# Power Control for Cognitive Radio Networks: Axioms, Algorithms, and Analysis

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***Abstract*—The deployment of cognitive radio networks enables efficient spectrum sharing and opportunistic spectrum access. It also presents new challenges to the classical problem of interference management in wireless networks. This paper develops an axiomatic framework for power allocation in cognitive radio networks based on four goals: QoS protection to primary users, opportunism to secondary users, admissibility to secondary users, and autonomous operation by individual users. Two additional goals, licensing and versatility, which are desirable rather than essential, are also presented. A general class of Duo Priority Class Power Control (DPCPC) policies that satisfy such goals is introduced. Through theoretical analysis and simulation, it is shown that a specific interference-aware power-control algorithm reaches such goals.**

***Index Terms*—Cognitive radio, distributed algorithms, dynamic spectrum access, power control.**

## I. INTRODUCTION

THE NOTION that spectrum is a scarce and diminishing commodity was derived from static frequency allocations that are increasingly labeled as outdated. The deployment of cognitive radios to combat the underutilization of spectrum brings forth interesting issues in radio resource management. A 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 nonlicense holders referred to as secondary users. Spectrum sharing is contingent upon the transmissions of secondary users having minimal impact on the operation of the primary users. Essentially, 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 power-control works [27] have focused on devising policies for cellular networks where satisfying a QoS constraint is a premium. In such a framework, transmitters increase power to cope with channel impairments and increasing levels of interference in an inconsiderate and competitive manner. 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. We shall discuss the necessity of interference-aware power control for users in a cognitive radio paradigm. Due to the existence of two classes of users, primary and secondary, the traditional problem of interference management through power control is different from that of cellular systems and ad hoc networks. In this paper, an axiomatic approach of how a general class of Duo Priority Class Power Control (DPCPC) policies can protect primary users from the entrance of secondary users, provide opportunism to secondary users, and prevent the most adverse types of admission errors is presented. This is followed by the discussion of a specific algorithm called Autonomous Interference-aware Power Control (AIPC), which belongs to the general class of DPCPC policies. Furthermore, the algorithm supports our notion of versatility and provides a licensing mechanism among users.

We reflect upon the applicability of the celebrated Foschini–Miljanic algorithm [3] within the shared use of primary licensed spectrum taxonomy. The Foschini–Miljanic algorithm will not belong to the general class of DPCPC policies since it will not satisfy any of the three axioms presented in this paper. This is because it does not provide primary and secondary users with differing power-control dynamics in response to interference. Within the dynamic spectrum access context, the presented DPCPC framework allows users to efficiently exploit the available spectrum. The efficiency arises by engineering protocols that do not disrupt the operation of a primary network while concurrently allowing for opportunistic secondary access. The AIPC power-control algorithm is an instance of such a protocol and thus supports Mitola's vision of the significance of radio environment awareness, goal-based decisions, and proactive adaptation [17].

In Section II, a system model of wireless users in a cognitive radio network is considered. The introduction of attributes which we deem as being essential or desirable of a power-control policy deployed by users in a cognitive radio network is

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provided in Section III. A general class of DPCPC policies are presented and shown to address certain attributes via an axiomatic framework. Sections IV and V present analytical and simulation results justifying the AIPC algorithm as a concrete example of power control satisfying the DPCPC criterion and allowing for etiquette to be imposed among autonomous users in a cognitive radio network. We conclude in Section VI by quantifying the notions of interference temperature, interference temperature limit, and spectrum holes in the context of a power-controlled network.

## 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 colocated. Alternatively, the network may consist of a collection of radio links with neither the transmitters nor receivers being colocated. In such a scenario, the network is a collection of separate radio links in space. The wireless channel will be modeled by the multiplicative link gains $\{G_{ij}(k)\}$, with $G_{ij}(k)$ denoting the attenuation from the $j$th user's transmitted signal to the $i$th user's intended receiver. In effect, $G_{ij}(k)$ determines the interference contributed by the $j$th user's presence to the signal of user $i$ at time $k$. 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 $i$th network user is defined as

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

with $\eta_i$ denoting the thermal noise power at the $i$th user's intended receiver. The $i$th 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 $i$th user's signal. The $i$th user has a desired QoS as characterized by a target SIR value of $\mathrm{SIR}_i^{\mathrm{tar}}$. The $i$th user's instantaneous SIR error

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

is viewed as a QoS measure since it indicates the deviation between a user's attained performance and desired (i.e., target) performance. Power-control works such as [3], [11], and [13] have also considered the linear difference between attained and desired SIR as a reflection of QoS. For the remainder of this paper, steady-state quantities obtained upon the convergence of a power-control policy will either be denoted by having the time index $k^{\mathrm{ss}}$ or will have their time index suppressed.

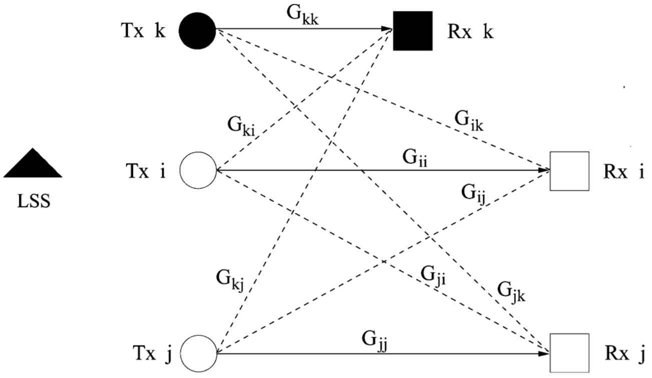

Fig. 1. Model of a cognitive network with transmitter and receiver pairs $i$ and $j$ constituting two primary users, and transmitter and receiver pair $k$ constituting a secondary user. Each link gain is written above the corresponding link with the solid lines denoting intended transmissions and the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

We shall restrict attention to the model of Fig. 1, which effectively represents the network as a collection of transmitter and receiver pairs. The practicality of this model has been advocated in power-control works such as [3], [10], [11], and [13]–[15]. The 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 colocated. Fig. 1 would also apply to the scenario of the primary users' and secondary users' receivers (transmitters) being colocated. 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 colocated transmitters or receivers, different link gains will be seen if the transmission or reception is achieved via distinct antenna elements. It should be noted that the same general network model can be used for an ad hoc network consisting of licensed primary users and unlicensed secondary users. Works such as [21] have incorporated the model in Fig. 1 in devising power control for wireless ad hoc networks. We shall restrict attention to all users using the same spectrum at a given time instant. We advocate the consideration of multichannel communication as an interesting extension to this work.

Thus far, we have not distinguished between primary and secondary users. We seek a power-control algorithm that will enable the primary network backbone (PNB) the flexibility to decide whether a user has a primary or a secondary application. In the specific case of cellular primary users, the base station would be regarded as the PNB. We 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 [4]–[7]. We adhere to the LSS concept 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 (upon the PNB's approval), the LSS will not have the capability to control the actions of the individual users.

## III. POWER CONTROL FOR COGNITIVE RADIO

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

- the dormancy of primary users;
- the relative immunity of primary users with favorable channels to weak cochannel interferers.

It is challenging to devise a power-control method that allows primary users to satisfy strict QoS requirements and yet is flexible enough to accommodate secondary users' opportunistic communication. We list four essential attributes of a prospective power-control policy for cognitive radio.

- *QoS protection:* 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.
- *Opportunism:* If a primary user leaves the network, the secondary users will witness an improvement in QoS while the remaining primary users maintain their target QoS.
- *Admissibility:* The power allocation policy allows for a means of dictating the admission of a secondary user into the network. An arbitrary number of secondary users should be allowed access to the spectrum so long as their admission solely deters the QoS of other secondary users.
- *Autonomous operation:* The power-control technique operates with transmitters having access to only local information. A transmitter would obtain the local information via feedback from its intended receiver.

We list two attributes that we deem as being more so elegant than critical.

- *Licensing:* The policy should allow the PNB and LSS to exercise control in assigning priorities to the applications of various users. For instance, it would be desirable if the power-control policy deployed by a user would autonomously know when (and if) that user should cease transmission and remain dormant.
- *Versatility:* The policy should be flexible enough so as to be deployed by all users in the network, whether primary or secondary.

