Power Control for Cognitive Radio Ad Hoc Networks†

Lijun Qian*, Xiangfang Li+, John Attia*, Zoran Gajic+

***Abstract*— While FCC proposes spectrum sharing between a legacy TV system and a cognitive radio network to increase spectrum utillization, one of the major concerns is that the interference from the cognitive radio network should not violate the QoS requirements of the primary users. In this paper, we consider the scenario where the cognitive radio network is formed by secondary users with low power personal/portable devices and when both systems are operating simultaneously. A power control problem is formulated for the cognitive radio network to maximize the energy efficiency of the secondary users and guarantee the QoS of both the primary users and the secondary users. The feasibility condition of the problem is derived and both centralized and distributed solutions are provided. Because the co-channel interference are from heterogeneous systems, a joint power control and admission control procedure is suggested such that the priority of the primary users is always ensured. The simulation results demonstrate the effectiveness of the proposed schemes.**

I. Introduction

Although the U.S. government frequency allocation data [1] shows that there is fierce competition for the use of spectra, especially in the bands from 0 to 3 GHz, it is pointed out in several recent measurement reports that the assigned spectrum are highly under-utilized [2], [4]. The discrepancy between spectrum allocation and spectrum use suggests that "spectrum access is a more significant problem than physical scarcity of spectrum, in large part due to legacy command-and-control regulation that limits the ability of potential spectrum users to obtain such access" [2]. In order to achieve much better spectrum utilization and viable frequency planning, Cognitive Radios (CR) are under development to dynamically capture the unoccupied spectrum [6], [7]. The Federal Communication Commission (FCC) has recognized the promising technique and is pushing to enable it to a full realization. As the first step, the FCC proposes to experiment unlicensed cognitive sharing in the TV bands (the VHF and UHF bands) [11], [12], [13]. The TV bands are chosen due to the better penetration of the frequency band, "strong" received signal of the primary TV users, and TV transmitters are left on more or less continuously, and infrequently change location or frequency [5].

Despite the advantages of using the TV bands for unlicensed cognitive spectrum sharing, there are some concerns to be solved first in order to convince FCC to finally open the TV bands. First, can secondary users (cognitive radio network) even operate without causing excessive interference to primary users (TV users)? Second, can certain quality-of-service (QoS) for secondary users be provided under such constraints? So far, most of the previous works address these two issues by time sharing the spectrum between the TV system and the cognitive radio network. In this case, there will be no co-channel interference. One of the main difficulties is to detect the presence of the TV signals accurately. Much work has been done in this area, such as [8], [10] and the references therein. In this paper, we consider a different case where the TV system and the cognitive radio network are ON simultaneously and they share the same spectrum through space separation. This case is mainly studied through MAC design, such as in [3]. Power control is only applied to address the non-intrusion to the services of the primary users [9], but not the QoS of the secondary users. We argue that the QoS of the secondary users is also very important [16]. If the capacity for the secondary users is not enough to realize their required QoS after meet the QoS constraints of the primary users, that channel might not be a good opportunity for secondary users to access.

According to the recent suggestions from the FCC [12], [13], two distinct types of unlicensed broadband devices may be used in the TV bands. One category will consist of lower power "personal/portable" unlicensed devices. The second category will consist of higher power "fixed/access" unlicensed devices that may provide wireless Internet access. This paper will consider the power control problem for the first category, and we focus on the case where both the TV system and the cognitive radio network operate simultaneously. The power control problem becomes tougher than that in cellular systems or pure wireless ad hoc networks because the interference tend to be more difficult to model and control in two heterogeneous systems. In this paper, we try to provide some preliminary analysis and design to address the two issues mentioned in the previous paragraph when two heterogeneous systems operate in the same channel at the same time. Specifically, a power control problem of the secondary users is formulated to maximize the energy efficiency of the secondary users and reduce the harmful interference to the primary users who have absolute priority. QoS guarantee of the secondary users is also included in the problem formulation. Feasibility conditions for the power control problem are highlighted and the corresponding joint power control and admission control procedures are provided.

The paper is organized as follows. Section II provides the model of spectrum sharing of a cognitive radio network with a TV broadcast system, and the associated power control problem is formulated. The solution of the power control

† This research work is supported in part by the National Science Foundation (NSF) under award HRD-0531507 and by the U.S. Army Research Office (ARO) under Cooperative Agreement No. W911NF-04-2-0054. Contents are solely the responsibility of the authors and do not necessarily represent the official views of the National Science Foundation, the Army Research Office or the U. S. Government.

