Ad Hoc Networks 11 (2013) 778–797

Contents lists available at SciVerse ScienceDirect

Ad Hoc Networks

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

Sequential opportunistic spectrum access with imperfect channel sensing ☆

Tao Shu [a,*], Marwan Krunz [b]

[a] Department of Computer Science and Engineering, Oakland University, Rochester, MI, United States
[b] Department of Electrical and Computer Engineering, The University of Arizona, Tucson, AZ, United States

ARTICLE INFO

Article history:
Received 17 July 2011
Received in revised form 16 August 2012
Accepted 12 September 2012
Available online 24 September 2012

Keywords:
Opportunistic spectrum access
Channel sensing and probing
Optimal stopping

ABSTRACT

In this paper, we exploit channel diversity for opportunistic spectrum access (OSA). Our approach uses *instantaneous* channel quality as a second criterion (along with the idle/busy status of the channel) in selecting channels to use for opportunistic transmission. The difficulty of the problem comes from the fact that it is practically infeasible for a cognitive radio (CR) to first scan all channels and then pick the best among them, due to the potentially large number of channels open to OSA and the limited power/hardware capability of a CR. As a result, the CR can only sense and probe channels sequentially. To avoid collisions with other CRs, after sensing and probing a channel, the CR needs to make a decision on whether to terminate the scan and use the underlying channel or to skip it and scan the next one. The optimal use-or-skip decision strategy that maximizes the CR's average throughput is one of our primary concerns in this study. This problem is further complicated by practical considerations, such as sensing/probing overhead and sensing errors. An optimal decision strategy that addresses all the above considerations is derived by formulating the sequential sensing/probing process as a rate-of-return problem, which we solve using optimal stopping theory. We further explore the special structure of this strategy to conduct a "second-round" optimization over the operational parameters, such as the sensing and probing times. The aggregate throughput performance when a network of CRs coexist with primary radios is evaluated under homogeneous and heterogeneous spectrum environments, respectively. We show through simulations that significant throughput gains (e.g., about 100%) are achieved using our joint sensing/probing scheme over the conventional one that uses sensing alone.

1. Introduction

1.1. Motivation

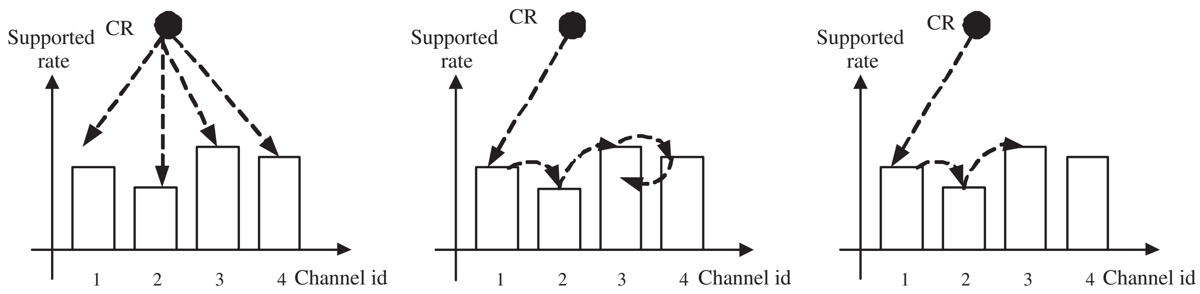
The benefit of *opportunistic spectrum access* (OSA) as a means of improving spectrum utilization is now well recognized [36]. OSA aims at opening under-utilized portions of the licensed spectrum for secondary re-use, provided that the transmissions of secondary radios do not cause harmful interference to primary radio (PR) transmissions. Because a secondary radio is supplied with more channels than what it can use for a single transmission, a critical challenge in OSA is to select real-time the channel that the secondary radios should use. In this paper, we focus on distributed channel selection algorithms that provide a secondary radio with the maximum possible throughput under the constraint that PR transmissions are not negatively affected by this selection.

Cognitive radios (CRs) have been proposed as the enabling technology for OSA [24]. The conventional way for a CR to select channels is to scan (sense) channels and access the ones that are deemed idle. Although this approach guarantees a safe (secondary) access to the spectrum, it generally does not give optimal throughput performance. This is because the CR does not account for the relative

☆ A preliminary version of this paper had been presented at the *ACM MobiCom 2009 Conference*, Beijing, September, 2009.