The QoS protection, opportunism, and admissibility attributes can be classified as being quantitative. Conversely, the autonomous operation, licensing, and versatility attributes are rather qualitative in nature.

We propose three axioms that we deem essential for power-control algorithms designed for cognitive radio networks where the spectrum is shared among primary and secondary users. The axioms will ensure satisfaction of the QoS protection, opportunism, and admissibility attributes presented above. Correspondingly, we label any policy satisfying these axioms as belonging to the general class of DPCPC. We shall denote the set $\mathsf{P}$ as containing the primary users' indices, and the set $\mathsf{S}$ as containing the secondary users' indices.

*Axiom 1*: The policy should provide a power allocation such that the following steady-state relations hold: $\partial P_i/\partial I_{-i} > 0 : i \in \mathsf{P}$ and $\partial P_i/\partial I_{-i} < 0 : i \in \mathsf{S}$

*Axiom 2*: The target QoS of a user should be dependent upon the user's channel state via the following steady-state relations: $\partial \mathrm{SIR}_i^{\mathrm{tar}}/\partial I_{-i} < 0 : i \in \mathsf{S}$ and $\partial \mathrm{SIR}_i^{\mathrm{tar}}/\partial I_{-i} = 0 : i \in \mathsf{P}$.

*Axiom 3*: The entrance of a secondary user should not cause the outage of a primary user via $\mathrm{SIR}_i < \mathrm{SIR}_i^{\mathrm{tar}} : i \in \mathsf{P}$.

The partial derivatives above depict relationships between the steady-state values attained upon the convergence of the power-control algorithm. Thus, $\partial P_i/\partial I_{-i} > 0$ states that at steady state, user $i$ will have a reduced transmit power if it is faced with a reduction in perceived interference. Prior to the convergence of the power-control algorithm, a secondary user experiencing continuously increasing interference will eventually transmit with its minimum allowable power level[1] of $P_i^{\min}$. This general action will be referred to as the $i$th user *opting out*.

A practical methodology to determine if a power-control technique is in the class of DPCPC policies is obtained via the notion that violation of any portion of Axioms 1–3 disqualifies an algorithm from the class of DPCPC policies. Such a methodology can be used to evaluate cognitive radio power-control algorithms in recent works [22], [23], and [24]. The first two works do not present DPCPC policies. More specifically, the algorithm introduced in [22] violates Axioms 1 and 2, while the technique presented in [23] violates Axiom 2. Conversely, the formulation presented in [24] is general enough to satisfy the above three axioms and thus be classified as DPCPC.

Etiquette refers to a collection of technical rules of operation. A violation of the essential attributes will assail our notion of etiquette and annul the utility of the power-control policy for a cognitive radio network. Contrarily, a violation of the desirable attributes will not violate our notion of etiquette. A discussion of how DPCPC policies allow for etiquette to be imposed in part by the LSS and in part by the users is vital. We aim to critique the utility of DPCPC policies in addressing the four essential attributes discussed.

### A. QoS Protection

Traditional methods for radio resource management have focused on ensuring the QoS of users rather than prioritizing among the QoS of users belonging to distinct priority classes. Naturally, primary users should maintain their target SIR values irrespective of the secondary users' presence. Conversely, the performance of secondary users should be contingent on the primary users' performance. Thus, we present an optimization problem in which the primary users have hard QoS requirements and the secondary users have soft QoS requirements.

- *Hard QoS requirement*: Dictated by a static target SIR value that is independent of channel state. This corresponds to a stringent QoS constraint for the user.
- *Soft QoS requirement*: Dictated by a nonstatic target SIR that is dependent on the channel state. The dynamic target

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

SIR may take an arbitrary small value such as zero for a dormant user.

From hereon, users with indices from the set $\mathsf{P} = \{1, 2, \ldots, N\}$ are designated as primary users, and users with indices from the set $\mathsf{S} = \{N+1, N+2, \ldots, N+M\}$ are designated as secondary users. Furthermore, we differentiate among the target QoS of the users via $\mathrm{SIR}_i^{\mathrm{tar}} : i \in \mathsf{P}$ and $\widetilde{\mathrm{SIR}}_i^{\mathrm{tar}} : i \in \mathsf{S}$. With $N = |\mathsf{P}|$ and $M = |\mathsf{S}|$, the optimization problem may be presented as

$$\begin{aligned} &\text{minimize} && \sum_{i=1}^{N+M} P_i \\ &\text{subject to} && \mathrm{SIR}_i^{\mathrm{tar}} \leq \frac{P_i G_{ii}}{\sum\limits_{j \neq i} P_j G_{ij} + \eta_i} : i \in \mathsf{P} \\ & && \widetilde{\mathrm{SIR}}_i^{\mathrm{tar}} \leq \frac{P_i G_{ii}}{\sum\limits_{j \neq i} P_j G_{ij} + \eta_i} : i \in \mathsf{S} \end{aligned} \tag{5}$$

and represented in matrix form via[2] $(\mathbf{I} - \mathbf{A})\mathbf{p} \geq \mathbf{b}$, 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 matrix $\mathbf{A}$ is assumed to be irreducible with entries specified as

$$A(i,j) = \begin{cases} 0, & \text{if } i = j \\ \frac{\mathrm{SIR}_i^{\mathrm{tar}} G_{ij}}{G_{ii}}, & \text{if } i \leq N,\ i \neq j \\ \frac{\widetilde{\mathrm{SIR}}_i^{\mathrm{tar}} G_{ij}}{G_{ii}}, & \text{if } i > N,\ i \neq j \end{cases} \tag{6}$$

with $i, j \in \mathsf{P} \cup \mathsf{S}$ and

$$\mathbf{b} = \left[ \frac{\mathrm{SIR}_1^{\mathrm{tar}} \eta_1}{G_{11}}, \ldots, \frac{\mathrm{SIR}_N^{\mathrm{tar}} \eta_N}{G_{NN}}, \frac{\widetilde{\mathrm{SIR}}_{N+1}^{\mathrm{tar}} \eta_{N+1}}{G_{N+1\ N+1}}, \ldots, \frac{\widetilde{\mathrm{SIR}}_{N+M}^{\mathrm{tar}} \eta_{N+M}}{G_{N+M\ N+M}} \right]^T. \tag{7}$$

When $(\mathbf{I} - \mathbf{A})^{-1} > \mathbf{0}$ exists, the problem given by (5) is deemed as being *feasible* in the power-control literature [13], [19] with $\mathbf{p}^* = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{b}$ being the Pareto optimal solution. The Pareto optimality condition states that for any power vector $\mathbf{p}'$ satisfying (5), $\mathbf{p}^* \leq \mathbf{p}'$. It is well known that if the system is infeasible, then every user can keep increasing its transmit power indefinitely and not satisfy its SIR constraint [13], [19] .

*Proposition 1:* Let $\mathbf{x} \geq 0$ and $\mathbf{x} \neq 0$. If the network consists of $N$ primary users and

$$\max_{\mathbf{x} \geq 0,\, \mathbf{x} \neq 0} \ \min_{1 \leq i \leq N,\, x_i \neq 0} \left\{ \frac{1}{x_i} \sum_{j=1}^{N} A(i,j) x_j \right\} < 1 \tag{8}$$

then the network will be feasible.

*Proof:* As previously stated, (5) can be written as $(\mathbf{I} - \mathbf{A})\mathbf{p} \geq \mathbf{b}$. The left-hand side of (2) is equivalent to $\rho(\mathbf{A})$ with $\rho(.)$ denoting the Perron–Frobenius eigenvalue. It is known that $\rho(\mathbf{A}) < 1$ is a sufficient condition for the existence of the matrix $(\mathbf{I} - \mathbf{A})^{-1} > \mathbf{0}$ and the solution $\mathbf{p}^* = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{b}$. ■

For the remainder of the paper, the network of $N$ primary users will be assumed to be feasible. In the case of an infeasible primary network, systematic (primary) user removal techniques such as the one in [20] can be applied to arrive at a feasible network of primary users.

