

Opportunistic Resource Allocation in Cognitive Femtocell Networks

Tai Manh Ho, Tuan LeAnh, S.M Ahsan Kazmi and Choong Seon Hong
 Department of Computer Engineering, Kyung Hee University, 446-701, Republic of Korea
 Email: {hmtai,latuan,ahsankazmi,cshong}@khu.ac.kr

Abstract

In this paper, we develop an opportunistic scheduling policy for cognitive femtocell network that maximizes the throughput utility of femtocell users subject to maximum channels' collision constraints. We consider a cognitive femtocell network with a subset of the femtocell users desire to opportunistically use multiple orthogonal channels. We use the technique of Lyapunov Optimization to design an online flow control, scheduling and resource allocation algorithm that meets the desired objectives and achieves efficient throughput along with system stability.

I. Introduction

Femtocells are now widely implemented as the home base stations connected to broadband backhaul with limited coverage area and low transmission power. It has numerous advantages such as large bandwidth, better indoor coverage, higher capacity and cost effective design. Therefore, femtocells are considered as an ideal choice to realize the macrocell indoor coverage and enhance the QoS of the home environment [1][7].

In traditional heterogeneous networks which include macrocells and femtocells, the same frequency band is shared between macrocells and femtocells, the performance of femtocell users could be impaired by interference due to the channel utilization of macrocell users [1]. Resource allocation is considered the most important problem in order to mitigate the interference between macrocells and femtocells and optimize the channel utilization of both macrocell users and femtocell users.

In this paper, we use the techniques of adaptive queueing and Lyapunov Optimization [3] to design an online flow control, scheduling and spectrum allocation algorithm for a cognitive femtocell network that maximizes the utility of femtocell users subject to maximum rate of collisions with the macrocell users. We develop a simple Lyapunov drift technique that enables system stability and performance optimization simultaneously [2][3][5].

The rest of the paper is organized as follows: Section II introduces the network model and defines the problem. In section III, we propose and analyze the dynamic algorithm based on the Lyapunov Optimization theory. Numerical results are illustrated in section IV. Finally, we conclude our work in section V.

II. System model and Optimization Problem

We consider a network with multiple femtocell users (FUEs) and multiple channels. Femtocells are overlaid within macrocell in a two-tier heterogeneous network and resource deployment is co-channel deployment.

The cognitive femtocell base station (CFBS) periodically senses spectrum surrounding to identify available channels [1]. Then CFBS broadcasts the information of available spectrums to FUEs in its coverage in order to mitigate interference and collision on the channels and to minimally disrupt macrocell communications.

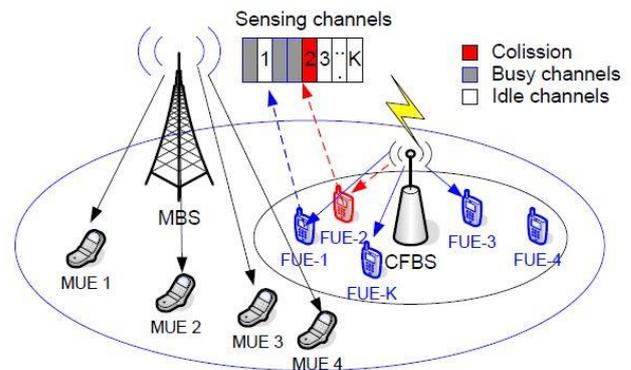


Fig. 1 System model

The network operates in slotted time with time slots $t \in \{0, 1, 2, \dots\}$ [3]. Every slot t , the network controller makes transmission actions that which channel is allocated for which FUE and the FUE will use the channel for its transmission. The set of all possible matrix options to choose is determined by the current states of channels. The availability of channels are characterized as two-state ergodic Markov Chain with idle probability π_m . We assume that π_m is obtained by CFBS through a knowledge of the traffic statistics

and/or the channels sensing. We assume that exactly 1 packet can be transmitted over any channel in a timeslot.

Let \mathcal{K} represents the set of femtocell users, and \mathcal{M} represents the set of channels. Let \mathbf{K} and \mathbf{M} respectively be the size of these sets. Define $x_k(t)$ as the total number of packets that femtocell user k transmits on slot t . Define an allocation process $\phi_{km}(t) = 1$ if channel m is allocated to FUE k at slot t , and $\phi_{km}(t) = 0$ if otherwise. We define the "collision" variable for the channels: $C_m(t) > 0$ if there was a collision in the channel m at slot t , and $C_m(t) = 0$ if otherwise. Define:

$$\begin{aligned} \bar{x}_k &= \lim_{t \rightarrow \infty} \frac{1}{t} \sum_{\tau=0}^{t-1} x_k(\tau), \bar{\phi}_{km} = \lim_{t \rightarrow \infty} \frac{1}{t} \sum_{\tau=0}^{t-1} \phi_{km}(\tau), \bar{c}_m = \lim_{t \rightarrow \infty} \frac{1}{t} \sum_{\tau=0}^{t-1} C_m(\tau) \\ C_m(t) &= \sum_{k \in \mathcal{K}} c_m \phi_{km}(t) (1 - \pi_m) \end{aligned} \quad (1)$$

