Distributed Power Control based on Convex Optimization in Cognitive Radio Networks

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Abstract—We consider the power efficiency optimization problem in the cognitive radio (CR) networks under both the average packet delay constraints of each CR transmitter (CR-Tx) and the interference constraint at primary receiver (PU-Rx). We propose a cooperative approach to make each CR-Tx know the interference level at the PU-Rx when there is no central control node in the network and no assistant sensors are deployed to do the interference measuring jobs. The power control problem is proved to be a convex problem. Since the powers of CR-Tx nodes are coupled in constraints, we apply the Lagrange relaxation of the coupling constraints method and construct the subgradient iterative algorithm to solve the dual problem in a distributed way. To reduce the payload of the message exchange at each iterative process, an improved algorithm is proposed that could be implemented through Lagrange dual decomposition. Numerical results show that the two algorithms can converge very fast. When the delay constraints of CR users are not very small, it is better to apply the improved algorithm which has a good performance but with a much lower complexity.

I. INTRODUCTION

Cognitive radio (CR) users have two spectrum access strategies: overlay model and underlay model [1]. In the underlay model, CR users share the same frequency bands with primary users but should keep the interference to primary receiver (PU-Rx) under a threshold that PU-Rx can tolerate. Power control plays a key role in reducing the interference in wireless communication. Intuitively, we need to design power control algorithms to satisfy the primary user interference constraints [1]. The information of the interference level at PU-Rx is critical for CR users to adaptively adjust their powers. How to design an effective power control algorithm to make each CR-Tx know the interference at PU-Rx instead of deploying assistant measuring sensors. Nevertheless, the deployment of the assistant nodes has no advantage in economics.

Unlike the traditional networks in which there are base stations or central control nodes, the cognitive nodes which are deployed in particular environments are usually distributed without any centralized nodes to do coordinating jobs, therefore it is critical to design and apply distributed power control algorithms (DPC) [3][4][5]. Gatsis et al. in [3] constructed a convex objective utility function and designed the DPC algorithm to maximize the throughput of CR users under delay constraints. In [4], Jin et al. studied the DPC algorithm to maximize the throughput of CR users in a CR network with a base station serving both primary users and CR users. Huang et al. in [5] proposed a strategy that CR users listen to the feedback channel of PU-Rx to calculate the outage probability of PU-Rx and upon this information, an estimation of their interference to PU-Rx can be derived by CR users. Based on this strategy, they designed a DPC algorithm to maximize the CR users’ throughput.

In the CR networks with energy limited CR nodes, minimizing the node power consumption to improve the energy efficiency has a great significance in practice. Despite the objectives in [3]-[5] are to maximize the CR users’ throughput, in this paper, our optimization objective is to minimize the total transmit power of all CR-Tx nodes under both the delay constraints of each CR-Tx and the interference constraint at PU-Rx. Our interest is to design a DPC algorithm in the CR networks without any central control node.

The main contributions of this paper go into three aspects. First, we propose a distributed and cooperative strategy to make each CR-Tx know the interference at PU-Rx instead of deploying assistant measuring sensors. Second, we prove that the power control problem is a convex optimization problem. A subgradient iterative algorithm is constructed to solve the dual problem based on the Lagrange relaxation of the coupling constraints method [6]. Third, to reduce the payload of message exchange at each iterative process, an improved DPC algorithm is also proposed based on Lagrange dual decomposition theory.

The rest of this paper is organized as follows. Section II presents the system model and basic assumptions. In Section III, we formulate the power control problem as a convex optimization problem. Subgradient iterative algorithm is constructed in Section IV to solve the dual problem based on the Lagrange relaxation of coupling constraints method. In Section V, an improved algorithm is proposed to reduce the complexity in implementing the DPC problem. Numerical results are provided in section VI to show the performance of the algorithms. Finally, section VII concludes the paper.