*Theorem 1:* Consider a feasible network consisting of $N$ primary users. With users adapting power according to a DPCPC 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 if

$$\max_{\mathbf{x} \geq 0,\, \mathbf{x} \neq 0} \ \min_{1 \leq i \leq N+M,\, x_i \neq 0} \left\{ \frac{1}{x_i} \sum_{j=1}^{N} A(i,j)\, x_j + \frac{1}{x_i G_{ii}} \sum_{j=N+1}^{N+M} \widetilde{\mathrm{SIR}}_i^{\mathrm{tar}} G_{ij}\, x_j \right\} < 1 \tag{9}$$

for the $N + M$ users. The proof rests upon the conjecture that the second term on the left-hand-side of (3) will not cause a violation to the inequality. Define $\mathbf{p}^{1*}$ as the $N$-dimensional power vector attained upon convergence with $N$ primary users, and define $\mathbf{p}^{2*}$ as the $N+M$-dimensional power vector attained upon convergence with $N$ primary users and $M$ secondary users. Since $\partial P_i / \partial I_{-i} > 0 : i \in \mathsf{P}$ and $\partial \mathrm{SIR}_i^{\mathrm{tar}} / \partial I_{-i} = 0 : i \in \mathsf{P}$, the notion of the network being infeasible is synonymous with $\lim_{k \longrightarrow \infty} P_i(k) \longrightarrow \infty : i \in \mathsf{P}$. It is sufficient to show that our conjecture will be true for the two extreme scenarios. First, consider the case of all $M$ secondary users being able to be supported by the network. This would correspond to a steady-state point with $\mathrm{SIR}_i = \mathrm{SIR}_i^{\mathrm{tar}} : i \in \mathsf{P}$ and $P_i^{2*} > P_i^{1*} : i \in \mathsf{P}$ since the advent of $M$ secondary users will increase the interference in the network and we have $\partial P_i / \partial I_{-i} > 0 : i \in \mathsf{P}$. Now consider the other extreme case where none of the $M$ secondary users can be supported by the network. The requirement that $\partial P_i / \partial I_{-i} < 0 : i \in \mathsf{S}$ would ensure that the interference witnessed by each primary user will not have diverged to infinity at the expense of having $P_i^{2*} = P_i^{\min} = 0\,\mathrm{mW} : i \in \mathsf{S}$ and thus $\widetilde{\mathrm{SIR}}_i^{\mathrm{tar}} = 0 : i \in \mathsf{S}$. Hence, we have proved that our above conjecture will hold for the two extreme cases. Any intermediate case will have $\mathsf{r} = |\mathsf{R}|$ secondary users from the set $\mathsf{R} \subset \mathsf{S}$ opting out and transmitting with minimal allowable power. The feasible network will have $M - \mathsf{r}$ secondary users achieving target SIR values of $\widetilde{\mathrm{SIR}}_i^{\mathrm{tar}} > 0 : i \in \mathsf{R}^{\mathsf{c}} \cap \mathsf{S}$ and $N$ primary users attaining their target SIR values of $\mathrm{SIR}_i^{\mathrm{tar}} : i \in \mathsf{P}$ with $P_i^{2*} > P_i^{1*} : i \in \mathsf{P}$. ■

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 2:* With a DPCPC policy, the entrance of secondary users will only adversely affect the QoS of other secondary users

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[2] 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.

sharing the same spectrum. The resulting system will remain feasible with the QoS of the primary users undeterred.

*Proof:* 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 $\mathrm{SIR}_i^{\mathrm{tar}} : i \in \mathsf{P}$, while the $M$ secondary users have a QoS of $\widetilde{\mathrm{SIR}}_i^{\mathrm{tar}} : i \in \mathsf{S}$ prior to the admission of the $L$ secondary users. After the entrance of the $L$ secondary users, the resultant network will be feasible if

$$\max_{\mathbf{x}\geq 0,\, \mathbf{x}\neq 0} \; \min_{1\leq i\leq N+M+L,\, x_i\neq 0} \left\{ \frac{1}{x_i}\sum_{j=1}^{N} A(i,j)x_j + \frac{1}{x_i G_{ii}} \sum_{j=N+1}^{N+M+L} \widetilde{\mathrm{SIR}}_i^{\mathrm{tar}} G_{ij}\, x_j \right\} < 1. \quad (10)$$

We deduce that the network will be feasible with the entrance of $M+L$ secondary users since we have proved feasibility with the entrance of $M$ secondary users in Theorem 1. Define $\mathbf{p}^{1*}$ as the $N+M$-dimensional vector attained upon convergence with the $N$ primary users and $M$ secondary users, and define $\mathbf{p}^{2*}$ as the $N+M+L$-dimensional power vector attained upon convergence with the $N$ primary users and $M+L$ secondary users. Note that the advent of $L$ secondary users will cause an increase in the perceived interference of every user. We shall have $\mathrm{SIR}_i = \mathrm{SIR}_i^{\mathrm{tar}} : i \in \mathsf{P}$ and $P_i^{2*} > P_i^{1*} : i \in \mathsf{P}$ since $\partial \mathrm{SIR}_i^{\mathrm{tar}}/\partial I_{-i} = 0 : i \in \mathsf{P}$ and $\partial P_i/\partial I_{-i} > 0 : i \in \mathsf{P}$, respectively. We recall that $\partial \mathrm{SIR}_i^{\mathrm{tar}}/\partial I_{-i} < 0 : i \in \mathsf{S} \cup \mathsf{V}$. Thus, the $M$ previously existing secondary users will attain a QoS of $\underline{\mathrm{SIR}}_i^{\mathrm{tar}} : i \in \mathsf{S}$ where $\underline{\mathrm{SIR}}_i^{\mathrm{tar}} < \widetilde{\mathrm{SIR}}_i^{\mathrm{tar}} : i \in \mathsf{S}$, and the $L$ recently admitted secondary users will have a QoS of $\widetilde{\mathrm{SIR}}_i^{\mathrm{tar}} : i \in \mathsf{V}$. With DPCPC, it may be that $\mathsf{r} = |\mathsf{R}|$ secondary users from the set $\mathsf{R} \subset \emptyset \cup \mathsf{S} \cup \mathsf{V}$ will have opted out upon convergence. The $M + L - \mathsf{r}$ secondary users in the set $\mathsf{R}^c$ may consist of any combination of secondary users from $\mathsf{S}$ and $\mathsf{V}$. 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 (with power vector $\mathbf{p}^{1*}$) prior to the entrance of the $L$ additional 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. The accommodation of each secondary will increase the transmit power of every primary. A resultant increase in energy expenditure and battery drain is inevitable. There is also an interesting notion regarding the possible protection[3] 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 challenge in etiquette design for cognitive radio is providing an effective means for opportunistic spectrum access by secondary network users. The opportunism offered by DPCPC is best illustrated by considering the network dynamics when primary users become dormant. In such a scenario, a nonopportunistic power-control policy would see a secondary user continue fulfilling a static target SIR while an opportunistic policy would demand that a secondary user be more ambitious by increasing its target QoS.

*Lemma 1:* With a DPCPC policy, the dormancy of primary users will lead to a power allocation such that we have the following.

1) The remaining primary users maintain their target QoS while conserving transmit power.
2) The secondary users improve their QoS.

*Proof:* We denote the set of dormant users by $\mathsf{D} \subset \mathsf{P}$ with $\mathrm{d} = |\mathsf{D}|$. The absence of $\mathrm{d}$ users' signals will lead to a reduction in the perceived interference seen by each network user. Since the Pareto optimal solution to (5) involves the primary users meeting their target SIR with equality, each primary user will continue to satisfy its target QoS of $\mathrm{SIR}_i^{\mathrm{tar}} : i \in \mathsf{P}$ while requiring less transmit power to do so via $\partial P_i/\partial I_{-i} > 0 : i \in \mathsf{P}$. For the second item, we note that $\partial \widetilde{\mathrm{SIR}}_i/\partial I_{-i} < 0$, thus confirming an increase in a secondary user's target SIR with the decrease in perceived interference. ■

The above result is conditioned upon a primary user's dormancy. An opportunistic power-control policy should allow a secondary user to benefit from improvements in the wireless channel stemming from geographical variations.

