Adaptive Transmission Protocol for Protection of Primary Users in Cognitive Radio

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Abstract—Recently, rapid advance in wireless technologies and development of wireless communication services have enabled a growing demand on wireless spectrum. Many research works also show that traditional fixed spectrum assignment can not use spectrum efficiently. Cognitive Radio, which allows temporary usage for the unlicensed (CR) users, is proposed to cope with the problem. In this work, we propose an adaptive transmission protocol by limiting transmission probability (LTP) of the CR users to guarantee the performance of Primary User under an 802.11 environment. Specifically, our LTP scheme uses 2 analytic models to figure out the relationship between current load of primary users and the optimal transmission parameter setting that can guarantee the throughput of primary users.

I. INTRODUCTION

With wireless technology advances and the proliferation of deployment of wireless systems, there is an increasing demand for wireless spectrum. On the other hand, many recent studies have shown that traditional fixed spectrum assignment can not use spectrum efficiently. Cognitive Radio was first proposed by Joseph Motila in [1] to deal with the above problem. Furthermore, Cognitive Radio, which allows temporary usage for the unlicensed (CR) users, is aimed to intelligently protect the primary users, utilize the unused frequency spectrum and increase overall utilization.

Many previous works [3], [4], [5], [6], [7] for Cognitive Radio have brought out a lot of interesting and important issues such as Spectrum Sensing, Spectrum Management, and Spectrum Sharing. We note that one of the most important concepts for Cognitive Radio is the exclusive spectrum idea for the primary users. Thus, we would like to propose a new spectrum access scheme, which is aware of its surrounding environment and uses the methodology of understanding-building to learn from the environment and adapt its internal status so as to provide highly reliable communication whenever needed and efficient utilization of the radio spectrum.

In this work, we propose an adaptive transmission protocol by limiting transmission probability (LTP) of the CR users to guarantee the performance of Primary User under an 802.11 environment. The idea of the LTP protocol is that each CR user will first sense the channel condition, figure out residual channel capacity, and then choose a proper transmission probability such that the primary user is unaware of its existence. Specifically, our LTP scheme makes use of 2 analytic models, i.e., a non-saturation Markov model of primary users and a saturation Markov model of CR users, to find out the relationship between current load of primary users and the optimal transmission parameter setting that can guarantee the performance of primary users.

Unlike most previous works, our LTP scheme is an adaptive protocol under a dynamic environment, i.e., the number of CR users or primary users may vary over time, and each host is able to make its own decision in a distributed manner. We note that in [9], they also propose a decentralized borrow scheme on primary user protection. The collision between primary users and cognitive radio users is avoided by adjusting the duty cycle (ratio of transmission time). Since this borrow scheme is based on the channel utilization and a simple prediction model, it only works well under a static or a light-loaded environment.

At last, we would like to point out that this work is focusing on transmissions over a single channel. The channel selection, of course, is another important issue for Cognitive Radio. We believe a good channel selection approach can be easily integrated with our LTP scheme. The remainder of the paper is organized as follows: Proposed ‘Primary User Protection Framework’ and detailed algorithm are introduced in Section II. We show model validation and evaluate the performance in Section III. Finally, Section IV gives a conclusion.

II. ADAPTIVE TRANSMISSION PROTOCOL

In this section, we present the details of the adaptive transmission protocol, including the Limit Transmission Probability algorithm, and the adaptation scheme.

A. Limit Transmission Probability Algorithm

To have minimal impact on the performance of primary users, we introduce a transmission probability for each CR user. That is, when a CR user has data to send and finishes its backoff procedure, it can send the data with probability $b(t)$ or go through another backoff procedure with probability $1 - q$. The intuition of our algorithm is that the smaller $q$ is, the less collision can happen between a CR user and a primary user.

We construct a Markov model, using 2 parameters, i.e., $b(t)$ and $s(t)$, to describe the current status of our Markov process, and to simulate the behavior of the CR user. $b(t)$ represents the backoff time counter of the targeted CR user, and $s(t)$ stands for the backoff stage of the cognitive radio station at time $t$. The size of the contention window is $W_i$, where $i = s(t)$. 

