Power Control Mechanism for Cognitive Radios via Spectrum Sensing with Interference Management

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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. However, increased levels of interference are expected with the introduction of secondary spectrum access, therefore, proper interference management within the cognitive framework is imperative. The interference management problem in cognitive radio networks is tackled from the transmitter power control perspective so that transmissions by cognitive radios does not violate the interference level thresholds at primary users. The interference management problem is herein tackled from the transmitter power control perspective so that transmission by cognitive radio network does not violate the interference level thresholds at the primary receiver. A fully distributed power control framework is proposed for cognitive radio network exploiting spectrum use and radio environment knowledge. The proposed algorithm called Distributed Power Control with Primary Protection via Spectrum Sensing has the ability to satisfy tight QoS constraints for cognitive radios as well as to meet interference constraints for primary users.

Keywords—Cognitive radio, Quality of Service, Signal to Interference Noise Ratio, Distributed Constrained Power Control, Generalized Distributed Constrained Power Control.

I. INTRODUCTION

Dynamic spectrum access techniques allow the cognitive radio to operate in the best available channel. The cognitive radio technology will enable the users to:

- Determine which portions of the spectrum are available and detect the presence of licensed users when a user operates in a licensed band (spectrum sensing).
- Select the best available channel (spectrum management).
- Coordinate access to this channel with other users (spectrum sharing).
- Vacate the channel when a licensed user is detected (spectrum mobility).

Cognitive Radio Network (CRN) is a promising multi-user wireless communication system for improving spectrum utilization. The idle spectrum in a particular spatio-temporal domain is called spectrum hole [1]. Cognitive radio networks can be designed to manage the radio spectrum more efficiently by utilizing the spectrum holes in primary user’s licensed frequency bands. The currently available unlicensed spectrum is reaching its limit and various demands for applications and data rates in wireless communications requires additional spectrum which imposes limits on spectrum access. These requirements demand for efficient and intelligent use of spectrum.

Fig. 1: Spectrum Utilization by Secondary Users

In a Cognitive Radio Network, a cognitive (secondary/unlicensed) user (SU) can access the frequency spectrum licensed to primary users (PUs) so long as its transmissions do not cause harmful interference to PUs. The key challenge is to re-use spectrum holes such that primary networks are protected from interference and that the quality of service (QoS) of the cognitive users (i.e. the
secondary users) is guaranteed. Transmit Power Control (TPC) is a well established technique for mitigating interference in wireless networks [2-5]. However, in cognitive radio networks (CRN), TPC is challenging due to the strict interference avoidance constraints on PUs. In [6] a model based on graph theory was presented while [7] addressed channel allocation problem using game theory. However, PUs were not explicitly protected in these approaches due to opportunistic access of CRs. Recently, there has been a flurry of research considering protection of PUs (e.g. see [7] and references therein), but to protect PUs, the transmit power of the CRs should be limited based on its proximity to PUs [8], however, in realistic scenarios, primary user location is difficult to obtain.

Spectrum sensing has been identified as one of the key enablers in the realization of a true cognitive system [1]. As most of the spectrum sensing techniques are based on transmitter detection, unfortunately spectrum sensing solely does not guarantee absolute interference free operation to the licensed users. We therefore empower the CR to perform TPC, whereby the power control actions are based on spectrum sensing results to prevent exacerbated powers propagating into unwanted primary domains whilst maintaining substantial QoS within its own network. Power control based on spectrum sensing information has been discussed in [9] for the case of a single secondary user. However, in future CRNs larger numbers of secondary transmitters and receivers can be expected, and further, the need to provide QoS within this resulting secondary network should also be maintained at the same time.

