Abstract  Spectrum sensing is a basic function of cognitive radio systems which detects spectrum holes. The spectrum sensing and spectrum access is a classic exploration vs. exploitation problem for cognitive radio overlay networks, where the unlicensed secondary users access the idle portion of licensed primary users. We propose a simple independent spectrum sensing architecture which can handle cooperative spectrum sensing for either coordinating or non-coordinating secondary users. The output hypotheses from secondary devices are combined by a simple algorithm to achieve better performance.

Keywords: cognitive radio networks, spectrum sensing, channel list, optimization

1. Introduction

The size of data and information of applications have dramatically increased in the past decade and so has data communications. This leads to congestion in wireless communications where more interference is susceptible due to its broadcast nature. However, studies show that some spectrums are overused while others are underused [1] [2]. The Dynamic Spectrum Access (DSA) has been proposed to solve the problem of spectrum shortage and congestion in wireless communications by exploiting uneven spectrum utility. Cognitive Radio (CR) is one such system [3-5].

The most underused spectrums are the TV channels named TV White Space (TVWS). In the previous decade, the research focus has been on CR in TVWS for broadband usage by fixed devices. The Regional Area Network (RAN) [6] was formed. Dynamic Spectrum Access for the most widely used air interface, WLAN or Wi-Fi is currently still under development in IEEE 802.11af task group.

The basic CR architecture has two types of users; Primary Users (PUs) to whom the channel is licensed by the authorities and unlicensed Secondary Users (SUs). SUs can access the channel when the channel is idle without interfering the Primary Users (PUs). If a PU appears on a channel, the SUs on that channel must stop transmitting. Then the SUs can switch to another channel to continue their communication. This fits the IEEE 802.11 Standard because IEEE 802.11 employs Time Division Duplex (TDD) for multiple access which reflects the data communication of the Internet.
There are two types of spectrum handoffs: reactive and proactive spectrum handoff. In reactive spectrum handoff, SUs perform spectrum handoff only when they detect a PU signal. Proactive spectrum handoff estimates the arrival of PU signal and performs spectrum handoff before it arrives.

The spectrum sensing and channel access is a classic exploration vs. exploitation problem for CR overlay access. Spectrum sensing is an integral part of CR to detect PU signals. However Federal Communications Commission (FCC) ruled spectrum sensing requirement as optional and authorize an access scheme with a geo-location database of TVWS [1].

We contend that without spectrum sensing function, the SU devices must always rely on the infrastructure and the overhead of the geo-location database is high. A fully independent SU device with spectrum sensing capability can build a small database of spectrum holes of its environment without incurring high overhead of infrastructure based solutions.

We develop a framework for multiple SU devices to cooperatively perform spectrum sensing. We then propose a method to combine the sensing hypotheses from multiple SU devices. This paper is organized as follows: In Section 2, we describe the network model for our proposal. Related works are mentioned in Section 3.1, and we give a brief discussion on spectrum sensing. Section 3.2 describes the basic energy detection and associated error probabilities. Our proposed sensing policy or methods are given in Section 3.3. We present our evaluation in Section 4. And finally, we give our conclusions in Section 5.

2. Network Model

One of the major issues in CR systems is network coordination. SU devices have to vacate a channel when a PU signal appears and moves to another channel to continue communication. And when a new SU device appears it needs to find its neighbors or in this scenario, the service AP. This problem is known as rendezvous problem. The networking coordination in CR systems is achieved by either one of the following two methods: i) by using a Common Control Channel (CCC) on which all control messages are exchanged; ii) by using a hopping sequence which ensures that any two SU devices or nodes can meet in every cycle sequence. Since CR environment is dynamically changing, so a dedicated channel for CCC might not be available and therefore the CCC method is not pragmatic. So, we will employ hopping sequence in our network model.

We will consider the conventional WLAN architecture for our proposal. There is an Access Point (AP) or wireless router acting as a gateway which is connected to the backbone network. There are $N_2$ number of SUs which the AP is serving as shown in Fig. 1. The SU devices can be any wireless device with a Wi-Fi interface. The hopping sequence must ensure that a new SU device will meet the AP within 2 cycle sequence. The generation of pseudo-random sequences is not a trivial problem and it is out of scope of this paper. After neighbor discovery, the network coordination between SUs can be achieved by Distributed Coordinated Function (DCF) or CSMA/CA of IEEE 802.11 standard.

3. Proposed Spectrum Sensing Framework

3.1 Spectrum Sensing

Spectrum sensing can be separated into two parts: detection and policy. Detection is the actual sensing of the spectrum by a wireless interface at the physical (PHY) layer whereas policy can be described as scheduling when the spectrum will be sensed. Energy Detection is the simplest and the most practical one. Energy Detection can be performed by any device with a wireless interface which can take measurement of the received signals.

