Physical Communication 1 (2008) 103–111

Contents lists available at ScienceDirect

Physical Communication

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

Full length article

Proactive channel access in dynamic spectrum networks☆

Lei Yang, Lili Cao, Haitao Zheng *

Department of Computer Science, University of California, Santa Barbara, CA 93106, United States

ARTICLE INFO

Keywords:
Spectrum access
Open spectrum
Proactive

ABSTRACT

Open Spectrum systems allow fast deployment of wireless technologies by reusing under-utilized pre-allocated spectrum channels, all with minimal impact on existing primary users. However, existing proposals take a reactive sense-and-avoid approach to impulsively reconfigure spectrum usage based solely on the latest observations. This can result in frequent disruptions to operations of both primary and secondary users. In this paper, we propose a *proactive spectrum access* approach where secondary users utilize past channel histories to make predictions on future spectrum availability, and intelligently schedule channel usage in advance. We propose two channel selection and switching techniques to minimize disruptions to primary users and maintain reliable communication at secondary users. Both simulation and testbed results show that the proactive approach effectively reduces the interferences to primary users by up to 30%, and significantly decreases throughput jitters at secondary users.

1. Introduction

Advance of wireless networks and technologies requires easily accessible spectrum where wireless devices can establish stable data communication. However, conventional spectrum management policies use static spectrum assignment to prevent interference. Over time, this has led to the well-known *artificial spectrum scarcity* problem. Recent surveys have shown that licensed spectrum are overly-allocated and yet critically under-utilized, often as low as 5%–10% [14]. To overcome such artificial scarcity, the most promising solution is *Open Spectrum* systems [2,14,19], where devices skip the licensing process and instead use next generation "Cognitive Radios" (CRs) [10,17], becoming *secondary users* that opportunistically access spectrum currently unused by legacy or *primary users*. Successful deployment of Open Spectrum systems requires secondary users to guarantee minimal interference to primary users.

Initial proposals for Open Spectrum systems take a *reactive* approach [15,20,21]. Secondary users reconfigure spectrum usages only after detecting changes in spectrum availability following some action by a primary user. Devices monitor spectrum channels through individual or collaborative sensing [3,5,8,9,12,16]. When detecting a change in spectrum, *e.g.* a primary user appears, secondary users pause existing transmissions, relinquish the band and seek other opportunities to resume communications [23]. Reconfiguration is impulsive and is based solely on the latest observations.

Such passive "sense and react" approach results in frequent disruptions to communications of both primary and secondary users. Specifically, periodic sensing and adaptation means that there is an unavoidable window of possible interference for primary users. As a result, primary users can experience short-term interference to transmissions before being detected by neighboring secondary users. Similarly, secondary users suffer from unexpected interruptions to communications, making it extremely difficult to satisfy application requirements. They have no expectations of future spectrum availability to help coordinate spectrum access or schedule transmissions.

☆ Part of this paper has been published at Second International Conference on Cognitive Radio Oriented Wireless Networks and Communications, CrownCom 2007.

* Corresponding author. Tel.: +1 805 893 3560; fax: +1 805 893 8553.
E-mail addresses: leiyang@cs.ucsb.edu (L. Yang), lilicao@cs.ucsb.edu (L. Cao), htzheng@cs.ucsb.edu (H. Zheng).

1874-4907/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.phycom.2008.05.001

In this paper, we propose a *proactive spectrum access* approach where secondary users proactively predict future spectrum availability and intelligently schedule channel access in advance. By adding limited "intelligence" to secondary users, they can take advantage of inherent patterns of primary users' spectrum usage; observe, model and make predictions about future changes in spectrum availability. Secondary users then use these predictions, along with current observations, to determine spectrum usage patterns to achieve reliable communication while minimizing disruption to primary users.

To achieve these goals, our proposed approach consists of two modules. First, to minimize disruption to primary users, secondary users should exit from a channel before encountering a primary user; referred to as *proactive channel switching*. Second, to quickly resume communication, secondary users should find another available (and reliable) channel; referred to as *intelligent channel selection*. Using these two modules, secondary users switch among different spectrum channels, and determine on-the-fly when to switch and which channel to switch to.

This paper makes the following contributions:

– *Proactive spectrum access framework*. We propose a framework for proactive spectrum access and provide detailed prediction methods assuming exponential and periodic traffic models. We also propose different prediction and schedule schemes using different sensing capabilities.
– *Comparison of reactive and proactive schemes*. We compare the performance of reactive and proactive spectrum access schemes by evaluating the rate of disruption to primary users, and the channel utilization at secondary users. The proposed schemes provide reasonable improvement (50% reduction of disruptions) over the reactive scheme. We show that the performance of proactive spectrum access depends heavily on the accuracy of spectrum availability prediction. Despite inherent patterns, primary users can act randomly, resulting in imperfect predictions and hence "dumb" switching choices.
– *Testbed implementation*. We implement both reactive and proactive spectrum access schemes using commodity 802.11 devices with MadWifi. Experimental results show that the proactive scheme can significantly improve the reliability of open spectrum access.

The rest of the paper is organized as follows. In Section 2 we provide background on the problem of dynamic spectrum access and outline the optimization goal. We also summarize existing approaches in this area. In Section 3 we present the proposed proactive spectrum access approach and discuss the detailed prediction methods for two types of primary user traffic models. We then evaluate both proactive and reactive spectrum access schemes in Section 4 and describe the testbed implementation and the results in Section 5. Finally, we discuss future work and conclude in Section 6.

