Journal of Network and Computer Applications 36 (2013) 523–532

Contents lists available at SciVerse ScienceDirect

Journal of Network and Computer Applications

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

Opportunistic medium access control for maximizing packet delivery rate in dynamic access networks ☆

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A R T I C L E   I N F O

Article history:
Received 20 September 2011
Received in revised form
23 February 2012
Accepted 13 April 2012
Available online 11 May 2012

Keywords:
Channel availability
Channel quality
Packet success probability
Opportunistic access

A B S T R A C T

One of the key challenges to enabling efficient cognitive radio (CR) communications is how to perform opportunistic medium access control (MAC) that maximizes spectrum efficiency. Several CRN MAC protocols have been designed assuming relatively static primary radio (PR) channels with average idle durations largely exceed CR transmission times. For such CR environment, typical multichannel MAC protocols, which select the best quality channel, perform reasonably well. However, when such mechanism is employed in a CRN that coexists with highly dynamic licensed PR networks (PRNs), where PR channel idle durations are comparable to CR transmission times, the forced-termination rate for CR transmission can significantly increase, leading to a reduction in network throughput. To reduce the forced-termination rate, many MAC protocols have been proposed to account for the dynamic time-varying nature of PR channels by requiring communicating CR users to consistently perform channel switching according to PR activities. However, such channel-switching strategy introduces significant overhead and latency, which negatively affect network throughput. Hence, in this paper, we propose a probabilistic channel quality- and availability-aware CRN MAC. Our protocol uses a novel channel assignment mechanism that attempts at maximizing the packet success probability of each transmission and hence avoids the significant overhead and latency of channel switching. Simulation results show that by being quality- and availability-aware, our protocol provides better spectrum utilization by decreasing the forced-termination rate and improving network throughput.

1. Introduction

The recent explosion of wireless applications and services has significantly increased the demand for more radio spectrum. While most of the available spectrum is statically licensed to different organizations, recent spectrum measurements conducted by the FCC and other agencies indicated that the licensed portion of the spectrum is vastly under-utilized (Bany Salameh and Krunz, 2009). These measurements triggered the need for a new radio technology, whose main purpose is to improve the spectrum utilization of the licensed spectrum through opportunistic spectrum access. For this purpose, cognitive radio (CR) technology has been proposed as a viable solution to allow for such opportunistic access to the limited spectrum resources. CRs are fully programmable software-defined radios that are mainly characterized by its cognitive capability and reconfigurability. The cognitive capability provides spectrum awareness whereas reconfigurability enables a CR user to dynamically adapt its operating parameters to the surrounding RF environment in order to effectively exploit the under-utilized portion of the licensed spectrum without affecting active PR users. Hence, the crucial challenge in this domain is to provide efficient spectrum access strategies for CR users that account for the peculiar characteristics of their operating environment. Specifically, after identifying spectrum opportunities, such strategies should make efficient spectrum assignment decisions that attempt at maximizing spectrum efficiency. These decisions should account for both the relative quality of idle channels and their availability durations. Thus, new MAC protocols that leverage the unique capabilities of CRs while considering their operating environment are needed to effectively utilize the available spectrum.

1.1. Motivation

The conventional channel assignment strategy in a CRN is to select the idle channel with the best quality that supports the highest instantaneous data rate (e.g., Clancy, 2007; Bany Salameh et al., 2009). This approach guarantees minimum transmission time (safer unlicensed access to the spectrum). It is worth mentioning that for traditional multi-channel networks, this

☆ An bridge version of this paper was presented at the IEEE WCNC 2012 Conference.

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http://dx.doi.org/10.1016/j.jnca.2012.04.004

approach is the best strategy in terms of throughput, since the availability duration of a free channel does not vary with time (Nasipuri and Das, 2000). In addition, this scheme performs well over a relatively static PR channels, where average idle durations for PR channels largely exceed CR transmission times (Bany Salameh et al., 2009; Salameh, 2010). However, when such channel assignment is employed in a CRN that coexists with highly dynamic PRNs, where their average channel idle durations are comparable to CR transmission times, the forced-termination rate for CR transmissions, defined as the percentage of CR packets that are terminated due to PR activities, can significantly increase, leading to a reduction in network throughput. This is because the CR transmitter does not account for the stochastic time-varying nature of PRN activities, and hence it may transmit over an available channel with relatively short idle duration. We refer to this channel quality-aware approach as the minimum transmission time (MIN-TX). On the other hand, selecting the idle channel with the highest average availability duration (e.g., Jones et al., 2005) can also increase the forced-termination rate. This is because relative-quality conditions of idle channels are not considered, and hence an idle channel of poor quality may be selected, leading to a significant reduction in network throughput. We refer to this channel availability-aware approach as the maximum availability duration (MAX-AV).