These limits are temporarily assumed to exist. The value \bar{x}_k is the time average transmission rate of FU k , and $\bar{\phi}_{km}$ is the fraction of time that a given channel m is allocated to FU k , and \bar{c}_m is the time average collision rate of channel m . The goal is to develop a control algorithm that maximize the throughput-utility subject to the constraint that the time average flow over the channel is less than or equal to the time average capacity of the channel and the time average of the packet collision rate cannot exceed the maximum packet collision rate that channel can tolerate. The infinite horizon utility problem of interest is thus:

$$\text{Maximize: } \sum_{k \in \mathcal{K}} U_k(\bar{x}_k) \quad (2)$$

$$\text{Subject to: } \bar{x}_k \leq \sum_{m \in \mathcal{M}} c_k \pi_m \bar{\phi}_{km}, \quad \forall k \in \mathcal{K} \quad (3)$$

$$\sum_{k \in \mathcal{K}} \phi_{km}(t) \leq 1, \sum_{m \in \mathcal{M}} \phi_{km}(t) \leq 1, \quad \forall k, m \quad (4)$$

$$\bar{c}_m \leq \rho_m c_m, \quad \forall m \in \mathcal{M} \quad (5)$$

$U_k(x)$ is utility concave functions and ρ_m is maximum packet collision rate that channel m can tolerate.

III. The Dynamic Algorithm

The problem (2)–(5) can be solved via the stochastic network optimization theory of [3]. We must transform the problem (2)–(5) to the problem that involves only time average (not function of time average), so that the Lyapunov framework can be applied. The problem (2)–(5) is equivalent to the following transformed problem:

$$\text{Maximize: } \sum_{k \in \mathcal{K}} \overline{U_k(\gamma_k)} \quad (6)$$

$$\text{Subject to: } \bar{\gamma}_k \leq \bar{x}_k, \quad \forall k \in \mathcal{K} \quad (7)$$

$$\bar{x}_k \leq \sum_{m \in \mathcal{M}} c_k \pi_m \bar{\phi}_{km}, \quad \forall k \in \mathcal{K} \quad (8)$$

$$\sum_{k \in \mathcal{K}} \phi_{km}(t) \leq 1, \sum_{m \in \mathcal{M}} \phi_{km}(t) \leq 1, \quad \forall k, m \quad (9)$$

$$\bar{c}_m \leq \rho_m c_m, \quad \forall m \in \mathcal{M} \quad (10)$$

$$0 \leq \gamma_k(t) \leq x_k^{\max} \quad (11)$$

where $\gamma_k(t)$ is auxiliary variables, and $\overline{U_k(\gamma_k)}$ is defined as the time average of the process $U_k(\gamma_k(t))$.

A. Virtual Queue

To facilitate satisfaction of the constraint (7), define a virtual queue $Q_k(t)$ with dynamics:

$$Q_k(t+1) = \max[Q_k(t) + \gamma_k(t) - x_k(t), 0] \quad (12)$$

To satisfy the constraints (8), define a virtual queue $Z_k(t)$ with dynamics:

$$Z_k(t+1) = \max[Z_k(t) + x_k(t) - \sum_{m \in \mathcal{M}} c_k \pi_m \phi_{km}(t), 0] \quad (13)$$

We define the collision queue $H_k(t)$ for each channel m as follows [2]:

$$H_m(t+1) = \max[H_m(t) - \rho_m c_m, 0] + C_m(t) \quad (14)$$

Stabilizing queues $Q_k(t)$, $Z_k(t)$, and $H_k(t)$ ensures constraints (7), (8), (10).

B. The Drift-Plus-Penalty Algorithm:

In order to use Lyapunov optimization theory, we define the following quadratic Lyapunov function $L(t)$:

$$L(t) \triangleq \frac{1}{2} \left[\sum_{k \in \mathcal{K}} Q_k(t)^2 + \sum_{k \in \mathcal{K}} Z_k(t)^2 + \sum_{m \in \mathcal{M}} H_m(t)^2 \right]$$

Intuitively, taking actions to push $L(t)$ down tends to maintain stability of all queues. Define $\Delta(t)$ as the drift on slot t :

$$\Delta(t) \triangleq L(t+1) - L(t)$$

The algorithm is designed to minimize the following drift-plus-penalty expression [3]:

$$\begin{aligned} \Delta(t) - V \sum_{k \in \mathcal{K}} U_k(\gamma_k(t)) &\leq B(t) - V \sum_{k \in \mathcal{K}} U_k(\gamma_k(t)) \\ &\quad + \sum_{k \in \mathcal{K}} Q_k(t) [\gamma_k(t) - x_k(t)] \\ &\quad + \sum_{k \in \mathcal{K}} Z_k(t) [x_k(t) - \sum_{m \in \mathcal{M}} c_k \pi_m \phi_{km}(t)] \\ &\quad + \sum_{m \in \mathcal{M}} H_m(t) [C_m(t) - \rho_m c_m] \end{aligned} \quad (15)$$