2. Background on dynamic spectrum access

In Open Spectrum systems, secondary users experience dynamic spectrum availability, subject to nearby primary users' traffic patterns. It is important to first model and understand these behaviors, and then to design appropriate spectrum access schemes. In this section, we will provide background on dynamic spectrum access and related work.

2.1. Dynamic spectrum availability

Like entities in other electronic and computing systems, the behavior of primary users are not statistically random. Instead, they are driven by human users with predictable patterns in their actions. In this subsection, we illustrate a number of models used by existing literatures.

The mostly used model is the alternative exponential ON–OFF model as studies have shown that it approximates the spectrum usage pattern at public safety bands [22]. Each channel alternates between two modes: ON (the channel is occupied by a primary user) and OFF (the channel is idle). The durations of the ON and the OFF period are independently exponentially distributed. For a channel i, the duration of ON period y_i follows an exponential distribution with mean $\frac{1}{\lambda_{Y_i}}$:

$$f(y_i) = \begin{cases} \lambda_{Y_i} e^{-\lambda_{Y_i} y_i} & : y_i \geq 0 \\ 0 & : y_i < 0. \end{cases}$$

Similarly, for each channel i, its length of OFF period X_i follows an exponential distribution with mean $\frac{1}{\lambda_{X_i}}$.

The second model is the periodic ON–OFF model where each channel displays a fixed pattern of busy and idle period. In this model, after a long-term observation, secondary users can make accurate predictions of future spectrum availability.

These two models represent two extreme cases in terms of prediction capability. The alternative exponential model has a large degree of randomness due to the "memoryless" property of exponential distributions; while the periodic model can be accurately predicted given adequate observation time. In this paper, we use the exponential distribution model as an initial step of this research. However, our proposed concepts can be extended to other traffic models. We plan to investigate the proposed approach using real spectrum measurement data in a future study.

2.2. Secondary user spectrum access

With dynamic spectrum availability, secondary users must monitor spectrum constantly and switch among channels to avoid disrupting primary users. The channel access behavior of secondary users depends on their sensing capability:

– *Built-in sensing*. Each user has only one radio, and hence cannot sense and communicate at the same time. Further, the radio can only sense one channel at a time. In this case, secondary users apply a sequential sense-transmit-sense approach. As illustrated in Fig. 1, a user senses a channel for a short period of time. If the channel is idle, the user transmits for a short period and then senses the channel again.

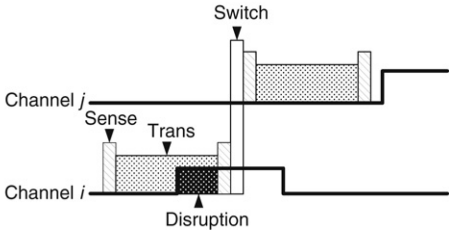


Fig. 1. The channel access model of secondary users. The bold lines describe the ON–OFF behaviors of different channels.

– *External sensing.* Each secondary user has multiple radios and can sense and communicate at the same time. Hence, each user can schedule sensing across different channels and monitor each channel continuously. Yet, it still has to perform a periodic sense-transmit-sense approach in order to avoid disrupting primary users.

Fig. 1 illustrates the reactive channel access model. Using reactive spectrum access, a secondary user remains on one channel until detecting that it becomes busy. Since there is detection delay, secondary user's communication could disrupt the operations of the nearby primary user, marked as a *disruption* in the figure.

2.3. Design goals

Dynamic spectrum access has the following goals:

– *Minimizing interference to primary users*—When transmits during the BUSY period of a channel, a secondary user/link can produce interference to primary user's signal reception. Or the secondary user/link can suffer from interference from a primary transmitter.
– *Fast recovery*—An inherent problem in open spectrum systems is the unstable channel access due to dynamic spectrum availability. Secondary users must switch across channels and identify usable spectrum. Delay due to improper channel searching, sensing and switching can lead to transmission gaps over time.
– *Maximizing throughput*—Finally secondary users intend to fully utilize the under-utilized spectrum.

2.4. Related work

There have been several prior works on dynamic spectrum access and sensing. The most relevant ones are [12,18]. In [18] the authors proposed a proactive access scheme based on the characteristics of TV-broadcast and explored the feasibility of proactive access method. Our work extends this work to a general primary user traffic model, *i.e.*, the exponential ON–OFF model. Moreover, [18] mainly focuses on throughput maximization, while our work focuses on minimizing disturbance to primary users and providing fast recovery.

In [12], the authors used ON–OFF channel model and proposed an adaptive sensing scheme to maximize discovery of channel opportunities and perform ordering of channels to minimize the delay. Our proactive channel selection technique uses a similar prediction method as in the optimal-ordering scheme in [12]. However, we focus on minimizing the disruption to primary users by predicting future spectrum availability and scheduling channel switch in advance.