*Corollary 1:* With a DPCPC policy, an improvement in the channel between a primary user and its intended receiver or a degradation in the channel between a primary user and the intended receiver of any other primary user will result in the following:

1) the primary users maintaining their target QoS while conserving transmit power;
2) the secondary users improving their QoS.

*Proof:* We make two observations. In the case of increasing $G_{ii} : i \in \mathsf{P}$, the $i$th primary user will need lower transmit power to attain $\mathrm{SIR}_i^{\mathrm{tar}}$. 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. In both scenarios, the decrease in the $i$th 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. The secondary users improve their QoS by increasing their target SIR via $\partial \widetilde{\mathrm{SIR}}_i/\partial I_{-i} < 0$. ■

It is noteworthy that the opportunism of DPCPC discussed above is achievable without the intervention of the LSS or the PNB. The fact that primary users and secondary users simultaneously benefit from dormancy is also appealing.

### 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 [13]–[15] have considered the integration of admission and power control. The caveat is that the aforementioned works have dealt exclusively with users of a single priority class. It is essential that fundamental aspects of existing admission control policies be reconsidered within the cognitive radio framework. Admission control works typically distinguish between two

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

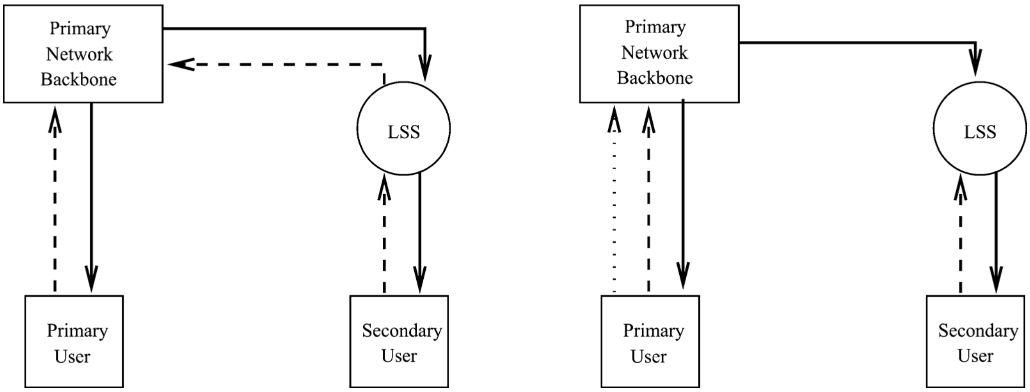

Fig. 2. Two architectures for admission control in a power-controlled cognitive radio network. The solid lines correspond to admission-related commands, the dashed lines indicate admission requests, and the dotted line represents a distress signal.

types of admission errors: a type-I error and a type-II error [14]. We conjecture that it is necessary to distinguish among the type-I and type-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 DPCPC policies. First, user $i \in \mathsf{S}$ transmitting with a minimal power level of $P_i^{\min} = 0$ corresponds to that user leaving the network, or performing *voluntary dropout* (VDO) [13]. Second, the opt-out state enables DPCPC to be viewed as providing *interactive admission control* [14]. It should be noted that interactive admission control does not fixate a specific admission criteria for a new user. Rather, a new arrival is permitted to interact with the active users before a decision is made. These two characteristics bring forth the following result.

*Theorem 3:* A DPCPC 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 cannot be accommodated would lead to the opting out of a subset of the $M + L$ secondary users. 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 2, which alludes to QoS protection). Thus, the composite network will be secondary-primary type-I error-free. A DPCPC policy is secondary type-II error-free since it allows for 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 Section III-A, we alluded to the possibility of the LSS regulating the admission of secondary users. Fig. 2 illustrates two possible admission control architectures for 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 [13] 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 its 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

Users in a cognitive radio network should be capable of performing dynamic power adaptation in a decentralized manner. While an LSS may govern a 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 works such as [16], which suggest 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 is uncertain whether the overhead would offset each individual user deploying an estimator and performing interference estimation. We believe it is sensible to initially restrict attention to DPCPC policies that require users to be efficient in requiring local information rather than relying on cooperation or the distribution of global information.

## IV. ETIQUETTE DESIGN VIA INTERFERENCE-AWARE POWER CONTROL

A general class of power-control algorithms for cognitive radio networks has been discussed thus far. A DPCPC policy is distinguished by the three axioms of Section III. We now discuss a specific power-control algorithm that satisfies the three axioms set forth by DPCPC. The AIPC algorithm was presented in [8] within the context of a multiple-access cellular network. We shall provide a brief overview of AIPC in prelude to a critique of how AIPC does the following:

- satisfies the DPCPC axioms;
- addresses the two desirable attributes proposed within the cognitive radio framework.

### *A. Overview of AIPC*

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

$$P_i(k+1) = P_i(k) + \alpha_i(k) I_{-i}(k) \tag{11}$$

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

$$\begin{aligned}\alpha_i^*(k) = &\left[\frac{1}{I_{-i}(k)G_{ii}(1+\rho_i I_{-i}^2(k+1))}\right]\Big[\rho_i I_{-i}^2(k+1)\\ &\times(-P_i(k)G_{ii} - I_{-i}(k+1))\\ &+ \mathrm{SIR}_i^{\mathrm{tar}} I_{-i}(k+1) - \mathrm{SIR}_i(k) I_{-i}(k)\Big]\end{aligned} \tag{12}$$

so as to minimize the convex cost function

$$J_i(k) = \rho_{i1} E_i^2(k+1) + \rho_{i2} I_i^2(k+1) \tag{13}$$

with $\rho_i \triangleq \rho_{i2}/\rho_{i1}$ in (12) and (13). The motivation behind (13) stems from an autonomous user adapting power so as to minimize cost. The SIR deviation alone is a cost that 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 transmit power. The positive weights $\rho_{i1}$ and $\rho_{i2}$ 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 its intended receiver. Within the context of power control, the benefits of predictive policies in providing improved robustness and convergence speed were initially motivated by [9] and [10]. Let $k^{\mathrm{ss}}$ denote the time instant at which the power-control algorithm has converged with the powers having reached their steady-state values. Upon the convergence of the AIPC algorithm, the $i$th user will have attained a modified target SIR of $\widetilde{\mathrm{SIR}}_i^{\mathrm{tar}} = \beta_i \mathrm{SIR}_i^{\mathrm{tar}}$, with

$$\beta_i = \max\left\{0,\ \frac{\mathrm{SIR}_i^{\mathrm{tar}} - \rho_i I_{-i}^2(k^{\mathrm{ss}})}{\mathrm{SIR}_i^{\mathrm{tar}}(1+\rho_i I_{-i}^2(k^{\mathrm{ss}}))}\right\} \in [0,1]. \tag{14}$$

Note that $\widetilde{\mathrm{SIR}}_i^{\mathrm{tar}} \leq \mathrm{SIR}_i^{\mathrm{tar}}$ with equality holding for $\rho_i = 0$ (in which case $\beta_i = 1$). 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 2:* In the case of $\rho_i = 0$, the AIPC policy reduces to the Foschini–Miljanic algorithm. Thus, the $i$th user would have a hard target SIR constraint of $\mathrm{SIR}_i^{\mathrm{tar}}$. Such a user will adapt power with the sole purpose of satisfying its SIR constraint irrespective of the amount of interference in the network.

*Proof:* From (11)–(13), it can be verified that in the case of $\rho_i = 0$, the AIPC power update and objective function reduce to $P_i^*(k+1) = \mathrm{SIR}_i^{\mathrm{tar}} I_{-i}(k+1)/G_{ii}$ 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 $i$th user satisfy its target SIR with equality irrespective of perceived interference. The Foschini–Miljanic policy also requires that a user satisfy its target SIR with equality irrespective of interference. Furthermore, the power update with the Foschini–Miljanic algorithm is $P_i(k+1) = \mathrm{SIR}_i^{\mathrm{tar}} I_{-i}(k)/G_{ii}$. Thus, we conclude that in the scenario of $\rho_i = 0$, the AIPC reduces to a predictive version of the Foschini–Miljanic algorithm. ■

*Proposition 3:* In the case of $\rho_i > 0$, the $i$th user will seek a soft target SIR constraint of $\widetilde{\mathrm{SIR}}_i^{\mathrm{tar}}$. In effect, the user will attain a modified target QoS of $\widetilde{\mathrm{SIR}}_i^{\mathrm{tar}} < \mathrm{SIR}_i^{\mathrm{tar}}$, with $\widetilde{\mathrm{SIR}}_i^{\mathrm{tar}}$ decreasing with interference.