II. SYSTEM MODEL

We consider a CR network without any central control node. Each CR node is powered by a battery and equipped with a finite buffer to store the data. There are M CR user links which are randomly distributed in an area that is away from the one primary user link just as the illustration in Fig. 1. There is no information exchange between primary users and
Let temperature model [7] recently has been introduced by FCC. The packets arrival process of link \( i \) is assumed to be a Poisson distribution with parameter \( \lambda_i \). The packets length has an exponential distribution with parameter \( \ell_i \). A FIFO queuing discipline and \( M/1 \) queue model are used in this paper for analysis. According to [9], we can get the expected packet delay at CR-Tx of link \( i \) as below:

\[
D_i = 1/(\ell_i R_i - \lambda_i). \tag{4}
\]

We assume that the average arrival rate is smaller than the average transmission rate, thus the queue will be stable [9].

III. PROBLEM FORMULATION

In this section, we will give the power control problem and prove it to be a convex optimization problem.

We assume there is a maximum delay bound constraint denoted by \( D_{i,\text{max}} \) for CR-Tx node of link \( i \), i.e. \( D_i \leq D_{i,\text{max}} \). Thus, by substituting (3) in (4) we can get

\[
ISR_i \leq K \left( 2^{T(D_{i,\text{max}} + \lambda_i)/\ell_i} - 1 \right), \tag{5}
\]

where \( ISR_i \) is the inverse of the \( SINR_i \). For simplicity, we define \( \Delta_i = K \left( 2^{T(D_{i,\text{max}} + \lambda_i)/\ell_i} - 1 \right) \), which is a constant when all the parameters of link \( i \) are fixed.

Our optimization objective is to minimize the total CR-Tx transmit power of all links under both the average packet delay constraints of each CR-Tx and the interference constraint at PU-Rx. The optimization problem can be written as:

\[
\min \sum_{i=1}^{M} P_i \quad \text{s.t.} \quad \begin{array}{l}
0 \leq P_i \leq P_{\text{max}} \\
\sum_{i=1}^{M} G_{PR_i} P_i \leq I \\
\sum_{i=1}^{M} \frac{G_{PR_i} P_i + G_{PR_i} P_{PT} + n_i}{G_{PR_i} P_i} \leq \Delta_i \end{array} \quad \forall i, \tag{6}
\]

where \( P_{\text{max}} \) is the maximum transmit power of CR-Tx.

**Proposition 1:** The power control problem (6) is a convex optimization problem in \( \{P_i\} \).

**Proof:** According to [10], we introduce a new variable \( y_i = \log P_i \), thus \( P_i = \exp(y_i) \). The optimization objective function in (6) is transformed as \( \sum_{i=1}^{M} \exp(y_i) \) which is convex in \( \{y_i\} \) as the sum-exp function is a convex function. The first constraint in (6) is transformed as \( \exp(y_i) \leq P_{\text{max}} \), which is also convex in \( \{y_i\} \). The second constraint in (6) is transformed as \( \sum_{i=1}^{M} G_{PR_i} \exp(y_i) \leq I \). The left part of the inequality is a sum-exp function in \( \{y_i\} \), thus is convex [10]. The transmit power of PU-Tx can be assumed to be fixed and its interference to each CR-Rx is an approximate constant. So for simplicity, we combine the interference generated by...
PU-Tx with the background noise at CR-Rx of link $i$ as $N_i \triangleq G_{i PT} P_{PT} + n_i$.

We assume that each CR-Rx has the capability to estimate the interference generated by CR-Tx of other links, i.e., $Z_i = \sum_{j \neq i} G_{ij} P_j$, where $Z_i$ is an auxiliary variable. By introduce a new variable $z_i = \log Z_i$, we have $\exp(z_i) = \sum_{j \neq i} G_{ij} \exp(y_j)$ and the third constraint in (6) can be transformed as:

\[
\frac{\sum_{j \neq i} G_{ij} P_j + G_{i PT} P_{PT} + n_i}{P_i} = \exp(z_i - y_i) + N_i \exp(-y_i) \leq \Delta_i G_{ii}.
\]

The left part of the inequality (7) is nonnegative sum of exponential function with affine mappings, which is convex in $\{y_j\}$ and $\{z_i\}$ according to [10].