* L. Qian and J. Attia are with Department of Electrical Engineering, Prairie View A&M University, Prairie View, TX 77446. Email: liqian, joattia@pvamu.edu

+X. Li and Z. Gajic are with WINLAB, Rutgers–The State University of New Jersey, Piscataway, NJ 08854. Email: xfli, gajic@winlab.rutgers.edu

Proceedings of the 2007 15th IEEE Workshop on Local and Metropolitan Area Networks

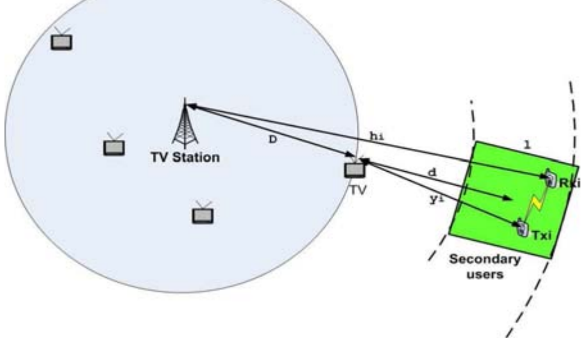

Fig. 1. An example of spectrum sharing of a cognitive radio network with a TV broadcast system.

problem for a single secondary transmitter is given in Section III. Both centralized and distributed power control algorithms are provided for the case of multiple secondary users in Section IV. The effectiveness of the proposed schemes is tested through simulations in Section V. Section VI contains the concluding remarks.

II. Model and Problem Formulation

Given an existing TV station with transmission power p_{TV}, the effective receiving range is D. The effective receiving range is defined by the successful decoding of the TV signals, i.e., the received signal-to-interference-plus-noise ratio (SINR) should be above a given threshold (10 dB or higher [5], that will depend on the type of TV station) such that the received TV signal is decodable. Note that the data of transmission power and effective receiving range of TV stations are publicly available, such as in [14], [15]. It is assumed that the secondary users locate in an $l \times l$ square area. The center of the cognitive radio network is d meters away from the nearest primary receiver. The distance from the TV station to the ith secondary receiver is h_i. y_i is the distance from the i^{th} secondary transmitter to the TV receiver at the border of the TV coverage area. An example of the model is given in Fig. 1, where only one pair of secondary users are shown. Note that although the effective receiving range of the TV station may not overlap with the transmission range of the cognitive radio network, the transmissions in both systems still cause non-negligible co-channel interferences to the other system's receivers. For instance, if both systems are ON simultaneously, the transmission from the secondary users will cause interference at the primary receivers and may cause the received TV signals degraded and become unacceptable. Hence, the co-channel interference is the major barrier for the successful co-existence of the two systems.

In this paper, we address the interference problem by considering the QoS at both the primary receivers and the secondary receivers in terms of the received SINR. Suppose there are totally N pairs of secondary users, and $p_{i,sec}$ is the transmission power of the i^{th} transmitter. Define the SINR at the m^{th} primary receiver as $\gamma_{m,TV}$, and the SINR at the i^{th} secondary receiver as $\gamma_{i,sec}$, the power control problem for energy efficiency maximization and interference suppression is formulated as follows

(P.1)

$$\min \sum_{i=1}^{N} p_{i,sec} \tag{1}$$

subject to

$$\gamma_{m,TV} \geq \gamma_{TV}^{tar}, \ \ \forall m \tag{2}$$

$$\gamma_{i,sec} \geq \gamma_{i,sec}^{tar}, \ \ i = 1, \cdots, N. \tag{3}$$

$$p_{sec}^{min} \leq p_{i,sec} \leq p_{sec}^{max}, \ \ i = 1, \cdots, N. \tag{4}$$

where γ_{TV}^{tar} and $\gamma_{i,sec}^{tar}$ are the target SINR for the primary receivers and the secondary receivers, respectively. p_{sec}^{min} and p_{sec}^{max} are the minimum and maximum allowable transmission power of the secondary users. These are "hard" limits including many considerations such as safety and hardware limitations that set by the standard organization or government agencies [13]. The objectives of power control in a cognitive radio network are to maximize the energy efficiency of the secondary users and suppress harmful interference to both the primary users and the secondary users. This can be achieved by minimizing the total transmission power of the secondary users (equation (1)) while guarantee both the QoS of the primary users (equation (2)) and the QoS of the secondary users (equation (3)).