*Proof:* We note from (14) that for $\rho_i > 0$, we shall have $\beta_i < 1$. A decrease in a user's target SIR with an increase in perceived interference is asserted via $\partial\beta_i/\partial I_{-i} = -2\rho_i I_{-i}(1+\mathrm{SIR}_i^{\mathrm{tar}})/\mathrm{SIR}_i^{\mathrm{tar}}(1+\rho_i I_{-i}^2)^2 < 0$. ■

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

*Lemma 2:* Upon the convergence of the AIPC policy, the transmit powers of the $N$ network users will reach a Nash equilibrium.

*Proof:* With AIPC, the $i$th 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 $\mathbf{p}(k) = [P_1(k), P_2(k), \ldots, P_N(k)]$ and $\rho_i = \rho_{i2}/\rho_{i1}$. Upon the convergence of the AIPC algorithm, the power vector $\mathbf{p}^*$ constitutes a Nash equilibrium if $J_i(P_1^*, \ldots, P_i^*, \ldots, P_N^*) \leq J_i(P_1^*, \ldots, P_i, \ldots, P_N^*)\,\forall i$. Applying the necessary condition for a Nash equilibrium, we obtain $\partial J_i/\partial P_i = (\rho_{i1}(P_i G_{ii} - \mathrm{SIR}_i^{\mathrm{tar}} I_{-i}))/(I_{-i}^2) + \rho_{i2}(P_i G_{ii} + I_{-i}) = 0.$

Solving the aforementioned expression for $P_i$ yields the condition $P_i^{\text{Nash}} = I_{-i}(\text{SIR}_i^{\text{tar}} - \rho_i I_{-i}^2)/G_{ii}(1 + \rho_i I_{-i}^2)$. It was shown in Proposition 3 that upon convergence of AIPC, the $i$th user will attain an SIR of $\widetilde{\text{SIR}}_i^{\text{tar}} = \beta_i \text{SIR}_i^{\text{tar}}$. Since $\widetilde{\text{SIR}}_i^{\text{tar}} = P_i^* G_{ii}/I_{-i}$, we have $P_i^* = \beta_i I_{-i} \text{SIR}_i^{\text{tar}}/G_{ii}$, with $\beta_i$ given by (14). We note that $P_i^* = P_i^{\text{Nash}}$ so long as the physical restriction of transmit power being nonnegative is satisfied. ■

The opt-out scenario in AIPC warrants attention. It was shown in [8] that the $i$th user with $\rho_i > 0$ and $P_i^{\min} < P_i(k)$ will transmit with a minimum allowable power level of $P_i^{\min}$ at time $k + 1$ if

$$I_{-i}(k) > \max\left\{\frac{P_i^{\min} - P_i(k)}{\alpha_i^*(k)}, \ \frac{\text{SIR}_i^{\text{tar}} I_{-i}(k+1)}{\text{SIR}_i(k)} - \frac{\rho_i I_{-i}^2(k+1)\left(P_i(k)\, G_{ii} + I_{-i}(k+1)\right)}{\text{SIR}_i(k)}\right\}. \tag{15}$$

This indicates that a 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

$$I_{-i} \geq \sqrt{\frac{\text{SIR}_i^{\text{tar}}}{\rho_i}} \tag{16}$$

would be transmitting with a minimal power level of $P_i^{\min}$. Inspection of (15) and (16) reveals the threshold at which dormancy occurs as being heavily dependent on the value of $\rho_i$. In fact, the decrease of the opt-out threshold with increasing $\rho_i$ indicates a lower interference tolerance level before the $i$th user decides to opt out.

### *B. Essential Attributes: QoS Protection, Opportunism, Admissibility, and 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. More specifically, a user requires knowledge of the current (estimated) and the next-step (predicted) values for the perceived interference. The following result states that AIPC allows for etiquette to be imposed in part by the users and in part by the LSS.

*Theorem 4:* The AIPC algorithm is a DPCPC policy so long as $I_{-i} > \sqrt{\text{SIR}_i^{\text{tar}}/\rho_i}/\left(\sqrt{\text{SIR}_i^{\text{tar}} + \rho_i I_{-i}^2 + 3}\right)$ for $\rho_i > 0$.

*Proof:* It was shown in Proposition 2 that the assignment $\rho_i = 0$ condenses AIPC to a predictive version of the Foschini–Miljanic algorithm for the $i$th user. It was shown in [3] that for a feasible network, the Foschini–Miljanic algorithm will reach a steady-state power vector such that the users meet their target SIR values with equality. Thus, from the first constraint in (5), we note that for $i : \mathsf{P}$ we shall have $P_i^* G_{ii} = \text{SIR}_i^{\text{tar}} I_{-i}$. With the target QoS of a primary user being a static constant, we have $\partial P_i^*/\partial I_{-i} > 0 : i \in \mathsf{P}$. In the case of secondary users, from the second constraint in (5), it is noted that for $i \in \mathsf{S}$ we shall have $P_i^* G_{ii} = \widetilde{\text{SIR}}_i^{\text{tar}} I_{-i}$, or equivalently $P_i^* G_{ii} = \beta_i \text{SIR}_i^{\text{tar}} I_{-i}$. Substitution of (14) allows us to obtain $P_i^* = \max\left\{P_i^{\min},\ I_{-i}(\text{SIR}_i^{\text{tar}} - \rho_i I_{-i}^2)/G_{ii}(1 + \rho_i I_{-i}^2)\right\}$, from which we evaluate $\partial P_i^*/\partial I_{-i} = (\text{SIR}_i^{\text{tar}} - \rho_i I_{-i}^2(\text{SIR}_i^{\text{tar}} + \rho_i I_{-i}^2 + 3))/G_{ii}(1 + \rho_i I_{-i}^2)^2$. It can be observed that $\partial P_i^*/\partial I_{-i} \gtrless 0$ for $\sqrt{\text{SIR}_i^{\text{tar}}/\rho_i} \gtrless I_{-i}\sqrt{\text{SIR}_i^{\text{tar}} + \rho_i I_{-i}^2 + 3}$, and $P_i^* = P_i^{\min}$ for $I_{-i} \geq \sqrt{\text{SIR}_i^{\text{tar}}/\rho_i}$. This states that a secondary user will either decrease power with a decreasing level of perceived interference, or increase power with a decreasing level of perceived interference before eventually opting out when $I_{-i} \geq \sqrt{\text{SIR}_i^{\text{tar}}/\rho_i}$. Hence, AIPC satisfies Axiom 3, and AIPC satisfies Axiom 1 if $\sqrt{\text{SIR}_i^{\text{tar}}/\rho_i} < I_{-i}\sqrt{\text{SIR}_i^{\text{tar}} + \rho_i I_{-i}^2 + 3}$ for $\rho_i > 0$. Next, it can be confirmed that $\partial\beta_i/\partial I_{-i} \gtrless 0 \Rightarrow \partial\widetilde{\text{SIR}}_i^{\text{tar}}/\partial I_{-i} \gtrless 0$. In the proof of Proposition 3, it was shown that for the $i$th secondary user, $\partial\beta_i/\partial I_{-i} < 0$ since $\rho_i > 0$. In the case of a primary, we have $\partial\beta_i/\partial I_{-i} = \partial\widetilde{\text{SIR}}_i^{\text{tar}}/\partial I_{-i} = 0$ since $\rho_i = 0$. Hence, AIPC satisfies Axiom 2. ■

Since the AIPC algorithm does not strictly satisfy Axiom 1, a more precise description of the opportunism offered by AIPC is necessary. We provide the following result without proof since it can be readily derived from the points raised in the proof of Lemma 1, Theorem 4, and Corollary 1.

*Corollary 2:* With AIPC, the dormancy of primary users, an improvement in the channel between a primary user and its intended receiver, or a degradation in the channel between a primary user and the intended receiver of any other primary user will result in a power allocation such that we have the following.