Since the objective function and the constraint functions are all convex, problem (6) is a convex optimization problem. Therefore, the power control problem (6) can be rewritten as the following convex problem:

\[
\begin{align*}
\min_{\{y_i\}} & \sum_{i=1}^{M} \exp(y_i) \\
\text{s.t.} & \quad \exp(y_i) \leq P_{\text{max}} \\
& \quad \sum_{i=1}^{M} G_{PR_i} \exp(y_i) \leq I \\
& \quad \log(\exp(-y_i)(\exp(z_i) + N_i)) \leq \log(\Delta_i G_{ii}) \\
& \quad \exp(z_i) = \sum_{j \neq i} G_{ij} \exp(y_j) \\
& \quad \forall i.
\end{align*}
\]

(8)

IV. DISTRIBUTED POWER CONTROL ALGORITHM

The power control problem (8) could be solved by solving its dual problem. In this section, we will construct the subgradient iterative algorithm to solve the dual problem.

The Lagrange function of problem (8) is:

\[
\begin{align*}
L(\{y_i\}, \{z_i\}, \{\mu_i\}, \nu, \{\zeta_i\}, \{\gamma_{ij}\}) &= \sum_{i=1}^{M} \exp(y_i) + \sum_{i=1}^{M} \mu_i (\exp(y_i) - P_{\text{max}}) \\
&\quad + \nu \left( \sum_{i=1}^{M} G_{PR_i} \exp(y_i) - I \right) \\
&\quad + \sum_{i=1}^{M} \zeta_i \left( \log(\exp(-y_i)(\exp(z_i) + N_i)) - \log(\Delta_i G_{ii}) \right) \\
&\quad + \sum_{i=1}^{M} \gamma_{ij} \left( \sum_{j \neq i} G_{ij} \exp(y_j) - \exp(z_i) \right),
\end{align*}
\]

(9)

where $\{\mu_i\}$, $\nu$, and $\{\zeta_i\}$ are Lagrange multipliers and $\{\gamma_{ij}\}$ are the consistency prices.

The objective function in problem (6) is decomposable and the third coupled constraint has been decomposed by introducing auxiliary variables and equality constraints. The powers of CR-Tx are only coupled in the second constraint. Therefore, we can apply the decomposition method of Lagrange relaxation of the coupling constraint which is proposed in [6], and construct the subgradient algorithm to solve the dual problem. The dual function of (8) is

\[
q(\{\mu_i\}, \nu, \{\zeta_i\}, \{\gamma_{ij}\}) = \sum_{i=1}^{M} \min_{y_i, z_i} L_i(y_i, z_i, \mu_i, \nu, \zeta_i, \gamma_{ij})
\]

(10)

where

\[
\begin{align*}
L_i(y_i, z_i, \mu_i, \nu, \zeta_i, \gamma_{ij}) &= \exp(y_i) + \mu_i (\exp(y_i) + \nu G_{PR_i} \exp(y_i) \\
&\quad + \zeta_i \log(\exp(-y_i)(\exp(z_i) + N_i)) \\
&\quad + \sum_{j \neq i} \gamma_{ij} G_{ji}) \exp(y_i) - \gamma_{ij} \exp(z_i).
\end{align*}
\]

(11)

The dual problem of (8) is given by:

\[
\begin{align*}
\max & \quad q(\{\mu_i\}, \nu, \{\zeta_i\}, \{\gamma_{ij}\}) \\
\text{s.t.} & \quad \mu_i \geq 0, \nu \geq 0, \zeta_i \geq 0, \forall i.
\end{align*}
\]

(12)