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We note that the value of $s(t)$ is between 0 and $m$ (m stands for maximum backoff stage), and the backoff time counter is within the range of $[0, W_i - 1]$.

Figure 1(a) illustrates the transition diagram of our Markov model. Thus, the one-step transition probabilities in Figure 1(a) are obtained as follows.

\[
\begin{align*}
  b_{0,k}^{CR} &= b_{0,k+1}^{CR} + \frac{1}{W_i} \left( \sum_{i=0}^{m} q(1 - p_{CR}) b_{i,0} + (1 - q) b_{0,0} \right) \\
  b_{i,k}^{CR} &= b_{i,k+1}^{CR} + \frac{1}{W_i} \left( q p_{CR} b_{i-1,0} + (1 - q) b_{i,0} \right) 
\end{align*}
\]

In addition, we also include the following equation to represent the normalization condition on our Markov process.

\[
1 = \sum_{i=0}^{m} \sum_{k=0}^{W_i-1} b_{i,k} = \sum_{k=0}^{W_0-1} b_{0,k} + \sum_{i=1}^{m} \sum_{k=0}^{W_i-1} b_{i,k} 
\]

We note that transmission happens with probability $q$ when the backoff time counter decreases to zero and $\tau$ is the probability which a CR user finishes its data transmission with. So, given $q$ and $b_{i,0}$, $\tau$ can be calculated in the following:

\[
\tau = q \sum_{i=0}^{m} b_{i,0} 
\]

Before we show how to compute the collision probability $p_{CR}$ of CR users and $p_{PU}$ of primary users, we need to get more understanding about the behaviors of them. In a general case, after a primary user finishes its data transfer, it is possible for it to wait for some time till it has data to send. Hence, we introduce a non-saturation model for the primary user. For primary users, they may wait for data to transmit again after a successful transmission. We want to point out that the difference is a new “idle state” is included into a non-saturation model. In non-saturation case, primary users could stay in the idle state after a successful transmission. When waiting at the idle state, nodes would have a probability $r$ to have data to send or a probability $1 - r$ to remain in the idle state.

From the above discussion, non-saturation model for primary users is depicted in Figure 1(b). In the non-saturation model, there are still two variables $\{s(t), b(t)\}$ representing the process of a primary user. Furthermore, the state (-1,0) is used to represent the buffer is empty. After a successful transmission, the current status of the PU will move into the state (-1,0) till there is a new packet arriving. $r$ is the probability of at least one packet arriving during a slot time. One-step non-zero transition probabilities for this non-saturation model are

\[
\begin{align*}
  b_{-1,0}^{PU} &= (1 - r)b_{-1,0}^{PU} + (1 - p_{PU}) \sum_{j=0}^{m} b_{j,0}^{PU} + p_{PU} b_{m,0}^{PU} \\
  b_{0,k}^{PU} &= b_{0,k+1}^{PU} + \frac{r}{W_i} \left( W_{0} p_{CR} b_{0,-1,0} + (1 - q) b_{0,0} \right) \\
  b_{i,k}^{PU} &= b_{i,k+1}^{PU} + \frac{1}{W_i} \left( q p_{CR} b_{i-1,-1,0} + (1 - q) b_{i,0} \right) 
\end{align*}
\]

where $i \in [0, m]$ and $k \in [0, W_i - 1]$. Similarly, to get $b_{0,0}$, which is a function of packet generation probability $r$, transmission probability $q$ and collision probability $p_{CR}$, we include the following normalization equation for the Markov process.

\[
1 = \sum_{i=0}^{m} \sum_{k=0}^{W_i-1} b_{i,k} + b_{-1,0} = \sum_{k=0}^{W_0-1} b_{0,k} + \sum_{i=1}^{m} \sum_{k=0}^{W_i-1} b_{i,k} + b_{-1,0} 
\]

