Spectrum Management in Cognitive Radio Networks: Modeling and Performance Evaluation

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Abstract—*Nowadays, 'Cognitive Radio' (CR) is one of the most promising concepts which facilitate the flexible usage of radio spectrum and enhance the spectrum utilization by enabling unlicensed users to exploit the spectrum in opportunistic manner. However, the most important challenge is to share the licensed spectrum without interfering with transmission of other licensed users. Therefore, to alleviate the above problems a proactive spectrum management schemes has been designed to access the unoccupied spectrum opportunistically with minimum latency. The primary function of the management schemes is to characterize the available channels based on spectrum sensing of CR node and create a backup channel list for further use. In this paper, we model the licensed users' activity and create a scheme to build up available channel list and backup channel list. Our simulation results show that, around 65% enhancement of channel utilization can be achieved through channel management.*

Keywords: Cognitive Radio, Channel prediction, Spectrum Sensing, Spectrum Management, spectrum Mobility

1. Introduction

T HE increasing demand for new wireless services and applications, as well as the increasing demand for higher capacity wireless networks, the wireless networks become highly heterogeneous, with mobile devices consisting of multiple radio interfaces. In this context, it is essential to have updated information on radio environment to enhance the overall network performance. The outcomes of several investigations have shown that the lack of spectrum is not an issue, but the fact that radio resources are used inefficiently. Therefore, a promising functionality is required to be built into future terminals to have the cognitive capability to assist with the Dynamic Spectrum Allocation (DSA), which allows more efficient utilization of radio resources by changing the spectrum allocation on demand. A cognitive radio is a self-aware communication system that efficiently uses spectrum in an intelligent way [1]. The most significant characteristic of a cognitive radio is the capability to sense surrounding radio environment such as information about transmission frequency, bandwidth, power, modulation, etc. and make a decision to adapt the parameters for maintaining the quality of service. It autonomously coordinates the usage of spectrum in identifying unused radio spectrum on the basis of observing spectrum usage. Therefore, spectrum handoff occurs when a licensed user further utilizes this unused radio spectrum and find that CR nodes occupy the channel [2]. In order to avoid service termination, the CR user will perform link maintenance procedure to reconstruct the communication. In general, channel management procedure can be categorized into a) proactive spectrum management b) reactive spectrum management. In proactive scheme, CR nodes observe all channels to obtain the channel usage statistics, and generate a list of candidate and backup channel list for spectrum mobility while maintaining the current transmission [3]. Reactive spectrum management operates in on-demand manner, i.e. CR nodes perform spectrum mobility after detecting the link failure [4]. From system design, point of view reactive spectrum management is more suitable than the proactive scheme as it requires very complex algorithm for concurrent operation. On the other hand, proactive spectrum management poses very faster spectrum switching with respect to reactive spectrum scheme, resulting better QoS in on-going transmission. Moreover, selection of reactive and proactive spectrum management schemes is depends on sensing time. In order to capture the dynamic and random behavior of both licensed and unlicensed users, we focus on proactive spectrum management issues to enhance the network wide performance in terms of throughput and collision. Therefore, we proposed proactive dynamic channel selection algorithms to deal with spectrum mobility more robustly and effectively based on proactive channel prediction. Based on channel prediction, al the observed channel is graded and form two different channel lists. In this paper, we also present a CR node modeling in OPNET which utilize the channel prediction and spectrum management functionalities.

The rest of this paper is organized as follows. An introductory idea of the work is presented in details in section one. Then, section II describe the background study of spectrum mobility in cognitive radio networks. In section III spectrum mobility is being characterized through primary user traffic prediction. Proactive spectrum management scheme is introduced based on the channel prediction in section IV. Finally, we present our performance study and node design in section V which is followed by conclusion and future works.

