Joint Scheduling and Flow Control for Multi-hop Cognitive Radio Network with Spectrum Underlay

Nguyen Tran Quang, Duc Ngoc Minh Dang, Choong Seon Hong
Department of computer Engineering, Kyung Hee Univ., 449-701, Republic of Korea
Emails: {nguyentrq, dnmduc, cshong}@.khu.ac.kr

Abstract

In this paper, we introduce a joint flow control and scheduling algorithm for multi-hop cognitive radio networks with spectrum underlay. Our proposed algorithm maximizes the total utility of secondary users while stabilizing the cognitive radio network and still satisfies the total interference from secondary users to primary network is less than an accepted level. Based on Lyapunov optimization technique, we show that our scheme is arbitrarily close to the optimal.

Key words: Cross-layer optimization, cognitive radio network, spectrum underlay.

1. Introduction

There are two main approaches for secondary users to access the licensed spectrum: spectrum overlay and spectrum underlay. In spectrum overlay approach, secondary users (SUs), unlicensed users, sense the available channels that are not in used by primary users (PUs), licensed user, so that they can opportunistically use those channels. On the other hand, SUs in spectrum underlay approach are allowed to transmit simultaneously on the same channels with PUs. As a result, interference from the SUs can be harmful to active PUs. Carefully allocating transmission power for SUs becomes critically important so that interference caused by SUs to PUs can be controlled at an acceptable level.

Admission control and scheduling policy in multi-channel single-hop CRNs has been proposed in [1] to maximize throughput/utility subject to PU constraints. Xue et al extended it by considering a multi-channel multi-hop CRN overlay with a primary network in [2]. In these papers, the secondary users are scheduled such that the long-term average of collision to primary users is kept under a certain threshold.

In this paper, we consider multi-hop cognitive radio network coexisting with cellular-based primary network. Secondary users share the same spectrum as the uplink of the primary network through spectrum underlay. We propose a joint flow control and scheduling algorithm for CRN in order to maximize total utilities of secondary network while the time average interference to primary network is kept under an accepted level. By using the stochastic optimization framework which is deeply studied in [3], we show that our proposed solution is arbitrarily close to the optimal solution.

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2. Network Model

In this paper, we consider a time-slotted multi-hop CRN coexisting with primary network. The primary network is cellular-based network, where different frequency bands are used for uplink and downlink transmissions. The multi-hop CRN consists of N secondary users and shares the same spectrum as the uplink of the primary network through spectrum underlay as shown in figure 1. Time is slotted corresponding to uplink frame of primary network. In this paper, we consider single channel for the uplink transmission of the primary network.

Let $\mathcal{F}$ be the set of all secondary flows. Each secondary flow f has a fixed single route from its source to destination. Let L_f be the set of links that flow f routes from its source $s(f)$ to its destination $d(f)$. Let $Q_n^f[t]$ denote the length of queue at secondary node n for flow f. Queue $Q_n^f[t]$ is said to be stable if and only if it satisfied the following condition [3]-[4]

$$\lim_{t\to\infty}\sup\frac{1}{t}\sum_{\tau=0}^{t-1}E\{Q_n^f[\tau]\}<\infty$$

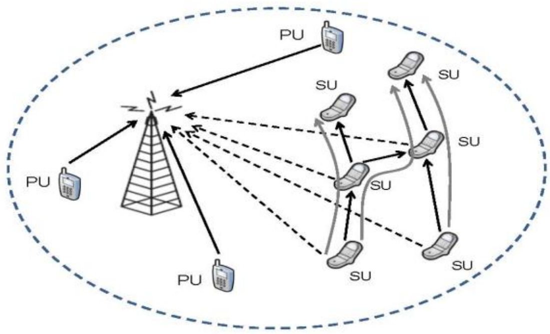

Fig.1. System Model

Network is said to be stable if and only if all of its queues are stable.

Let $\mu_{mn}^{f}[t]$ be the transmission rate on link *(m,n)* dedicating to flow *f*. Let *I[t]* denote the ratio of total interference from secondary users to desired signal from a primary user at base station. $I[t]=\sum_{(m,n)\in\mathcal{L}}\sum_{f\in\mathcal{F}}\mu_{mn}^{f}[t]*P_{mn}$, where P_{mn} denotes ratio of the interference from link *(m,n)* to desired signal from primary user at base station per each data packet. in this paper, we will keep long term time average of *I[t]* less than threshold instead of it at every time slot. By using the concept of virtual queue in [3], we define queue $X[t]=[X[t]-\rho]^{+}+I[t]$. According to queueing theory, the time-average of *I[t]* less than ρ if queue *X[t]* is stable.

Let $r_{s(f)}^{f}$ be the time average admitted rate for flow *f* at it source node *s(f)*. We define a set of utility functions $U^{f}(r)$ representing the satisfaction of secondary source nodes. The utility functions are assumed to be non-decreasing and concave. The optimal solution is the solution of the following optimization problem:

$$Maximize:\ \sum_{f}U^{f}(r_{s(f)}^{f}) \tag{1}$$

$$s.t\ \ (r_{s(f)}^{f})\in\mathbf{\Lambda}\ \&\ X[t]\ is\ stable \tag{2}$$

where $\mathbf{\Lambda}$ is the network capacity region [4], the set of all feasible admission rate vectors so that the network can support in sense that there exists a scheduling algorithm which stabilizes the network. It is shown in [4] that it is convex, closed and bounded.