In this paper, we extend the approach presented in [9] for the case of multiple secondary transmitter and receiver pairs by enforcing tight bounds on the QoS of both primary and secondary users. QoS is translated to the maximum permissible interference limit (ITL) at the primary receivers while QoS of secondary users is ensured by maintaining their Signal-to-Interference-Noise ratios (SINR) (or Bit Error Rate) above to a predefined threshold. We show that interference at PUs can be limited, or at least maintained by utilizing spectrum sensing mechanisms while QoS of secondary users can be ensured by implementing modified versions of distributed power control (DPC) algorithms. In DPC algorithms, a user controls its transmitted power by utilizing local information only following some power updating rules [4, 5]. However, in CRNs with explicit primary user protection, it is difficult to implement classical DPC algorithms since the total interference level at PUs cannot be identified by the local information. Approaches employing feedback reporting from sensors localized in the vicinity of the primary receiver [10] or genie aided [11] solutions are prone to inherent failures and delays therefore the primary user experiences transient interferences which may be unpleasant.

Autonomous Distributed Power (DPC) algorithm was developed in the CR context [12] with interference consideration to the primary receiver. In this paper, we focus on DPC mechanisms without feedback reporting and employ spectrum sensing algorithms to derive its link gain to the worst case location of the PU. The solutions advanced in this paper leads to a truly distributed framework for cognitive radios while ensuring that the interference environment of the primary user is unperturbed at all times. In this paper, the cognitive radio harnesses the spectrum sensing capabilities while implementing the modified DPC algorithms proposed in [12] with the following improvements:

1) The cognitive radios perform localized spectrum sensing of primary TV signals and make individual decisions about their interference environment and link gains to the primary system.
2) Increased number of supported CR users is expected since different constraint is executed at individual terminals rather the same constraint being applied to all CR devices as in [12].

The rest of the paper is organized as follows: section II provides the model and problem formulation for CR coexistence with the primary system. We revisit the spectrum sensing algorithms and make a brief recap on distributed power control algorithms for cellular networks in section III. Afterwards, we formulate in section IV, the explicit derivation of the link gain to the primary receiver and the proposed algorithm called distributed power control for CRs with primary protection via spectrum sensing. Simulation results supporting the algorithm are presented in section V followed by conclusion of paper in section VI.

II. MODEL AND PROBLEM FORMULATION

Let us consider the system model of Fig. 1, consisting of a primary TV broadcast system, characterized by an effective communication range called the noise limited radius $r_0$ with an effective radiating power $P_n$. The CRN consist of $N$ opportunistic transmit-receive pairs deployed in a randomly distributed fashion in an $m \times m$ square area with the $i^{th}$ CR at some distance $D_i$ to the primary transmitter. The Euclidean distance between randomly distributed CRs are calculated, from
where the overall gain matrix G of the CRN can be deduced. The CRN transmitter power vector is defined as, \( P = [p_1, p_2, ..., p_N] \) for \( i = 1, ..., N \) and bounded by \( 0 \leq p_i \leq p_{\text{max}} \) where \( p_{\text{max}} \) is the peak power. The effective communication range of an \( i \)th CR transmit-receive pair is denoted as \( r_i \) while the range from \( j \)th transmitter to \( i \)th receiver is \( r_{ij} \) such that \( r_{ij} \geq r_i \) due to the unpredictable random distribution of CRs and \( r_i \leq 500 \text{m} \).

We consider \( D_i \) and \( d_i \) as the distance from the \( i \)th CR to the primary transmitter and receiver respectively and are derived using spectrum sensing, as explain in section IV and a voting decision rule detailed in [14]. A path-loss exponent of \( \alpha_p = 3 \) is assumed for the primary transmitter and \( \alpha_c = 4 \) for CRs. Our aim is to re-use spectrum holes on a non-interfering basis to the primary network, while maximizing opportunistic throughput within the CRN. We therefore formulate the quality of service objective for cognitive co-existence. Without loss of generality, we consider an ad-hoc based system for the CR network with duo QoS objectives:

(1) Interference Expectation (\( I_E \)) at Primary user: In ensuring that QoS levels is unperturbed due to the CRN operation at the worst case primary receiver, the IE must be satisfied the following,

\[
I_E = P_{\text{tv}} r_{ni}^{-\alpha_p} \geq P_{nli}^{\text{th}} q \left( \sum_{i=1}^{N} p_i d_i \leq \xi_{nli}^{\text{th}} \right)
\]

(1)

Where \( P_{nli}^{\text{th}} \) is the primary signal threshold power at the coverage end beyond which TV signal becomes undecodable, while \( \xi_{nli}^{\text{th}} \) is the ITL at the primary coverage end. Therefore, provided the primary is not in outage, the aggregate interference power from all CR transmitters must always be less than the ITL at the primary receiver.