2. Literature Review

In cognitive radio ad-hoc networks spectrum mobility is one of the main performance bottlenecks which include transmission delay, routing discovery as a consequence throughput degradation. This problem is somehow related to multichannel MAC problem in traditional mobile ad hoc networks despite of fixed channel assignment. Therefore, we need a novel spectrum management schemes where CR users will pause the current transmission and vacate the operating channel due to presence of license user as well as determine the available channel to re-establish the communication. In this regard author in [5] proposed two different kind of observation method called proactive method and on-demand or reactive method. In the proactive method, the CR user periodically observes all the channel usage statistics and determines the candidate set of channels for spectrum handoff. In contrast to proactive method, the candidate channels are searched with an on-demand manner in reactive method. Therefore, the instantaneous outcomes from wideband sensing will be used to determine the candidate channel list for spectrum handoff [6]-[4]. Such sense and react approach causes for frequent service disruption in communication and degrade the QoS due to higher handoff latency. While the proactive approach, the latency of spectrum handoff would be smaller even though it incurs a larger overhead due to periodic observation. In [7] a detailed proactive spectrum framework has been proposed assuming exponential and periodic traffic model where CR users utilize past channel histories to make prediction on future spectrum availability. In [8] author proposed MAC layer proactive sensing schemes to maximize the probability of channel opportunities and minimize the channel switching delay for spectrum mobility. The problem of spectrum mobility in cognitive radio network has been widely investigated in the last few years. L. Giupponi, in [9] proposed a fuzzy-based spectrum handoff to deal with the incompleteness, uncertainty and heterogeneity of a cognitive radio scenario and spectrum quality grading scheme is presented in [10] to enhance the QoS. In [11], Chang and Liu proposed a strategy that optimally determines which channel to probe and when to transmit in a single channel transmission. A sensing sequence is proposed in [5] to maximize the chances of finding and idle channel but it does not guarantee the minimum discovery delay. To minimize the delay, in [12]authors proposed a Bayesian learning method which could predict the underutilized radio spectrum proactively. Further enhancement is shown in [13] through the concept of building a backup and candidate channel list, unfortunately no algorithm or schemes has been provided. In most of the literature spectrum mobility is mainly concern to licensed band although CR nodes have the capability to use any portion of the spectrum not only from licensed band but also unlicensed band. Therefore authors in [14] first come up with an idea to build the backup channel list from unlicensed band in static manner and proposed a Markov channel model to evaluate the scheme. It is observed that, in these studies, the dropping probability and the number of handoff is reduced in case of the appearance of primary users. So far we consider about the spectrum sensing methods, but how we could share this sensing information among different CR nodes is a network architectural issue. Hence from the network architectural perspective, different spectrum mobility management schemes are presented in [15] and illustrate the basic comparison of centralized and distributed methods. In case of centralized architecture, spectrum mobility management is maintained by CR base station whereas in distributed ad-hoc networks each particular node is responsible to carry out the same task. Therefore, a reliable common control channel is required to exchange channel information is common control channel (CCC) or rendezvous problem. So far in the literature a reasonable amount of work has been done on CCC problem based on either dedicated global control channel [16], [17],[18],[19],[20],[21],[22],[23],[24] or network wide synchronization channel hopping sequence [25],[26],[27],[28]. However due to the dynamic nature of licensed users dedicated CCC is impractical and it suffers from CCC saturation and single point failure problem in high dense network. Like other distributed networks, network wide synchronization is not a feasible assumption for large distributed networks. In order to fully utilize the scare radio spectrum, several dynamic spectrum sharing schemes have been extensively studied [29],[30],[31],[32] from game theoretic view point for flexible and fair spectrum usages through analyzing the intelligent behaviors of network users.

The preliminary literature review reveals that most researchers have focused on spectrum selection processes in a static manner which failed to capture the dynamic behavior of radio environments. A study of spectrum mobility under dynamic radio environment is required to assist efficient design and deployment of such networks. In our proposal, proactive licensed users' traffic predictive model is used to predict the best available spectrum and classify them according to expected channel duration and SNR which will further use to build the candidate and backup channel list.