III. Power control for a single secondary transmitter

In this section, a simple case where there is only *one* secondary transmitter will be considered. We will first check the feasibility of the power control problem **(P.1)**. We assume that the received power is only a function of the transmitted power and path loss, i.e., the fading effects (shadowing and small-scale fading) are omitted for now. We further assume that the path loss factor from the TV transmitter is α_1, and the path loss factor from the cognitive radio transmitter is α_2. Because the antenna height of the TV transmitter is usually several hundred meters higher [14] than that of the cognitive radio transmitters, it is expected that the path loss factor from the TV transmitter (α_1) will be better (smaller) than the path loss factor from the cognitive radio transmitter (α_2). The interference between the primary users and the secondary users depends on many factors such as modulation schemes and waveform design, and we assume the orthogonality factors are f_1 and f_2, respectively.

Based on the above assumptions, the SINR of the TV receiver at the worst location of the TV coverage area is (please refer to Fig. 1)

$$\gamma_{TV} = \frac{p_{TV}/D^{\alpha_1}}{f_2 p_{sec}/y^{\alpha_2} + \sigma^2} \tag{5}$$

and the SINR of the secondary receiver is

$$\gamma_{sec} = \frac{p_{sec}/r^{\alpha_2}}{f_1 p_{TV}/h^{\alpha_1} + \sigma^2} \tag{6}$$

where r is the distance between the secondary transmitter and the secondary receiver, σ^2 is the background noise.

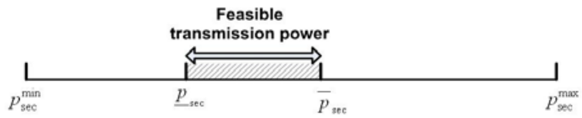

Fig. 2. Feasible transmission power of the secondary user.

In order to satisfy the two constraints on the primary and secondary SINR values, inequality (2) and (3), we need

$$p_{sec} \leq [\frac{p_{TV}}{D^{\alpha_1}\gamma_{TV}^{tar}} - \sigma^2] y^{\alpha_2}/f_2 \, , \tag{7}$$

and

$$p_{sec} \geq (f_1 p_{TV}/h^{\alpha_1} + \sigma^2)\gamma_{sec}^{tar} r^{\alpha_2} \, . \tag{8}$$

If the power control problem is feasible, equations (7), (8), and (4) have to be satisfied simultaneously.

Theorem 1: Given the transmission power of the primary transmitter (p_{TV}) and the background noise (σ^2), the target SINR values of the primary receiver and the secondary receiver (γ_{TV}^{tar} and γ_{sec}^{tar}), and the distances (D, y, h, r), the feasibility condition of the power control problem **(P.1)** for a single secondary transmitter is

$$\max\{p_{sec}^{min}, \underline{p}_{sec}\} \leq p_{sec} \leq \min\{\bar{p}_{sec}, p_{sec}^{max}\} \tag{9}$$

where $\bar{p}_{sec} = [\frac{p_{TV}}{D^{\alpha_1}\gamma_{TV}^{tar}} - \sigma^2] y^{\alpha_2}/f_2$ and $\underline{p}_{sec} = (f_1 p_{TV}/h^{\alpha_1} + \sigma^2)\gamma_{sec}^{tar} r^{\alpha_2}$.

The feasibility condition given in Theorem 1 may be interpreted as follows:

Collary 1: Define two transmission power sets, $S_1 = \{p_{sec}^{min} \leq p_{sec} \leq p_{sec}^{max}\}$, and $S_2 = \{\underline{p}_{sec} \leq p_{sec} \leq \bar{p}_{sec}\}$, the power control problem **(P.1)** for a single secondary transmitter is feasible iff $S_1 \cap S_2 \neq \emptyset$.

One possible case of feasible transmission power of the secondary user is shown in Fig 2. If the feasibility condition (inequality (9)) is satisfied, the optimal transmission power of the secondary user is $\max\{p_{sec}^{min}, \underline{p}_{sec}\}$. If the minimum allowable transmission power is 0, the optimal transmission power of the secondary user is $\underline{p}_{sec}$.