According to convex optimization theory [10], when all constraints of optimization problem (8) are satisfied, the optimal solution does exist. The problem (8) is a convex optimization problem, thus strong duality holds, i.e., the duality gap between primal problem and dual problem is zero. According to KKT condition [10], the optimal transmit power of each CR-Tx can be obtained through the following equation:

\[
\frac{\partial L_i(y_i, z_i, \mu_i, \nu, \zeta_i, \gamma_{ij})}{\partial y_i} = 0,
\]

(13)

and the solution is

\[
P_i^* = \exp(y_i) = \frac{\zeta_i}{1 + \mu_i + \nu G_{PR_i} + \sum_{j \neq i} \gamma_{ji} G_{ji}}.
\]

(14)

The dual problem can be solved using subgradient method [6]. We construct the subgradient iteration algorithm to update the Lagrange multipliers and consistency prices as follows:

\[
\begin{align*}
\mu_i(t) &= [\mu_i(t-1) + \alpha(t)(\exp(y_i) - P_{\text{max}})]^+, \\
\nu(t) &= [\nu(t-1) + \beta(t)(I_{PU} - I)]^+, \\
\zeta_i(t) &= [\zeta_i(t-1) + \phi(t)(\log(ISR_i) - \log(\Delta_i G_{ii}))]^+, \\
\gamma_{ij}(t) &= \gamma_{ij}(t-1) + \eta(t)(I_{CR_i} - \exp(z_i)),
\end{align*}
\]

(15)-(18)

where $[x]^+ = \max\{x, 0\}$, $t$ denotes the iteration time and $\alpha(t)$, $\beta(t)$, $\phi(t)$, $\eta(t)$ are the step sizes. Here, we define $I_{PU} = \sum_{i=1}^{M} G_{PR_i} \exp(y_i)$ to represent the total interference generated by all CR-Tx nodes to PU-Rx. Define $ISR_i = \exp(-y_i)(\exp(z_i) + N_i)$ to represent the inverse of $SINR_i$. 

at CR-Rx node of link $i$, which can be measured by CR-Tx node of link $i$ locally. Define $I_{CR_i} = \sum_{j \neq i} G_{ij} \exp(y_j)$ to denote the interference generated by CR-Tx of other links to CR-Rx of link $i$, which can be estimated by CR-Rx node of link $i$ locally. Thus, iteration (17) could be carried out at each CR-Rx node with local information.

To update iteration (16), we need to know the interference $I_{PU_i}$ at PU-Rx. Haykin in [2] proposed that some sensors could be deployed near the PU-Rx to do the interference measuring job. However, this approach has no advantage in economics and is not suitable for PU-Rx whose position is mobile. In practice, each CR-Tx could estimate the channel gain $G_{PR_i}$ by listening to the feedback signals, like ACK/NACK, which are transmitted by PU-Rx to PU-Tx under the open wireless environment\(^1\). Then, each CR-Tx broadcasts channel gain $G_{PR_i}$ and its power $P_i(t)$. Consequently, all the CR-Tx can calculate the total interference at the PU-Rx and the iteration (16) can be carried out at each CR-Tx node.

The auxiliary variable $z_i$ in iteration (18) can be achieved according to KKT necessary condition [10] through the following equation:

$$\frac{\partial L_i(y_i, z_i, \mu_i, \nu_i, \zeta_i, \{\gamma_{ij}\})}{\partial z_i} = 0,$$

and the solution is $\exp(z_i) = \zeta_i / \gamma_{ij} - N_i$.

The consistency price $\gamma_{ij}(t)$, channel gains $G_{PR_i}, G_{ji}$ and power $P_i(t)$ are all broadcasted at each iterative process. We summarize the Standard Distributed Power Control (S-DPC) Algorithm as below:

