i. In fact, the decrease of the "bad-channel threshold" value with increasing ρ_i, indicates a lower interference tolerance level before the ith user decides to opt-out.

IV. Etiquette Design via Interference-Aware Power Control

Etiquette refers to a collection of technical rules of operation. A discussion of how the AIPC policy allows for etiquette to be imposed in part by the LSS and in part by the autonomous users is vital. In [9] the terms user-centric, network-centric, greedy, and energy efficient were discussed within the context of autonomous power control. We avoid reference to such terms from here on since the context is quite different, and aim to critique the utility of the AIPC policy in addressing the four essential and two desirable attributes discussed in the previous section.

A. QoS Protection

Traditional methods for radio resource management have focused on ensuring the QoS of users rather than prioritizing their performance within a heterogeneous environment. Naturally, the primary users should maintain their target SIR values irrespective of the secondary users. Conversely, the performance of the secondary users should be contingent on the parameters of the primary users. We argue that such dependence should stem from the opportunistic nature of the secondary users and will make the secondary users' QoS variable over their lifetime. Thus we present an optimization problem for which the primary users have hard (i.e. stringent) QoS requirements and the secondary users have soft QoS requirements. From hereon we shall designate users with indices from the set $\mathsf{P} = \{1, 2, \ldots, N\}$ as primary users, and users with indices from the set $\mathsf{S} = \{N+1, N+2, \ldots, N+M\}$ as secondary users. With $N = |\mathsf{P}|$ and $M = |\mathsf{S}|$ the optimization problem may be presented as

$$\begin{aligned} \text{minimize} \quad & \sum_{i=1}^{N+M} P_i \\ \text{subject to} \quad & \mathrm{SIR}_i^{tar} \leq \frac{P_i G_{ii}}{\sum_{j\neq i} P_j G_{ij} + \eta_i} \qquad i \in \mathsf{P} \\ & \widetilde{\mathrm{SIR}}_i^{tar} \leq \frac{P_i G_{ii}}{\sum_{j\neq i} P_j G_{ij} + \eta_i} \qquad i \in \mathsf{S} \end{aligned} \tag{11}$$

and represented in matrix form via[3] $(\mathbf{I} - \mathbf{BA})\mathbf{p} \geq \mathbf{Bb}$ where the vector $\mathbf{p} = [P_1, P_2, \ldots, P_{N+M}]^T$ denotes the transmit powers of the users upon convergence of the power control algorithm. The entries of the matrix $\mathbf{A}$ are specified as

$$A(i,j) = \begin{cases} 0 & \text{if} \quad i = j \\ \frac{\mathrm{SIR}_i^{tar} G_{ij}}{G_{ii}} & \text{otherwise} \end{cases} \tag{12}$$

with $i, j \in \mathsf{P} \cup \mathsf{S}$, $\mathbf{b} = \left[\frac{\mathrm{SIR}_1^{tar}\eta_1}{G_{11}}, \frac{\mathrm{SIR}_2^{tar}\eta_2}{G_{22}}, \ldots, \frac{\mathrm{SIR}_{N+M}^{tar}\eta_{N+M}}{G_{N+M\,N+M}}\right]^T$, and $\mathbf{B} = \mathrm{diag}(\beta_1, \beta_2, \ldots, \beta_{N+M})$. In the case of $i \in \mathsf{P}$ we shall assign $\rho_i = 0$ and have $\beta_i = 1$ from (8). When $(\mathbf{I} - \mathbf{BA})^{-1} > \mathbf{0}$ exists, the problem given by (13) is deemed as being *feasible* in the power control literature with $\mathbf{p}^* = (\mathbf{I} - \mathbf{BA})^{-1}\mathbf{Bb}$ being the Pareto optimal solution. The Pareto optimality condition states that for any power vector $\mathbf{p}'$ satisfying (13), $\mathbf{p}^* \leq \mathbf{p}'$. It is well known that if the system is infeasible then every user will keep increasing its transmit power indefinitely while never satisfying its SIR constraint.

Theorem 2: Let $\mathbf{x} \geq 0$ and $\mathbf{x} \neq 0$. If the network consists of N primary users, and is feasible, then we must have

$$\max_{\mathbf{x}\geq 0, \mathbf{x}\neq 0} \ \min_{1\leq i\leq N, x_i\neq 0} \left\{ \frac{1}{x_i} \sum_{j=1}^{N} A(i,j) x_j \right\} < 1\,. \tag{13}$$

[2]It will be presumed that $P_i^{min} = 0$ mW for the duration of this presentation.

[3]We adopt the convention that the matrix inequality $\mathbf{X}_1 \geq \mathbf{X}_2$ or the vector inequality $\mathbf{x}_1 \geq \mathbf{x}_2$ denotes inequality in all components.

Conversely, if the network consist of only primary users and the above condition holds, then the network is feasible.

Proof: As previously stated, (13) can be written as $(\mathbf{I}-\mathbf{BA})\mathbf{p} \geq \mathbf{Bb}$. Since all network users are primary users we have $\mathbf{B}=\mathbf{I}$. The left hand side of (13) is equivalent to $\rho(\mathbf{A})$ with $\rho(.)$ denoting the Perron-Frobenius eigenvalue. The fact that $\rho(\mathbf{BA})<1$ is a necessary and sufficient condition for the existence of the matrix $(\mathbf{I}-\mathbf{BA})^{-1}>\mathbf{0}$ and the solution $\mathbf{p}^*=(\mathbf{I}-\mathbf{BA})^{-1}\mathbf{Bb}$ is documented in [16]. ■

It was shown in [9] that for a feasible system with $\rho_i=0\forall i$ (thus $\mathbf{B}=\mathbf{I}$), the transmit powers would converge to $\mathbf{p}^*$ with each user dynamically updating transmit power via (5) with $\alpha_i^*(k)$ given by (6). For the remainder of the paper the network of N primary users will be assumed to be feasible.

Corollary 1: Consider a feasible network consisting of N primary users. With users adapting power according to the AIPC policy, the same network consisting of N primary users and M secondary users will be feasible.

Proof: The resulting network consisting of N primary users and M secondary users will be feasible iff

$$\max_{\mathbf{x}\geq 0,\mathbf{x}\neq 0}\ \min_{1\leq i\leq N+M, x_i\neq 0}\left\{\frac{1}{x_i}\sum_{j=1}^{N+M}\beta_i A(i,j)x_j\right\} < 1 \tag{14}$$

or equivalently

$$\max_{\mathbf{x}\geq 0,\mathbf{x}\neq 0}\ \min_{1\leq i\leq N+M, x_i\neq 0}\left\{\frac{1}{x_i}\sum_{j=1}^{N}A(i,j)x_j + \frac{1}{x_i}\sum_{j=N+1}^{N+M}\beta_i A(i,j)x_j\right\} < 1 \tag{15}$$

since $\beta_i=1$ for the primary users. If (15) does not hold then all the primary users will keep increasing their transmit powers. We note that $\partial\beta_i/\partial I_{-i} = -2\rho_i I_{-i}(1+\mathrm{SIR}_i^{tar})/\mathrm{SIR}_i^{tar}(1+\rho_i I_{-i}^2)^2<0$ thus stating a decrease in a secondary user's target SIR with an increase in perceived interference. Hence, the primary users will continue increasing their transmit powers and the secondary users will continue to decrease $\beta_i : i\in\mathsf{S}$ until a feasible equilibrium point $\mathbf{p}^*$ is reached. This will continue until $\mathsf{r}=|\mathsf{R}|$ secondary users from the set $\mathsf{R}\subseteq\oslash\cup\mathsf{S}$ opt-out and transmit with minimal allowable power $\{P_i^{min}: i\in\mathsf{R}\}$ due to their interference threshold being surpassed. With the network being feasible, the secondary users achieve a modified target SIR of $\widetilde{\mathrm{SIR}}_i^{tar}\leq\mathrm{SIR}_i^{tar} : i\in\mathsf{S}$ while the primary users attain their target SIR of $\mathrm{SIR}_i^{tar}: i\in\mathsf{P}$. ■

A claim of QoS protection would require an investigation of the primary users' performance upon the entrance of secondary users into the network. Although we would expect the performance of secondary users to be deterred by the entrance of additional secondary users; a deterioration of the primary users' QoS would violate the notion of QoS protection.

