Joint Flow and Power Control in Multi-hop Cognitive Radio Networks: A Cross-Layer Optimization

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Abstract

In this paper, we consider the problem of joint congestion and power control over time-varying channels for all secondary user (SU) nodes communicate each other in multi-hop cognitive radio network (CRN). Firstly, we consider how SUs transmit data from infinite transmission buffer to maximize its utility under constraints on tranmission cost without affecting primary user (PU) activity. Then we propose a distributed algorithm for jointly optimal rate and power control (JORPC) via message passing to achieve a joint performance. Finally, the simulation results demonstrate that the proposed algorithm achieves significantly high utility and energy efficiency when comparing to existing works which the optimization-based cross layer design between physical and transport layer has not been thoughtfully taken into consideration in CRNs yet.

1. Introduction

Multi-hop CRNs have been really attracting many researchers in recent years for improving the overall spectrum efficiency and coexistence of heterogeneous networks in future internet. In fact, opportunistic spectrum access has been encouraged by FCC policy initiatives and IEEE standardization activities in both time and spatial domain [1]. However, transmission from cognitive devices can make physically harmful interference to PU's reception. Shenhua Huang [2] shows that Listen-Before-Talk technique, applied by SUs to detect the presence or absence of PU's signals before channel access, imposes some limitations. It does not consider the aggregate interference at PU receivers from multiple potential SUs's transmission, allows no transmission from SUs while a PU system operating under full load with possibility of tolerating more interference.

Exploring data link control information such as channel quality indicator (CQI) feedback in CDMA cellular system or ACK/NACK feedback in [7] can help SUs have good knowledge of their actual interference impact on PU communication link [2], [3]. In this paper we investigate the JORPC problem proposed recently in some works [5] and [6] and propose a new framework in the interference-limited multihop CRNs. By taking the PUs's outage feedback information's advantage into framework of network utility maximization (NUM) as a constraint for PU link protection, we can formulate the joint flow and power control problem for multi-hop CNRs. The main objective of this paper is to maximize the utility subject to the flow conservation, whose capacity is constrained by the interference levels which in turn decided by power control policy.

2. Network Model and Assumptions

We consider a multi-hop CRN consisting of a set of N secondary nodes with a single primary channel. Let $\mathbb{S} = \{1, 2, ..., S\}$ and $\Im = \{1, 2, ..., L\}$ denote the set of flows and the set of logical links of secondary nodes in network, respectively. And $\Im' = \{0, 1, 2, ..., L\}$ is the set of all links in network system including both secondary links and primary link. Note that we use the special index of $i = 0$ denotes those relevant to primary link. Suppose that flow $s \in S$ traverses multiple hops to get its destination throughout the ordered set of links $L(s) \subseteq \Im$ which is called routes. At transport layer, we assume that each source has infinite amount of data to send. With an allocated data rate $x_s \geq 0$, source s attains a utility $U_s(x_s): \mathbb{R}_+ \to \mathbb{R}$ which is continously differentiable, nonedecreasing and strictly concave. We also adapt the code devision multiple access (CDMA) technique to physical layer model

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where all SU nodes are given access to the entire channel all the time.

A. Capacity and Fading Model

Let η_l denote the thermal noise power under the baseband bandwidth W at receiver of link l. The average signal-to-interference ratio at link l:

$$\overline{SIR}_l(\mathbf{P}) = \frac{G_{ll}P_l}{\eta_l + \sum_{k\in\Im'\setminus\{l\}} G_{lk}P_k} \quad (1)$$

Where $\mathbf{P} = [P_1, P_2, ..., P_L]$ is a vector of transmitter powers of SU-Tx and P_0 is the transmit power of PU-Tx. The average capacity of link $l \in \Im$ modeled on the Shannon capacity is a global and nonlinear function of transmit power vector P

$$c_l(\mathbf{P}) = W\log\left(1 + K.\overline{SIR}_l(\mathbf{P})\right) \quad (2)$$

Here K is constant depending on the modualtion, coding scheme and bit-error rate (BER) [7]. We also assume that there is no fading-margin at each link and is much larger than 1. This assumption may seem reasonable in some applications where link rate needs to be ensured at the least value. That means $K.\overline{SIR}_l(\mathbf{P})$ which is assumed to be greater than 10dB is quite practical. Then we have approximation for link capacity as following

$$c_l(\mathbf{P}) \approx W\log\left(K.\overline{SIR}_l(\mathbf{P})\right) \quad (3)$$

For flow conservation, the aggregated source rate allocated to the traversing flows can not exceed its link capacity.

$$\sum_{s:l\in L(s)} x_s \le c_l(\mathbf{P}) \approx W\log\left(K.\overline{SIR}_l(\mathbf{P})\right), \quad \forall l \quad (4)$$

Without loss of generality, we assume that K and W is one, henceforth.