$\tau_{PU}$ is the probability that a primary user transmits in a random slot when the backoff time counter reaches zero.

\[
\tau_{PU} = \sum_{i=0}^{m} b_{i,0} 
\]

Now, the collision probability of primary users and CR users can be calculated as follows.

\[
\begin{align*}
  p_{PU} &= 1 - (1 - \tau_{PU})^{N_{PU} - 1} (1 - \tau_{CR})^{N_{CR}} \\
  p_{CR} &= 1 - (1 - \tau_{CR})^{N_{CR} - 1} 
\end{align*}
\]

Note that given $N_{PU}$, $N_{CR}$, transmission probability $q$ and packet generation probability $r$ when primary users are idle, we can compute $\tau_{PU}$ and $\tau_{CR}$.

After we solve the non-saturation and saturation models for primary users and CR users, we can obtain the throughput as follows. Let $S_{PU}$ and $S_{CR}$ be the normalized system throughput of primary users and CR users. The normalized system throughput is defined as the fraction of time that the channel is used to successfully transmit payload bits. $P_{tr}$ is the probability of at least one transmission happening in a time slot. Since there are $N_{PU}$ and $N_{CR}$ users contending the usage for this channel, with the transmission probability of primary user $\tau_{PU}$, transmission probability of CR user $\tau_{CR}$,

\[
\begin{align*}
  P_{tr} &= 1 - (1 - \tau_{PU})^{N_{PU} - 1} (1 - \tau_{CR})^{N_{CR}} \\
  P_{s_{PU}} &= \frac{N_{PU} \tau_{PU} (1 - \tau_{PU})^{N_{PU} - 1} (1 - \tau_{CR})^{N_{CR}}}{P_{tr}} \\
  P_{s_{CR}} &= \frac{N_{CR} \tau_{CR} (1 - \tau_{PU})^{N_{PU} - 1} (1 - \tau_{CR})^{N_{CR} - 1}}{P_{tr}} 
\end{align*}
\]
The throughput \( S_{\text{user}} \) can be expressed as
\[
S_{\text{user}} = \frac{E[\text{payload information transmitted in a slot time}]}{E[\text{length of a slot time}]} \tag{12}
\]
Recall that \( E[P] \) is the average packet payload size. So, the average amount of payload information successfully transmitted in a slot time is \( P_tr P_{\text{user}} E[P] \), given that a successful transmission occurs in a slot time with probability \( P_tr P_{\text{user}} \). The average length of a slot is calculated as follows: with probability \( 1 - P_tr \) the slot time is empty; with probability \( P_tr P_{\text{user}} \) it contains a successful transmission; and with probability \( P_tr(1 - P_{\text{user}}) \) it contains a collision. Hence, by considering the average length of a slot, the equation (12) is converted into
\[
S_{\text{user}} = \frac{P_{\text{user}} P_tr E[P]}{(1 - P_tr)\sigma + P_tr P_{\text{user}} T_s + P_tr(1 - P_{\text{user}}) T_c} \tag{13}
\]
where \( T_s \) is the average time for which the channel is busy due to a successful transmission, \( T_c \) is the average time for which the channel is busy because of a collision, and \( \sigma \) is the duration of an empty slot time.

We also note that \( T_s \) and \( T_c \) are dependent on the access mechanism. Here, we consider the basic access case. Let \( H = \text{PHY}_{\text{hdr}} + \text{MAC}_{\text{hdr}} \) be the packet header, and \( \delta \) be the propagation delay. In the basic access mechanism of 802.11,
\[
\begin{aligned}
T_s &= H + E[P] + SIFS + \delta + ACK + DIFS + \delta \\
T_c &= H + E[P] + DIFS + \delta
\end{aligned}
\tag{14}
\]
Using these formulas, we can find the relationship among \( r \), \( S_{PU} \), and \( q \).