3. Joint flow control and scheduling for Cognitive Radio Network

1. Proposed algorithm

At every time slot t

Flow control: Each source node *s(f)* injects an amount of traffic $R_{s(f)}^{f}$ into the network which is equal to the solution of the following optimization problem

$$maximize\ \sum_{f\in\mathcal{F}}(VU^{f}(x_{s(f)}^{f})-Q_{s(f)}^{f}[t]x_{s(f)}^{f}[t])$$

$$s.t\ 0\le x_{s(f)}^{f}\le R_{s(f)}^{max},\forall f \tag{3}$$

where $V>0$ is a control parameter.

Scheduling:

Each link *(m,n)* finds the flow f^{*} which maximizes

$$(Q_{m}^{f}[t]-Q_{n}^{f}[t]-X[t]P_{mn}) \tag{4}$$

among all flow going through it and sets the corresponding value to its link weight $w_{mn}[t]$

For the network, a link schedule is selected which solves

$$\max_{\mu[t]\in\Pi}\sum_{(m,n)\in\mathcal{L}}\mu_{mn}[t]w_{mn}[t] \tag{5}$$

In (5) Π is the set of all feasible schedules. Optimization problem (5) finds an optimal schedule and not schedule any link with non-positive weight. The resulting transmission rate is offered to flow f^{*} of this link in this time slot.

2. Performance analysis

Let $(r_{s(f)}^{*f}(\epsilon))$ be the optimal solution of optimization problem (1)-(2) where $\mathbf{\Lambda}$ is substituted by $\mathbf{\Lambda}_{\epsilon}=\{(r_{s(f)}^{f})\,|\,(r_{s(f)}^{f}+\epsilon)\in\mathbf{\Lambda}\}$.

Theorem 1: Our proposed algorithm stabilizes network and yields the following performance bounds:

$$\limsup_{t\to\infty}\frac{1}{t}\sum_{\tau=0}^{t-1}\sum_{n,f}E\{Q_{n}^{f}[\tau]\}\le\frac{B+VG^{max}}{\epsilon} \tag{6}$$

$$\limsup_{t\to\infty}\frac{1}{t}\sum_{\tau=0}^{t-1}E\{X[\tau]\}\le\frac{B+VG^{max}}{\beta(\epsilon)} \tag{7}$$

$$\liminf_{t\to\infty}\sum_{f\in\mathcal{F}}U^{f}(r_{s(f)}^{f}[t])\ge\sum_{f\in\mathcal{F}}U^{f}(r_{s(f)}^{*f}(\epsilon))-\frac{B}{V} \tag{8}$$

where $B,G^{\max},\beta(\varepsilon)$ is constant.

The proof of theorem 1 is based on stochastic optimization and the same with proof of theorem 5.1 in [3]. Because of the limitation of space, interested readers can refer [3] for details.

From (6)-(8), we can see that there is a tradeoff between the total queue length and the optimal value.

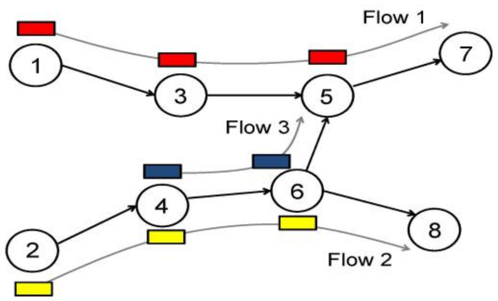

Fig.2. Network topology

When V increases, the total queue length increases and the optimal value decreases vice versa. Following Little's Law, larger queue length means longer network delay. In our simulation, we will select different value of V to show the tradeoff.

4. Simulation results

We consider a multi-hop CRN with 3 flows as illustrated in fig.2. Queues are indexed from 1 to 9 in the order of $Q_1^1, Q_3^1, Q_5^1, Q_2^2, Q_4^2, Q_6^2, Q_4^3$ and Q_6^3. The utility function is chosen to be $U^f(x) = x$ in order to maximize the total throughput. The wireless link rate is assumed to be 15 packets per slot. Maximum admitted rate R^{max} is assumed to be 20 packets per slot. P_{mn} is set to be 0.0625. We select this accepted level ρ=0.1 means that the accepted signal to interference noise ratio at base station of primary user is at least 10dB. Every simulation is executed within 100000 time slots.

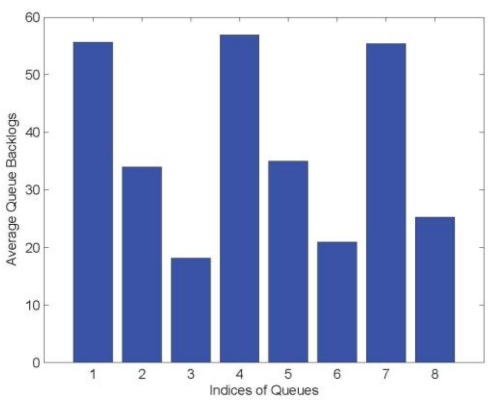

Fig.3 Average queue backlogs in the network for V=50.

Figure 3 shows an example of the average queue length when V=50. Table 1 shows the admitted rates, throughput and total queue length with different value of V. From this table, we can see that when V increases, the throughput increases and the total average backlogs (or queue length) decreases. This illustrates the tradeoff between throughput and the delay as our comment in previous section.

V	r^1	r^2	r^3	Throughput	Backlogs
50	2.729	1.775	5.726	10.23	301
100	3.413	0.494	7.009	10.916	606
150	3.564	0.619	6.885	11.069	902

Table 1: Admitted rate, throughput and total queue backlogs with different value of V

5. Conclusion

In this paper, we propose a joint flow control and scheduling for multi-hop cognitive radio network with spectrum underlay. To protect primary users, we use the time-average interference constraints. Our simulation results support the performance analysis of our proposed algorithm in term of the backlog-utility tradeoff. In future, we will consider multi-channel network and congestion control when the incoming traffic is arbitrary.

6. References

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