(2) SINR for CR user: QoS within CRN can be maintained if SINR for the \( i \)th CR terminal is greater than a predefined SINR threshold given as:

\[
Y_{cr.i} = \frac{P_i T_{li}^{-\alpha_c}}{\sum_{i=1}^{N} P_i T_{li}^{-\alpha_c} + P_{tv} D_i^{-\alpha_c} + N_o} \geq \gamma_{cr}^{\text{th}}
\]

(2)

Where \( Y_{cr.i} \) is the SINR at the \( i \)th CR terminal, \( \gamma_{cr}^{\text{th}} \) is the SINR threshold and \( N_o \) is the noise power at the CR receiver.

III. PRELIMINARIES

In this section we recap on the spectrum sensing mechanism and DPC schemes as a precursor to the proposed DPC algorithm.

A. Spectrum Sensing for Cognitive Radios

Spectrum opportunity identification via spectrum sensing is one of the requirements for devices trying to access the TV spectrum on an opportunistic basis [1]. For CR to effectively limit it’s transmit power to the primary receiver, perfect knowledge of its link to the primary user is desirable. This is unfortunately not the case, since CRs do not generally know their channel and range to the primary receiver. We therefore in this paper enable the CRs to perform spectrum sensing for idle channel identification. More to it, we derive an estimate of the link gain to the primary user based on statistical and computational tools available to us from literature using the energy detector [13] and voting algorithms developed in [14].

Performance of the energy detector is usually characterized by two well known probabilities, namely, probability of false alarm (\( P_{fa} \)) and probability of detection (\( P_d \)). \( P_{fa} \) is the probability of declaring that a channel is occupied when in fact it is vacant (i.e. only noise is present) and is given by [13],

\[
P_{fa} = \frac{\Gamma(m, \lambda/2)}{\Gamma(m)}
\]

(3)

\( \Gamma(\cdot, \cdot) \) is the upper incomplete gamma function which is defined by the integral form

\[
\Gamma(a, x) = \int_{x}^{\infty} t^{a-1} e^{-t} \, dt \quad \text{and} \quad \Gamma(a,0) = \Gamma(a)
\]

(4)

The numerator and denominator are incomplete and complete gamma functions with time-bandwidth product \( m \) and decision threshold \( \lambda \). \( P_d \) is therefore the probability...
of correctly detecting the primary signal in a target channel when it is truly present and is given as [13],
\[
P_{d_1} = \left( \frac{\Gamma (m-1, \frac{\lambda}{\gamma_{tr,i}^*})}{\Gamma(m-1)} \right) \frac{1}{\gamma_{tr,i}^*} + \frac{1}{m\gamma_{tr,i}^*} \left( \frac{\lambda}{2(1+m\gamma_{tr,i}^*)} \right)^{m-1} \left( e^{-\frac{\lambda}{2(1+m\gamma_{tr,i}^*)}} \right)
\]
(5)

where \(\gamma_{tr,i}^*\) is the mean SNR of TV signal at the \(i^{th}\) CR receiver. It is recommended that all CRs synchronize their quite periods so that SNR is what is sensed and not the SINR. From (5), it is obvious that the probability of detection is a function of received SNR, and hence distances \(D_i\) as in (6).
\[
P_{d_1} = f(\gamma_{tr,i}^*) = f(D_i)
\]
(6)

Probability of missed detection at the \(i^{th}\) CR \((P_{m,i})\) is therefore the probability of declaring the primary signal is vacant when in fact it is occupied and is given by
\[
P_{m,i} = 1 - P_{d_1}
\]