Theorem 3: With the AIPC policy the entrance of secondary users will only adversely affect the QoS of other secondary users sharing the same spectrum. The resulting system will remain feasible with the QoS of the primary users undeterred.

Proof: The result follows readily from Corollary 1. Consider L secondary users with indices from the set $\mathsf{V}=\{N+M+1, N+M+2,\ldots,N+M+L\}$ being admitted to a feasible network consisting of N primary users and M secondary users. The N primary users have a QoS of $\mathrm{SIR}_i^{tar}: i\in\mathsf{P}$ while the M secondary users have a QoS of $\widetilde{\mathrm{SIR}}_i^{tar}: i\in\mathsf{S}$ prior to the admission of the L secondary users. After the entrance of the L secondary users the resultant network will be feasible iff

$$\max_{\mathbf{x}\geq 0,\mathbf{x}\neq 0}\ \min_{1\leq i\leq N+M+L, x_i\neq 0}\left\{\frac{1}{x_i}\sum_{j=1}^{N}A(i,j)x_j + \frac{1}{x_i}\sum_{j=N+1}^{N+M+L}\beta_i A(i,j)x_j\right\} < 1. \tag{16}$$

The primary users will still meet their target SIR values albeit with increased transmit powers. The M previously existing secondary users will now experience a QoS of $\underline{\mathrm{SIR}}_i^{tar}: i\in\mathsf{S}$ where $\underline{\mathrm{SIR}}_i^{tar}<\widetilde{\mathrm{SIR}}_i^{tar}$. The L recently admitted secondary users will have a QoS of $\widetilde{\mathrm{SIR}}_i^{tar}: i\in\mathsf{V}$ with $\widetilde{\mathrm{SIR}}_i^{tar}<\mathrm{SIR}_i^{tar}$. If (16) does not hold then all the primary users will keep increasing their transmit powers. This will continue until $1\leq\mathsf{r}\leq M+L$ of the secondary users will see their interference threshold being exceeded. With AIPC, the $\mathsf{r}=|\mathsf{R}|$ secondary users constructing the set $\mathsf{R}\subseteq\oslash\cup\mathsf{S}\cup\mathsf{V}$ will opt-out and transmit with minimal allowable power $\{P_i^{min}: i\in\mathsf{R}\}$. A resultant feasible system consisting of N primary users and $M+L-\mathsf{r}$ secondary users will be attained. The $M+L-\mathsf{r}$ secondary users constructing the set R^c may consist of any combination of secondary users from the sets S and V. In the special scenario that all of the L admitted secondary users opt-out we shall have $\mathsf{r}=L$ and $\mathsf{R}=\mathsf{V}$ with the network returning to its original feasible point prior to the admission of the L secondary users. ■

Although the above result assures the primary users' attained SIR will be unaffected by the presence of secondary users, there is a consequence to admitting a secondary user. The admission of each secondary user will increase the transmit power of every primary user. A resultant increase in energy expenditure and battery drain is inevitable. There is also an interesting notion regarding the possible protection[4] of secondary users. We shall elaborate on the LSS's role in addressing these two issues in the upcoming discussion on admissibility.

B. *Opportunism*

A formidable challenge in etiquette design for cognitive radio is providing an effective means for opportunistic spectrum access by secondary network users. Upon the dormancy of a primary user, it would be desirable that the remainder of the primary users maintain desired QoS, while the secondary users power control allow them to see improved performance in autonomous fashion. The degree of opportunism offered by AIPC is best illustrated by considering the network dynamics when primary users becomes dormant. In such a scenario a non-opportunistic power control policy would order a secondary user to continue fulfilling it's static target SIR while

[4]By protection in this case we mean protection from having to opt out, rather than protecting their QoS, which in general is not possible for secondary users.

an opportunistic policy would demand that a secondary user be more ambitious by increasing it's target QoS.

Theorem 4: With the AIPC policy the dormancy of primary users will lead to a power allocation such that:

1) the remaining primary users maintain their target QoS while conserving transmit power

2) the secondary users improve their QoS

3) the ith secondary user conserves transmit power if $I_{-i} < \sqrt{\mathrm{SIR}_i^{tar}/\rho_i}/(\sqrt{\mathrm{SIR}_i^{tar}+\rho_i I_{-i}^2+3})$.

Proof: We denote the set of dormant users by $\mathsf{D} \subset \mathsf{P}$ with $\mathsf{d} = |\mathsf{D}|$. The absence of d users signals will lead to a reduction in the perceived interference seen by each network user. Since the Pareto optimal solution to (11) involves the primary users meeting their target SIR with equality, each primary user will satisfy its target QoS of $\mathrm{SIR}_i^{tar} : i \in \mathsf{P}$ while requiring less transmit power to do so. For the second item, we note that $\partial\beta_i/\partial I_{-i} < 0$ thus confirming the increase in a secondary user's target SIR with a decrease in perceived interference (recall that $\beta_i = 1 : i \in \mathsf{P}$ while $\beta_i \in [0,1] : i \in \mathsf{S}$). Finally, we note from the second constraint in (11) that for $i \in \mathsf{S}$ we shall have $P_i^* G_{ii} = \widetilde{\mathrm{SIR}}_i^{tar} I_{-i}$ or equivalently $P_i^* G_{ii} = \beta_i \mathrm{SIR}_i^{tar} I_{-i}$. Substitution of (8) allows us to obtain $P_i^* = \max\left\{P_i^{min},\, I_{-i}(\mathrm{SIR}_i^{tar} - \rho_i I_{-i}^2)/G_{ii}(1+\rho_i I_{-i}^2)\right\}$ from which we evaluate $\partial P_i^*/\partial I_{-i} = (\mathrm{SIR}_i^{tar} - \rho_i I_{-i}^2(\mathrm{SIR}_i^{tar} + \rho_i I_{-i}^2 + 3))/G_{ii}(1+\rho_i I_{-i}^2)^2$. It can be observed that $\partial P_i^*/\partial I_{-i} < 0$ if $\sqrt{\mathrm{SIR}_i^{tar}/\rho_i} < I_{-i}\sqrt{\mathrm{SIR}_i^{tar} + \rho_i I_{-i}^2 + 3}$. We note that $\mathrm{SIR}_i^{tar} + \rho_i I_{-i}^2 + 3 > 1$ and recall that the ith secondary user will opt-out if $I_{-i} \geq \sqrt{\mathrm{SIR}_i^{tar}/\rho_i}$. From this we conclude that we shall have $\partial P_i^*/\partial I_{-i} \leq 0$ for $\sqrt{\mathrm{SIR}_i^{tar}/\rho_i} \leq I_{-i}\sqrt{\mathrm{SIR}_i^{tar} + \rho_i I_{-i}^2 + 3}$, and $\partial P_i^*/\partial I_{-i} > 0$ for $\sqrt{\mathrm{SIR}_i^{tar}/\rho_i} > I_{-i}\sqrt{\mathrm{SIR}_i^{tar} + \rho_i I_{-i}^2 + 3}$. This states that a secondary user will either decrease power with a decreasing level of perceived interference (when $\sqrt{\mathrm{SIR}_i^{tar}/\rho_i} > I_{-i}\sqrt{\mathrm{SIR}_i^{tar} + \rho_i I_{-i}^2 + 3}$), or increase power with a decreasing level of perceived interference before eventually opting-out when $I_{-i} \geq \sqrt{\mathrm{SIR}_i^{tar}/\rho_i}$. ∎

The above result relies upon an action initiated by primary users. An opportunistic power control policy should allow a secondary user to benefit from improvements in the wireless channel stemming from geographical changes in the primary users' locations.