B. Primary User Protection

To protect its transmission and maintain quality of service (QoS), PU-Rx would require its outage probability to stay below a certain threshold, denoted by η_{th}. The constraint for this is set as followings

$$\Pr\left(SIR_0(\mathbf{P}) \le \gamma_{th}\right) \le \eta_{th} \quad (5)$$

An upper bound on a posynomial function in P[3]

$$\prod_{l=1}^{L}\left(1 + b_l P_l\right) \le \mu \quad (6)$$

Where $\mu = (1-\eta_0)/(1-\eta_{th})$ and γ_{th} is the SIR threshold at PU-Rx. We assume that the PU protection requirement including the transmit power P_0 at PU-Tx, η_{th} must be decalered a priori to all SUs.

3. Jointly Optimal Flow and Power Control via NUM

Our JORPC problem with PU QoS is formulated via NUM problem as following

$$\textit{Problem } \mathfrak{M}: \qquad \max_{\mathbf{x},\mathbf{P}\ge 0} \sum_{s\in S} U_s(x_s)$$

$$\textit{subject to} \qquad \sum_{s:l\in L(s)} x_s \le \log\left(\overline{SIR}_l(\mathbf{P})\right), \quad \forall l$$

$$\Pr\left(SIR_0(\mathbf{P}) \le \gamma_{th}\right) \le \eta_{th}$$

The flow conservation constraint on each link now becomes the non-linear constraint on $(\mathbf{x}, \mathbf{P})$ space. As a result, the problem is the non-linear convex optimization problem which has a unique solution with respect to source rates and link powers. By relaxing constraints of problem $\mathfrak{M}$, the dual function can be decomposed into two subproblems

1. The congestion control subproblem.

$$\max_{\mathbf{x}\ge 0}\left\{L_x(\mathbf{x}, \boldsymbol{\lambda}, p) = \sum_s U_s(x_s) - \sum_s p_s x_s\right\} \quad (6)$$

2. The power control subproblem.

$$\max_{\mathbf{P}}\left\{L_P(\mathbf{P}, \boldsymbol{\lambda}, p) = \sum_{l\in L} \lambda_l \log\left(\overline{SIR}_l(\mathbf{P})\right) - p\sum_{l\in L}\log\left(1 + b_l P_l\right) + p\log\mu\right\} \quad (7)$$

where the link data rate of each source s is adjusted via the aggregate price $p_s = \sum_l \lambda_l$ for all links in the path of s. Making use of gradient-descent method [8] to solve its dual problem, we have the distributed JORPC algorithm as following

Distribuited JORPC Algorithm

Rate Control: source rate update

$$x_s^{(t+1)} = \left[U_s^{'-1}\left(p_s^{(t)}\right) \right]_{m_f}^{M_f} \quad (8)$$

Where $[x]_a^b = \min\left(\max(x,a), b\right)$.

Power Control: link power update

$$P_l^{(t+1)} = \left[P_l^{(t)} + \beta_t \left(\frac{\lambda_l^{(t)}}{P_l^{(t)}} - \sum_{k \neq l} m_k^{(t)} G_{kl} - p^{(t)} \frac{b_l}{1 + b_l P_l^{(t)}} \right) \right]_{P_{\min}}^{P_{\max}} \quad (9)$$

where $m_k^{(t)} = \frac{\lambda_k^{(t)} SIR_k^{(t)}}{G_{kk} P_k^{(t)}}$ received from link k .

Link congestion price update:

$$\lambda_l^{(t+1)} = \left[\lambda_l^{(t)} + \alpha_t \left(\sum_{s \in S(l)} x_s^{(t)} - c_l(\mathbf{P}^{(t)}) \right) \right]^+ \quad (10)$$

PU Link outage price update:

$$p^{(t+1)} = \left[p^{(t)} + \beta_t \left(\sum_{l=1}^{L} \log\left(1 + b_l P_l^{(t)}\right) - \log \mu \right) \right]^+ \quad (11)$$

Proposition 1: The distributed JORPC algorithm converges to the global optimum with an appropriate choice of stepsize α_t and β_t [8].

4. Simulation Results

A. Simulation Settings

We set up a multihop CRN system with 5 SU nodes and a pair of PUs with topology illustrated in Fig.1. Each SU link with a maximum transmit power of 60dBm can use the whole liccensed baseband bandwidth of 125 KHz. The minimum data rate for each elastic flow is 100bps and the target BER is 10^{-3}. The power allocation P_l for each link products its link capacity formulated as in (2) with $K = -1.5 / \log(5.BER)$ [7]. For PUs, we require the outage probability must be smaller than 10% for the SIR threshold 0.95 dB at transmit power 46dBm.

B. Numerical Results

The simulation results are shown in Fig.2. We observe that the proposed JORPC algorithm for multi-hop CRNs converges well with an acceptable convergence speed. The optimally allocated link powers are [299, 19.2, 8.9, 1.5] mW. This shows that the transmit power of an SU depends on not only the mutual interference levels among SUs but also its physical distance to PU-Rx. Furthermore, source rates are decided by the power control policy to avoid overwhelming any link capacity.

5. Conclusion

We propose a distributed JORPC algorithm for multi-hop CRNs using high-SIR approximation to transform the original NUM problem into the non-linear convex optimization problem. The global optimal solution then is obtained by using the descent-gradient method. The simulation results show that our porposal can out-perform previous work.