B. Distributed Power Control in Wireless Networks

Transmitter power control plays an important role in limiting the interference levels in a wireless environment as well as conserving terminal power. Power control is well researched for cellular communications systems and is designed for centralized and distributed systems. Here, we focus on DPC since an ad-hoc CRN is assumed in this paper. The DPC implements Signal to Interference Ratio (SIR) balancing adapted to the wireless communication environment by Zander in [2]. SIR balancing schemes are optimal since it maximizes the aggregate power usage of all co-channel users by choosing a power vector which drives every mobile in the system to meet but not exceed the required minimum SINR. Distributed systems, implement iterative power control, which is governed by a set of pre-defined power updating rules to fulfill certain QOS requirements. Since the \(i^{th}\) CR transmitter only knows its channel to its receiver and totally oblivious of its channel gain to other CR users, it therefore adjusts its power according to the perceived SINR \((\gamma_{cr,i}^*)\) (2) at its receiver. So after some manipulations in equation (2), the distributed algorithm as suggested by Foschini and Miljanic (7) is derived [3]. This is called the standard Distributed Power Control (DPC), defined as,
\[
p_i(t+1) = \frac{\gamma_{cr,i}^*}{\gamma_{tr,i}^*} p_i(t), \quad t \in \{0, 1, 2, \ldots\}
\]
(7)
The expression in (7) is shown to converge to a power level solution that fulfils \(\gamma_{cr,i}^*\) for some users; however, this may be achieved at health endangering and impractical powers as a result of continued power updating. Putting a cap (constrain) on the allowable power disposable to the CR seems very appropriate by defining a maximum power \(P_{max}\) for the CRs. The algorithm that fulfills this is called the Distributed Constrained Power control (DCPC) [4] which is shown to converge faster than the standard DPC (7) because maximum power cannot be exceeded whether or not \(\gamma_{cr,i}^*\) is fulfilled.

An improved version of the DCPC is the Generalized Distributed Power Control algorithm, GDPC [5]. In GDPC, devices transmitting at \(P_{max}\) without fulfilling their QOS are made passive. This has the benefit of reducing the interference environment leading to increased number of supported users.

IV. DISTRIBUTED POWER CONTROL WITH PRIMARY USER PROTECTION VIA SPECTRUM SENSING

Conventional DCPC and GDPC algorithms do not guarantee primary user protection; therefore it becomes imperative to modify these algorithms in order to protect the primary receivers. Autonomous distributed power control algorithm was developed in [12] guaranteeing interference free operation to the primary at all times. This algorithm is simple yet effective since CRs communication is possible even at close proximity to the users without raising the interference at the primary user beyond limits. If the ITL threshold \(\xi_{tr}^*\) and the number of transmitting CRs are known (e.g. using some routing protocol [10, 15]), a further cap on the maximum individual cognitive power \(p_i^{cap}\) can be can be conditioned as (8),
\[
p_i^{cap} \leq \frac{\xi_{tr}^* d_{tx,i}^{cr}}{N} \quad i \in \{1, 2, \ldots, N\}
\]
(8)

Since each of the CR users is now constrained by (8), the ITL at the primary receiver is never violated at any distance from the worst case primary receiver. The simulation in [12] implicitly considered \(d_{tx,i}^{cr} \approx d_{tx}\) for all CRs, it follows that the same \(p_i^{cap}\) constraint would be applied to all N transmitting CRs which is quite conservative. In our model, we relax this assumption by empowering each CR user with spectrum sensing capabilities such that CR users explicitly determine their respective link gains to the primary receiver and as such
compute their respective power constraints. Therefore, CRs in the boundary region of the m x m block, further away from the primary user, would ideally, contribute lesser interference power to the primary user than CRs in close proximity. A CR transmitter at such boundary locations may therefore be able to communicate effectively with its receiver due to a little more predisposed power achievable depending on its true distance to the primary receiver without violating the ITL. We therefore briefly describe the explicit determination of link gains and formulate the transmission power for CRs.