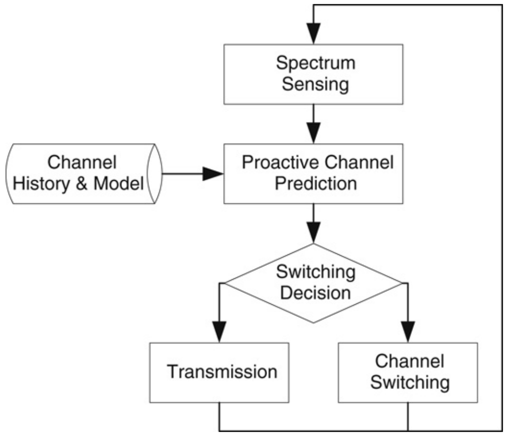


Fig. 2. Flow chart of our proactive spectrum access system.

3. Proactive spectrum access

Under reactive spectrum access model, secondary users switch channels only after detecting a primary user. Hence, there is an unavoidable window of possible interference to primary users. Further, secondary users suffer from unexpected interruptions to communications, making it extremely difficult to satisfy application requirements. The root to these limitations is that secondary users have no expectations of future spectrum availability and hence cannot make intelligent decisions on spectrum access.

In this section, we show that by proactively predicting future spectrum availability, secondary users can intelligently switch channels before primary users' reappearance. As a result, they can maintain reliable high-throughput communication while minimizing disruptions to primary users. Fig. 2 illustrates the operations at secondary users using the proposed proactive spectrum access. Our proposed mechanism consists of the following core modules:

– *Proactive Channel Prediction*—After each spectrum sensing, secondary users utilize past channel observations to estimate future spectrum availability.
– *Intelligent Channel Switching*—Utilizing prediction results, secondary users decide when to exit from a channel and which channel to switch to.

Next, we will describe these two modules in detail. We start by describing the assumptions on secondary users. First, a secondary user will coordinate with its communicating pair to schedule a channel switch. Second, we only consider a single pair of secondary users and ignore the impact of contention from other coexisting secondary users. Our proposed approach can be extended into multiple secondary user cases by using distributed coordination [1,4]. For example, our proposed scheme can be combined with the coordination scheme of [1] to consider both the spectrum availability and the level of contention from other secondary peers when deciding the channel to use.

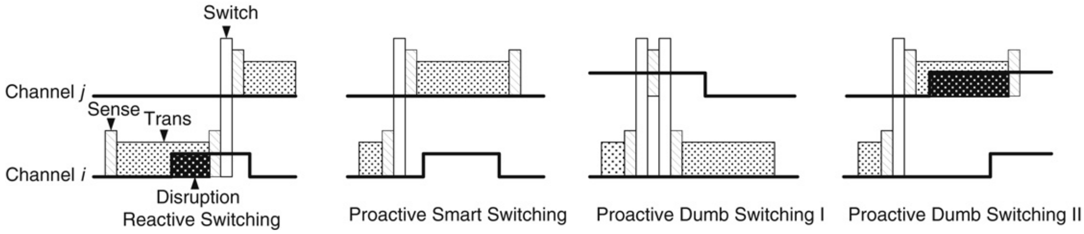


Fig. 3. The four types of channel switching decisions: Reactive, Proactive Smart, Proactive Dumb I and Proactive Dumb II.

3.1. Proactive channel prediction

The dynamic nature of open spectrum systems makes channel access relatively instable compared to conventional systems. Upon detecting any primary user on a channel, affected secondary users must exit quickly and find another available channel to resume communication. Hence, the first challenge of dynamic spectrum access is how to find an available channel with minimum delay. Clearly, having the knowledge of current (or near future) spectrum availability can significantly reduce the searching latency. Therefore, before searching channels one by one through sensing, we propose to first predict the probability that a channel i will be idle in the next time slot, referred to as P_i.

The prediction mechanism depends on the usage model of primary users. In this paper, we assume that secondary users have the knowledge on the statistical property of each channel's usage pattern, including statistical models and parameters. Secondary users can acquire this knowledge by observing the channel over a long period of time or from assistance of a spectrum server. Next, we outline different mechanisms for predicting P_i for three specific traffic models.

– *Alternative Exponential Model*—In this model, the distribution of channel idle/busy status in the next time slot only depends on the latest sample of channel history s_i. Using renewal theory [7], we can calculate P_i as [12]:

$$P_i = \begin{cases} \dfrac{\lambda_{Y_i} + \lambda_{X_i} \cdot \mathrm{e}^{-(\lambda_{X_i}+\lambda_{Y_i})\Delta t_i}}{\lambda_{X_i} + \lambda_{Y_i}} & s_i = IDLE \\ \dfrac{\lambda_{Y_i} - \lambda_{X_i} \cdot \mathrm{e}^{-(\lambda_{X_i}+\lambda_{Y_i})\Delta t_i}}{\lambda_{X_i} + \lambda_{Y_i}} & s_i = BUSY\,. \end{cases} \quad (1)$$

Here Δt_i is the length of the time from the last history s_i to the next time slot. Note that this model has a large degree of randomness due to the "memoryless" property of the exponential distribution.

– *Periodic model*—With adequate observations, secondary users can always accurately predict the channel status in future slots.

– *Alternative Periodic-Exponential model*—This model is an intermediate model between the previous two extreme cases. The duration of ON (or OFF) periods is fixed to T, and the duration of OFF (or ON) periods is exponential distributed with a rate parameter λ. We can calculate P_i as: (the detailed derivation is omitted due to space limit).

$$P_i = \begin{cases} \dfrac{1}{T}\displaystyle\int_0^T \sum_{n=0}^{\lfloor \frac{\Delta t_i - x}{T} \rfloor} \dfrac{\lambda^n (\hat{\Delta t_i} - x)^n}{n!\mathrm{e}^{\lambda(\hat{\Delta t_i} - x)}}\mathrm{d}x, & \Delta t_i > T \\ \dfrac{1}{T}\displaystyle\int_0^{\Delta t_i} \mathrm{e}^{-\lambda(\Delta t_i - x)}\mathrm{d}x, & \Delta t_i < T \end{cases} \quad (2)$$

where $\hat{\Delta t_i} = \Delta t_i - nT$.