Corollary 2: With AIPC an improvement in the channel between a primary user and it's intended receiver, or a degradation in the channel between a primary user and the intended receiver of any other primary user will result in:

1) the primary users maintaining their target QoS while conserving transmit power

2) the secondary users improving their QoS

3) the ith secondary user conserving transmit power if $I_{-i} < \sqrt{\mathrm{SIR}_i^{tar}/\rho_i}/(\sqrt{\mathrm{SIR}_i^{tar}+\rho_i I_{-i}^2+3})$.

Proof: We make two observations. In the case of increasing $G_{ii} : i \in \mathsf{P}$ the ith primary user will need lower transmit power to attain SIR_i^{tar}. In the case of decreasing $G_{ij} : i \neq j, i; j \in \mathsf{P}$ the perceived interference of user $i \in \mathsf{P}$ will decrease causing that user to decrease transmit power while still meeting its target QoS. For both scenarios the decrease in the ith primary user's transmit power will lead to a decrease in the perceived interference seen by all other users (i.e. $I_{-j} : j \neq i, j \in \mathsf{P} \cup \mathsf{S}$). Thus, the remaining primary users will transmit with less power while maintaining their target QoS. Since $\partial P_i^*/\partial I_{-i} > 0$ if $\sqrt{\mathrm{SIR}_i^{tar}/\rho_i} > I_{-i}\sqrt{\mathrm{SIR}_i^{tar} + \rho_i I_{-i}^2 + 3}$, the ith secondary user may concurrently conserve transmit power. ∎

It is noteworthy that the opportunism of the AIPC policy discussed in the above theorem is achievable without the intervention of the LSS or the primary network backbone (PNB). The fact that primary users and secondary users simultaneously benefit from dormancy is also appealing. In the critique of AIPC we have aimed to stress a user's adaptation of transmit power in response to perceived interference. Through Theorem 4 and Corollary 2 we have advocated the utility of AIPC as far as enabling a secondary user to opportunistically use the spectrum after sensing the environment. The sensing corresponds to the user performing interference estimation and prediction prior to performing a power update.

C. Admissibility

The regulation of transmit power is a natural means of dictating the admission of a user into a network. Established works such as [17] [18] have considered the integration of admission and power control. The caveat is that the aforementioned works have dealt exclusively with users of a single QoS class. It's essential that the fundamental aspects of existing admission control policies be reconsidered within the cognitive radio framework. Admission control works typically distinguish between two types of admission errors: a type I error and a type II error [18]. Primary and secondary users of distinct QoS priority would govern varying dynamics for network admission and require differing etiquette. Thus we conjecture that it's necessary to distinguish among the type I and II errors of primary and secondary users.

- Secondary-primary type I error: a new secondary user is erroneously admitted causing the outage of a primary user.
- Primary-secondary type I error: a new primary user is erroneously admitted causing the outage of a secondary user.
- Primary (Secondary) type I error: a new primary (secondary) user is erroneously admitted causing the outage of a primary (secondary) user.
- Primary (Secondary) type II error: a new primary (secondary) user is erroneously denied admission while it could have been supported.

Naturally, the primary type I and primary type II errors would be addressed by the admission control policy of the primary network irrespective of the secondary network's operation or presence. The primary-secondary type I error does not warrant attention since the QoS of the primary users is of utmost priority. Prior to discussing potential remedies for a secondary-primary type I error, secondary type I error, and secondary type II error; we state two admission control mechanisms offered by AIPC. First, user $i \in \mathsf{S}$ transmitting with a minimal power level of $P_i^{min} = 0$ corresponds to that user leaving the network,

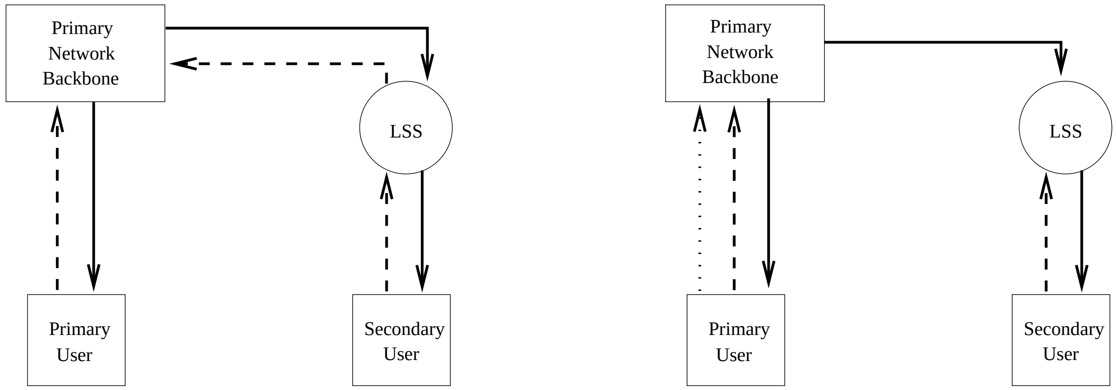

Fig. 2. Two possible architectures for admission control in a power-controlled cognitive radio network. The solid lines correspond to admission-related commands, the dashed lines indicate admission requests, and the dotted line represents a distress signal.

or autonomously performing *voluntary drop-out* (VDO) [17]. Secondly, the opt-out state allows AIPC to be viewed as a form of *distributed interactive admission control* [18]. These two characteristics bring forth the following result.

Theorem 5: The AIPC policy is secondary-primary type I error free, secondary type II error free, and prone to secondary type I errors.

Proof: Consider L secondary users being erroneously admitted to a network consisting of N primary users and M secondary users. The fact that the L newly admitted secondary users can not be accommodated would lead to an increase in each users' interference level, at which point a subset of the $M+L$ secondary users would opt out. Thus we see that we have not assured secondary type I error protection. Conversely, the opting-out of secondary users would lead to the network reaching a feasible point and the primary users maintaining their target SIR (see Theorem 3 which alludes to QoS protection). Thus, the composite network will be secondary-primary type I error free. The AIPC policy is secondary type II error free since it allows for distributed interactive admission control among the secondary users. In other words, an arbitrary secondary user may enter and interact with the network prior to attaining or being denied (i.e. opting-out) admission. ■

At the conclusion of the QoS protection subsection we alluded to the possibility of the LSS regulating the admission of secondary users. Figure 2 illustrates two possible admission control architectures within a licensed spectrum system. In the first case the LSS would query the primary network of whether each secondary user could be admitted. The primary network would either approve or disapprove and the LSS would convey this result to the prospective secondary user. In the second case the LSS admits all prospective secondary users until instructed by the primary network to cease admission. The PNB would convey such an order following the reception of a distress signal from the primary users. The idea of users sending a distress signal has been presented in [17] within the context of admission control for power-controlled cellular networks. We briefly discuss the reasons behind the distress signal. Although the presence of each secondary user will not deteriorate the attained SIR of any primary user; each secondary user's transmission causes every primary user to transmit with higher power. At some point a particular primary user may object to the additional increase in transmit power. It is at this point that such primary user may express it's discontent by sending a distress signal in the form of a simple probe. Alternatively the distress signal may be piggybacked on a primary user's traffic.