**Algorithm 1 Standard Distributed Power Control (S-DPC)**

1. Initialization:
   $t = 0$; $0 \leq P_i(0) \leq P_{\text{max}}, \mu_i(0) > 0, \nu_i(0) > 0, \zeta_i(0) > 0, \gamma_{ij}(0) > 0; \forall i$
2. Algorithm at the CR-Rx of link $i$
   1) Measure the interference $I_{CR_i}$ generated by CR-Txs of other links and $SNR_i$: Estimate the channel gains $\{G_{ij}\}$;
   2) Calculate $\exp(z_i) = \zeta_i(t-1)/\gamma_{ij}(t) - N_i$
   3) Update the Lagrange multiplier $\zeta_i$ and consistency price $\gamma_{ij}$ according to (17) and (18) respectively
   4) Transmit $\zeta_i(t)$ to CR-Tx of link $i$; Broadcast $\gamma_{ij}(t)$ and $\{\gamma_{ij}\}$
3. Algorithm at the CR-Tx of link $i$
   1) Estimate channel gain $G_{PR_i}$ and receive $\{G_{PR_j}\}_{j \neq i}$, $\{P_j\}_{j \neq i}$, to calculate the total interference $I_{PU_i}$ at PU-Rx; Receive Lagrange multiplier $\zeta_i$, constraint prices $\{\gamma_{ij}\}_{j \neq i}$, channel gains $\{G_{ji}\}_{j \neq i}$
   2) Update Lagrange multipliers $\mu_i$ and $\nu_i$ according to (15) and (16) respectively
   3) Calculate the power value of CR-Tx $P_i(t) = \frac{1+\mu_i(t-1)+\nu_i(t-1)}{\gamma_i(t-1)}G_{PR_i} + \sum_{j \neq i} \gamma_{ij}(t-1)G_{ji}$
   4) Broadcast $G_{PR_i}$ and $P_i(t)$

The subgradient iterative algorithm is guaranteed to converge to the optimal value provided that the step sizes are sufficiently small [6].

\(^1\)We assume that the pilot information and transmit power of PU-Rx are priori to CR-Tx. The channel gain $G_{ji}$ can also be estimated by CR-Rx of link $j$ locally in a similar way.

V. IMPROVED ALGORITHM

In the S-DPC algorithm, to achieve the interference information at PU-Rx, each CR-Tx node has to broadcast the channel gain between itself and PU-Rx with transmit power value to all other CR-Tx nodes. The broadcast information would increase the message exchange burden and more time would be costed before the convergence of the algorithm. Therefore, in this section we propose an improved algorithm with much fewer message exchange.

The main idea of the improved DPC (I-DPC) algorithm is to divide the maximum interference level $I$ that PU-Rx can tolerate into $M$ parts equally, where $M$ is the number of CR links in the network. Each CR-Tx makes sure that its interference to PU-Rx would not exceed $I/M$. The optimization problem can be written as follows:

$$\min \sum_{i=1}^{M} \exp(y_i)$$

s.t. $\exp(y_i) \leq P_{\text{max}}$ $\forall i$

$$\log(G_{PR_i} \exp(y_i)) \leq \log(I/M)$ $\forall i$

$$\log(\exp(-y_i)) (\exp(z_i) + N_i) \leq \log \Delta G_{ii} \forall i$$

$$\exp(z_i) = \sum_{j \neq i} G_{ij} \exp(y_j) \quad \forall i.$$  (20)

Different from problem (8), the powers of CR-Tx nodes are no longer coupled in problem (20), thus it can be solved through the Lagrange dual decomposition method [11][12]. The dual function of (20) is

$$q (\{\mu_i\}, \{\nu_i\}, \zeta_i, \{\gamma_{ij}\})$$

$$= \sum_{i=1}^{M} \min_{y_i, z_i} L_i (y_i, z_i, \mu_i, \nu_i, \zeta_i, \{\gamma_{ij}\})$$

$$= \sum_{i=1}^{M} \left( \mu_i P_{\text{max}} + \nu_i \log(I/M) + \zeta_i \log \Delta G_{ii} \right)$$

$$- \sum_{i=1}^{M} \left( \mu_i P_{\text{max}} + \nu_i \log(I/M) + \zeta_i \log \Delta G_{ii} \right)$$

$$+ \sum_{i \neq j} \gamma_{ij} G_{ji} \exp(y_j) - \gamma_{ij} \exp(z_i).$$  (22)