Prediction accuracy depends on the distance between the next time slot to the last observation on this channel. An ideal case is when secondary users can quickly scan multiple channels during the sensing period, and use these immediate observations as the channel status in the next time slot. However, this does require sophisticated hardware, such as a stand-alone sensing radio.

It should be mentioned that the proposed prediction mechanism is similar to that of [12]. However, the difference is that [12] uses P_i to compute an order of channels and search for available channels in this order; while our approach chooses one channel at a time and recomputes P_i after each sensing attempt. More importantly, our proposed mechanism also uses prediction results to switch channels before "bumping" into any primary users. Next, we describe the proposed intelligent channel switching in detail.

3.2. Intelligent channel switching

Utilizing observation history and prediction results, secondary users can schedule future channel switchings to avoid disrupting primary users and maintain reliable communication. Fig. 3 compares the behavior of reactive switching and proactive switching. Using reactive spectrum access, secondary users interfere with primary users until detecting them. Channel switching is impulsive, leading to unavoidable disruptions to primary users. On the other hand, using proactive spectrum access, secondary users can exit from the channel before primary users enter the channel, avoiding affecting primary users and minimizing interruptions to their own communication.

However, we note that the effectiveness of proactive spectrum access depends on the prediction accuracy. Under imperfect prediction, secondary users can make "dumb" switching decisions. Fig. 3 illustrates two types of dumb switching. In the dumb switching I, a secondary user predicts channel j is better than channel i and switches to channel j which is busy, leading to unnecessary disruptions to its own communication. Similarly, in the dumb switching II, the user switches to a channel that has shorter remaining idle period than the current channel,

Table 1
Summary of different switching behaviors

Behavior	Description
Reactive switching	Switch channel after detecting primary users
Proactive smart switching	Switch to a channel with longer remaining idle time than the current channel
Proactive dumb switching I	Switch to a busy channel
Proactive dumb switching II	Switch to a channel with shorter remaining idle time than the current channel

leading to additional interference to primary users. We summarize different switching behaviors in Table 1.

Our goal is to increase the occurrence of smart switching and avoid dumb switching. The key difference between smart and dumb switching is the length of the remaining idle period: if the remaining idle period in the current channel c is shorter than that in another channel i, then switching from channel c to i is smart. Therefore, we propose to choose the channel using the following two criteria:

– *Proactive Planning I*—switch to a channel with the largest expectation of the remaining idle period. The expectation of the length of the remaining idle period can be calculated as

$$E(T_i) = \frac{P_i}{\lambda_{X_i}} \tag{3}$$

– *Proactive Planning II*—switch to i if with high probability that the length of the remaining idle period of another channel i is larger than that of the current channel c. We first calculate the probability that channel i has longer remaining idle time than c:

$$P(T_i > T_c) = P_i - \frac{\lambda_{X_i}}{\lambda_{X_i} + \lambda_{X_c}} P_i P_c. \tag{4}$$

In this case, the secondary user finds the maximum $P(T_i > T_c)$, and if it is above a threshold T (*e.g.* $T = 0.5$), then switches to channel i.

4. Simulation results

We use matlab simulations to evaluate the performance of both reactive and proactive spectrum access schemes under different system settings. Table 2 summarizes different reactive and proactive schemes. Table 3 summarizes the simulation parameters. We note that the absolute value of these parameters is not as important as the relative ratio between them. To evaluate the performance of both secondary users and primary users, we examine the average primary users' disruption rate (the number of disruptions per second) and the average secondary users' channel utilization.

4.1. Channel utilization and disruption rate

Using Alternative Exponential traffic model, Fig. 4 illustrates the CDF and average channel utilization of each access scheme, and Fig. 5 illustrates the CDF and average primary user disruption rate. These results show that the proposed proactive approach can increase the secondary user's channel utilization by around 5%, and reduce the primary user hit rate by up to 30% compared to the reactive random approach. By introducing future prediction and smart switching, our proactive approach reduces up to 12% primary user hit rate compared to the existing proactive channel selection scheme (RE_P_HIS) [12].

Table 2
Spectrum access schemes

Method	Description
RE_RANDOM	Reactive switching; random channel selection.
RE_P_HIS	Reactive switching [12]; use (1) to derive P_i, and choose the channel with the highest P_i.
PRO_I	Proactive switching; use (1) to derive P_i; use (3) to choose the channel with the longest expected remaining idle period $E(T_i)$.
PRO_II	Proactive switching; use (1) to derive P_i; use (4) to choose the channel with the largest probability of having longer remaining idle period than that of the current channel.
PRO_MULTI_SEN	Proactive switching with multi-channel sensing ability and perfect prediction of P_i; use (3) to choose the channel with the longest expectation of remaining idle period T_i.
PRO_PERFECT	Proactive switching with perfect knowledge of the current channel status and the remaining idle period; switch to a channel with longest remaining idle time; the upper bound of system performance.