If the interference is dominant, i.e., if $f_2 p_{sec}/y^{\alpha_2} \gg \sigma^2$ and $f_1 p_{TV}/h^{\alpha_1} \gg \sigma^2$, which is usually the case, the sum of the SINR (in dB) of the TV receiver at the border of the TV coverage area and the SINR of the secondary receiver can be expressed as

$$\gamma_{TV}^{dB} + \gamma_{sec}^{dB} \approx \alpha_1 \frac{h}{D}(dB) + \alpha_2 \frac{y}{r}(dB) - [f_1 + f_2](dB) \, . \tag{10}$$

The achievable SINR of the secondary users can be estimated by substracting γ_{TV}^{tar} from the sum of the SINR.

It is observed that the sum of these two SINR values (in dB) is only a function of the relative distances. One example simulation result is plotted in Fig. 3. The parameters used in the simulation are given in Table I and it is assumed that $h \approx D + d$ and $y \approx d$ since $d \gg l$. It is observed that the distance between the secondary transmitter and the secondary receiver, r, has the dominant effect on the sum of the SINR values. For example, if r decreases from 300 meters ($\frac{r}{D} = 0.005$) to 60 meters ($\frac{r}{D} = 0.001$), the gain of the sum of the SINR values is about 30 dB. In addition, if r is large, say r is 480 meters ($\frac{r}{D} = 0.008$), even if the secondary user is far away from the TV coverage area (say, $\frac{d}{D} = 1$), the sum of the SINR values is still very low, about 30 dB. In other words, if the required primary SINR is 34 dB, the maximum achievable SINR for the secondary user is about -4 dB. The results suggest that only low power secondary users with short range transmissions (low power personal/portable devices [13]) are allowed when the primary users are ON. This also calls for multi-hop communications rather than single hop long range transmissions in the cognitive radio network.

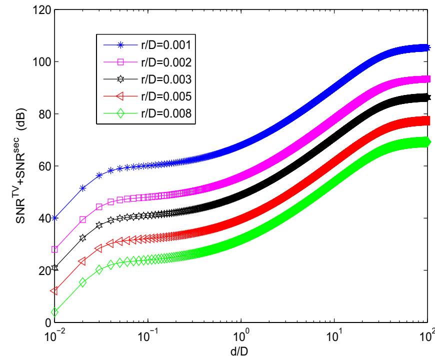

Fig. 3. The sum SINR values (in dB) vs. $\frac{d}{D}$ and $\frac{r}{D}$, $f_1 = 1, f_2 = 1$.

We would like to point out that although the transmission powers are not explicitly included in the formula for the sum SINR, they indeed will determine the proportion of the SINR that the primary user and the secondary user will get.

IV. Power Control for multiple secondary users

In this section, we are going to provide both centralized and distributed solutions to the power control problem **(P.1)**. In order to evaluate the interference and solve the power control problem, we assume that the distances such as d and y_i can be estimated accurately. Indeed, geolocation devices (e.g. GPS), control signals, or spectrum sensing may be applied to detect the primary transmissions and get an accurate estimate of the distances [13].

A. Centralized Solution

The SINR of the TV receiver at the worst location of the TV coverage area is

$$\gamma_{TV} = \frac{p_{TV}/D^{\alpha_1}}{f_2 \sum p_{i,sec}/y_i^{\alpha_2} + \sigma^2} \tag{11}$$

The SINR of the i^{th} secondary receiver is

$$\gamma_{i,sec} = \frac{g_{ii} p_{i,sec}}{\sum_{j \neq i} g_{ij} p_{j,sec} + f_1 p_{TV}/h_i^{\alpha_1} + \sigma^2} \tag{12}$$

where g_{ij} is the link gain from the j^{th} secondary transmitter to the i^{th} secondary receiver.

The following theorem gives the feasibility condition of the power control problem **(P.1)**.

Theorem 2: The power control problem **(P.1)** is feasible for all N simultaneous transmitting-receiving pairs of secondary users within the same channel as long as

(1). The matrix $[I - \Gamma_{sec}^{tar} Z]$ is non-singular (thus invertible);