* Corresponding author.
E-mail address: shu@oakland.edu (T. Shu).

1570-8705/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.adhoc.2012.09.004



(a) Parallel channel scan.

(b) Sequential channel scan with recalled channel selection: ch3 is skipped in the first place and then picked after scanning ch4

(c) Sequential channel scan without channel recall: ch3 is selected in the first place and channel scan process terminates after that

Fig. 1. Various channel scan and selection paradigms.

quality of an idle channel, and hence it may transmit over an idle channel of poor condition, hampering the CR's throughput.

In this paper, we study a *joint sensing/probing* mechanism that achieves higher throughput than the classic binary channel selection approach. Under this scheme, a CR not only senses the binary status (idle/occupied) of a channel, but also probes idle channels to decide the instantaneous maximum data rates that can be supported on these channels. Such information is then used as a second criterion for channel selection. This mechanism is motivated by the rich channel diversity in CR environments, where signal fluctuations over various channels become *independent* once the channel bandwidth is greater than the coherence bandwidth of the signal. For example, in an IEEE 802.22 WRAN (the first standard for CR networks (CRNs)), each channel occupies a 6-MHz bandwidth, while the signal's delay spread typically ranges between 100 ns and 10 μs [26], corresponding to a coherence bandwidth ranging from 16 kHz to 1.6 MHz (coherence bandwidth $= 1/(2\pi \times \text{delay spread})$ [26]). Thus, it is possible for a CR to exploit this multi-channel diversity by opportunistically selecting a good channel for transmission.[1]

This work focuses on the operational aspects of the above mechanism. This is in contrast to related works that study the conceptual aspects of multi-channel diversity from a high-level mathematical standpoint and tend to ignore its operational details. Specifically, we account for the following practical considerations in developing our mechanism. First, the instantaneous condition of a channel is unknown to a CR until it is sensed and probed by that CR. Due to the potentially large number of channels and the CR's power/hardware limitations, it is infeasible for the CR to first scan all channels simultaneously and then pick the best among them. A CR's channel sensing and probing can only be conducted sequentially. After sensing and probing a channel, the CR needs to decide whether to terminate the scan and use the last scanned channel, or to skip it and scan the next one. To avoid collisions with PRs and other CRs, a CR cannot recall (use) a channel it previously skipped without sensing and probing it again, because of the staleness of previous sensing/probing outcome (e.g., the channel may have been occupied by other CR or PR, or its quality has changed). To better understand the above process, we illustrate various channel scan/selection paradigms in Fig. 1, among which sub-figure (c), i.e., sequential channel scan and non-recalled channel selection, is the one we pursue in this work. Under this paradigm, the optimal use-or-skip decision strategy that maximizes the CR's average throughput is one of the key issues investigated in this paper.

The above decision making process is further complicated when the CR's sensing and probing overheads need to be considered in each step. Empirical data shows that sensing a channel takes tens of ms and probing a new one takes from 10 to 133 ms, depending on the association and capture speed between the transmitter and receiver after each channel hopping [2]. At the same time, to reduce collisions with newly activated PRs, a CR's continuous transmission over an idle channel must be limited, e.g., in the order of hundreds of ms or at most few seconds. After that, the CR needs to sense/probe channels again.[2] As such, the accumulated overhead after sequentially sensing/probing several channels could be comparable with or even greater than the CR's actual transmission time. When such overhead is accounted for, the gain that may be potentially achieved by looking for a slightly better channel than the currently scanned one may not be justifiable.

Furthermore, we need to account for the impact of sensing errors on the CRN throughput. Sensing errors exist in all real systems and, as shown shortly, they significantly impact the throughput. When sensing errors are present, a CR may, for example, falsely identify an idle channel as being occupied, thus missing a transmission opportunity. Under this setup, the CR's sensing time (i.e., the amount of time the CR spends on sensing a channel) becomes a var-

[1] Without channel diversity, all idle channels exhibit comparable quality.

[2] Probing is required to account for the fluctuation of channel quality.