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Delay-Optimal Channel Selection Method for Wireless Cognitive Networks

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Abstract—**Driven by government policy and advanced front-end radio technologies, cognitive radio offers an ever-promising future in the next generation communication system. Due to the random characteristics of primary users, it is impossible to fully describe the activity feature in terms of time and space, rendering opportunity access *unsafe* to primary user. In order to minimize interference to primary users and find available channel as fast as possible, a history knowledge based algorithm is proposed in this work, which compound historical information with current observed information. Random early detection (RED) algorithm, which proves to be efficient in active queue management (AQM) for switching fabrics, is introduced to help select the desirable channel. In order to further suppress the collision probability, all the channels are sorted according to availability. Simulation results show that, compared with completely random spectrum selection method, the proposed RED-based channel access method gives better performance in terms of channel selection delay.**

Keywords-cognitive networks; proactive channel selection; random early detection; channel selection delay.

I. INTRODUCTION

The rapid developments in wireless communication technologies and excessive growth of short-distance devices have resulted in ever-crowding spectrum usage. For the sake of static allocation of radio frequency, the entire spectrum band has already been handed out. Due to shortage of available licensed spectrum, wireless communication systems seem to encounter a bottleneck. However, according to authoritative reports of spectrum usage observation, at any given time and location, only a small proportion (less than 15%) of valuable spectrum is working, leaving much of the precious resources critically underutilized. Cognitive radio (CR) is proposed as a promising technology to cope with current spectrum scarcity problem by means of enabling cognitive users (or, secondary user) to dynamically adjust its operating parameters and thus dynamically reuse the spectrum which is always statistically underutilized by authorized users (or, primary users (PU)) in a intelligent and cautious manner [1]. One challenging issue that CR networks inevitably encounter is channel selection when initiating a data link between the cognitive users. Compared to other hot topics of CR (i.e., spectrum sensing, spectrum management, and resources allocation) [1], spectrum handoff problem receives little attention and is less investigated in the research area.

Spectrum handoff occurs when detecting the *usual* return of primary user. This leads to: 1) interruption of the communication between cognitive users, 2) interference to primary users according to system mechanisms. Nearly all the current literatures simply assume that all the channels are well synchronized, whether by primary users (usually infrastructures of primary user network, such as GSM base station, etc.) or just omitted such complicated scenario. Current channel scheduling methods concentrate mainly on sense-and-react approach, which means to randomly pick up a channel to access from preferable channel lists (PCL) if it were sensed idle at some given time t. This always leads to disruptions to both primary users and cognitive users. Proactive method in a sense-and-avoid manner instead seems more reasonable. However, due to the randomness of the reappearance of primary users, it is extremely challenging to perform fast, smooth and seamless channel handoff for cognitive communicating parties, leading to inevitable performance degradation during a spectrum handoff. This problem becomes even more difficult in ad hoc networks where there is no centralized infrastructure to coordinate the spectrum mobility.

II. RELATED WORK

A. *Proactive Channel Handoff*

Currently, most channel selection algorithms take a reactive sense-and-react approach to perform spectrum handoff based entirely on the latest observations. One common way employed in relevant literatures is that cognitive users (CU) perform spectrum handoff as soon as

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perceiving the return of primary user [2]–[5]. Borrowing the idea of proactive routing protocols designed for wireless Ad-hoc networks, proactive channel selection adopts a similarly active way that prepares one or more channel(s) *before* there is a need for communication parties. Although the merits of this approach are obvious, preparation of channels, or rather prediction of channel availability status is relatively difficult. Until very recently, only a few literatures focus on the spectrum handoff issue, among which fewer are concerned with proactive channel selection. But the idea is widely accepted of performing spectrum handoff and RF reconfiguration *before* a PR user reoccupies the spectrum band based on historical channel usage statistics, usually referred to as proactive channel selective approach. In [2], a comprehensive introduction is presented and a framework of proactive channel selection is briefly given without detailed analysis. A predictive model is proposed in [6] for dynamic spectrum access based on the past channel usage history. In [7], spectrum occupancy features and channel prediction model is proposed by means of the analysis of binary time series. In these few proposals, the multi-user network coordination problem is either not taken into consideration [5] or purely assumed that there exists a stable global common control channel (CCC) [6]-[8], which in practice seems impossible due to the high dynamical nature of primary user. Nearly all the existing literatures pay little attention to the channel selection method employed in the cognitive users, nor does the residual time on each selected channel[7]-[9].