(2). The transmission power vector p^*_{sec} satisfies inequality (4) element-wise, where

$$p^*_{sec} = [I - \Gamma^{tar}_{sec} Z]^{-1} u \ , \tag{13}$$

matrix Γ^{tar} is a diagonal matrix

$$\Gamma^{tar}_{sec ij} = \begin{cases} \gamma^{tar}_{i,sec} & i = j \\ 0 & otherwise \end{cases} , \tag{14}$$

matrix Z is the following nonnegative matrix

$$Z_{ij} = \begin{cases} \frac{g_{ij}}{g_{ii}} & i \neq j \\ 0 & i = j \end{cases} , \tag{15}$$

u is the vector with elements

$$u_i = \gamma^{tar}_{i,sec} \eta_i^2 / g_{ii}, \qquad i = 1, 2, ..., N \tag{16}$$

and

$$\eta_i^2 = f_1 p_{TV} / h_i^{\alpha_1} + \sigma^2 \ . \tag{17}$$

(3). The transmission power vector p^*_{sec} also satisfies the following inequality

$$\frac{p_{TV}/D^{\alpha_1}}{f_2 \sum p^*_{i,sec}/y_i^{\alpha_2} + \sigma^2} \geq \gamma^{tar}_{TV} \ . \tag{18}$$

Proof: A target SINR vector $\gamma^{\mathbf{tar}}$ is achievable for all simultaneous transmitting-receiving pairs of secondary users within the same channel if the following conditions are met [21], [17]

$$\gamma_{i,sec} \geq \gamma^{tar}_{i,sec} \tag{19}$$

$$p \geq 0 \tag{20}$$

where p is the vector of transmitting powers. Define η_i^2 as in equation (17). Replacing $\gamma_{i,sec}$ with equation (12) and rewriting the above conditions in matrix form gives

$$[I - \Gamma^{tar} Z] p \geq u \tag{21}$$

$$p \geq 0 \tag{22}$$

where matrix Γ^{tar}, matrix Z and vector u are defined in equations (14), (15), and (16), respectively.

It is shown in [17] that if the system is feasible, the matrix $[I - \Gamma^{tar} Z]$ must be invertible and the inverse should be element-wise positive, thus prove part (1) of the theorem.

It is also shown in [17] (Proposition 2.1) that if the system is feasible, there exists a unique (Pareto optimal) solution which minimize the transmitted power. This solution is obtained by solving a system of linear algebraic equations

$$[I - \Gamma^{tar} Z] p^* = u \tag{23}$$

In order to satisfy the constraints (2) and (4) in the power control problem **(P.1)**, the transmission power vector p^*_{sec} must satisfy the inequality (4) element-wise and the inequality (18), thus prove the theorem. ■

The above proof highlighted the centralized solution to the problem **(P.1)**. Although it seems that the power control problem **(P.1)** is similar to that in cellular systems [20] and in wireless ad hoc networks [23], the power control problem considered here addressed interference from *heterogeneous* systems and additional constraint (2) has to be satisfied and the interference between primary and secondary users has to be taken into account in the problem formulation. It also calls for joint design of power control and admission control for the cognitive radio network such that the QoS of the primary users is ensured all the time. The procedures of joint power control and admission control is summarized below.

Joint power control and admission control

1) Solve the transmission power vector p^*_{sec} using equation (13).
2) Check whether the transmission powers are within limit, i.e., $p^{min}_{sec} \leq p^*_{i,sec} \leq p^{max}_{sec}$, $\forall i$? If Yes, goes to the next step; otherwise, the power control problem **(P.1)** is not feasible. Remove the jth secondary user that has the largest $\sum_{i=1}^{N} [Z_{ij} + Z_{ji}]$ and return to Step 1 with reduced number of transmitters.
3) Check whether the transmission powers satisfy inequality (18). If Yes, set the transmission power vector as p^*_{sec}; otherwise, the power control problem **(P.1)** is not feasible. Remove the secondary user that requires the largest transmission power ($p = max\{p^*_{i,sec}\} \ \forall i$) and return to Step 1 with reduced number of transmitters.

It worth pointing out that Step 2 and 3 implement admission control for the secondary users. When the power control problem **(P.1)** is not feasible, the secondary user that caused the worst interference should be silenced. The central controller can verify the transmission power limits in a straight forward way in Step 2 after solving p^*_{sec} using equation (13). The worst interferer to other secondary users inside the cognitive radio network is the one that has the largest row and column sum of matrix Z. In Step 3, given that p_{TV}, γ^{tar}_{TV}, and D are publicly available data, and y_i can be estimated accurately, the central controller can verify the inequality (18). This time the worst interferer to the primary receivers is the one that has the largest transmission power since all the secondary transmitters have more or less the same distance to the primary receivers. In a cognitive radio network with centralized management, such as in a cluster based architecture, the above procedures may be implemented.

