Computer Networks 58 (2014) 87–98

Contents lists available at ScienceDirect

Computer Networks

journal homepage: www.elsevier.com/locate/comnet

Sequential sensing based spectrum handoff in cognitive radio networks with multiple users

Wenjie Zhang *, Chai Kiat Yeo

Centre for Multimedia and Network Technology, School of Computer Engineering, Nanyang Technological University, N4-B2c-06, Nanyang Avenue, Singapore 639798, Singapore

ARTICLE INFO

Article history:
Received 24 August 2012
Received in revised form 13 August 2013
Accepted 26 August 2013
Available online 4 September 2013

Keywords:
Sequential sensing
Spectrum estimation
Spectrum handoff
Cognitive radio

ABSTRACT

Spectrum handoff occurs when the primary users appear in the licensed spectrum temporarily occupied by the secondary users and aims to help the secondary users to vacate the spectrum rapidly and to resume transmission on new selected available channels. However, a spectrum handoff policy that comprehensively considers spectrum sensing, target channel selection as well as spectrum estimation has yet to be developed. In this paper we present a sequential sensing based spectrum handoff policy for multiple-user cognitive radio networks. First, we select the appropriate candidate channels for each secondary user, then their associated optimal sensing order together with the best target handoff channel is determined through sequential sensing based on Dynamic Programming (DP). Note that many spectrum handoff will occur during one secondary user transmission and our objective is to minimize the total number of spectrum handoff. The sequential sensing based spectrum handoff policy is evaluated through a comprehensive simulation study. The results reveal significant improvements in the system performance by reducing the number of spectrum handoff over conventional approaches. Moreover, our proposed DP method can significantly lower the computational complexity compared to exhaustive search and common DP (performing sequential sensing over all the channels in the system using Dynamic Programming).

1. Introduction

The rapid growth of wireless technologies has led to a dramatic increase in demand for spectrum. However, according to a report by Federal Communications Commission (FCC), most of the allocated spectrum is significantly under-utilized [1] [2] due to the inefficient fixed spectrum allocation policy. Cognitive radio is an emerging technique to mitigate the spectrum scarcity by allowing the secondary users to temporarily utilize the licensed spectrum unoccupied by the primary user [3] [4]. Due to the high priority of the primary user, the secondary user is required to vacate the occupied channel when the primary user appears and determine a new suitable channel to resume its unfinished transmission. This process is referred to as spectrum handoff. Compared with other major functionalities: spectrum sensing, spectrum decision and spectrum sharing, spectrum handoff is less well explored in the research community.

In general, the spectrum handoff can be categorized into two types [5]: (1) Proactive spectrum handoff which decides the target channel before the interruption occurs according to the long term traffic statistics [6–8]. (2) Reactive spectrum handoff which selects the target channel when it is required via spectrum sensing [9,10]. One issue related to proactive spectrum handoff is that the preselected channel may be no longer available at the moment that spectrum handoff is initiated. While for reactive spectrum handoff, additional time is required for spectrum sensing to search an idle channel, which results in an increase in

* Corresponding author. Tel.: +852-90759761.
E-mail addresses: zhan0300@ntu.edu.sg (W. Zhang), asckyeo@ntu.edu.sg (C.K. Yeo).

1389-1286/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.comnet.2013.08.025

handoff delay. In our paper, we propose a spectrum handoff mechanism which can reliably determine an idle target channel through sequential spectrum sensing. This mechanism can help to resolve the obsolescent channel issue in proactive spectrum sensing handoff where the preselected channel may no longer be available.

On the other hand, our spectrum sensing handoff is triggered when the residual idle time (which is defined as the duration from the time instant that the channel is detected to be idle and able to be utilized by the secondary user until the time instant that the interrupting event occurs and a spectrum handoff is required) of the current utilized channel reaches a threshold. By doing so, spectrum sensing and spectrum analysis can be overlapped with the ongoing transmission. As a consequence, the high handoff delay occurring in the reactive spectrum handoff can be addressed. Compared with other work on spectrum handoff where the secondary user greedily selects the target channel which either results in minimum transmission latency [11–13] or has the highest probability of being idle [17], in our paper, we choose the target channel with maximum residual idle time as our overall objective to reduce the number of spectrum handoff as much as possible.