D. Autonomous operation

The autonomous nature of AIPC when deployed by either a primary or secondary user is indicated by the fact that, in performing a power update, a user only requires local information pertaining to its perceived interference and the link gain to its intended receiver. It appears crucial that users in a cognitive radio network should be capable of performing dynamic power adaptation in a decentralized manner. While a LSS may govern the user's entrance into the network; it would be rather infeasible to expect the LSS to relay power control commands to users at each time instant. Attempting such a task would require the LSS to have knowledge of the users' link gains.

We briefly reflect upon the works of [20] [21] which propose that secondary users cooperate so as to collectively detect the presence of a primary user's transmitted signal. Although elegant in nature, it is uncertain at this point whether such cooperative sensing can be performed in distributed fashion by potentially distant secondary users. Even if this is feasible, it's uncertain whether the overhead would offset each individual user deploying an estimator and performing interference estimation. With the advancements of software-defined radios and the deployment of such devices in cognitive radio networks, it will be interesting to see the amount of processing power available to a user. Perhaps users will indeed be capable of effectively cooperating with other users for more sophisticated purposes other than spectrum sensing. Nevertheless, we believe it's sensible to initially consider a policy such as the AIPC which requires a user to be efficient in requiring local information rather than having to rely upon cooperation or the dissipation and distribution of global information.

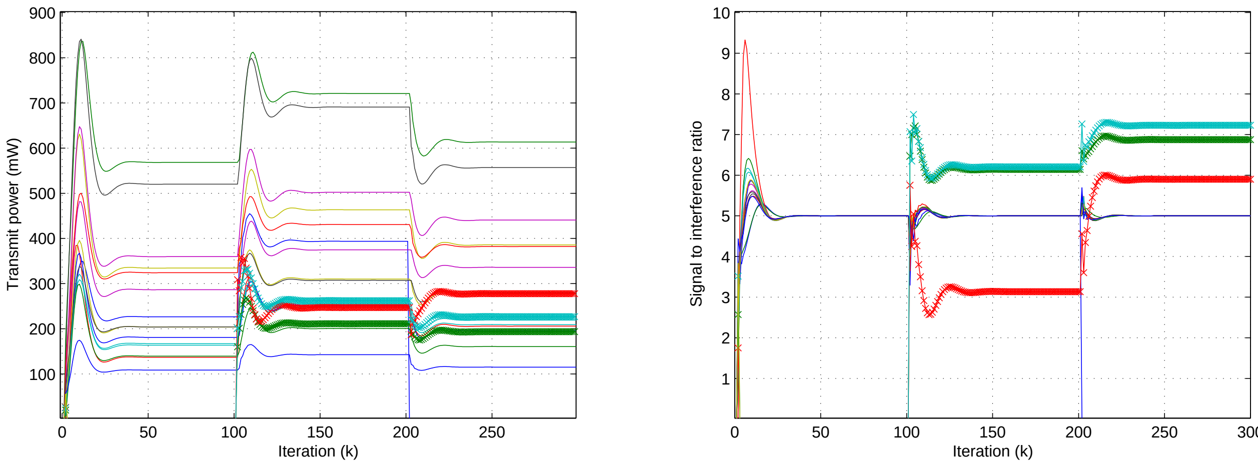

Fig. 3. Dynamics of the transmit power and SIR of the primary and secondary users with the AIPC policy. The solid lines correspond to the primary users while the thick lines correspond to the secondary users. A target SIR of $\mathrm{SIR}_i^{tar} = 5$ was specified for each primary user. The network consisted of $N = 15$ primary users during $0 < k \leq 100$, $N = 15$ primary users and $M = 3$ secondary for $100 < k \leq 200$, and $N = 14$ primary users and $M = 3$ secondary users for $200 < k \leq 300$. The secondary users were assigned $\rho_i = 200 : i \in \mathsf{S}$ by the LSS upon their entrance into the network at $k = 100$.

E. Licensing

In the primary-secondary sharing paradigm it has been stated that applications which require a guaranteed QoS should be given exclusive access to the spectrum via some licensing mechanism [1]. The network may perform such licensing via the assignment of $\{\rho_i\}$ to the license holders and the secondary users. As we have discussed throughout the presentation the AIPC policy would dictate that the primary users have $\rho_i = 0 : i \in \mathsf{P}$ and the secondary users be assigned $\rho_i > 0 : i \in \mathsf{S}$. The assignment of $\rho_i > 0 : i \in \mathsf{S}$ is performed by the LSS upon the admission of the secondary user. In performing this assignment it's essential that the primary network interact with the LSS since the QoS and power expenditure of the primary users will always be of utmost priority. With AIPC the two extreme scenarios of $\rho_i = 0$ and $\rho_i = \infty$ can be viewed as giving a user unlimited spectrum rights and denying a user service,[5] respectively. Furthermore, the "degree" of a user's license is dictated by it's assigned ρ_i value. For instance an increase in the ith user's ρ_i parameter dictates the less right to the spectrum given to that secondary user's soft QoS constraint. The ith secondary user would not be entitled to change ρ_i much the same as a user would not be allowed to upgrade it's own license. Naturally, the primary user with $\rho_i = 0$ has exclusive access to the spectrum in the sense of being allowed to inject any amount of interference into the network in order to satisfy a stringent QoS constraint. Finally, we remark that there is an interplay between power control, admission control, and licensing of users. By giving priority to the QoS of a certain class of users over the QoS of another class of users we are in effect distinguishing among users having differentiated rights to the shared spectrum.

[5]It can be verified from (10) that a user with $\rho_i = \infty$ will transmit with minimal allowable power P_i^{min} irrespective of it's channel state L_i.

F. Versatility

With radio resource management of cognitive radio networks being relatively unexplored, its yet to be determined whether its more sensible to have autonomous network users deploy distinct resource allocation policies; or having users deploy a single sophisticated policy that is versatile enough to be fine-tuned to address heterogeneous user and network objectives. An apparent consequence of autonomous users deploying drastically distinct power control algorithms lies in the fact that it's not evident if issues such as QoS protection, opportunism, or even the feasibility of the network can be analytically investigated. At the same time, the dynamics of a unified power control algorithm should be flexible enough so as to distinguish among differing requirements such as ensuring the QoS of primary users and prioritizing among the performance of opportunistic secondary users. In the design of such a unified power control policy we postulate that a user's objective function should incorporate multiple criterion. The multi-criterion objective function (7) was proposed with the purpose of allowing for differing dynamics among users. With AIPC such differentiation occurs for two classes of network users: those with $\rho_i = 0$ and those with $\rho_i > 0$. Such versatility circumvents issues which may be associated with primary users deploying a greedy power control algorithm such as [13] and the secondary users deploying utility-based policies such as [3] [4].