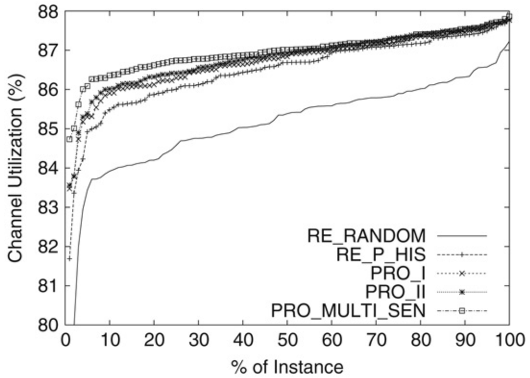
Table 3
Simulation parameters

Parameter	Value
Sensing period t_s	20 ms
Transmission duration T_s	180 ms
Switching delay D_s	10 ms
Number of channels	10
Primary user traffic models	$(1/\lambda_{X_i}$ and $1/\lambda_{Y_i})$ uniformly distributed in $[\mu_{\min}, \mu_{\max}]$
Simulation time	10 000 s

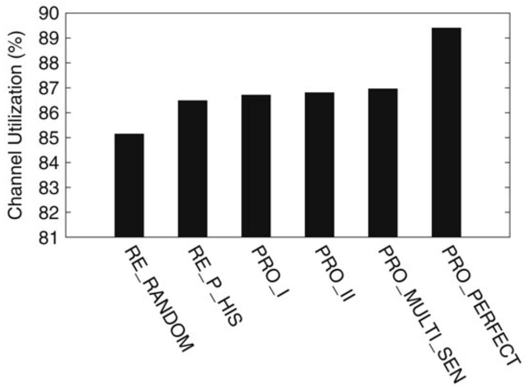
Fig. 6 shows the system performance when the primary user on each channel follows the Fixed OFF and Exponential ON time traffic model. In this case, with multi-channel sensing ability, secondary users can obtain perfect information of past and current channel status, and make accurate prediction of the future channel status. From Fig. 6, we see that the performance of proactive approach is almost perfect.

4.2. Smart switching

The proposed proactive schemes (PRO_I and PRO_II) are designed to increase the number of smart switching. In Table 4, we examine the numbers of smart switching in different proactive schemes over 10 000s. The percentage of smart switching is not high due to the randomness of the exponential ON–OFF model. In this case, predictions of remaining idle period are imperfect, and secondary users choose to stay at the current channel until detecting primary users. However, with multi-channel sensing, the number of smart switching improves to 30% due to perfect estimation of P_i. However, because of the imperfect prediction of the remaining idle period, the number of dumb switching type II also increases significantly.



(a) CDF.



(b) Average.

Fig. 4. Secondary users' channel utilization, assuming $\mu_{\min} = 0.5$, $\mu_{\max} = 5.0$.

Table 4
The percentage of proactive switching

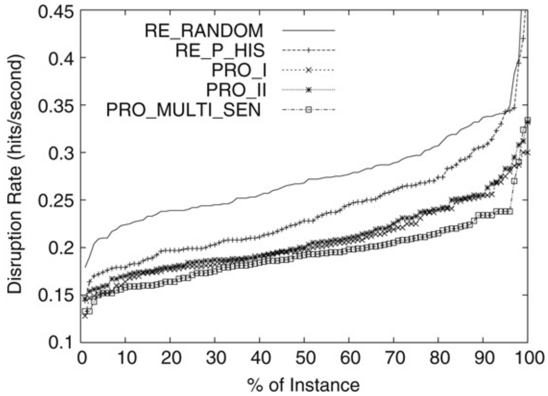
Method	Switch no.	Smart (%)	Dumb I (%)	Dumb II (%)
PRO_I	10 690	3.7	5.2	1.5
PRO_II	10 258	6.1	2.9	2.4
PRO_MULTI_CHAN	10 269	30.0	0	21.8
PRO_PERFECT	5 131	100	0	0

4.3. Effect of prediction errors

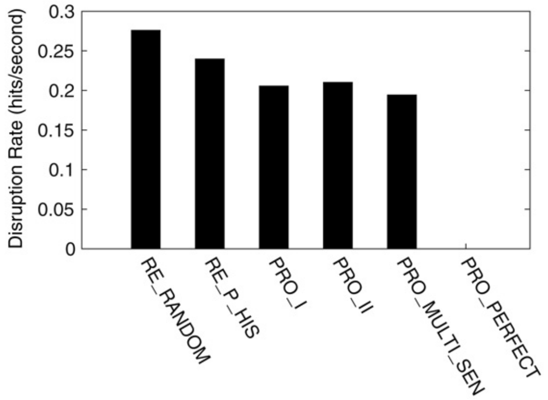
The randomness of the alternative exponential traffic model limits the effectiveness of the proposed proactive schemes. Although multi-channel sensing can get accurate information about the current status of every channel, it still cannot obtain good estimation of future channel activities. To examine the impact of prediction error for remaining idle period without limitation by our current prediction mechanisms, we modify the PRO_PERFECT scheme by adding a Gaussian noise $N(0, \delta^2)$ to the estimation of the remaining idle time. In Fig. 7 we examine the performance degradation at different δ. Not surprisingly, the channel utilization drops gracefully as the noise increases.

4.4. Impact of traffic burstiness

The performance of dynamic spectrum access depends heavily on the traffic model and statistics. Using the



(a) CDF.