B. Distributed Solution

The centralized solution (equation (13)) needs a central controller and *global* information of all the link gains, and centralized power control requires extensive control signaling in the network and it is difficult to be implemented in practice, especially for an infrastructure-less wireless ad hoc network. Therefore, a distributed implementation which only use local information to make a control decision is proposed for realistic scenarios.

Distributed power control schemes may be derived by applying iterative algorithms to solve equation (23). For example, using the first-order Jacobian iterations [18], the following distributed power control scheme is obtained

$$p_{i,sec}(k+1) = \min\{\frac{\gamma^{tar}_{i,sec}}{\gamma_{i,sec}(k)} p_i(k), \ \ p^{max}_{sec}\} \ , i = 1, 2, ..., N. \tag{24}$$

Note that each node only needs to know its own received SINR at its designated receiver to update its transmission power. This is available by feedback from the receiving node through a control channel. As a result, the algorithm is fully distributed. Convergence properties of this type of algorithms were studied by Yates [19], [20]. An interference function $I(p)$ is standard if it satisfies three conditions: positivity, monotonicity and scalability. It is proved by Yates [19] that the standard iterative algorithm $p(k+1) = I(p(k))$ will converge to a unique equilibrium that corresponds to the minimum use of power. The distributed power control scheme (equation (24)) is a special case of the standard iterative algorithm.

Since the Jacobi iteration is a fixed-point iterative method, it usually has slow convergence speed to the sought solution. However, we select equation (24) as the power control algorithm in cognitive radio networks due to its simplicity. Other advanced algorithms with faster convergence speed can be found in [21], [22].

The distributed power control algorithm given in equation (24) does not enforce the QoS requirement of the primary users represented by the inequality (18). Thus, the secondary users apply equation (24) alone may violate the QoS requirement of the primary users. In order to address this issue, we propose two possible solutions. The first solution is a direct solution, where a "genie" is placed near the primary receiver at the border of the TV coverage area. The genie will monitor the interference level and inform the secondary users (such as using a beacon signal) if the interference level is too high and the QoS requirement of the primary users will be violated. One possible implementation of the genie is a secondary user that happens to locate inside the TV coverage area. The second solution is an indirect solution. Assume that $y_i \approx y_j = d, \ \forall i \neq j$[1], then the inequality (18) may be written as

$$\sum_i p_{i,sec} \leq [p_{TV}/(D^{\alpha_1}\gamma_{TV}^{tar}) - \sigma^2]\frac{d^{\alpha_2}}{f_2} \ . \quad (25)$$

Suppose that all secondary users that planning to transmit will report to a manager their respective transmission power, $p_{i,sec}$ for user i, the manager will be able to verify the QoS requirement of the primary users by checking the inequality (25).

V. Simulation Results

In this section, the performance of the proposed power control algorithm is examined. It is assumed that a group of $N = 50$ transmitting-receiving pairs of secondary users using low power devices are communicating with each other in a 2000 meter $\times$2000 meter area. They share the same spectrum with a TV system, and the TV station is located $D+d$ meters away. The locations of the transmitting-receiving pairs are chosen such that $r_{ij} > 3r_{ii}$ to ensure the feasibility of the power control problem, where r_{ij} is the distance from the jth transmitter to the ith receiver and $g_{ij} = 1/r_{ij}^{\alpha_2}$. The initial transmission power of the secondary users are randomly chosen between p_{sec}^{min} and p_{sec}^{max}. The rest of the simulation parameters are: p_{TV} = 100 kW; γ_{TV}^{tar} = 34 dB; p_{sec}^{min} = 0 mW; p_{sec}^{max} = 100 mW; γ_{sec}^{tar} = 3 dB; $\sigma^2 = 10^{-14}$; D = 60 km; α_1 = 3; α_2 = 4.

[1]This assumption is expected to be true most of the time, since typically the secondary users must reside far away enough from the TV coverage area.

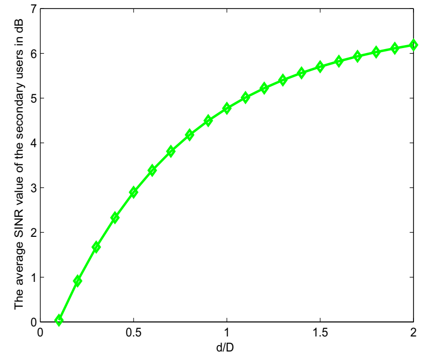

Fig. 4. The average achievable SINR value of the secondary users (γ_{sec}^{avg}) vs. d/D.