3. Problem Formulation

In this paper, a single hop cognitive radio based ad-hoc wireless LAN is considered which is composed of several primary users and CR users as shown in figure 1. Moreover a cognitive radio is assumed to search N licensed channel for spectrum opportunities. Each CR user is assumed to have equipped with two transceiver, one is for data communication and the additional one is for acquiring the control information including sensing. Although having an additional antenna may increase the size and price of CR node, eventually it overcome the problem of common control channel. A channel is modeled as widely used renewal

process alternating between ON and OFF states. An ON (OFF) period can be considered as a time period in which licensed users are present i.e. as a binary time series. Hence, one of the main tasks is to model the ON (OFF) period so that CR users can utilize any portion of OFF periods for their transmission. The channel usages model is depicts in figure 2. Suppose *i* is the channel index and X_t^i denote the number of channel *i* at time *t* such that:

$$X_t^i = \begin{cases} 1 & \text{if channel is ON (BUSY),} \\ 0 & \text{if channel is OFF (FREE).} \end{cases} \quad (1)$$

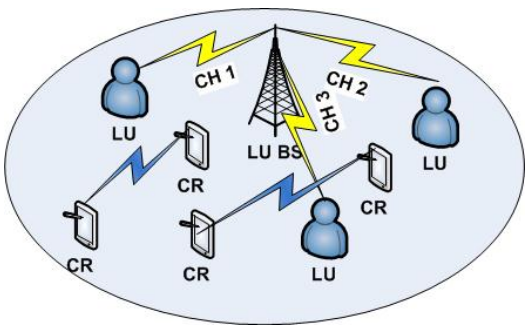


Fig. 1: Cognitive Radio Networks.

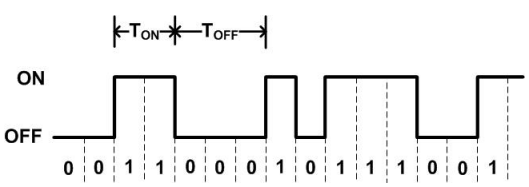


Fig. 2: Binary Channel Model.

For an alternating renewal process[33], let $f_{T_{ON}}(X)$ be the Pdf of the ON duration and $f_{T_{OFF}}(X)$ be the Pdf for the channel's OFF duration. Hence, the channel utilization μ is the expected fraction of time when the channel stays in its OFF state:

$$\mu = \frac{E[T_{OFF}]}{E[T_{ON}] + E[T_{OFF}]} \quad (2)$$

In equation 2, both ON and OFF periods are assumed to be independent and identically distributed (i.i.d). Since each licensed user arrival is independent, each transition follows the Poisson arrival process. Hence the length of ON and OFF period can be expressed using exponential distribution [34],[35] with pdf $f_X(t) = \lambda_X \times e^{-\lambda_X t}$for ON state and $f_Y(t) = \lambda_Y \times e^{-\lambda_Y t}$ for OFF state. Therefore, channel utilization μ in equation 2 can be written as:

$$\mu = \frac{\lambda_X]}{\lambda_X] + \lambda_Y]} \quad (3)$$

Where $E[T_{ON}^i = \frac{1}{\lambda_X}$ and $E[T_{OFF}^i = \frac{1}{\lambda_Y}$ are the rate parameter for exponential distribution. $E[T_{ON}^i]$ and $E[T_{OFF}^i]$ is the mean of distribution. Let $P_{ON}(t)$ be the probability of channel *i* in ON state at time *t* and $P_{OFF}(t)$ be the probability of channel *i* in OFF state at time *t*. The probabilities of $P_{ON}(t)$ and $P_{OFF}(t)$ can be calculated as:

$$P_{ON}(t) = \frac{\lambda_Y}{\lambda_X + \lambda_Y} - \frac{\lambda_Y}{\lambda_X + \lambda_Y} e^{-}(\lambda_X + \lambda_Y)t \quad (4)$$

$$P_{OFF}(t) = \frac{\lambda_X}{\lambda_X + \lambda_Y} + \frac{\lambda_Y}{\lambda_X + \lambda_Y} e^{-}(\lambda_X + \lambda_Y)t \quad (5)$$