V. Simulation Results

In this section the dynamics of the AIPC policy are evaluated by considering a network comprised of primary and secondary users. The primary network shall consist of the uplink of a cellular CDMA system with voice users having a hard QoS constraint of $\mathrm{SIR}_i^{tar} = 5 : i \in \mathsf{P}$. The backbone of the primary network is a single base station containing the users' intended receivers. The secondary users are assumed to be delay-insensitive CDMA data users with a soft QoS constraint of $\mathrm{SIR}_i^{tar} = 10 : i \in \mathsf{S}$. The use of a linear receiver allows the ith user's SIR to be defined as

$$\mathrm{SIR}_i(k) = \frac{P_i(k)h_i\left[\mathbf{c}_i^T(k)\mathbf{s}_i(k)\right]^2}{\sum_{j\neq i} P_j(k)h_j\left[\mathbf{c}_i^T(k)\mathbf{s}_j(k)\right]^2 + \mathbf{c}_i^T(k)\mathbf{c}_i(k)\eta_i} \qquad (17)$$

with $\mathbf{s}_i(k) \in \mathbb{R}^L$ and $\mathbf{c}_i(k) \in \mathbb{R}^L$ denoting the user's codeword and receive vector, respectively. The constant L denotes the processing gain, and the gains $\{h_j\}$ represent the path-loss. The signature sequence $\mathbf{s}_i = \frac{1}{\sqrt{L}}[s_{i1},\ s_{i2},\ \ldots,\ s_{iL}]^T$ is fixed for the duration of convergence of the power control algorithm, and a matched filter receiver (i.e., $\mathbf{c}_i = \mathbf{s}_i$) will be used for demodulation. We consider randomly generated signature sequences with $s_{ij} \in \{-1,1\}$. Comparison of (17) with (1) reveals that the link gains may be represented as

$$G_{ij} = \begin{cases} h_i & \text{if} \quad i = j \\ h_j(\mathbf{s}_i^T\mathbf{s}_j)^2 & \text{if} \quad i \neq j\,. \end{cases} \qquad (18)$$

A frequently used path loss model for terrestrial radio communication is given by $h_i = P_R\,(d_R/d_i)^n = A/d_i^n$ where d_R is a reference distance, P_R is the received power at the reference distance, d_i is the distance between the ith user and the base station, and n denotes the path loss exponent. We shall assume a path loss exponent of $n = 4$ and assign $A = 10^{-4}$ in correspondence to a path gain of -40 dB at a reference distance of 1 km with a 1.9 GHz carrier frequency [22]. A receiver noise power of $\eta = 10^{-3}$ mW will be assumed along with a single circular cell with a coverage range of radius $r = 1$ km. Within the cell the primary and secondary users locations' will be generated uniformly on the interval of $(0, r]$. A processing gain of $L = 128$ will be allocated to each primary and secondary user. Initially each user will transmit with a power level of $P_i(0) = P_i^{min} = 0.0$ mW. In the admission of secondary users we restrict attention to the second scheme in Fig. 2. Thus, all prospective secondary users will be admitted by the LSS and assigned a value of $\rho_i > 0$. A primary user that is displeased with the increase in transmit power necessary to meet it's target QoS will send a distress signal to the base station.

In an autonomous system the dynamics of the ith user's perceived interference is given by

$$\begin{aligned} I_{-i}(k+1) &= I_{-i}(k) + w_i(k) \\ Y_i(k) &= I_{-i}(k) + v_i(k) \end{aligned} \qquad (19)$$

with $w_i(k)$ representing the driving disturbance, $v_i(k)$ denoting the measurement noise, and $Y_i(k)$ denoting an interference measurement obtained by the ith user via a feedback channel from it's intended receiver. The variances of the stochastic disturbances are given by $W_i(k) = \mathrm{E}\left[w_i^2(k)\right]$ and $V_i(k) = \mathrm{E}\left[v_i^2(k)\right]$. With AIPC each user will autonomously perform interference estimation and prediction prior to each power update via

$$\hat{I}_{-i}(k+1) = \hat{I}_{-i}(k) + K_i(k)(Y_i(k) - \hat{I}_{-i}(k))\,. \qquad (20)$$

If the ith user deploys a Kalman filter we shall have

$$\begin{aligned} K_i(k) &= B_i(k)/\left(B_i(k) + V_i(k)\right) \\ B_i(k+1) &= B_i(k) - B_i^2(k)(B_i(k) + V_i(k))^{-1} + W_i(k)\,. \end{aligned}$$

For clarity in the illustration of the AIPC dynamics in allowing for QoS protection, opportunism, and admissibility we shall ignore the stochastic detriments giving rise to the measurement and process noise and consider a deterministic evolution of the interference. It can be readily verified that in the absence of the stochastic disturbances (20) reduces to $\hat{I}_{-i}(k+1) = Y_i(k)$.

The power and SIR evolution of the users is shown in Fig. 3 with all users adapting power according to the AIPC policy. The first time interval consists of $0 < k \leq 100$ with the network being comprised of $N = 15$ primary users and no secondary users. The users have a hard QoS constraint as dictated by $\rho_i = 0 : i \in \mathsf{P} = \{1,2,\ldots,15\}$, and due to the feasibility of the target SIRs, attain their target QoS upon convergence of the transmit powers. In the next time interval of $100 < k \leq 200$ the LSS allows the admission of three secondary users and assigns $\rho_i = 200 : i \in \mathsf{S} = \{16,17,18\}$. The network now consists of $N = 15$ primary users and $M = 3$ secondary users. Upon convergence of the AIPC we note that the primary users maintain their hard QoS constraint of $\mathrm{SIR}_i^{tar} = 5 : i \in \mathsf{P}$ albeit while transmitting at higher power. Two of the secondary users attain a SIR value of approximately 6, and the third user attains a SIR value of approximately 3. Clearly the secondary users have $\widetilde{\mathrm{SIR}}_i^{tar} \leq \mathrm{SIR}_i^{tar}$ via a soft QoS constraint as dictated by $\rho_i > 0 : i \in \mathsf{S}$. During the third interval of $200 < k \leq 300$ a primary user leaves the network. The three secondary users aim for and attain a higher modified target SIR value. Concurrently, two of the secondary users conserve transmit power while the third secondary user increases power. The 14 non-dormant primary users maintain their SIR constraint while conserving power. In effect, the second time interval illustrates the QoS protection offered by AIPC, whereas the third time interval illustrates opportunism.