1) The remaining primary users maintain their target QoS while conserving transmit power.
2) The secondary users improve their QoS.
3) The $i$th secondary user conserves transmit power if $I_{-i} < \sqrt{\text{SIR}_i^{\text{tar}}/\rho_i}/\left(\sqrt{\text{SIR}_i^{\text{tar}} + \rho_i I_{-i}^2 + 3}\right)$.

In the discussion of AIPC, we have aimed to stress a user's adaptation of transmit power in response to perceived interference. The utility of AIPC has been advocated as far as enabling a secondary user to opportunistically use the spectrum after sensing the environment. The sensing corresponds to a user performing interference estimation and prediction prior to performing a power update.

### *C. Desirable Attribute: Licensing*

In the primary-secondary sharing paradigm, it has been stated that applications that 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. 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 $i$th secondary user. It is essential that the primary network interact with the LSS during this process 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,[4] respectively. Furthermore, the "degree" of a user's license is dictated by its assigned $\rho_i$ value. For instance, an increase in $\rho_i$ dictates

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[4] It can be verified from (16) that a user with $\rho_i = \infty$ will transmit with minimal allowable power $P_i^{\min}$ irrespective of its channel state $I_{-i}$.

a reduction to the $i$th user's spectrum rights in light of the resultant decrease in its soft QoS constraint. The $i$th secondary user would not be entitled to change $\rho_i$, much the same as a user would not be entitled to unilaterally upgrade its license. Naturally, the primary user with $\rho_i = 0$ has exclusive access to the spectrum in the sense of being entitled to introduce an unlimited amount of interference in order to satisfy a stringent QoS constraint.

### D. Desirable Attribute: Versatility

Resource allocation for cognitive radio remains a relatively unexplored area. It is yet to be determined whether it is more sensible for network users to deploy distinct resource allocation policies, or deploy a single sophisticated policy versatile enough to be fine-tuned to suit users of distinct priority classes. A consequence of network users deploying drastically distinct power-control algorithms lies in the fact that it is not evident if issues such as QoS protection, opportunism, or even the feasibility of the network can be analytically investigated (or assured) *a priori*. At the same time, the dynamics of a unified power-control algorithm should be flexible enough to distinguish among differing requirements such as ensuring the QoS of primary users and prioritizing among opportunistic secondary users. In the design of such versatile power-control policies, we postulate that a user's objective function should incorporate multiple criterion. The multicriterion objective function (13) was proposed with the purpose of allowing for differing dynamics among users. With AIPC, the differentiation occurs among two classes of network users: those with $\rho_i = 0$ and those with $\rho_i > 0$. In effect, versatility circumvents issues that may be associated with primary users deploying a power-control algorithm such as [3] and the secondary users deploying utility-based policies such as [11].

## V. SIMULATION RESULTS

In this section, the dynamics of DPCPC policies are evaluated by considering a wireless network composed of primary and secondary users. We shall specifically consider the AIPC algorithm. This algorithm was proven to be a DPCPC policy and was shown to satisfy the desirable attributes of licensing and versatility. The primary network shall consist of the uplink of a cellular CDMA system with voice users having a hard QoS constraint of $\mathrm{SIR}_i^{\mathrm{tar}} = 5 : i \in \mathsf{P}$. The backbone of the primary network is a 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 $\mathrm{SIR}_i^{\mathrm{tar}} = 10 : i \in \mathsf{S}$. The use of a linear receiver allows the $i$th user's SIR to be defined as

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

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

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

A frequently used path-loss model for terrestrial radio is $h_i = P_{\mathrm{R}}\left(d_{\mathrm{R}}/d_i\right)^n = A/d_i^n$, where $d_{\mathrm{R}}$ is a reference distance, $P_{\mathrm{R}}$ is the received power at the reference distance, $d_i$ is the distance between the $i$th 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 [18]. 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 $P_i(0) = P_i^{\min} = 0.0$ mW. In the admission of secondary users, we restrict attention to the second scheme in Fig. 1. 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 its target QoS will send a distress signal to the base station.

In an autonomous system, the dynamics of the $i$th user's perceived interference is given by

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

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 $i$th user via a feedback channel from its intended receiver. The stochastic disturbances' variances are denoted 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

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

If the $i$th user deploys a Kalman filter, we shall have $K_i(k) = B_i(k)/\left(B_i(k) + V_i(k)\right)$ with $B_i(k+1) = B_i(k) - B_i^2(k)(B_i(k) + V_i(k))^{-1} + W_i(k)$. For clarity in the illustration of the DPCPC 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 above simulation model is general enough to be applicable to a CDMA wireless ad hoc network. Specifically, a cluster head [25] or a supernode [26] would supplant the base station as the primary network backbone. Also, the primary and secondary users would be licensed and unlicensed devices, respectively, constituting transmitter–receiver pairs across a geographical area.

The power and SIR evolution of the users is shown in Fig. 3, with all users adapting power according to the AIPC policy.

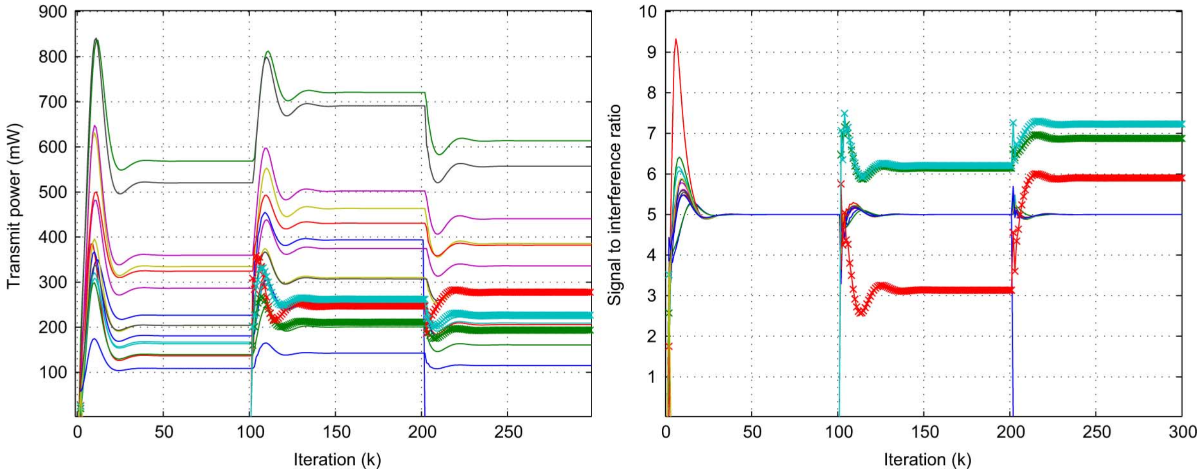

Fig. 3. Dynamics of the transmit power and SIR of the primary and secondary users with a DPCPC policy. The solid lines correspond to the primary users, while the thick lines correspond to the secondary users. A target SIR of $\mathrm{SIR}_i^{\mathrm{tar}} = 5$ was specified for each primary user. The network consisted of $N = 15$ primary users during $0 < k \leq 100$, $N = 15$ primary users and $M = 3$ secondary users 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 $k = 100$.