Thus by adding equation 4 and equation 5, we can get

$$P_{ON}(t) + P_{OFF}(t) = 1 \quad (6)$$

4. Spectrum Management

The main focus of this section is to make an efficient channel selection and decision model which assists the CR user to spectrum mobility and enhance the spectrum utilization. The proposed spectrum management cognition cycle shows in figure 3 involves four major tasks such as spectrum sensing, spectrum analysis, spectrum classification and spectrum mobility. In the model, we also consider single hop network operation and ignored the route selection and route maintenance issues. Moreover, we consider two radio transceivers architecture which are sensing radio and data radio. The sensing radio is dedicated to spectrum monitoring includes particular radio environment and incumbent PU data base. The output of spectrum sensing process then feed into spectrum analysis process to characterize the spectrum hole information. All of this information is then processed by spectrum classifier and create available channel list based on channel duration (licensed spectrum ideal time) and quality of service. If there is no primary channel detected to be free then it will select unlicensed spectrum according to traditional CSMA/CA protocol. Due the dynamic nature of radio environment, the spectrum hole information or PU activities would be changed over time. Therefore, spectrum mobility is the processes which conveys this information from spectrum sensing process to spectrum classifier and relist the available channels. Further classification has been done on available channel list to create candidate channel list through fine scanning on the channels listed in available channel list. In the next step a back up channel list will form so that any CR node will select the channel which could maximize the channel utilization and finally transmit on that particular channel. In this report, we subdivided the model in two steps where CR users firstly perform proactive channel prediction to create available channel list. The usability status of all the channels is varying over time due to licensed user activities. Therefore, in the second step, CR user will update the available channel list that created in step one to adapt the radio environment dynamics.

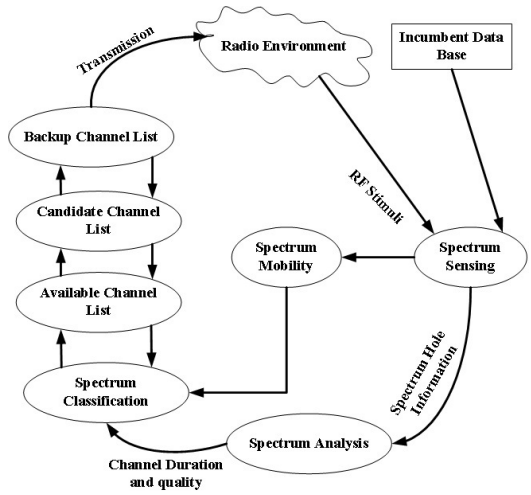


Fig. 3: Cognition Cycle of Spectrum management.

4.1 Step 1: Available Channel List

In our proposed model, an additional radio transceiver is assumed to monitor the radio environment continuously and create an available channel list to use for data transmission. Algorithm 1 shows the operational flow of step one where CR node will perform spectrum sensing to find unoccupied available channels through fast scanning. We also consider the geographical constrained imposed by regulatory authority of the particular place to protect per-defined incumbent licensed user using incumbent database. Moreover, CR user also uses the knowledge of previous scanning result to estimate the $P_{OFF}(t)$ of current channel selection. Here is $E[T^i_{MIN}$ the expected time required for minimum data transmission with the lowest packet size.

Algorithm 1 Available Channel List with Proactive Channel prediction

Load:Licensed User Database
K = Number of Licensed Users (Protected by Regulation)
for $i = 1$ to $N - K$ **do**
  Calculate $P_{OFF}(t)$
  if $E[T_{OFF}] \geq E[T_{MIN}]$ **then**
    $Avail_ch_list \leftarrow Channel(i)$
  else
    $Avail_ch_list \leftarrow Channel(unlicensed)$
  end if
end for

4.2 Step 2: Channel Classification and Update

The aim of this step is to classify the available channel list in two categories named as candidate channel and backup channel list. All the channels that are in available channel list can be treated as candidate channel as long as there is no licensed user operating. This candidate channel can become a backup channel through fine scanning. To be more precise all the candidate channels are scan at every 6 s for at least 30 s and outcome of the scanning result is the backup channel list. Any CR users before switching to the backup channel must be scan for at least 6 s to deal with any imperfect prediction of channel state in step one. Algorithms 2 illustrate the operational flow of channel classification as well as update scheme.

Algorithm 2 Candidate Channel List

Load:Available Channel List from Step 1
L = Number of Available Channel
M = Number of Licensed Channel in the System
U = Channel Utilization
C = Number of Candidate Channel
for $S = 1$ to L **do**
  Sense Channel (S)
  for $V = 1$ to M **do**
    if $P_{threshold}(S) \geq P_{threshold}(V)$ **then**
      $Candidate_{ch} \leftarrow 1$
    else
      $Candidate_{ch} \leftarrow 0$
    end if
  end for
end for
for $P = 0$ to $C - 1$ **do**
  $Backup_{ch} \leftarrow max(U(Candidate_{ch}), Backup_{ch}(P))$
end for