We use the parameter setting from Table I and obtain numerical results using GNU Octave programming language. The results are shown in Figure 2. From Figure 2, we can see that to figure out the optimal setting of transmission probability \( q \) we need to get the number of primary users and CR users, the total throughput and the packet generation probability \( r \) of primary users. These information could be obtained at the spectrum information collection phase. Due to lack of space, we do not go through the details of the spectrum information collection phase.

### Table I

<table>
<thead>
<tr>
<th>Frame payload</th>
<th>4000 bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAC header</td>
<td>224 bits</td>
</tr>
<tr>
<td>PHY header</td>
<td>192 bits</td>
</tr>
<tr>
<td>ACK</td>
<td>112 bits + PHY header</td>
</tr>
<tr>
<td>Channel Bit Rate</td>
<td>1 Mbit/s</td>
</tr>
<tr>
<td>Propagation delay</td>
<td>1 ( \mu ) s</td>
</tr>
<tr>
<td>Slot time</td>
<td>20 ( \mu ) s</td>
</tr>
<tr>
<td>SIFS</td>
<td>10 ( \mu ) s</td>
</tr>
<tr>
<td>DIFS</td>
<td>50 ( \mu ) s</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Access Mechanism</th>
<th>Basic mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_{PU} )</td>
<td>10</td>
</tr>
<tr>
<td>( N_{CR} )</td>
<td>5</td>
</tr>
</tbody>
</table>

### B. Adaption Scheme

Note that the above algorithm is suitable for a static case, i.e., the number of primary users does not change. In general, a primary user could join or leave the system at any time. To make our LTP protocol work well under a dynamic environment, we develop the following adaption scheme. That is, each CR user will first monitor the requested throughput of primary users, and adjust its transmission probability according to the request and current usage of primary users.

To favor the primary users in our protocol, CR users are required to adjust transmission probability according to the expected throughput of primary users. If the measured throughput is larger than the requested throughput, we use the measured throughput as the expected throughput for the primary user. On the contrary, the expected throughput is the measured throughput plus the difference between measured throughput and requested throughput. This is because we would like to provide more chance for the primary user to send its data. The details about our adaption scheme is given in Algorithm 1.

#### Algorithm 1 Dynamic Adaption Scheme

**Require:** \( tp_{\text{request}} \)

1. \( tp_{\text{request}} \): Throughput that primary users request
2. \( tp_{\text{measured}} \): Measured throughput of primary users
3. \( \text{reset\_parameters}(x) \): setting that guarantees throughput of primary user to be \( x \)
4. \( tp_{\text{protect}} \leftarrow tp_{\text{request}} \)
5. for each slot do
6. if \( tp_{\text{measured}} < tp_{\text{request}} \) then
7. \( \text{reset\_parameter}(tp_{\text{protect}}) \)
8. \( tp_{\text{protect}} \leftarrow tp_{\text{protect}} + (tp_{\text{request}} - tp_{\text{measured}}) \)
9. else
10. \( \text{reset\_parameter}(tp_{\text{measured}}) \)
11. \( tp_{\text{protect}} \leftarrow tp_{\text{request}} \)
12. end if
13. end for

---

**Fig. 2.** Relationship between \( r \), \( q \), and throughput \( S_{PU} \)


**TABLE II**

<table>
<thead>
<tr>
<th>Frame payload</th>
<th>4000 bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAC header</td>
<td>224 bits</td>
</tr>
<tr>
<td>PHY header</td>
<td>192 bits</td>
</tr>
<tr>
<td>ACK</td>
<td>112 bits + PHY header</td>
</tr>
</tbody>
</table>

| Channel Bit Rate | 1 Mbit/s |
| Propagation delay | 1 μs |
| Slot time        | 20 μs |
| SIFS            | 10 μs |
| DIFS            | 50 μs |

| Access Mechanism | Basic mechanism |

**TABLE III**

<table>
<thead>
<tr>
<th>q</th>
<th>Percentage Error (%E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>4.83%</td>
</tr>
<tr>
<td>0.5</td>
<td>6.57%</td>
</tr>
<tr>
<td>0.9</td>
<td>3.77%</td>
</tr>
</tbody>
</table>

Note that we have performed extensive experiments and those results are similar to the trend of those presented here. Due to the space constraint, we only illustrate the experiments as $q$ is equal to 0.1, 0.5 or 0.9 and the traffic load ranges from 0.1 (low traffic load) to 5 (heavy traffic load). In general, the percentage error between LTP model and the simulation is within or around 6% as shown in Table III. That is, this empirical evidence indicates our analytic model of LTP scheme is fast and fairly accurate. Next, we demonstrate how to apply our proposed LTP framework as a useful tool for improving the network utilization by using the wireless spectrum efficiently.