We examine a second random realization of the user locations and codewords with the purpose of critiquing the admissibility offered by AIPC with the entrance of primary users into the network. Figure 4 shows the power and SIR evolution with the users adapting power according to the AIPC policy. In the first time interval of $0 < k \leq 100$ the network is comprised of $N = 15$ primary users and $M = 2$ secondary users. The primary users satisfy their stringent SIR constraints due to the feasibility of the target SIR values. The secondary users have been assigned $\rho_i = 200 : i \in \mathsf{S} = \{16,17\}$ by the LSS, and consequently satisfy a modified target SIR of $\widetilde{\mathrm{SIR}}_i^{tar} \leq \mathrm{SIR}_i^{tar} = 10 : i \in S$. In the subsequent time interval of $100 < k \leq 200$ two primary users enter the network leading to $N = 17$ and $M = 2$. The two secondary users concurrently decrease power and target SIR due to their increase in perceived interference. A power increase is still incurred by each of the 15 previously admitted primary users since they now experience interference from two additional primary users. During the final interval of $200 < k \leq 300$ four new primary users enter the network leading to $N = 21$ and $M = 2$. A further decrease in transmit power and target SIR is incurred by the secondary user with index $i = 16$. The secondary user with index $i = 17$ decides to opt-out via a converged transmit power of $P_{17}^{min} = 0\,\mathrm{mW}$. This secondary user has experienced condition (9) for $k \geq 210$ and $I_{-17} \geq \sqrt{\mathrm{SIR}_{17}^{tar}/\rho_{17}}$ upon convergence of the AIPC

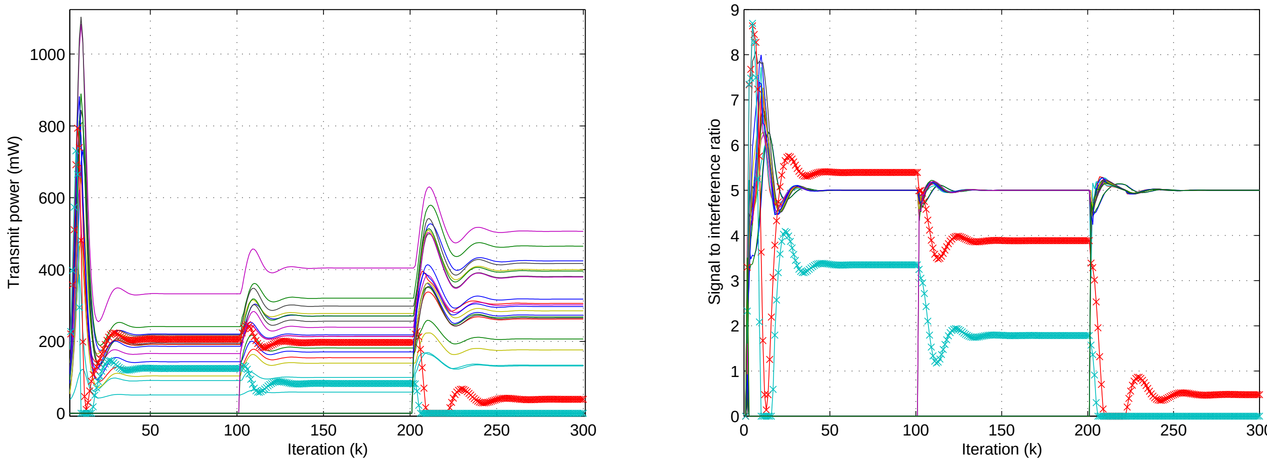

Fig. 4. Dynamics of the transmit power and SIR of the primary and secondary users with the AIPC policy. The solid lines correspond to the primary users while the thick lines correspond to the secondary users. A target SIR of $\mathrm{SIR}_i^{tar} = 5$ was specified for each primary user. The network consisted of $N = 15$ primary users and $M = 2$ secondary users during $0 < k \le 100$, $N = 17$ primary users and $M = 2$ secondary for $100 < k \le 200$, and $N = 21$ primary users and $M = 2$ secondary users for $200 < k \le 300$. The secondary users were assigned $\rho_i = 200 : i \in \mathsf{S}$ by the LSS upon their entrance into the network at $k = 0$.

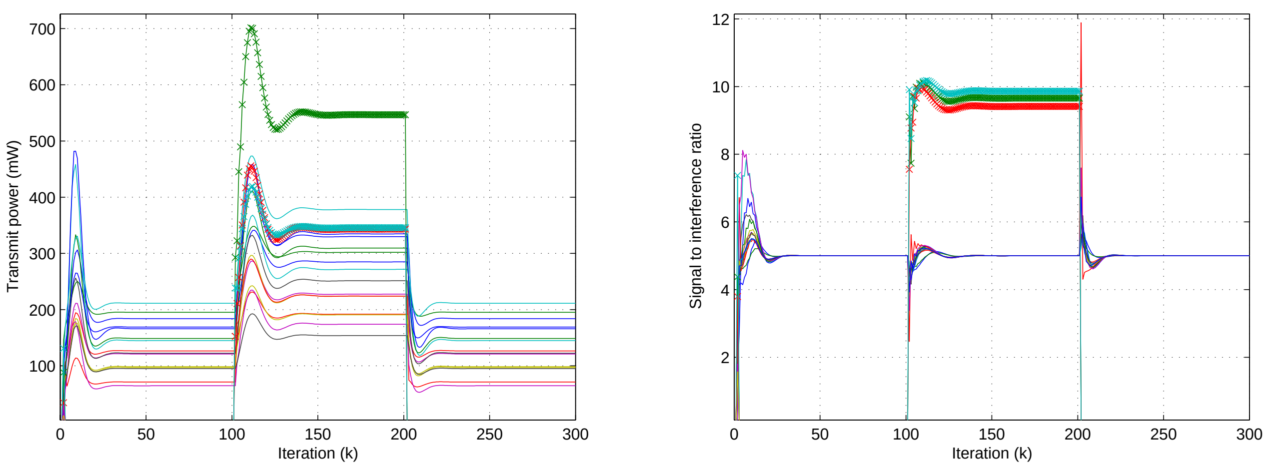

Fig. 5. Dynamics of the transmit power and SIR of the primary and secondary users with the AIPC policy. The solid lines correspond to the primary users while the thick lines correspond to the secondary users. A target SIR of $\mathrm{SIR}_i^{tar} = 5$ was specified for each primary user. The network consisted of $N = 15$ primary users during $0 < k \le 100$, $N = 15$ primary users and $M = 3$ secondary for $100 < k \le 200$, and $N = 15$ primary users for $200 < k \le 300$. The secondary users were assigned $\rho_i = 20 : i \in \mathsf{S}$ by the LSS upon their entrance into the network at $k = 100$, and assigned $\rho_i = 10^4 : i \in \mathsf{S}$ for $k > 200$.

algorithm. Aside from demonstrating the AIPC's opt-out state as a mechanism for interactive admission control; this example illustrates a distinct differentiation in QoS priority offered by AIPC amongst primary and secondary users.

The power and SIR evolution is shown in Fig. 5 for a final random realization of the user locations and codewords. We now aim to show the interaction of the primary users, PNB, LSS, and secondary users. In the first time interval of $0 < k \le 100$ the network is comprised of $N = 15$ primary users and no secondary users. The users satisfy their stringent SIR constraints due to the feasibility of the target SIR values. In the next interval of $100 < k \le 200$ the LSS admits three secondary users and assigns $\rho_i = 20 : i \in \mathsf{S} = \{16, 17, 18\}$. Despite having lower QoS priority via $\rho_i > 0 : i \in \mathsf{S}$, the secondary users come rather close to meeting their soft SIR constraint of 10. The presence of the secondary users brings about a mean power increase of nearly 70 percent among the primary users. Primary users transmit a distress signal to their intended receivers (or equivalently, the base station) at $k = 200$. The base station orders the LSS to reduce the interference caused by the secondary users. The LSS follows the order via a new assignment of the arbitrarily large value $\rho_i = 10^4 : i = 16, 17, 18$ to the secondary users. A resultant opting-out of the secondary users takes place upon the convergence of AIPC for $200 < k \le 300$ as we have $P_i^* = P_i^{min} = 0\,\mathrm{mW} : i \in \mathsf{S}$. Obviously the primary users transmit powers return to those obtained upon convergence during the first time interval. This demonstrates rapid network recovery in terms of the PNB mitigating an adverse effect incurred by the primary users due to the presence of the secondary users.