The dual problem is

$$\max q (\{\mu_i\}, \{\nu_i\}, \zeta_i, \{\gamma_{ij}\})$$

s.t. $\mu_i \geq 0, \nu_i \geq 0, \zeta_i \geq 0, \gamma_{ij} \geq 0, \forall i.$  (23)

The optimal power of CR-Tx can be obtained according to the KKT condition [10] through the following equation:

$$\frac{\partial L_i(y_i, z_i, \mu_i, \nu_i, \zeta_i, \{\gamma_{ij}\})}{\partial y_i} = 0,$$  (24)

and the solution is $P_i^* = \exp(y_i) = \left[ \frac{\zeta_i - \nu_i}{1+\mu_i + \sum_{j \neq i} \gamma_{ij} G_{ji}} \right]^+.$
We then construct the subgradient iterative algorithm to solve the dual problem. Compared to S-DPC algorithm, the difference happens in iteration (16) which is transformed as:

\[ \nu_i(t) = [\nu_i(t-1) + \beta(t) \left( \log(I_i) - \log(I/M) \right)]^+, \quad (25) \]

where \( I_i = G_{PRI} \exp(y_i) \). Iteration (25) can be carried out at each CR-Tx node without knowing the information of other links.

The Improved Distributed Power Control (I-DPC) Algorithm is summarized as follows:

**Algorithm 2 Improved Distributed Power Control (I-DPC)**

1. **Initialization:**
   - \( t = 0; \)
   - \( 0 \leq P_i(0) \leq P_{\text{max}}, \mu_i(0) > 0, \nu_i(0) > 0, \zeta_i(0) > 0, \gamma_{ij}(0) > 0, \forall i; \)
2. **Algorithm at the CR-Rx of link \( i \)**
   1. Measure the interference \( I_{CR_i} \) generated by CR-Txs of other links and \( SINR_i \); Estimate the channel gains \( \{G_{ij}\} \).
   2. Calculate \( \exp(z_i) = \zeta_i(t-1)/\gamma_{ij}(t-1) - N_i \).
   3. Update the Lagrange multiplier \( \zeta_i \) and consistency price \( \gamma_{ij} \) according to (17) and (18) respectively.
   4. Transmit \( \zeta_i(t) \) to CR-Tx of link \( i \); Broadcast \( \gamma_{ij}(t) \) and \( \{G_{ij}\} \).
3. **Algorithm at the CR-Tx of link \( i \)**
   1. Estimate channel gain \( G_{PRI} \) to calculate interference \( I_i \) at PU-Rx; Receive consistency prices \( \{\gamma_{ij}\}_{j \neq i} \) and channel gains \( \{G_{ij}\}_{j \neq i} \).
   2. Update Lagrange multipliers \( \mu_i \) and \( \nu_i \) according to (15) and (25) respectively.
   3. Calculate the power value of CR-Tx

\[
P_i(t) = \left[ \frac{\zeta_i(t-1)-\nu_i(t-1)}{1+\mu_i(t-1)+\sum_{j \neq i} \gamma_{ij}(t-1) G_{ij}} \right]^+.
\]

Each CR-Tx no longer needs to broadcast any information in I-DPC algorithm. Therefore, it can greatly reduce the complexity and convergence time of the algorithm.

**VI. NUMERICAL RESULTS**

In this section, we provide numerical results for the two DPC algorithms developed in Section IV and V.

We assume there is one primary link and three CR links distribute randomly in a region which is away from the primary link. The distances between three CR-Tx nodes and PU-Rx are 1300m, 1800m and 2000m respectively. Transmit power of each CR-Tx is limited to 1W and background noise is assumed to be \( 1 \times 10^{-10} \)W. Channel gains are defined using a simple path loss model, \( G_{ij} = L d_{ij}^{-4} \) and \( G_{PRI} = L d_{PRI}^{-3} \), where \( L \) is a constant. Packet traffic at each CR-Tx node is assumed to be Poisson with intensity \( \lambda_i = 200 \)packets/s and packet length is exponentially distributed with an expectation of 100bits. The symbol period is set to 1/4000s.