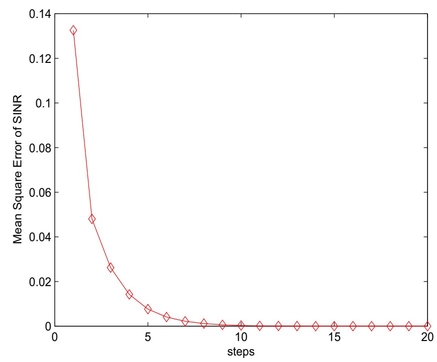

Fig. 5. The convergence of the mean square error of the secondary user's SINR.

The average achievable SINR value of the secondary users (γ_{sec}^{avg}) vs. d/D is shown in Fig 4. It is observed that γ_{sec}^{avg} increases monotonically with d as expected. It is also shown that the gain in γ_{sec}^{avg} decreases when d increases, because the interference between the two systems play less a role in the achievable SINR value when they are further away. When $d/D > 2$, γ_{sec}^{avg} is pretty much limited by the interference of its own system.

In the following part of the simulation, $d = 0.5D$ and the distributed power control algorithm, equation (24), is applied. The convergence of the mean square error of the secondary user's SINR ($e_{sec}^2 = E[(\gamma_{sec} - \gamma_{sec}^{tar})^2]$) is given in Fig 5. It is observed that the power control algorithm converges very fast (in about 10 steps). Similarly, the convergence of the transmission power of some randomly chosen secondary users is shown in Fig 6.

The minimum SINR value of the primary users during the power control process of the secondary users is shown in Fig 7. It is confirmed that the QoS of the primary users is not violated during the power control process.

The performance of the joint power control and admission control for the infeasible case will be included in an extended version of the current manuscript. In addition, the effects of inaccurate estimates of the distances will also be justified.

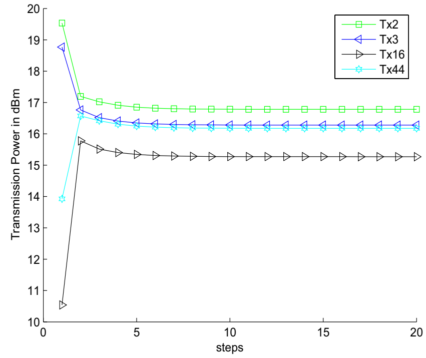

Fig. 6. The convergence of the transmission power of the secondary users.

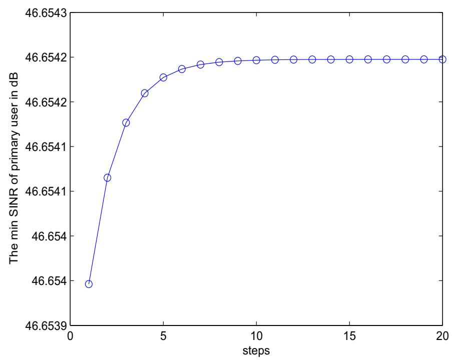

Fig. 7. The minimum SINR value of the primary users during the power control process of the secondary users.

VI. Conclusions

In this paper, a power control problem is formulated for a cognitive radio network that operates simultaneously in the same frequency band with a TV system. Both centralized and distributed solutions are given to maximize the energy efficiency of the cognitive radio network and provide QoS support for both primary and secondary users. In addition, the feasibility condition is derived and a joint power control and admission control procedure is suggested such that the priority of the primary users is ensured all the time. Furthermore, the proposed power control and admission control procedure may be combined with MAC design to enhance the promise of non-intrusion to the primary system during spectrum sharing.

It worth pointing out that the results obtained in this paper can be extended to CDMA cognitive radio network in a straight forward manner. In the case of TDMA as the MAC scheme and only one secondary user is allowed to transmit during one time slot, the results of the single secondary transmitter case in Section III give the optimal power control for one TDMA cognitive radio network. The results in Section IV correspond to the power control of co-channel secondary users in multiple TDMA cognitive radio networks.

Although the TV broadcast system is chosen as an example of the primary system in this paper, the proposed methods can be extended to other cases where heterogeneous systems share the same spectrum. In the current work, only one cognitive radio network is considered. The power control for multiple cognitive radio networks is one of our future research efforts.