Thus far we have examined the deterministic evolution of AIPC in allowing for etiquette to be imposed in accordance to the discussion of the previous section. The robustness of AIPC to stochastic impairments such as stochastic link gains, noisy feedback measurements, and the loss of feedback has been investigated and quantified in [9]. Our focus here is quite different in that, within the cognitive network framework, we are interested in examining the degree of deterioration caused by potentially non-robust secondary users to robust primary users.

In a wireless channel the fading process and the mobility of the users render the channel response as a stochastic process. The time varying nature of the channel shall be depicted by representing each link gain by a first-order Gauss-Markov model

$$G_{ij}(k+1) = G_{ij}(k) + g_{ij} \tag{21}$$

with $g_{ij} \sim N(0,\ \mathrm{Var}[g_{ij}])$. At time k, the link gain

$$G_{ij}(k) = G_{ij} + \tilde{G}_{ij}(k) \tag{22}$$

shall consist of a deterministic component $G_{ij} = \mathrm{E}[G_{ij}(k)]$ given by (18), and a stochastic component $\tilde{G}_{ij}(k) \sim N(0,\ \mathrm{Var}[\tilde{G}_{ij}(k)])$ denoting fluctuations brought on by small-scale effects such as user mobility and multipath fading. Since $0 < G_{ij}(k) \leq 1.0$, the stochastic perturbations shall be limited to the interval $\tilde{G}_{ij}(k) \in (-G_{ij}, 1-G_{ij}]$. We shall model the variance of the perturbations in (22) as $\mathrm{Var}[\tilde{G}_{ij}(k)]) = \mu_1 G_{ij}$ with $\mu_1 < 1$, and model the variance of the sequence of random variates $\{g_{ij}\}$ in (21) as $\mathrm{Var}[g_{ij}] = \mu_2 G_{ij}$ with $\mu_2 < 1$.

The measurement noise is locally impingent upon the received feedback of the ith user, and hence it's statistics are assumed to be known a priori as $v_i(k) \sim N(0,\ V_i(k))$ with $V_i(k) = \eta_v I_{-i}(k)$. We note that the dynamics of the ith user's next-step perceived interference can be expressed as

$$\begin{aligned}
I_{-i}(k+1) &= \sum_{j\neq i} P_j(k+1)G_{ij}(k+1) + \eta_i \\
&= \sum_{j\neq i} \left(P_j(k) + \alpha_j^*(k)I_{-j}(k)\right)\left(G_{ij}(k) + g_{ij}\right) + \eta_i \\
&= I_{-i}(k) + w_i(k)
\end{aligned} \tag{23}$$

with the stochastic process

$$w_i(k) = \sum_{j\neq i} \alpha_j^*(k)I_{-j}(k)G_{ij}(k) + P_j(k)g_{ij} + \alpha_j^*(k)I_{-j}(k)g_{ij}$$

denoting the driving disturbance acting upon the perceived interference of the ith user. Inspection of $w_i(k)$ reveals that the distribution of the driving disturbance may not be very instructive to derive since it is a function of parameters which are not locally known by the ith user. More specifically, an arbitrary user would not be aware of the transmit power of other users nor have statistical information pertaining to the stochastic link gains of the other transmitters. With $\{G_{ij}(k)\}$ and $\{g_{ij}\}$ being Normal, we invoke a Gaussian assumption on the process noise by assuming $w_i(k) \sim N(b_i(k),\ W_i(k))$. From the state equation in (19) it follows that $b_i(k) = \mathrm{E}[I_{-i}(k+1) - I_{-i}(k)]$. Therefore, we designate the sequences

$$\begin{aligned}
\hat{b}_i(k) &= \frac{1}{K}\sum_{n=k-K+1}^{k} \hat{I}_{-i}(n+1) - \hat{I}_{-i}(n) \\
\hat{W}_i(k) &= \frac{1}{K}\sum_{n=k-K+1}^{k} \left(\hat{I}_{-i}(n+1) - \hat{I}_{-i}(n)\right)^2 - \hat{b}_i^2(k)
\end{aligned} \tag{24}$$

as approximations to the maximum-likelihood (ML) estimates of the mean and variance of the driving disturbance $w_i(k)$, respectively. The deviation between the two approximations above and the ML estimates is dependent upon the accuracy of the approximation $I_{-i}(k+1) - I_{-i}(k) \cong \hat{I}_{-i}(k+1) - \hat{I}_{-i}(k)$. A window size of $K = 100$ samples will be used in empirically obtaining the statistics of the driving disturbance.

VI. Spectrum Hole Transmission and Interference Temperature Consideration with AIPC

The notions of a spectrum hole, interference temperature, and interference temperature limit have been illuminated and discussed in a unified manner in [2]. The definitions of these three terms can be found in [2] and will not be reproduced here. The purpose of this section is to discuss the operation of AIPC with respect to these three notions. Haykin provides the following foresight:

"...the FCC Spectrum Policy Task Force [15] has recommended a paradigm shift in interference assessment, that is, a shift away from largely fixed operations in the transmitter and toward real-time interactions between the transmitter and receiver in an adaptive manner. The recommendation is based on a new metric called the interference temperature, which is intended to quantify and manage the sources of interference in a radio environment."

Thus reinforcing our claim of the importance of etiquette design, interference management, real-time operation, and power allocation for cognitive radio networks. Barring a scaling factor we note that $I_{-i}(k)$ in our discussion is analogous to the interference temperature. Subsequently, we define Γ as the interference temperature limit discussed by Haykin, and note that this is analogous to our notion of a secondary user's "bad channel threshold" in Section III.B. Specifically, from the discussion leading up to and including (10) we see that with AIPC we have

$$\Gamma = \sqrt{\frac{\mathrm{SIR}_i^{tar}}{\rho_i}} \qquad i \in \mathsf{S} \tag{25}$$

with the ith secondary user[6] transmitting with P_i^{min} for $I_{-i} \geq \Gamma$. Thus we have a rather intuitive interpretation of a user's interference temperature limit being dependent upon it's self-serving QoS requirement and a quantitative priority level assigned to the user by the PNB. With AIPC, a transient interpretation of the enforcement of an interference temperature limit is given by (9). The autonomous nature

[6]Naturally, in the case of $i \in \mathsf{P}$ we would have $\Gamma = \infty$ via $\rho_i = 0$. This is consistent with the idea that the primary users should not have interference temperature limit.