(b) Average.

Fig. 5. Disruption rate, assuming $\mu_{\min} = 0.5$, $\mu_{\max} = 5.0$.

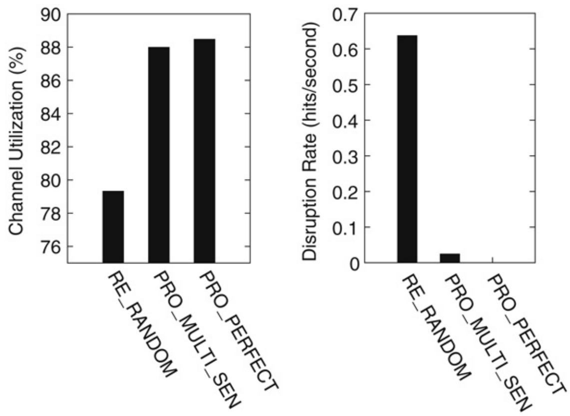


Fig. 6. Channel utilization and disruption rate of Fixed OFF-Exponential ON model.

Alternative Exponential ON–OFF model, we generate $1/\lambda_i$ by using uniform distribution from $[\mu_{\min}, \mu_{\max}]$, fixing $\mu_{\min}$ to 0.5, and varying $\mu_{\max}$ from 1.5 to 5.5. Figs. 8 and 9 show the channel utilization and disruption rate for different $\mu_{\max}$ values. We observe that the channel utilization increases with $\mu_{\max}$ while the disruption rate decreases with it. This is because increasing $\mu_{\max}$ reduces the average rate of primary user activity on each channel,

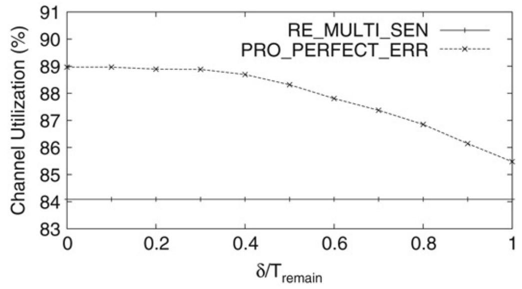


Fig. 7. Effect of prediction errors on channel utilization rate: Gaussian noise $N(0, \delta^2)$ is added to the perfect proactive scheme (PRO_PERFECT), T_{remain} is the accurate remaining idle period.

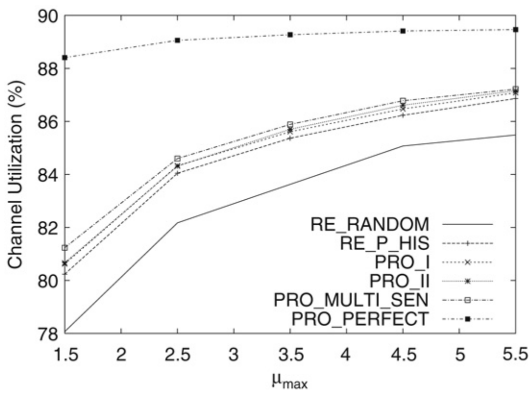


Fig. 8. Channel utilization of different channel parameters: increase $\mu_{\max}$ from 1.5 to 5.5.

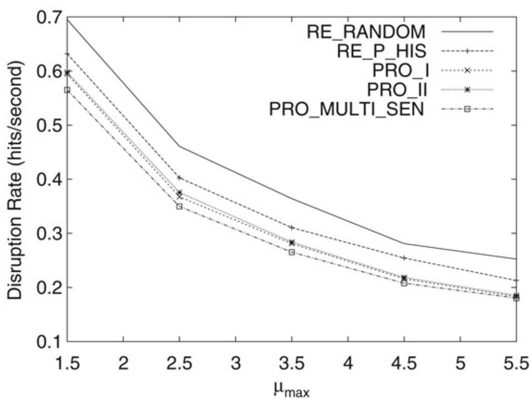


Fig. 9. Disruption rate of different changing channel parameters: increase $\mu_{\max}$ from 1.5 to 5.5.

and hence secondary users can utilize more spectrum. Similarly, our proposed proactive approaches achieve noticeable improvement over reactive approaches.

5. Testbed results

5.1. Implementation

We implement both proactive and reactive spectrum access approaches in a hardware testbed using 802.11 devices. We select 802.11 devices because they are capable of fast channel switch and can be reconfigured using the Madwifi driver [13]. We use two DELL laptops with Ubuntu Linux OS, each equipped with one Linksys 802.11 a/b/g WiFi card. We use 802.11b to perform data transmission.

Table 5
Testbed settings

Parameter	Value
Sensing period	20 ms
Transmission duration	180 ms
Switching delay	5 ms
Number of channels	10
Primary user traffic models	λ_{X_i}:1.77, 3.57, 5.03, 2.25, 2.55, 4.89, 3.60, 3.72, 4.50, 5.04 λ_{Y_i}:1.34, 2.12, 0.74, 4.68, 2.12, 1.49, 2.15, 4.49, 4.59, 2.05
Simulation time	100 s

We modify the built-in Madwifi driver to implement the following three features of dynamic spectrum access:

- *Fast Channel Switching*—The Madwifi driver allows users to switch channels using IO control calls. However, using the original Madwifi driver, the channel switching delay can be up to 100 ms due to the slow re-association process. We bypass the association process [6] and reduce the channel switching delay to 5 ms.
- *Link Maintenance*—Secondary users need to maintain data links during channel switching. In our testbed, to switch channels, a secondary user first notifies its peer via a channel switching request and synchronize channel usage at both ends.
- *Proactive Channel Access*—We implement the proposed proactive schemes in a user space daemon. Using this daemon, a secondary user performs prediction and makes switching decision, and then uses IOCTL calls to reconfigure the underlining wireless card to change channels accordingly.