B. Random Early Detection

Random early detection algorithm is first proposed in active queue management for gateways to keep the average queue size reasonably low while allowing occasional bursts of packets in the queue [10]. Using a feedback mechanism, RED are capable of timely reconfiguration *before* congestion happens. According to [10], the average length of queue is:

$$q_{ave} = \alpha \times q_{ave} + (1-\alpha)\times q_{current} \tag{1}$$

In other words, the expectation value of the length of queue should be calculated according to the long history and latest observation. This means some unusual busty arrival must be dropped. Such a tradeoff between admission rate and buffer size have to be carefully chosen. Numerical results are shown in Figure 1.

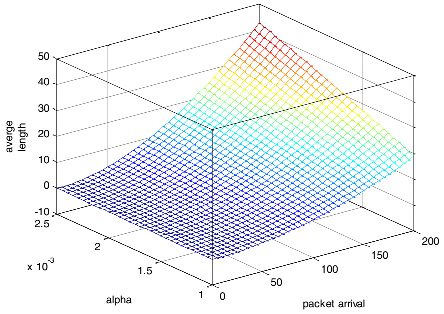

Figure 1. RED algorithm

It can be seen that with a big enough (more than 0.975), the average value is less than 50 even if instantaneous arrivals reaches 200. This fits much well with the idea that impulsive congestion is smoothly averaged at the cost of dropping some packets. The parameter $\beta = 1 - a$ is called time constant in term of low-pass filter. This is similar to the time constant in low-pass filter, which is an exponential weighted moving average (EWMA):

$$\begin{aligned} q_n &= \alpha * q_{n-1} + (1-\alpha) * x_n \\ &= a[\alpha \times q_{n-2} + (1-\alpha) * x_{n-1}] + (1-\alpha) * x_n \\ &= \alpha^2 q_{n-2} + (1-\alpha) * (a x_{n-1} + x_n) \\ &= \alpha^2 (\alpha * q_{n-3} + (1-\alpha) * x_{n-2}) + (1-\alpha) * (a x_{n-1} + x_n) \\ &= \alpha^3 q_{n-3} + (1-\alpha) * (a^2 x_{n-2} + a x_{n-1} + x_n) \\ &\vdots \\ &= \alpha^{n-1} q_1 + (1-\alpha) * (a^{n-1} x_1 + \cdots + a^2 x_{n-2} + a x_{n-1} + x_n), \end{aligned} \tag{2}$$

$$\text{hence } q_1 = 1 - \alpha, \textit{ then we get}$$

$$q_n = \alpha^{n-1} + (1-\alpha) * (a^{n-1} x_1 + \cdots + a^2 x_{n-2} + a x_{n-1} + x_n)$$

Where $x_n = n$, by solving the sum of polynomial $a^{L-1} x_1 + \cdots + a^2 x_{n-2} + a x_{n-1} + x_n$

$$(1-\alpha) * (a^{n-1} x_1 + \cdots + a^2 x_{n-2} + a x_{n-1} + x_n) = 1 + n - \frac{1-\alpha^{n+1}}{1-\alpha} \tag{3}$$

We can obtain:

$$\begin{aligned} q_n &= \alpha^{n-1} + (1-\alpha) * \frac{\alpha^{n+1} - n\alpha - \alpha + n}{(1-\alpha)^2} \\ &= \alpha^{n-1} + \frac{\alpha^{n+1} - n\alpha - \alpha + n}{1-\alpha} \\ &= \frac{\alpha^{n-1} - \alpha^n + \alpha^{n+1} - n\alpha - \alpha + n}{1-\alpha} \\ &= n + 1 + \frac{\alpha^{n+1} + \alpha^n - \alpha^{n-1} - 1}{1-\alpha} \end{aligned} \tag{4}$$

This is the same with the conclusion of [10]. The determination of a is the key of using RED. To the best of our knowledge, this is the first paper that incorporates the random early detection algorithm in the spectrum handoff design.

III. SYSTEM MODEL

The cognitive networks contain two kinds of nodes, or rather users, namely primary users and cognitive users. The resource of cognitive users comes from the primary users, in a manner of opportunistic usage. In this work, resources are actually frequency channels authorized to licensed users. Each channel is of two states, busy (occupied) or idle. So, an alternative renewal process can be used to model the licensed channel. The model of a primary networks is shown Figure 2.