**B. Performance Evaluation**

In this section, we present the simulation results that implement our proposed algorithm under a dynamic scenario. The performance matrices are (a) the throughput of primary users, and (b) the system throughput, i.e., the total throughput including the primary user’s throughput and the cognitive user’s throughput. This could be explained as follows. The purpose of cognitive radio is to guarantee an invisible damage for the primary users and efficiently utilize the unused frequency spectrum to increase overall utilization.

The simulation setting of this experiment is as follows. There are total $N = 10$ primary users and $M = 5$ cognitive radio users. Primary users and cognitive radio users will join into the system sequentially at certain random time between 0 sec and 10 sec. Once nodes join into the system, they start transmission till the end of the simulation, i.e., $t = 60$ sec. For simplicity of discussion, we assume that each node has a constant bit rate. All primary users have the same bit rate, and all CR users have the same bit rate, which might be different from that of primary users. The maximum wireless capacity of an access point is $C$ and $C$ is equal to 1Mbps. Let $C_p$ and $C_r$ be the total load of the primary users and the CR users respectively. To illustrate the benefit of the LTP scheme for different network environments, we vary the load of the primary users, i.e., $C_p$, from 0.1C to C. Moreover, the bit rate of each CR user is set to be $C_r/M$, where $C_r = C - C_p$. In other words, the total load of the primary users and CR users is equal to $C$.

In this performance study, there are 3 different methods: the ideal, LTP and borrow schemes. The ideal approach means the system only has the primary users and there is no CR user at all. This is the best case for the primary users since there is no interference or damage that is caused by the CR users. Hence, the result of the ideal approach is used to measure the goodness...
of the protection of the primary user for different cognitive radio schemes. The borrow scheme represents the work in [9], which is a decentralized algorithm and uses a simple collision probability calculation to (1) protect the performance of the primary user, and (2) increase the spectrum utilization.

In Figure 4(a), we show the comparison of 3 different schemes in terms of the throughput of primary users. The axis of X refers to the primary user offered load, i.e., the sum of all primary users’ offered load normalized channel bit rate, and the Y axis is the sum of primary users’ throughput. As the load of the primary user increases, we can see the LTP algorithm outperforms the borrow scheme and performs as almost the same as the ideal scheme does. Moreover, as the traffic of the primary users becomes heavy, the performance degradation of the primary users in the borrow scheme could be up to 40%. This is because that, for the borrow scheme, the traffic of primary users could collide with traffic of cognitive radio users and exhibit throughput degradation. On the other hand, the LTP scheme is aware of its surrounding environment and makes fast and better adaptation so that it is able to protect the traffic of primary users from influence by the traffic of cognitive radio users.

Figure 4(b) presents the results of 3 different schemes under the metric of the total system throughput. In general, the LTP algorithm can efficiently utilize the unused channel resource and increase overall channel utilization no matter the load of

IV. Conclusion

In this work, we proposed an adaptive transmission framework for primary user protection in a cognitive radio system. That is, we apply the idea of limiting transmission probability to intelligently control the transmission of CR users. We use the Markov model to analyze the LTP scheme and also develop a fast and precise adaptation algorithm. Simulation results show that the analytic model of the LTP algorithm is accurate. Moreover, the LTP scheme is able to protect the primary users’ traffic from CR users’ i.e., to guarantee an invisible damage for the primary users, and efficiently utilize the unused frequency spectrum to increase overall utilization.

REFERENCES