Due to hardware limitations, we did not implement spectrum sensing. Instead, we generate traces of primary user's activity off-line, and incorporate the activity traces into the user daemon program to notify the Madwifi driver with the instantaneous channel status. During the time that a secondary user conflicts with a primary user, we drop all the received packets at the corresponding secondary user receiver.

5.2. Results

We use Iperf [11] tool to measure the UDP throughput between two Dell laptops. One laptop runs Iperf in client mode sending UDP packets at rate 3 Mbps while the other laptop records the received packet throughput every second. We use 10 channels, and randomly generate the λ_X and λ_Y for each channel, shown in Table 5.

Fig. 10 shows the throughput of RE_RANDOM and PRO_I schemes where PRO_I achieves 10% improvement in terms of the average throughput. However, we see that the rate fluctuation in RE_RANDOM is much higher than that of PRO_I. To further exploit this issue, Fig. 11 shows the CDF of these instantaneous throughput results. We see that PRO_I can significantly reduce the throughput fluctuations,

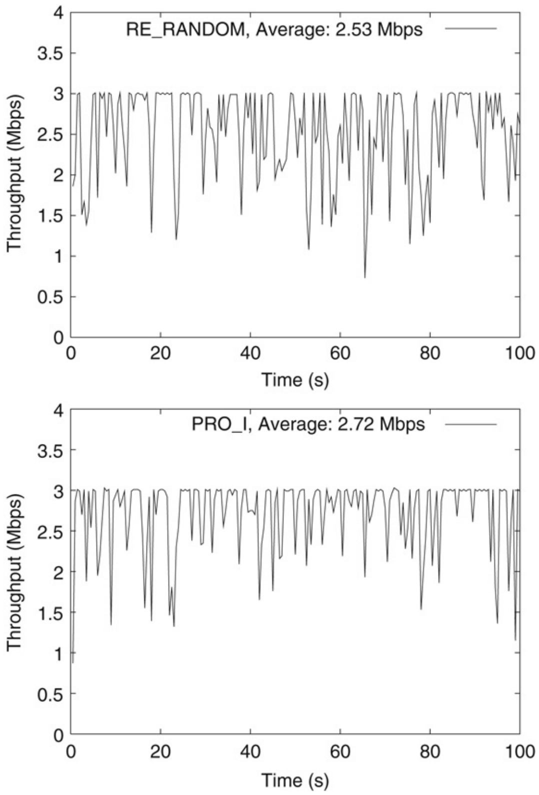


Fig. 10. Measured instantaneous throughput using reactive and proactive method I with CBR load of 3 Mbps.

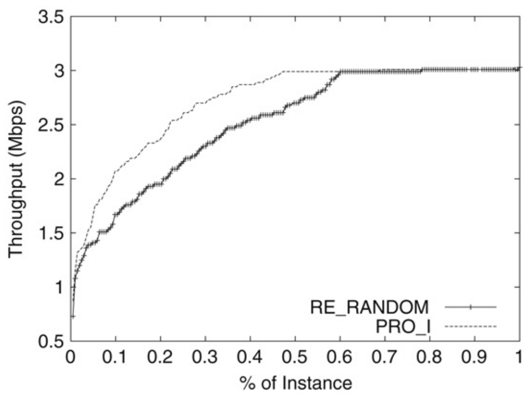


Fig. 11. CDF of the instantaneous throughput.

and improve the outage throughput. Assuming 10% outage, PRO_I achieves data rate of 2.05 Mbps while RE_RANDOM can only support 1.5 Mbps.

6. Conclusion and future work

In this paper we propose a proactive spectrum access scheme in Open Spectrum systems. Conventional approaches apply a reactive sense-and-adapt solution based solely on current observations, which leads to disruptions because users cannot foresee future channel status. The proposed proactive approaches use primary user traffic model and history observations to predict near future spectrum availability. Using these predictions, secondary users can intelligently reconfigure their spectrum usage to avoid disruption to primary users and maintain reliable communication. We use both simulations and hardware implementations to evaluate the proposed approach and compare it to those reactive approaches. Results confirm that the proactive approaches improve spectrum utilization and reduce disruptions to primary users. We also examine the impact of system settings such as prediction accuracy and traffic statistics.

We note that using Alternative-Exponential primary user traffic model, our proposed proactive approaches do not lead to significant performance improvement. This is mainly because that the quality of prediction is limited by the "memoryless" property of the exponential distribution. When combined with sophisticated prediction mechanisms, the proactive approach can achieve significant performance improvement. We are currently researching on extending the proactive approach to other primary user scenarios with predictable traffic patterns.

Acknowledgements

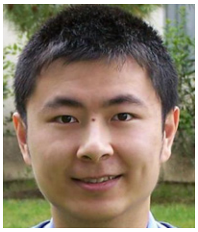
The authors would like to thank Dr. Eric Horvitz for his insightful suggestions for this paper. This research was in part supported by Microsoft Research and National Science Foundation grants CNS-0721961.