A. Explicit Estimation of Distance d

In order to estimate distance d, each CR performs spectrum sensing (measures energy $Y_i$) in T number of time slots and calculate $I(Y_i^k)$ in each time slot such that:

$$I(Y_i^k) = \begin{cases} 1, & Y_i^k \geq \lambda \\ 0, & \text{otherwise} \end{cases} \quad i = 1, \ldots, N \text{ and } k = 1, \ldots, T$$

(9)

Hence estimated probability of detection $\hat{p}_{d,i}$ for $i^k$ is:

$$\hat{p}_{d,i} = \frac{1}{T} \sum_{k=1}^{T} I(Y_i^k) \quad \text{for } i = 1, \ldots, N$$

(10)

Once the probability of detection is estimated, an estimate on the distance from the $i^k$ CR to the primary transmitter can be derived based on the closed form expression of (5). Since estimated $\hat{p}_{d,i} \approx P_{d,i}$ it suffice to say $\tilde{D}_i = f^{-1}(1 - P_{m,i})$. It is then possible to plot the graph of probability of missed detection with estimated distance $\tilde{d}$ as in Fig. 3 [9].

Fig. 3 shows how the probability of missing a primary signal varies with distance from the primary contour for various primary transmitter powers. The lower the primary transmission powers the better the opportunity for CRs. The improved maximum individual CR power is given in (11),

$$p_i^{\text{cap}} \leq \frac{\xi_i f^{-1}(1 - P_{m,i})}{N} \quad \text{ie } \{1,2, \ldots, N\}$$

(11)

We therefore modify the DCPC and GDPC algorithms to include spectrum sensing capabilities and call them DCPC/GDPC with Primary Protection via Spectrum Sensing.

B. DCPC with Primary Protection via Spectrum Sensing(DCPC-PPSS)

The DCPC-PPSS algorithm advanced here implements spectrum sensing to estimate its distance to the primary receiver. The iterative power process is therefore written as,

$$p_i(t + 1) = \min \left\{ \frac{\xi_i^0}{f_{\text{cr}}} p_i \cdot \frac{\xi_i^0 f^{-1}(1 - P_{m,i})}{N}, p_{\text{max}} \right\} , i \in \{0,1,\ldots\}$$

(12)

When the CRs are sufficiently far from the primary system, equation (12) would tend to increase making $p_i^{\text{cap}} \geq P_{\text{max}}$, hence (12) ensures that the CR never exceeds its maximum available power.

C. GDPC with Primary Protection via Spectrum Sensing(GDPC-PPSS)

The GDPC-PPSS algorithm implemented here is similar to the DCPC-PPSS algorithm in that they both implement the same mechanism. However, like conventional GDPC algorithm, GDPC-PPSS has the ability to support an increased number of CR transmitters compared to the DCPC-PPSS. The power updating rule for GDPC-PPSS is as in equation (13).

$$p_i(t + 1) = \begin{cases} \frac{\xi_i^0}{f_{\text{cr}}} p_i(t) \cdot \frac{\xi_i^0 f^{-1}(1 - P_{m,i})}{N}, p_i(t) \leq \min \left\{ \frac{\xi_i^0 f^{-1}(1 - P_{m,i})}{N}, p_{\text{max}} \right\} \\ \hat{p}_i, & \text{if } \frac{\xi_i^0}{f_{\text{cr}}} p_i(t) > \min \left\{ \frac{\xi_i^0 f^{-1}(1 - P_{m,i})}{N}, p_{\text{max}} \right\} \end{cases}$$

(13)

Where $i \in \{0,1,2,\ldots\}$ and $\hat{p}_i$ is an arbitrary power value.

V. SIMULATION AND RESULTS

Now we provide simulation results to get an insight into the performance of our proposed scheme. First we have to obtain the missed power detection for different power levels of the TV signal. As the power level of the TV signal is defined earlier, the interference power at TV for DCPC and GDPC must be less than the interference limit.