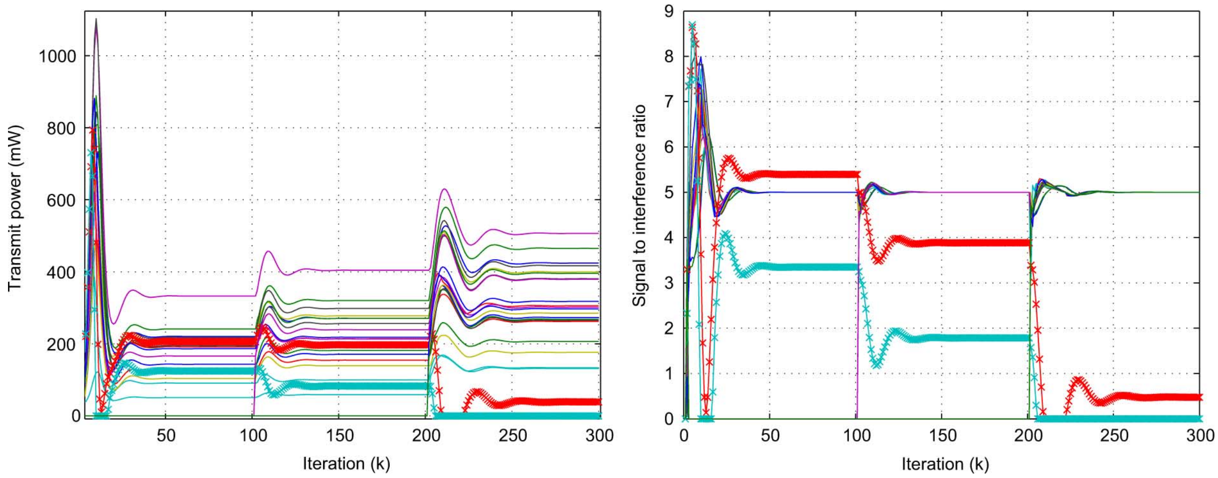

Fig. 4. Dynamics of the transmit power and SIR of the primary and secondary users with a DPCPC policy. The solid lines correspond to the primary users, while the thick lines correspond to the secondary users. A target SIR of $\mathrm{SIR}_i^{\mathrm{tar}} = 5$ was specified for each primary user. The network consisted of $N = 15$ primary users and $M = 2$ secondary users during $0 < k \leq 100$, $N = 17$ primary users and $M = 2$ secondary users for $100 < k \leq 200$, and $N = 21$ primary users and $M = 2$ 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 $k = 0$.

The first time interval consists of $0 < k \leq 100$, with the network being composed 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 AIPC, we note that the primary users maintain their hard QoS constraint of $\mathrm{SIR}_i^{\mathrm{tar}} = 5 : i \in \mathsf{P}$, albeit while transmitting with 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 $\widetilde{\mathrm{SIR}}_i^{\mathrm{tar}} \leq \mathrm{SIR}_i^{\mathrm{tar}}$ 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 nondormant primary users maintain their SIR constraint while conserving power. In effect, the second time interval illustrates the QoS protection offered by DPCPC policies, whereas the third time interval illustrates opportunism. The dormancy of the primary user during the third time interval may have been due to the user having no traffic to transmit. With AIPC, a primary user striving to be dormant would amend its target QoS to $\mathrm{SIR}^{\mathrm{tar}} = 0$, leading to a transmit power of 0 mW.

We examine a second random realization of the user locations and codewords with the purpose of critiquing the admissibility offered by a DPCPC policy with the entrance of primary users into the network. Fig. 4 shows the power and SIR evolution with the users adapting power according to the AIPC algorithm. In the first time interval of $0 < k \leq 100$, the network is composed of $N = 15$ primary users and $M = 2$ secondary users. The primary users satisfy their stringent SIR constraints

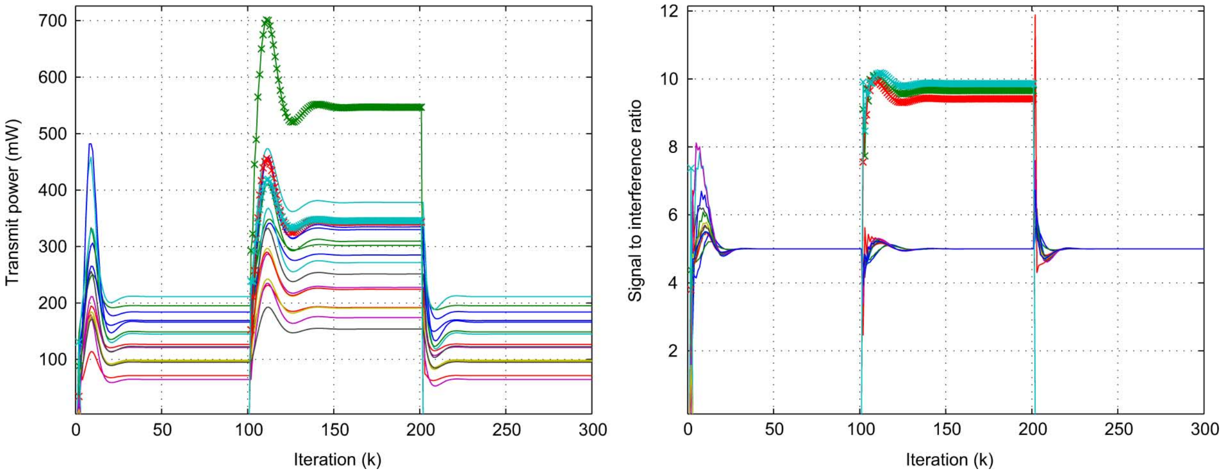

Fig. 5. Dynamics of the transmit power and SIR of the primary and secondary users with a DPCPC policy. The solid lines correspond to the primary users, while the thick lines correspond to the secondary users. A target SIR of $\mathrm{SIR}_i^{\mathrm{tar}} = 5$ was specified for each primary user. The network consisted of $N = 15$ primary users during $0 < k \leq 100$, $N = 15$ primary users and $M = 3$ secondary users for $100 < k \leq 200$, and $N = 15$ primary users for $200 < k \leq 300$. 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 $k > 200$.

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 value of $\widetilde{\mathrm{SIR}}_i^{\mathrm{tar}} \leq \mathrm{SIR}_i^{\mathrm{tar}} = 10 : i \in S$. 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 additional 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 $P_{17}^{\min} = 0$ mW. This secondary user has experienced condition (15) for $k \geq 210$ and $I_{-17} \geq \sqrt{\mathrm{SIR}_{17}^{\mathrm{tar}}/\rho_{17}}$ upon convergence of the AIPC algorithm. Aside from demonstrating the opt-out state of a DPCPC policy as a mechanism for interactive admission control, this example illustrates the distinct differentiation in QoS priority enforced among 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 $0 < k \leq 100$, the network is composed 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 $100 < k \leq 200$, 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% among the primary users. A primary user transmits a distress signal to its intended receiver (or equivalently the base station in this case) 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 an 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 $200 < k \leq 300$ as we have $P_i^* = P_i^{\min} = 0$ 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 relatively aggressive secondary users. Thus far, we have examined the deterministic evolution of a DPCPC policy in allowing for etiquette to be imposed in accordance with the discussion in Section III. The robustness of AIPC to stochastic impairments such as stochastic link gains and noisy feedback measurements has been investigated and quantified in [8]. Our focus here is quite different in that, within the cognitive network framework, we would like to examine the deterioration caused by potentially nonrobust 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 in (19) acts locally on the received feedback of the $i$th user, and hence its 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 $i$th 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 $i$th user. With $\{G_{ij}(k)\}$ and $\{g_{ij}\}$ being Gaussian, 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

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

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.

We deem a user as robust if it uses the Kalman filter in (20) for interference estimation in conjunction with (24). The nonrobustness of the $i$th secondary user will correspond to that user performing interference estimation and prediction via $\hat{I}_{-i}(k) = \frac{1}{K-1}\sum_{n=k-K+1}^{k-1} Y_i(n)$ and $\hat{I}_{-i}(k+1) = Y_i(k)$, respectively. It is clear that the QoS of a secondary user will suffer if that user is nonrobust (i.e., unable to obtain a reliable estimate of its perceived interference). It is not clear to what extent nonrobust secondary users would degrade the performance of primary users. Thus, we are primarily interested in investigating the impact of nonrobust secondary users on the QoS of primary users. We define a primary user's *outage rate* as the percentage of time during which that user's attained SIR is below 95% of the target value. The mean outage rate of the primary users will be examined for three different instances of the CDMA system:

- Case 1: no secondary users;
- Case 2: $M = 5$ robust secondary users;
- Case 3: $M = 5$ nonrobust secondary users.