To implement a better spectrum handoff in the event of primary user activity with seamless communication, wideband sensing is essential for designing a maximally effective cognitive network. It can detect multiple opportunities and enable the choice of the best available channel. However, the literature of wideband spectrum sensing for cognitive radio networks is very limited. In [33], sequential sensing is introduced, in which a wideband radio channel is sensed using tunable narrowband bandpss filter at the RF front-end to sense one narrow frequency band at a time. There have also been studies on sensing different frequency bands simultaneously. In [34], multiband joint detection approach is proposed where the wideband channel is divided into K non-overlapping narrow subbands. In [35], an optimal algorithm is presented for wideband spectrum sensing with the aim of maximizing the achievable throughput of the secondary user while keeping the interference with the primary network bounded to a reasonably low level.

One important issue related to wideband spectrum sensing is the optimal sensing order problem. Most prior work on sensing order issue [14–16] only considers single user or two-user scenario. In [14], the channel sensing problem is formulated as an optimal stopping rule problem and it is shown that the optimal sensing order does exist in some special scenarios for single user case. In [16], the authors extend the sensing order issue to two-user multi-channel case. The problem is still open for multiple secondary users case. In [17,18], the authors propose the spectrum switching algorithm according to descending order of channel idle probability. When primary user appears on the current operating channel, the secondary user must vacate the channel immediately and resume its transmission on the channel which has the highest idle probability. This approach has proven that the spectrum switching delay can be significantly reduced. However, if multiple secondary users perform spectrum sensing at the same time, switching channel according to the descending order of channel idle probability may no longer be optimal, since these selections will cause collisions among secondary users.

Recently, study on the optimization of spectrum sensing in cognitive radio network has attracted a lot of attention. There are two approaches that are commonly used to schedule the spectrum sensing [15]. The first one is periodic spectrum sensing [19–22], in which the secondary users perform spectrum sensing at the beginning of each frame and transmit if the channel is detected as idle. Otherwise, the secondary users have to wait until the next frame. The other approach is sequential spectrum sensing [15,16,23]. In this case, spectrum is searched by sensing the channels one by one until an idle channel with satisfied quality is detected. This approach allows secondary users to explore diversity in the licensed spectrum. Hence, in the case that one channel is sensed to be busy, the secondary user can quickly continue to sense the next spectrum opportunity without waiting until the next frame as in the case of periodic sensing. Obviously, sequential sensing can have better performance than periodic sensing. Currently, the spectrum sensing techniques can be mainly classified into matched filter, covariance matrix based detection, cyclostationary feature detection and energy detection [36], each has its own disadvantages and advantages. Matched filter requires perfect knowledge of the PUs' signaling features such as operating frequency, modulation type and order, which is not practised in reality. Cyclostationarity feature detection not only requires a priori knowledge of the signal characteristics, but also needs a much longer sensing duration for a channel which may be more than 20 ms [37]. Comparing with them, energy detection is the most common way of spectrum sensing due to its low computational and implementation complexity and less sensing time. In our paper, each secondary user may sequentially perform sensing up to N channels in a slot. Thus, a short sensing duration is reasonable. Due to the above reasons, the energy detection based sequential sensing is of our concern in this paper. We propose a sequential sensing based spectrum handoff scheme to determine the optimal sensing order as well as the best target handoff channel for each secondary user in a multiple-user cognitive network using DP.

Whenever a secondary user needs to switch channel, it must perform sequential sensing to discover a new opportunity with minimum delay so that the secondary user in the network can resume its communication quickly. However, one has to account for the fact that finding the optimal sensing order as well as the best target channel has huge computational complexity. To address this problem, instead of performing sequential sensing over all the channels in the network, we select candidate channels for each secondary user, which analyzes the tradeoff among the three key characteristics: (1) keep the probability of detecting at least one idle channel high; (2) reduce the sensing overhead and computational complexity as much as possible; and (3) avoid collision with other secondary users. Therefore, each secondary user only scans its associated candidate channels every time when the spectrum handoff is triggered. It is shown that the computational complexity is significantly reduced while the system