Simulation parameters are given in Table 1. For ease of presenting our simulation result, we estimate:

$$d = \frac{1}{N} \sum_{i=1}^{N} \hat{p}_i - r_{\text{nl}} \quad i = 1, \ldots, N$$

(14)

There are N =50 transmitting-receiving pairs of SUs in a 2000m x 2000m square region. The secondary transmitters are uniformly distributed in the square area, and the secondary receivers are located within the transmission range of the corresponding transmitter with a uniform distribution. In such a network, we varied $d$, which is the distance between the TV receiver and the center of the square region, from 1000m to 4000m. It affects the interference temperature at the TV receiver. The longer $d$ is, the less the PU is interfered from the SU.
Table 1: Simulation Parameters for fully distributed CRN

<table>
<thead>
<tr>
<th>Simulation Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Transmit Power ($P_{t0}$)</td>
<td>80dBm</td>
</tr>
<tr>
<td>Effective Coverage range of TV station ($r_{st}$)</td>
<td>70Km</td>
</tr>
<tr>
<td>Noise power for 8MHz UK TV channel</td>
<td>-105dBm</td>
</tr>
<tr>
<td>Interference level at $r_{st}$</td>
<td>-100dBm</td>
</tr>
<tr>
<td>Number of CR Transmitters ($N$)</td>
<td>50</td>
</tr>
<tr>
<td>CR maximum terminal power ($P_{\text{max}}$)</td>
<td>20dBm</td>
</tr>
<tr>
<td>CR coverage area</td>
<td>2000m x 2000m</td>
</tr>
<tr>
<td>Path loss exponent for primary transmitter ($\alpha_p$)</td>
<td>3</td>
</tr>
<tr>
<td>Path loss exponent for CR transmitter ($\alpha_{cr}$)</td>
<td>4</td>
</tr>
<tr>
<td>Distribution of CR terminals</td>
<td>Random($r_{ij}\geq r_{ijkl}$)</td>
</tr>
<tr>
<td>Probability of false alarm ($P_{ifa}$)</td>
<td>0.01</td>
</tr>
<tr>
<td>Time bandwidth product (m)</td>
<td>5</td>
</tr>
<tr>
<td>Arbitrary power $\bar{P}$</td>
<td>0dBm</td>
</tr>
<tr>
<td>No of time slots for sensing operation</td>
<td>1000</td>
</tr>
</tbody>
</table>

![Fig.3: $P_m$ vs. $d$ for $P_{ifa}=0.01$ and $m=5$.](image)

Simulation results in Fig. 4 show that by implementing the proposed algorithm, ITL at primary receivers is never exceeded. It also shows that the interference powers of the CRs decreases significantly as the CRN moves further away from the noise limited contour of the TV receiver. The number of supported users is expected to increase with further distance from the primary contour as shown in Fig. 5. DCPC-PPSS experiences a slight decline at an estimated distance of 2500m due to increased maximum power available for each user, however GDPC-PPSS tries to maintain the number of supported CR users. The algorithm is seen to stabilize with distances greater than 2500m owing to reduced downlink intersystem interference from TV transmitter. GDPC-PPSS supports more number of than DCPC-PPSS due to reduced interference levels experienced in the network.

![Fig.4: CR Interference Power with Estimated Distance.](image)

![Fig.5: Supported CR transmitters with Estimated Distance](image)

VI. CONCLUSION

DCPC/GDPC-PPSS offers a more realistic model for a fully distributed CRN framework since power control and link gain estimation (achieved through spectrum sensing)
are performed at the individual CR terminal without any co-operation or co-ordination from the primary system. We have therefore been able to re-use the primary TV spectrum owing to spatial opportunity while ensuring that the total transmission power of CR users in all TV channels does not exceed the interference threshold limit at the worst case primary receiver at any time. DCPC/GDPC-PPSS are a viable approach as fully distributed schemes for the cognitive radio framework.

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