References

[1] United States Frequency Allocations. [Online]. Available: http://www.ntia.doc.gov/osmhome/allochrt.pdf
[2] Federal Communication Commission, "Spectrum Policy Task Force" Rep. ET Docket no.02-135, Now. 2002
[3] Q. Zhao, L. Tong, A. Swami, and Y. Chen, "Decentralized Cognitive MAC for Opportunistic Spectrum Access in Ad Hoc Networks: A POMDP Framework", *to appear in IEEE JSAC*.
[4] M. A. McHenry, "NSF spectrum occupancy measurements project summary", Shared Spectrum Company, Tech. Rep., Aug. 2005. [Online]. Available: http://www.sharedspectrum.com/inc/content/measurements/nsf/NSF_Project_Summary.pdf
[5] M. Marcus, "Unlicensed Cognitive Sharing of TV Spectrum", *IEEE Comm. Mag.*, pp.24-25, May 2005.
[6] I. J. Mitola, et al., "Cognitive radio: Making software radios more personal", *IEEE Pers. Commun.*, vol. 6, no. 4, pp. 13?8, Aug. 1999.
[7] J. Mitola, "Cognitive radio: An integrated agent architecture for software defined radio", *Doctoral Dissertation*, Royal Inst. Technol. (KTH), Stockholm, Sweden, 2000.
[8] A. Sahai, N. Hoven, S. M. Mishra, and R. Tandra, "Fundamental tradeoffs in robust spectrum sensing for opportunistic frequency reuse", *Tech. Rep.*, 2006. [Online]. Available: http://www.eecs.berkeley.edu/ sahai/Papers/CognitiveTechReport06.pdf
[9] N. Hoven and A. Sahai, "Power scaling for cognitive radio", *WirelessCom 05 Symposium on Emerging Networks, Technologies and Standards*, Maui, Hawaii, June 2005.
[10] X. Liu and S. Shankar, "Sensing-based opportunistic channel access", *ACM Journal on Mobile Networks and Applications (MONET)*, Vol.11, No.1, pp. 577-591, May 2006.
[11] FCC, "Facilitating opportunities for flexible, efficient, and reliable spectrum use employing cognitive radio technologies, notice of proposed rule making and order", FCC 03-322. [Online]. Available: http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-03-322A1.pdf
[12] FCC, "Unlicensed operation in the TV broadcast bands, ET Docket No. 04-186; additional spectrum for unlicensed devices below 900 mhz and in the 3 ghz band", ET Docket No. 02-380, FCC 04-113. [Online]. Available: http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-04-113A1.pdf
[13] FCC, "Unlicensed Operation in the TV Broadcast Bands; Additional Spectrum for Unlicensed Devices Below 900 MHz and in the 3 GHz Band", FCC 06-156. [Online]. Available: http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-06-156A1.pdf
[14] FCC, " KRON-TV at san francisco". [Online]. Available: http://www.fcc.gov/fcc-bin/tvq?list=0facid=65526
[15] FCC, "KRON-TV service contour map". [Online]. Available: http://www.fcc.gov/fcc-bin/FMTV-service-area?x=TV282182.html
[16] M. Andrews, L. Qian and A. Stolyar, "Optimal Utility Based Multi-User Throughput Allocation subject to Throughput Constraints," *Proc. of IEEE INFOCOM*, Miami, March 2005.
[17] D. Mitra, "An asynchronous distributed algorithm for power control in cellular radio systems", *in Proceeding of 4th WINLAB Workshop of 3rd Generation Wireless Information Networks*, pp. 177?86, Oct. 1993.
[18] D. Bertsekas and J. Tsitsiklis, *Parallel and Distributed Computation: Numerical Methods*, Prentice Hall, NJ, 1989.
[19] R. Yates, "A Framework for Uplink Power Control in Cellular Radio Systems," *IEEE Journal on Selected Areas in Communications*, vol.13, No.7, pp.1341-1348, Sept. 1995.
[20] S. Grandhi, J. Zander and R. Yates, "Constrained Power Control," *International Journal of Wireless Personal Communications*, Vol. 1, No. 4, Apr 1995.
[21] G. Foschini and Z. Miljanic, "A simple distributed autonomous power control algorithm and its convergence," *IEEE Transactions on Vehicular Technology*, vol.42, No.4, pp. 641-646, Nov. 1993.
[22] X. Li, *Uplink Power Control and Scheduling in CDMA Systems*, M.S. thesis, WINLAB, Rutgers University, 2003.
[23] T. ElBatt, and A. Ephremides, "Joint Scheduling and Power Control for Wireless Ad-hoc Networks," *Proc. of IEEE INFOCOM*, pp.976-984, 2002.