5. Performance Study

5.1 Simulation Setup

Here, we simulate an ad-hoc based cognitive radio IEEE 802.11g ad-hoc network consisting of multiple CR users operating at 2.4 GHz with eight license users. Each CR user is uniformly distributed over the network is assumed. We consider the case where a CR user tries to exchange packets with its neighbors. All the channels are assumed to have exponential distributed ON/OFF periods. To test our proposed algorithm we created a customized Cognitive radio wireless node where proactive predicted model is implemented in MATLAB and networking operation is done through OPNET 16.0. Our CR node is developed based on two wireless radio transceivers architecture which is shown in Figure 4(a). In the node model, the scanning radio is dedicated to listen the radio environment and creates a channel list that could be used for data transmission. The process model for scanning radio is a simple function $CR-Scan-data()$ which call the MATLAB library function and perform scanning and eventually updates the channel status table. This channel information is then sent to the data radio transceiver as an input to initiate the data transmission. In order to exchange the channel information of the neighboring nodes we adopt SYN-MAC[28] network initialization state protocol where it is assumed that all neighboring CR nodes are synchronized and has the channel set information of their neighboring nodes. We've designed our system having 5 different frequency channels and each User is assigned a particular frequency band which is designated as licensed user. At a particular time maximum five users can be present in the system. Therefore, the number of CR user is totally depending on how many empty slots is present. If the entire

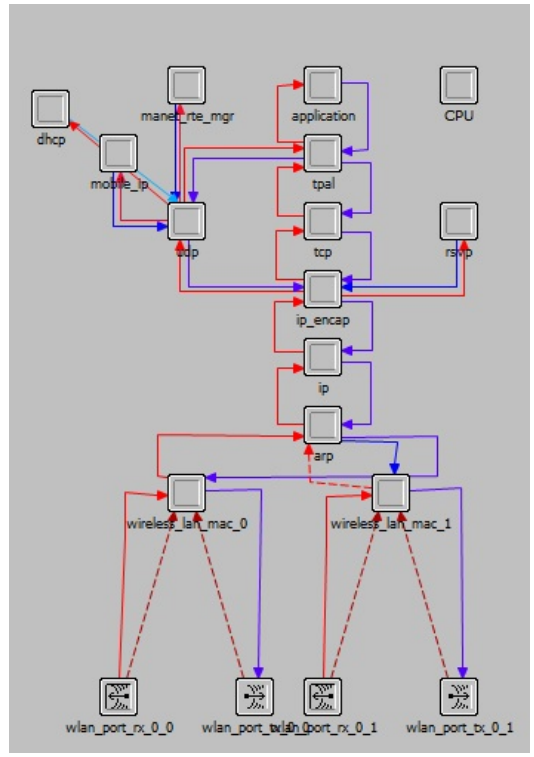
five licensed user are accessing the channels simultaneously then there is no room for CR user to operate in licensed user band. In that case CR user should go for unlicensed band which is out of scope or our current work. The network topology that has been used in order to measure the network performance is shown in Figure 4(b).