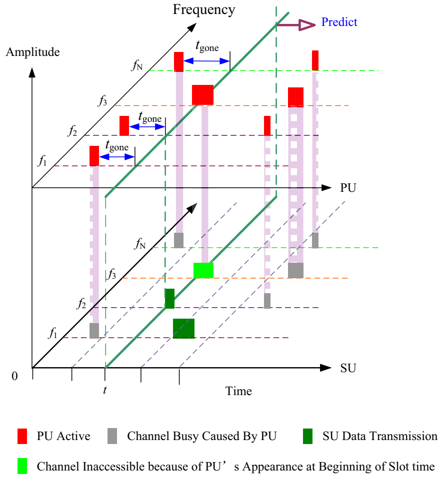

Figure 2. Primary networks modeled as alternative renewal process.

In this work, we assume that each cognitive user is equipped with two radio units, one for channel statistics (both long and near history) and the other for data transmission (Sending, receiving and sensing). The one for channel statistic is further assumed to be wide enough, capable of scanning all the licensed channels among the cognitive networks.

A. Statement of the Problem

As assumed above, each channel is modeled as an alternative renewal process. Then the aim of cognitive users is to opportunistically utilize the idle fraction (mostly large part) of time. Assume that the beginning state of channel is busy (idle is also acceptable and it does not matter in the long run), it lasts a random time, say X_1, then it changes to the contrary state, lasting a random time, say Y_1, then goes to busy state again with random duration X_2, and so on and so forth. In this sense, random vector $\{X_n, Y_n\}_{n=1}^{\infty}$ is obtained. X_n, Y_n is independent of each other. Without losing generality, we identify each channel a different parameter, i.e., the random variable sequence $\{X_n, Y_n\}_{n=1}^{\infty}$ are subjected to different parameters, noted as $(X_n^i, Y_n^i), 1 \le i \le N, n \ge 1$. The distribution function of X^i and Y^i is expressed as F_{X^i}, F_{Y^i}. Let $Z_n^i = X_n^i + Y_n^i$ be the renewal process of channel i, then the interval of each channel is

$$\begin{aligned} F_{Z^i}(t) &= P\{Z_n^i \le t\} = P\{X_n^i + Y_n^i \le t\} \\ &= \int_0^{\infty} P\{X_n^i + Y_n^i \le t \mid Y_n^i = s\} dF_{Y^i} \\ &= \int_0^t P\{X_n^i \le t - s\} dF_{Y^i} \\ &= F_{X^i} * F_{Y^i}(t) \end{aligned} \tag{5}$$

Where $C(t) = A * B(t)$ is convolution of *A(t)* and *B(t)*. The renewal function of *Z(t)* can be calculated as $m(t) = \sum_{k=1}^{\infty} [F_{Z^i}(t)]^k$, where $[F_{Z^i}(t)]^k$ is the *k-fold* convolution of $F_{Z^i}(t)$.

The available channel for cognitive users is the licensed channel with idle state. This work aims to pick up a more reliable channel in terms of remaining time of idle phase. At any specified time, there are several (even many as stated above that 85% of total channels are unused) channel for cognitive users to select. Our questions turn out to be that choose a channel with more idle time left.

B. Channel reliability and average remaining time

Based on the renewal theory [10], given the existence of $E(Y^2)$, namely $E(Y^2) < \infty$, then the average remaining time of any specified time t can be calculated as $\lim_{t \to \infty} E[Y(t)] = E(Y_i^2) / [2 \times E(Y_i)]$. Such a result can be interpreted that when the system enters equilibrium state, the average remaining time of any specified time is expected to be $E(Y_i^2) / [2 \times E(Y_i)]$. Furthermore, the probability density function of remaining time of any given time t is $f(y) = [1 - F_{Y^i}(y)] / E(Y_i)$,where $F_{Y^i}(y)$ is the probability distribution function of Y in channel i. Based on *f(y)* of each channel, the probability distribution function of *Y(t)* can be calculated. That is to say, given any time length that cognitive user needs to use, full knowledge about the channel are known, it is self-evident that the probability of availability may vary. From the perspective of reducing the interference with primary users, the channel with larger probability as well as more remaining time than others is desirable.