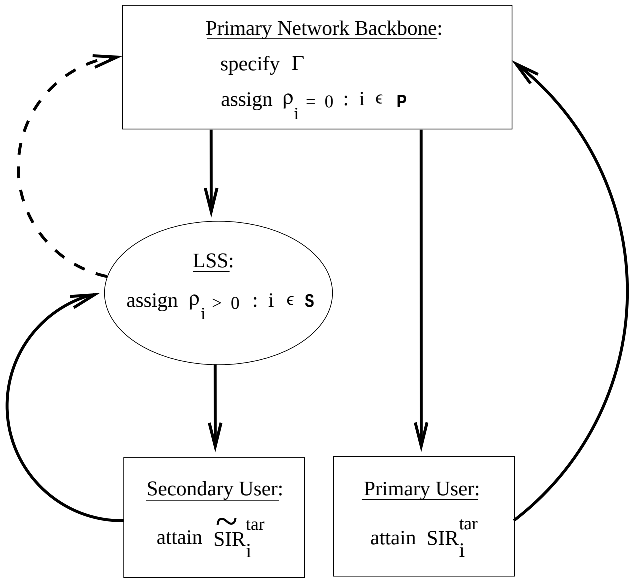

Fig. 6. An abstract illustration of the interaction amongst the PNB, LSS, and network users. The solid lines correspond to required interaction, while the dashed line corresponds to optional interaction.

of AIPC allows for the enforcement of the interference temperature limit without centralization or extensive overhead. The limiting scenario of $\Gamma = 0$ corresponds to the PNB wanting no secondary user interference to the communication of the primary users. We deem it sensible that the value of Γ be assigned by the PNB either on a network-wide basis or per LSS. This is in light of Haykin's exposition:

"For obvious reasons, regulatory agencies would be responsible for setting the interference-temperature limit, bearing in mind the condition of the RF environment that exists in the frequency band under consideration."

It's sensible that an LSS located in a geographical proximity where secondary user interference is tolerated should have a high value for Γ. Conversely, an LSS with a low value of Γ should correspond to a location where secondary user interference is not very welcome. Lastly, an LSS with $\Gamma = 0$ denotes an exclusive region where no secondary transmission is allowed. Figure 6 illustrates the interaction of the PNB, LSS, and the network users as we have discussed. AIPC allows for such interaction by allowing etiquette to by imposed via power control, and providing differentiation among a primary user and a secondary user.

Another important notion discussed in [2] is the idea of a spectrum hole. More specifically, it's stated that:

"A spectrum hole is a band of frequencies assigned to a primary user, but, at a particular time and specific geographic location, the band is not being utilized by that user."

In effect, the spatial and temporal dependence of a spectrum hole are captured by the values of the link gains $\{G_{ij}\}$. A consequent discussion of the detection of spectrum holes via statistical signal processing techniques is provided in [2]. Our methodology is quite different since with AIPC a secondary user need not remain dormant until the occur Rather, a secondary user may transmit so long as it's interference temperature limit is not exceeded. The following proposition sheds light on the special scenario in which a secondary user is only allowed to communicate in the occur For the following proposition we shall assume a common thermal noise floor of $\eta = \eta_i \, \forall i$.

Proposition 3: With the AIPC policy an assignment of $\Gamma = \eta$ corresponds to the ith secondary user either transmitting during a spectrum hole or remaining dormant. A secondary user will attain a converged transmit power of $P_i^* = \max\{P_i^{min}, \eta(\mathrm{SIR}_i^{tar} - \rho_i\eta^2)/(G_{ii}(1+\rho_i\eta^2))\}$ and a modified target SIR of $\widetilde{\mathrm{SIR}}_i^{tar} = \max\{0, (\mathrm{SIR}_i^{tar} - \rho_i\eta^2)/(1+\rho_i\eta^2)\}$.

Proof: It can be verified from (8) that with $I_{-i} = \eta$ we shall have $\beta_i = \max\{0, (\mathrm{SIR}_i^{tar} - \rho_i\eta^2)/(\mathrm{SIR}_i^{tar}(1+\rho_i\eta^2))\}$. The attained SIR and transmit power readily follow from noting that $\widetilde{\mathrm{SIR}}_i^{tar} = \beta_i \mathrm{SIR}_i^{tar}$ and $P_i^* = \beta_i I_{-i} SIR_i^{tar}/G_{ii}$. ■

There are two noteworthy implications of the above proposition

- only one secondary user (e.g. user i) will be able to transmit during a spectrum hole since with $\Gamma = \eta$ we shall have $\Gamma < P_i^* G_{ji} + \eta \, \forall \, j \neq i$.
- the transmitting user will attain $\widetilde{\mathrm{SIR}}_i^{tar} \cong \mathrm{SIR}_i^{tar}$ since in general $\mathrm{SIR}_i^{tar} >> \rho_i\eta^2$.

VII. Conclusion

In this paper a discussion of power control for wireless users in a cognitive radio network was given. We have elaborated upon several attributes that we deem essential of a power control policy for cognitive radio. This was followed by an analytical discussion and simulation results showing the applicability of the AIPC algorithm for cognitive radio networks.

APPENDIX I
PROOF OF THEOREM 1

With AIPC the ith user's cost function is defined as $J_i(\mathbf{p}(k)) = \rho_{i1}E_i^2(k+1) + \rho_{i2}I_i^2(k+1)$ with $\mathbf{p}(k) = [P_1(k), P_2(k), \ldots, P_N(k)]^T$ and $\rho_i = \rho_{i2}/\rho_{i1}$. Upon the convergence of the AIPC algorithm, the power vector $\mathbf{p}^*$ constitutes a Nash equilibrium iff $J_i(P_1^*, \ldots, P_i^*, \ldots, P_N^*) \leq J_i(P_1^*, \ldots, P_i, \ldots, P_N^*)\,\forall i$. Applying the necessary condition for a Nash equilibrium we obtain

$$\frac{\partial J_i}{\partial P_i} = \frac{\rho_{i1}(P_i G_{ii} - \mathrm{SIR}_i^{tar} I_{-i})}{I_{-i}^2} + \rho_{i2}(P_i G_{ii} + I_{-i}) = 0. \quad (26)$$

Solving the above expression for P_i yields the condition

$$P_i^{Nash} = \frac{I_{-i}(\mathrm{SIR}_i^{tar} - \rho_i I_{-i}^2)}{G_{ii}(1+\rho_i I_{-i}^2)}. \quad (27)$$

The physical restriction of transmit power being non-negative implies that the Nash equilibrium will be confined to $P_i^{Nash+} = \max\{P_i^{min}, P_i^{Nash}\}$ with $P_i^{min} \geq 0$. In Theorem 2 of [9] it was shown that upon convergence of the AIPC policy the ith user will attain a SIR of $\widetilde{\mathrm{SIR}}_i^{tar} = \beta_i \mathrm{SIR}_i^{tar}$. Since $\widetilde{\mathrm{SIR}}_i^{tar} = P_i^* G_{ii}/I_{-i}$ we have $P_i^* = \beta_i I_{-i} \mathrm{SIR}_i^{tar}/G_{ii}$ with β_i given by (8). It can be readily verified that $P_i^{Nash+} = P_i^*$ thus proving the existence of a Nash equilibrium. We now need to prove the uniqueness of the Nash equilibrium attained upon the convergence of AIPC. In Corollary 1 we have shown that with AIPC, the network consisting of $N+M$ users (N primary users) and (M secondary users) will be feasible so long as the primary network is feasible. The asynchronous convergence of iterative power control techniques of the form $\mathbf{p}(k+1) = g\{\mathbf{p}(k)\}$ for feasible systems has been addressed in [14]. It was shown that if $g.$ is a *standard* interference function, then the iterative algorithm $\mathbf{p}(k+1) = g\{\mathbf{p}(k)\}$ will achieve asynchronous convergence to a unique fixed point. With the interference function $g\{\mathbf{p}\} = \mathbf{Ap} + \mathbf{b}$ being standard for a primary network consisting of N primary users, it can be readily verified that $g'\{\mathbf{p}\} = \mathbf{BAp} + \mathbf{Bb}$ is standard for a network consisting of the same N primary users and M secondary users. Thus we have proved the uniqueness of the Nash equilibrium, and the fact that the AIPC will allow users to achieve asynchronous convergence with distributed power updates to the unique point.

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