Where $B(t)$ is defined:

$$\begin{aligned} B(t) &\triangleq \frac{1}{2} \sum_{k \in \mathcal{K}} [\gamma_k(t) - x_k(t)]^2 + \frac{1}{2} \sum_{k \in \mathcal{K}} [x_k(t) - \sum_{m \in \mathcal{M}} c_k \pi_m \phi_{km}(t)]^2 \\ &\quad + \frac{1}{2} \sum_{m \in \mathcal{M}} [C_m(t) - \rho_m c_m]^2 \end{aligned}$$

The value of $B(t)$ can be upper bounded by a finite constant B every slot, where B depends on the maximum possible values that $x_k(t)$ and $\gamma_k(t)$ can take. The algorithm below is defined by observing the queues states and channel state $\pi_m(t)$ at every slot t , and choosing actions to minimize the last four terms on the right-hand-side of (15) (not including the first term $B(t)$):

The Drift-Plus-Penalty Algorithm:

- (Auxiliary Variables) Every slot t , each FU observes $Q_k(t)$, and chooses $\gamma_k(t)$ as the solution to:
 Maximize: $VU_k(\gamma_k(t)) - Q_k(t)\gamma_k(t)$
 Subject to: $0 \leq \gamma_k(t) \leq x_k^{max}$ (16)
- (Flow Control) Every slot t , each FU observes $Q_k(t)$, and $Z_k(t)$ and choose $x_k(t)$ to maximize:
 Maximize: $(Q_k(t) - Z_k(t))x_k(t)$
 Subject to: $x_k(t) \leq x_k^{max}$ (17)
- (Scheduling) The CFBS observes all queues $(Q_k(t), Z_k(t), H_k(t))$ and channel state $\pi_m(t)$ on slot t , and chooses vector $\phi(t)$ to maximize:
 Maximize: $\sum_{k \in \mathcal{K}} Z_k(t) \sum_{m \in \mathcal{M}} c_m \phi_{km}(t) - \sum_{m \in \mathcal{M}} H_m(t) \sum_{k \in \mathcal{K}} c_m \phi_{km}(t) (1 - \pi_m)$
 Subject to: $\sum_{k \in \mathcal{K}} \phi_{km}(t) \leq 1, \sum_{m \in \mathcal{M}} \phi_{km}(t) \leq 1$ (18)
- (Queues update) Update virtual queues $Q_k(t)$, $Z_k(t)$, and $H_k(t)$ for all FUs via (12), (13) and (14).

IV. Numerical Results.

We consider a network of 5 FUs which opportunistically access to 9 orthogonal channels. Link capacities of all FUs and channels are chosen randomly, from a uniform distribution on $[0,1]$. We choose the utility function of FUs $U_m(x_m) = \ln(1 + w_k x_m)$, the QoS constraint ρ_m is set to 0.2 for all channels and using $V = 10$, $x_k^{max} = 1, w_k = 1$ for all FUs. The Hungarian algorithm [6] is used to solve (18). In order to show that our algorithm can adapt to the change of traffic statistics, we consider two cases: high and low channel-occupancy, where the channel-idle probability π is assumed to have a uniform distribution on $[0.1, 0.3]$ and $[0.7, 0.9]$ respectively.

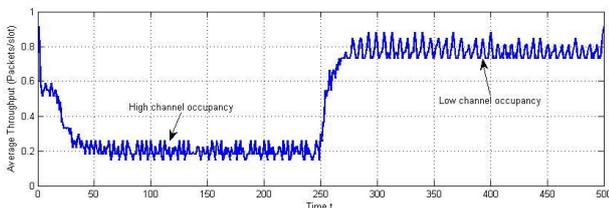


Fig. 2: Average throughput versus time

Fig. 2 shows that the throughput can converge to the optimal value when V 's value gets large enough. Fig.3 illustrates the stability of queues, and the values of queue backlogs which never exceeds an upper bound value.

V. Conclusions

This paper considered a problem of resource allocation in cognitive femtocell networks. An algorithm is developed for choosing policies on each timeslot in order to maximize concave functions of the time average transmission rate vector of femtocell users, subject to capacity of channels and maximum channels' collision tolerance. The algorithm is based on Lyapunov optimization concepts and involves minimizing a drift-plus-penalty over each timeslot. Our results reveal that using this technique we achieve optimal throughput values along with network stability.

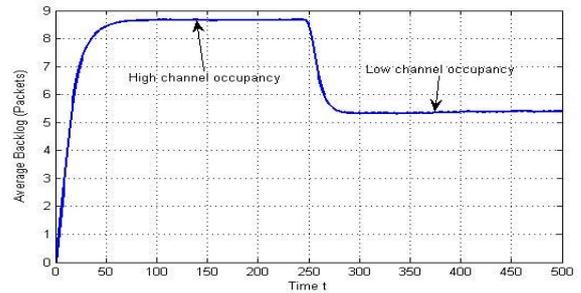


Fig 3: Average queues backlog versus time

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