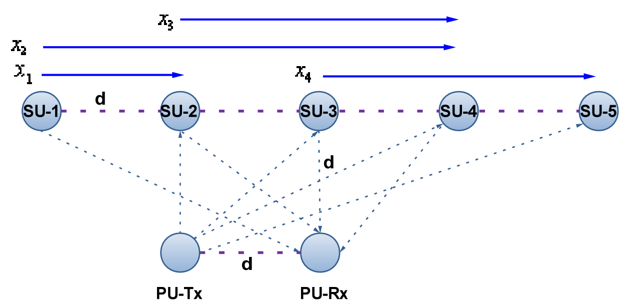
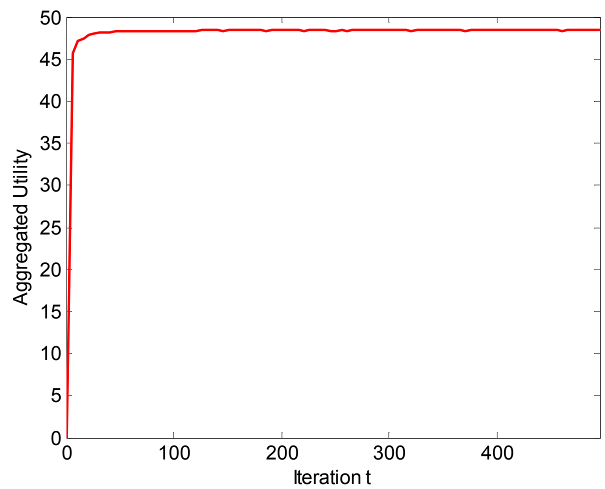
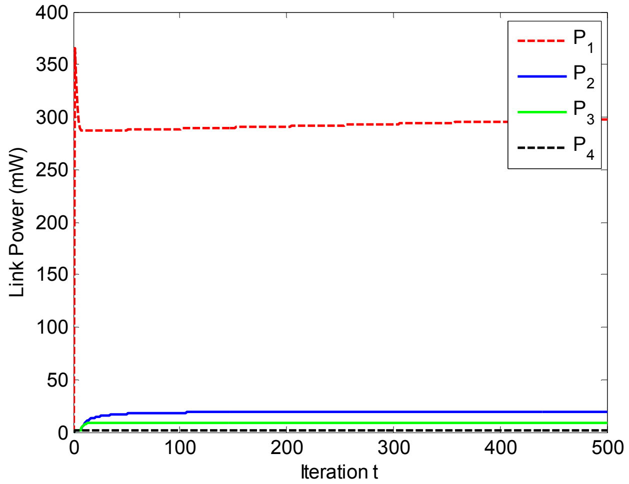


Fig. 1: Multihop CRN with 4 flows and PUs



(a)



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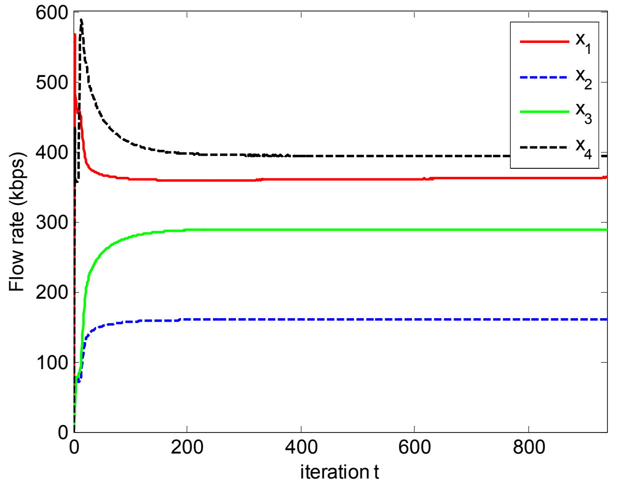

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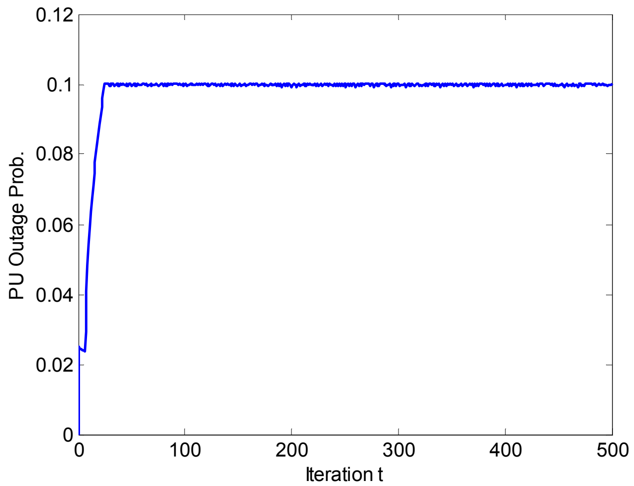

(d)

Fig. 2: Convergence of Algorithm with (a) Agrregated Utility, (b) Link Power; (c) Source Rate and (d) PU outage probability

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