Based on the above discussion, an efficient channel assignment scheme for dynamic CRN environment should jointly consider the rapid fluctuations in link quality conditions of idle channels and statistical information regarding their availability durations to maximize the probability of successful packet delivery, and consequently enhance network throughput. To illustrate, consider an environment in which three PRNs and one CRN coexist. PRN i operates over frequency channel i, where $i=1,2,3$. Suppose that, for a PR channel i, the idle duration $T_I^{(i)}$ follows an exponential distribution with mean μ_i (i.e., $P_r(T_I^{(i)} \geq t) = e^{-t/\mu_i}$, where $i=1,2,3$). The appropriateness of using this distribution is described in Section 3. Assume that a CR user A needs to send a data packet of size D to CR user B. Let $R^{(i)}$ and $T_{pkt}^{(i)} = D/R^{(i)}$ respectively denote the maximum achievable rate and required transmission time for $A \rightarrow B$ transmission over channel i. Suppose that $R^{(2)} = 10R^{(1)}$ and $R^{(3)} = 12R^{(1)}$. Thus, $T_{pkt}^{(2)} = (1/10)T_{pkt}^{(1)}$ and $T_{pkt}^{(3)} = (1/12)T_{pkt}^{(1)}$. Also, suppose that $\mu_1 = T_{pkt}^{(1)}$, $\mu_2 = 0.9T_{pkt}^{(1)}$, and $\mu_3 = 0.1T_{pkt}^{(1)}$. Note that the packet transmission is successful if the idle duration of the selected channel is greater than the required transmission time over that channel (i.e., $T_I^{(i)} \geq T_{pkt}^{(i)}$). When the CR users employ the MIN-TX approach, the transmission $A \rightarrow B$ selects channel 3. In this case, the packet success probability of $A \rightarrow B$ transmission is $e^{-1/1.2} = 0.4346$. When the MAX-AV approach is employed, the transmission $A \rightarrow B$ uses channel 1, which has $e^{-T_{pkt}^{(1)}/T_{pkt}^{(1)}} = e^{-1} = 0.368$ probability of success. However, $A \rightarrow B$ has much better chances of proceeding successfully if A selects a channel while considering channel-quality conditions and availability durations of idle channels. In this case, channel 2 is selected, which has $e^{-1/9} = 0.895$ probability of success.

1.2. Contribution

The contributions of this paper are as follows;

- We analytically characterize the packet success probability of a given CR transmission based on a stochastic model of PR activities under a Rayleigh fading channel model. We show that the packet success probability depends on link-quality conditions and average-availability durations of idle channels.
- We then develop an intelligent stochastic channel assignment scheme that attempts at improving the CRN throughput by assigning the channel with maximum probability of success to a given CR transmission. Our scheme exploits the rich channel diversity in CR environments while considering the prevailing local PR traffic conditions.
- Based on the developed channel assignment scheme, we design a distributed CSMA/CA-based MAC protocol for CRNs (MAX-PS-MAC) that aims at enhancing network throughput. Through a local exchange of control messages, MAX-PS-MAC enables a pair of CR users to select the idle channel with highest probability of packet success, which significantly reduces the overhead and delay of consistent channel switching due to PR activities. MAX-PS-MAC has other attractive features. First, it is easy to implement in practical settings and its processing overhead is small. Second, MAX-PS-MAC does not require active coordination with PRNs. Finally, under available channels with comparable availability periods (channel quality conditions), the CRN performance under MAX-PS-MAC gracefully degrades into the MIN-TX-MAC (MAX-AV-MAC) protocol.

In our performance evaluation, we conduct simulations over a dynamic CRN. Our simulation results show that the joint channel quality and availability awareness significantly improves network throughput. The results also indicate that compared with typical CSMA-based CRN MAC protocols, MAX-PS-MAC significantly decreases the CR forced-termination rate, which consequently improves the CRN throughput by up to 110% under low to moderate CR and PR traffic loads.

1.3. Organization

The rest of the paper is organized as follows. Section 2 overviews related work. In Section 3, we introduce our system model and state our assumptions. In Section 4, we formulate the optimal channel assignment problem. Section 4.3 introduces our proposed quality- and availability-aware channel-assignment algorithm. Section 5 describes the proposed MAC design. We evaluate our proposed MAC protocol in Section 6. Finally, Section 7 gives concluding remarks.

2. Related work

Many MAC protocols for CRNs have been proposed in the literature (e.g., Clancy, 2007; Bany Salameh et al., 2009; Jones et al., 2005; Zhao et al., 2005; Nie and Comaniciu, 2005; Wang et al., 2008; Bany Salameh et al., 2010; Yuan et al., 2007; Salameh, 2010; Salameh and Krunz, 2011; Xing et al., 2006; Min and Shin, 2008; Geirhofer et al., 2009; Yang et al., 2008; Feng et al., 2009; Hu et al., 2007). CRN MAC protocols can be generally classified according to the employed channel assignment strategy into two classes. In the first class (e.g., Xing et al., 2006; Clancy, 2007; Salameh, 2010; Bany Salameh et al., 2009, 2010; Yuan et al., 2007; Zhao et al., 2005; Nie and Comaniciu, 2005; Wang et al., 2008; Salameh, 2011), the proposed MAC protocols use the conventional multi-channel assignment strategy of selecting the idle channel with the best quality conditions. The main design issue here is that these protocols do not account for the stochastic and dynamic behavior of PRNs (i.e., PR channel availability durations). As explained before, using the channel-quality conditions alone for assigning channels can significantly degrade network performance because of the dynamic nature of PRNs. We now mention a number of spectrum access protocols that belong to this class. DC-MAC (Zhao et al., 2005) is a cross-layer distributed scheme for spectrum allocation/sensing. It provides an optimization