References

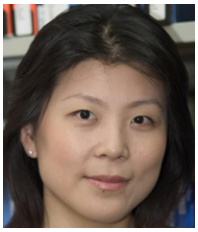
[1] P.A.K. Acharya, S. Singh, H. Zheng, Reliable open spectrum communications through proactive spectrum access, in: Proc. of TAPAS, August 2006.
[2] R.J. Berger, Open spectrum: A path to ubiquitous connectivity, ACM Queue 1 (3) (2003).
[3] D. Cabric, S.M. Mishra, R.W. Brodersen, Implementation issues in spectrum sensing for cognitive radios, in: Proceedings of Asilomar Conference on Signals, Systems and Computers, 2004.
[4] L. Cao, H. Zheng, Spectrum allocation in ad hoc networks via local bargaining, in: Proc. of SECON, September 2005.
[5] K. Challapali, S. Mangold, Z. Zhong, Spectrum agile radio: Detecting spectrum opportunities, in: International Symposium on Advanced Radio Technologies, ISART, March 2004.
[6] C. Chereddi, P. Kyasanur, N.H. Vaidya, Design and implementation of a multi-channel multi-interface network, in: Proc. of REALMAN, 2006.
[7] D. Cox, Renewal Theory, Spottiswoode Ballantyne and Co. Ltd, 1962.
[8] G. Ganesan, Y.G. Li, Cooperative spectrum sensing in cognitive radio networks, in: Proc. of IEEE DySPAN, November 2005.
[9] A. Ghasemi, E.S. Sousa, Collaborative spectrum sensing for opportunistic access in fading environments, in: Proc. of IEEE DySPAN, November 2005.
[10] S. Haykin, Cognitive radio: Brain-empowered wireless communications, IEEE Journal on Selected Areas in Communications 23 (2) (2005) 201–220.
[11] Iperf. http://dast.nlanr.net/Projects/Iperf/.
[12] H. Kim, K.G. Shin, Adaptive MAC-layer sensing of spectrum availability in cognitive radio networks, Technical Report, University of Michigan, CSE-TR-518-06.
[13] Madwifi FAQ. http://www.madwifi.net.
[14] M. McHenry, Spectrum white space measurements, New America Foundation Broadband Forum, June 2003.
[15] S. Mishra, A. Sahai, R. Brodersen, Cooperative sensing among cognitive radios, in: IEEE International Conference on Communications, ICC 2006.
[16] S. Mishra, A. Sahai, R. Brodersen, Cooperative sensing among cognitive radios, in: Proc. of IEEE ICC, May 2006.

[17] J. Mitola III, Wireless architectures for the 21st century. http://ourworld.compuserve.com/homepages/jmitola.
[18] P.A. Kumar Acharya, S. Singh, H. Zheng, Reliable open spectrum communications through proactive spectrum access, in: TAPAS 2006.
[19] M.K. Powell, Broadband migration III: New directions in wireless policy. Remarks at the Silicon Flatirons Telecommunications Program, October 2002.
[20] A. Sahai, N. Hoven, R. Tandra, Some fundamental limits on cognitive radio, in: Forty-Second Allerton Conference on Communication, Control and Computing, Monticello, IL, October 2004.
[21] A. Sahai, R. Tandra, N. Hoven, Opportunistic spectrum use for sensor networks: The need for local cooperation, in: Proc. of Information Processing in Sensor Networks, IPSN 2006.
[22] B. VujičCić, N. Cackov, S. VujičCić, L. Trajković, Modeling and characterization of traffic in public safety wireless networks, in: Proc. of SPECTS, 2005.
[23] D. Willkomm, J. Gross, A. Wolisz, Reliable link maintenance in cognitive radio systems, in: Proc. of IEEE DySPAN, November 2005.

Lei Yang received the B.S. and M.S. degrees from the Department of Electronic Engineering at Tsinghua University, Beijing, China in 2004 and 2006, respectively. He is pursuing his Ph.D. degree in the Department of Computer Science at University of California, Santa Barbara. His research interests are on wireless communication and networks, with a current focus on improving reliability in dynamic spectrum networks.



Lili Cao received the B.S. and M.S. in Computer Science from Shanghai Jiaotong University, Shanghai, China, in 2002 and 2005, respectively. He is currently a Ph.D. student in the Department of Computer Science, University of California, Santa Barbara. His research interests include cognitive radio systems, spectrum allocation, and distributed algorithms for large-scale networks.



Haitao Zheng received her B.S. degree (with highest honor) from Xian Jiaotong University in July 1995, her M.S.EE and Ph.D. degree in Electrical and Computer Engineering from University of Maryland, College Park, in May 1998 and July 1999, respectively. Since Sept. 2005, she has been an assistant professor in Computer Science Department, University of California, Santa Barbara. Zheng was recently named as the 2005 MIT Technology Review Top 35 Innovators under the age of 35 for her work on cognitive radios. Her work was selected by MIT Technology Review as one of the 10 Emerging Technologies in 2006. She also received 2002 Bell Laboratories President's Gold Award from Lucent Bell-Labs, and 1998–1999 George Harhalakis Outstanding Graduate Student Award from Institute of System Research, University of Maryland, College Park. Zheng's research interests include wireless systems and networking and multimedia computing.