**A. The convergence of DPC algorithms**

We set the delay bound as 0.015s, i.e., \( SINR_i = 20 \)dB. When the maximum interference level \( I \) is not very small, for example \( I = 10 \times 10^{-10} \)W, Fig. 2 and Fig. 3 illustrate the power convergence properties of each CR-Tx node under the two algorithms respectively. The numerical results show that both S-DPC algorithm and I-DPC algorithm can converge very fast. By making a lot of simulations, we find that both the algorithms can converge to the same optimal solutions as those attained in centralized algorithms (like the inter-point method).

**B. Delay simulation**

In I-DPC algorithm, the interference generated by the nearest CR-Tx node to PU-Rx should not exceed \( I/M \). When both the maximum interference level \( I \) and delay bound set for CR-Tx node are small, the power of CR-Tx node 1 should not increase too much, which results in a longer delay. On the contrary, the interference allocation under S-DPC algorithm is globally considered, thus CR-Tx node 1 could generate more interference to PU-Rx in S-DPC algorithm than that under I-DPC algorithm. As a result, the transmit power under S-DPC algorithm can be higher than that under I-DPC algorithm, i.e., a lower delay can be achieved.

When \( I = 5 \times 10^{-10} \)W, Fig. 4 illustrates the relationship between actual delays of CR-Tx node 1 and delay bound constraints under the two proposed algorithms respectively.

\(^2\)In the simulation setup, we call it CR-Tx node 1.
It shows that when the delay bounds are large, the actual delays under the two proposed algorithms are exactly equal to the delay bound. This means that the transmit power of each CR-Tx node is minimum, i.e., it is optimal for node energy efficiency. As the delay bound is becoming smaller, the power increase of CR-Tx node 1 under I-DPC algorithm is limited prior to that under S-DPC algorithm and as a result, the actual delay of CR-Tx node 1 is longer than that under S-DPC algorithm.\footnote{It should be noted that when the values of both the interference and delay bound constraints are very small, the power control problem might have no solutions. But in such a situation the DPC algorithms can still converge and CR-Tx nodes transmit at a lower rate to protect PU-Rx, as a result, a bigger delay. The admission control scheme could be introduced which will be investigated in our future work.}

C. Tradeoff between energy efficiency and delay constraints

There is a tradeoff between the node energy efficiency and the node delay constraints. Fig. 5 illustrates that when the average delay bound constraint is less than 0.05s, the total power consumption of all CR-Tx nodes is quite high and change greatly. When the average delay bound constraint is larger than 0.05s, the power consumption is small and change smoothly. From Fig. 4, we have already known that when the delay bound constraints are not very small, I-DPC algorithm and S-DPC algorithm can converge to the same optimal solutions. Thus, if the applications are not very sensitive to delay, we can make a little bigger delay bound constraint for CR-Tx nodes, which will increase the node energy efficiency. More importantly, by doing that, we can use I-DPC algorithm instead of S-DPC algorithm, to significantly reduce the payload of message exchange at each iterative process.

VII. CONCLUSIONS

In this paper, we have studied the power control problem in CR networks without any central control node or assistant sensors to do the interference measuring jobs. Thus, it is critical to design and apply distributed algorithms in such CR networks. To attain the interference information at PU-Rx, we propose a strategy based on local channel estimation and information exchange among CR-Tx nodes. Our optimization objective is to minimize the total power consumption of CR-Tx nodes to increase the node energy efficiency under both the interference and delay constraints. Based on convex optimization theory, we have designed two distributed algorithms to solve the dual problem since the duality gap of a convex problem is zero. The algorithms proposed in this paper could be carried out at each CR nodes with limited message exchange and have fast convergence performances.

REFERENCES