5.2 Simulation Results

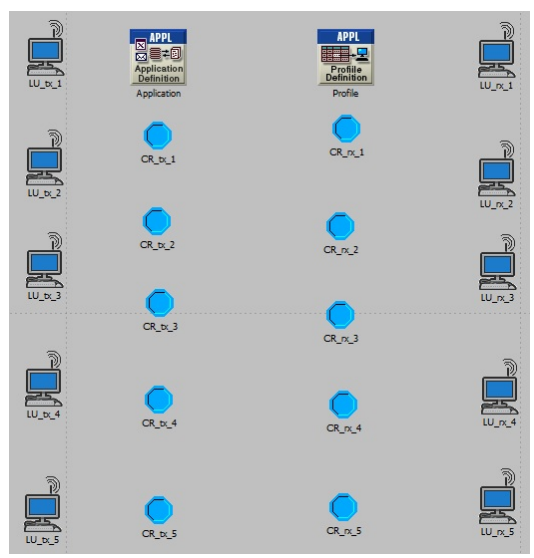
In the first phase of our simulation we present the concept of cognitive radio networks along with proactive channel prediction. Figure 5 depicts the CR node performance in present of licensed user and shows that there is only one primary user operating that means we have four empty slots at 2,3,4,5 MHz band for the CR user to operate. In this case, with dedicated sensing transceiver, CR users can obtain perfect information of past and current channel status, and make accurate prediction of the future channel. In the first run we only allowed one CR user to enter in the system and find the available spectrum to start communication with CR receiver which is in 2 MHz In the second run another CR node enter the system and get the free channel at 3 MHz But in the third run we allow another licensed user who is owner of 3MHZ frequency band to initiate the data transmission. Therefore CR node 2 should vacate the 3 MHz frequency band immediately for the LU3 which is shown in left bottom side of figure 5. Right bottom side of figure 5 also shows the same cognitive radio concept for LU 2 and CR 1. The only exception is that, in this case CR 1 has to force to terminate or migrate to unlicensed band due to unavailability of licensed frequency band. In this part of research we didn't take consider the unlicensed frequency band as available channel list. Definitely, it could increase the system performance even though it might need more complex algorithm to mitigate CR users' coexistence with other unlicensed users coexistence with other unlicensed users. The next part of the simulation is to show how much spectrum utilization can be achieved when licensed user share the radio spectrum with other radio i.e. cognitive radio. The simulation scenario that has been used is shown in Figure 4(b) where we have 5 LUs, 5 CR nodes and low resolution video as LU application data. When only licensed users are using the network the overall utilization is 98.4kbps where as it could reach up to 286 kbps if we allowed the CR users to coexist with licensed users (figure 6). Hence, proactive predictive channel management schemes explore the cognitive radio concept for best utilization of unused spectrum while avoiding collision with the licensed users.

6. Conclusion

In this paper we have presented proactive predictive channel management scheme in dynamic spectrum allocation systems. We have also proposed algorithms to construct the available channel list and backup channel list using the predictive traffic pattern of license users and maximize the



(a) Node Model



(b) Network Topology

Fig. 4: Cognitive Radio in OPNET.

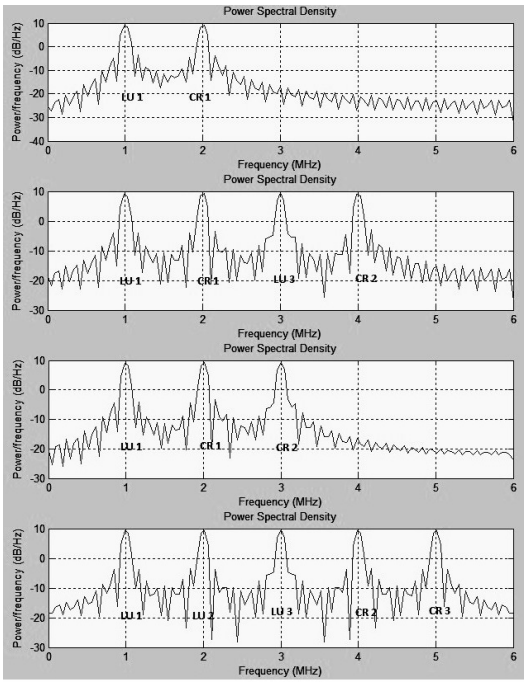


Fig. 5: Cognition Cycle of Spectrum management.

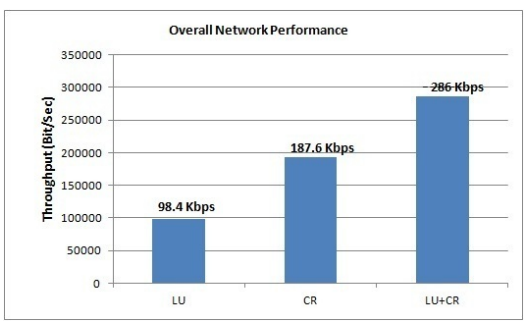


Fig. 6: Cognition Cycle of Spectrum management.

network utilization. To ensure the protection of incumbent licensed user, these channel lists is also being updated in dynamic manner. Our simulation result shows that performance enhancement and better network utilization is possible when CR users utilize the unused spectrum of licensed user in proactively.

7. Future Works

In the future, we would like to extend the proposed channel management scheme from single hop scenario to multi-hop scenarios. Future work may also involve co-existence among CR users for efficient channel selection algorithm.

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