For the sake of mathematical tractability, we assume that each group of X and Y is exponentially distributed, and each channel owns different X and Y, then the probability that the channel i is idle at given time t can be represented as :

$$P^i(t) = \frac{E(Y^i)}{E(X^i) + E(Y^i)} - \frac{E(X^i)}{E(X^i) + E(Y^i)} e^{-\frac{E(X^i)}{E(X^i)+E(Y^i)}t} \tag{6}$$

Here we can calculate the expected time left of any given time t:

$$E^i[Y(t)] = \frac{1}{E(Y^i)} + \frac{E(Y^i)}{E(X^i)[E(X^i) + E(Y^i)]} - \frac{1}{E(X^i) + E(Y^i)} e^{-\frac{E(X^i)}{E(X^i)+E(Y^i)}t} \tag{7}$$

Recall in RED algorithm, long-term history and latest observation are both considered in determining the average queue. For the simplicity of implementation, a go-back-to-M history is taken for "long history". Every time when evaluating the availability of a specific channel, we have:

$$t_{remain} = \alpha \times t_{aveager\_M-1} + (1 - \alpha) t_{latest\_observation} \tag{8}$$

$$t_{aveager\_M-1}=\frac{1}{M-1}\sum_{i=1}^{M-1}Y_i, t_{latest\_observation}=t-S_{M(t)} \qquad (9)$$

Where $S_{M(t)}$ is the starting time of M-th idle time interval up to a given time t. We now obtain:

$$t_{remain}=\alpha\times\frac{1}{M-1}\sum_{i=1}^{M-1}Y_i+(1-\alpha)S_{M(t)} \qquad (10)$$

Now, we are going to find the channel that owns bigger idle time left:

$$k=\arg\{\max_{1\le i\le N}[t_{remain}]\} \qquad (11)$$

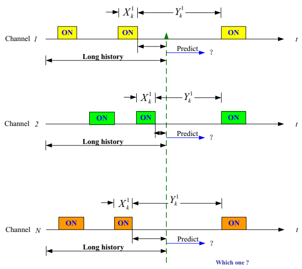

Figure 3. Proposed proactive channel selection algorithm

An instance with N channels is shown in Figure 3. Without losing generality, we assume all the channels are different, namely with different parameters, or even different distributions. Compared with most literatures assuming memoryless exponential distribution, the proposed algorithm can be widely used to estimate channel availability with generally distributed random variable sequences.

Until now, we just find a channel that mostly seems to be idle at some t. In practical circumstances, such a method is far from being satisfied. This is somewhat like tossing a coin; nobody can claim that the next toss is head even though the probability of head is 50% (big enough). The detailed operation about selecting channel will be discussed in the next section.

C. *Prediction-based proactive channel selection*

The proposed proactive channel selection algorithm depend not only on the probability of being idle but also on the current state of given time t, that is to say, combining the historical statistic results with current sample to make the future decision.

As stated above, the proposed proactive channel selection algorithm sorts the licensed channel of primary users according to the idle probability. Based on the history records from the statistical radio, the probability characteristics of each channel can be obtained. As to the means of getting such characteristic is *beyond* the topics of this paper. We now carry on out work with the assumption that the probability feature of each channel is obtained and the entire channels are listed in an ascending order of the probability that channel is idle.

Suppose that a cognitive user want to launch a data link in the cognitive network, it follows that the cognitive user first checks the seemingly most available channel in the top place of channel list, if it turns out to be idle, then a data link can be established. But if not, it has to move to the next position to check the secondary-optimal (in the sense of idle probability) channel. The whole trial process goes on till it finds an available channel. If all the channel are happened to be busy (Though seemingly available), then the data link can not be established. Yet we believed that our proposed algorithm outperforms the randomly selected method in terms of collision rate and throughput of cognitive users, which can be seen in the evaluation section.