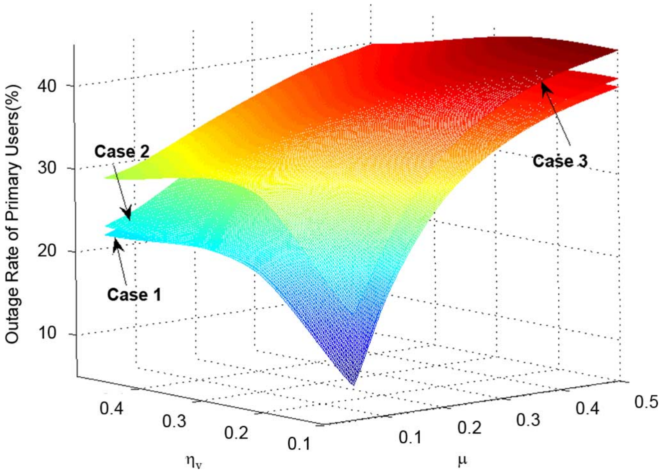

Fig. 6. Comparative analysis of the mean outage rate obtained by $N = 15$ primary network users with differing degrees of variation in the stochastic link gains and the measurement noise. Three distinct cases were considered: Case 1 consisted of no secondary network, Case 2 involved $M = 5$ secondary users with Kalman filters, and Case 3 consisted of $M = 5$ secondary users without estimators. Each secondary user was assigned $\rho_i = 200 : i \in \mathsf{S} = \{16, 17, \ldots, 20\}$ by the LSS.

The $M = 5$ secondary users will be assigned $\rho_i = 200 : i \in \mathsf{S} = \{16, 17, \ldots, 20\}$ by the LSS. The mean outage rate of the $N = 15$ primary users is shown in Fig. 6 for differing degrees of variation in the link gains (with $\mu = \mu_1 = \mu_2$) and measurement noise. The degree of similarity between the mean outage rate obtained for Cases 1 and 2 indicates that the presence of secondary users has minimal effect on the robustness of the primary users. This is expected since we have shown in Section III that DPCPC policies allow for QoS protection within a deterministic framework. Fig. 6 indicates that robust secondary and primary users can coexist in a stochastic environment without deterioration to the QoS of the primary users. As in the deterministic setting, coexistence within a stochastic framework is conditional upon the primary users not objecting to the increase in transmit power caused by the entrance of secondary users. With a DPCPC policy, primary user discontent is rectified via transmission of distress signals to the PNB. The disparity in the mean outage rates between Cases 2 and 3 warrant attention. An increase in mean outage rate of up to 10% is noted among primary users when comparing the scenario of robust secondary users to that of nonrobust secondary users. One can expect a user to adapt power in erratic fashion when provided with unreliable interference estimates. Such volatile power adaptation by secondary users would adversely affect the QoS of the primary users by increasing the variance of their perceived interference. Thus, within a stochastic environment, the QoS of the primary users can be noticeably deteriorated by the nonrobustness of secondary users. Fig. 6 also illustrates the applicability of the AIPC algorithm in the scenario of the channel changing as rapidly as the rate at which power updates are performed.

## VI. POWER-CONTROLLED INTERFERENCE TEMPERATURE CONSIDERATION AND SPECTRUM HOLE TRANSMISSION

The notions of a spectrum hole, interference temperature, and interference temperature limit have been discussed in a unified manner by Haykin in [2]. The aim of this section is to discuss the operation of DPCPC policies with respect to these three notions. We first quote from Haykin:

> *"... the FCC Spectrum Policy Task Force [12] 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."*

This highlights 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 $\Gamma$ as the interference temperature limit discussed by Haykin, and note that this is analogous to our notion of a secondary user's opt-out threshold. In the specific case of AIPC, from the condition set forth by (16), we shall have

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

with the $i$th secondary user[5] transmitting at $P_i^{\min}$ when $I_{-i} \geq \Gamma$. In essence, (25) provides a connection between the interference temperature limit and a set of tunable priority levels assigned to secondary users by the LSS. With AIPC, a transient interpretation of the enforcement of an interference temperature limit may be obtained from (15). The autonomous nature of AIPC allows for enforcement of an interference temperature limit without centralization or extensive overhead. The limiting scenario of $\Gamma = 0$ corresponds to the primary network refusing to tolerate secondary interference. We deem it sensible that $\Gamma$ be assigned by the PNB 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 is sensible that an LSS located in a geographical region where secondary user interference is tolerated should have a high value for $\Gamma$. Conversely, an LSS with a low value of $\Gamma$ should correspond to a region where secondary user interference is not very welcome. Lastly, an LSS with $\Gamma = 0$ denotes an exclusive region where no secondary transmission is allowed. Fig. 7 illustrates the interaction of the PNB, LSS, and the network users as discussed in this section within the context of AIPC. Such constructive interaction is possible because a DPCPC policy (AIPC in this case) is capable of differentiating among the dynamics of primary and secondary users. 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 from [2] is a spectrum hole:

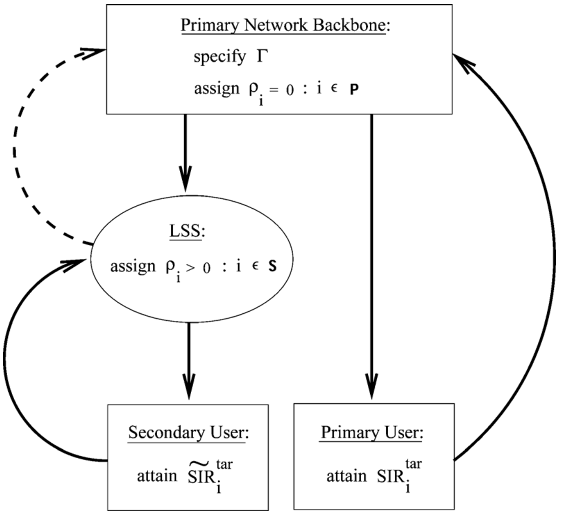

Fig. 7. Interaction among the PNB, LSS, and network users with AIPC. Solid lines denote required interaction, and the dashed line denotes optional interaction.

> *"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 on the detection of spectrum holes via statistical signal processing techniques was provided in [2]. Our methodology is quite different since, with DPCPC, a secondary user need not remain dormant until the detection of a spectrum hole. Rather, a secondary user may transmit so long as the interference temperature limit is not exceeded. For the following proposition, we shall assume a common thermal noise floor of $\eta = \eta_i \, \forall \, i$.

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

*Proof:* It can be verified from (14) that with $I_{-i} = \eta$, we shall have $\beta_i = \max\{0, (\mathrm{SIR}_i^{\mathrm{tar}} - \rho_i\eta^2)/(\mathrm{SIR}_i^{\mathrm{tar}}(1+\rho_i\eta^2))\}$. The attained SIR and transmit power follow via $\widetilde{\mathrm{SIR}}_i^{\mathrm{tar}} = \beta_i \mathrm{SIR}_i^{\mathrm{tar}}$ and $P_i^* = \beta_i I_{-i} \mathrm{SIR}_i^{\mathrm{tar}}/G_{ii}$. ■

Two noteworthy implications follow this result. First, only one secondary user (e.g., user $i$) will be able to transmit during a spectrum hole since, with $\Gamma = \eta$, the $j$th secondary user shall experience $\Gamma < P_i^* G_{ji} + \eta \quad \forall \, j \neq i$. Second, the transmitting user will attain $\widetilde{\mathrm{SIR}}_i^{\mathrm{tar}} \approx \mathrm{SIR}_i^{\mathrm{tar}}$ since in general $\mathrm{SIR}_i^{\mathrm{tar}} \gg \rho_i\eta^2$. It is difficult to envision a cognitive radio network with non-power-controlled users attaining the interference management and etiquette discussed in this paper without a formidable level of intervention by the LSS and the PNB. Consequently, we

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

hope to have stressed the importance of intelligent power adaptation within the cognitive radio paradigm.

## VII. CONCLUSION

This paper presents the first axiomatic approach to power control in cognitive radio networks. Four attributes have been proposed as being essential of a power-control policy deployed by users in a cognitive radio network. The general class of DPCPC policies were introduced as addressing such essential attributes via an axiomatic framework. This was followed by a discussion of the AIPC algorithm as being a DPCPC policy and also satisfying the desirable licensing and versatility attributes presented in this paper.

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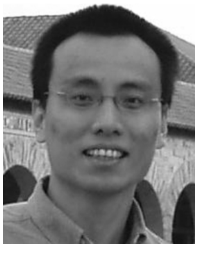

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