Here we are concerned with the time delay of finding a better channel. According the trial process stated in the previous paragraph, let $\mu^i(t)$ be the busy probability of channel i at given time t, it's easy to see that $\mu^i(t)=1-P^i(t)$, denoted as μ_i for convenience. We can get that the average searching time of finding an available channel is:

$$\begin{aligned}
&E(T_{order\_serach})\\
&=(1-\mu_1)T_1+\mu_1(1-\mu_2)(T_1+T_2)+\mu_1\mu_2(T_1+T_2)\\
&+\mu_1\mu_2(1-\mu_3)(T_1+T_2+T_3)+\mu_1\mu_2\mu_3(T_1+T_2+T_3)+\cdots\\
&+\mu_1\mu_2\cdots\mu_{N-1}(1-\mu_N)(T_1+T_2+\cdots+T_N)+\\
&\mu_1\mu_2\cdots\mu_{N-1}(1-\mu_N)(T_1+T_2+\cdots+T_N)\\
&=T_1+\mu_1T_1+\mu_1\mu_2T_3+\cdots+\mu_1\mu_2\cdots\mu_{N-1}T_N\\
&=\sum\nolimits_{i=1}^{N}\{[\prod\nolimits_{k=1}^{i}\mu_{k-1}]T_i\}
\end{aligned} \qquad (12)$$

Where T_i denotes the time of sensing and determining the channel availability of each channel i.

The average channel searching time of finding an available channel in randomly selective method can also be calculated. The only difference between the randomly selective method and our proposed algorithm is that the prior method picks up a channel without using any historical statistics information but selects a channel with equal possibility. But the trial process can be any sequence of *N!* possible sets. By conditioning on any given sequence, we obtain:

$$\begin{aligned}
&E(T_{random\_search})=E[E[T_{random\_search}\,|\,random\_search=S_k]]\\
&=\sum\nolimits_{m=1}^{N!}E[T_{random\_search}\,|\,random\_search=S_k]\\
&\times P\{random\_search=S_k\}
\end{aligned} \qquad (13)$$

Where $P\{random=S_k\}=1/N!$

$E[T_{random}\,|\,random=S_k]=\sum\nolimits_{i=S_k^1}^{N}\{[\prod\nolimits_{k=1}^{i}\hat{\mu}^{i=S_k^m}]T_I^{i=S_k^n}\}$,

where S_k is a sequence among all *N!* sequences set, numbered as $k, 1\le k\le N!$, S_k^j is the j-th element in the sequence S_k. So, we can get the average channel searching time in randomly selective method:

$$E(T_{random}) = \frac{1}{N!}\sum_{i=1}^{N}\{[\prod_{j=1}^{i-1}\mu_{S_k^j}]\}T_{S_k^i} \qquad (14)$$

IV. PERFORMANCE EVALUATION

In this section we evaluate the performance of our proposed algorithm by Matlab-based simulation. We compare our algorithm with randomly opportunistic spectrum access method. Parameters are summarized below:

TABLE I. SIMULATION SETTINGS

Parameter	Value
Primary User model	$\lambda_x^i \in rand(4,5), \lambda_y^i \in rand(8.5,15)$
Data Link Rate	100 kbps
Number of PU Channels	20
Number of SU	10
Cognitive user model	The same as primary user
Packets length of CR User	Exponentially distributed, para = 1
Simulation time	1000 Time Units

The interesting metrics of this simulation is access delay cognitive users. All the results are obtained by both proactive channel selection algorithm and randomly selective access method. Figure 4. shows the delay of channel selection with different Primary user models. It can be seen that the proposed algorithm outperforms the one in random way. The number of collided transmission of random method increases dramatically with the increasing of PU busy parameters. On the contrary, the proposed algorithm are shows a competent capability when the data transmission time gradually grows.

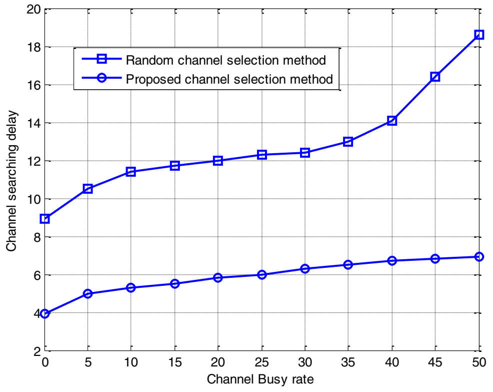

Figure 4. Channel searching delay comparison

V. CONCLUSION AND FUTURE WORK

This work provides a simple framework of proactive channel selection in wireless cognitive networks, with general primary user modeled as alternative renewal process. Such a work gives a better performance in exploiting the largely underused spectrum band. While conventional randomly selective method shows a dramatic deterioration as the primary user becoming relatively more active, the proposed algorithm presents a stable performance. Future works include a more general distribution of the busy and idle periods of primary users and more metrics about the overall performance of cognitive users.

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