Suppose we want to observe a channel-$i$ for time, $T$ and the actual sensing time or interval to get $N_2$ samples is time $t$. The channel can be continuously
3.2 Energy Detection

We assumed that each SU has a single channel spectrum sensor and energy detection at physical (PHY) layer is used for spectrum sensing. We can draw hypothesis of either idle channel state, $H_0$ or busy channel state $H_1$ in discrete time as:

$$H_0: y(t) = u(t) \quad \text{OR} \quad H_1: y(t) = x(t) + u(t)$$

where $u(t)$ is complex-valued independent and identically distributed (i.i.d) Gaussian with zero mean and variance $\sigma_u^2$; $x(t)$ is the PU signal and $y(t)$ is the received signal at SU spectrum sensor. $x(t)$ is also assumed to be i.i.d complex Gaussian with zero mean and variance $\sigma_x^2$. The testing using optimal energy detector with sufficient statistic is:

$$E(y) = \frac{1}{N_s} \sum_{r=1}^{N_s} \left| y(r) \right|^2$$

where $\epsilon$ is the decision threshold and $N_s$ is the total number of samples. The probability of false alarm and miss-detection probabilities of ED are given in [7] as:

$$\eta = 1 - \Gamma \left( N_s, \frac{\xi}{\sigma_u^2} \right)$$

$$\psi = 1 - \Gamma \left( N_s, \frac{\xi}{\sigma_x^2 + \sigma_u^2} \right)$$

where

$$\Gamma(x, t) = \int_0^t e^{-y} y^{x-1} dy$$

$$\Gamma(x) = \int_0^0 e^{-y} y^{x-1} dy$$

are the incomplete gamma function and the complete gamma function respectively.

3.3 Sensing Policy

In conventional sensing policies for CR, quiet periods in which there is no SU transmission are scheduled to detect the PU signal. In our proposal, we assumed that one SU can sense one channel while another SU transmit in another channel. This assumption is valid since every logical channel is separated by guard bands to mitigate interference from neighboring channels. Our proposed sensing policy is depicted in Fig. 3. The network is operating on CH1, for example, SU1 is downloading data from AP. As it is usual case in DCF, all other SUs which overheard the RTS/CTS exchange will update their Network Allocation Vector (NAV). But during the NAV countdown, instead of going to sleep, the idle SUs will sense different channels in allocated time.

The SUs will continue to sense and store the PU activity information, namely BUSY or IDLE, over a period of time $T$. This can be stored in a bitmap with size $N \times T$ (bits) as depicted in Fig. 2. The SUs will send their sensed information bitmap to AP at the end of each beacon interval. AP has the default IEEE 802.11 beacon interval which is 100 time units (TU) (1 TU = 1024 microseconds). So, the SUs will update the PU activity on every beacon interval which will be maintained in the database stored in the AP.

The proposed independent framework can handle SU devices with different spectrum sensing sequences. SU devices can have different protocols concerning spectrum sensing policy or even different method of detection in PHY layer. Our goal here is to combine information gained from all SU devices in the network to build a database locally. With this database we can perform estimation for channel access.
Fig. 3 Independent cooperation sensing policy

Here, it can be observed that sensing function for updating the database is separated from channel access. Note that carrier sensing is still carried out before channel access to confirm the channel is free.

4. Performance Evaluation

Spectrum sensing policy plays a key role in the performance of a sensing algorithm. To evaluate the performance we will compare two metrics: probability that there exists a sensing delay: \( P[s\text{Delay}>0] \) and average delay incurred \( E[s\text{Delay}] \). The best case scenario in sensing is that the PU signal arrival coincides with a scheduled sensing interval where as the worst case scenario is when PU signal arrives just after a schedule sensing interval. In this case, the PU signal will not be detected until next scheduled sensing interval. And in each sensing interval, there is probability of miss detection and false alarm as described in section 4. Then we can formulate \( P[s\text{Delay}>0] \) as:

\[
P[s\text{Delay}>0] = P(A \cap S)(1-\psi) = P(A)P(S)(1-\psi)
\]

where \( P(S) \) is the scheduled sensing interval between \( t_1 \) and \( t_2 \) and \( P(A) \) is the probability of PU signal arrival between time interval \( t_3 \) and \( t_4 \) as depicted in Fig. 4. The events \( A \) and \( S \) are independent. The probability that a sensing interval is schedule between \( t_1 \) and \( t_2 \) is:

\[
P(S) = (t_2-t_1)/T
\]

The probability the PU signal appears between \( t_3 \) and \( t_4 \) is:

\[
P(A) = P(t_3 \leq x \leq t_4) = F_x(t_4) - F_x(t_3)
\]

where \( F_x(x) \) is the arrival distribution of PU signal.

We performed Monte–Carlo’s simulations to evaluate the performance of our proposal. Some simulations parameters are given in Table 1. The results are the averages of twenty samples. We are interested in how the proposed framework performs when the number of channels to sense is large. As depicted in Fig. 5, the probability that there will be sensing delay follows exponential c.d.f. The more the number of SU devices cooperate in spectrum sensing, the less the probability of sensing delay. Fig. 6 depicts the average delay incurred and it is linear. As the number of SU devices increases, it can be clearly seen that slope of average delay is reduced. This is expected since there will be more sensing intervals scheduled on a channel. In our simulations, we only simulated up to four SU devices cooperatively sensing the channel. The overhead of hypothesis bitmaps exchange after time \( T \) increases linearly with number of SU devices participating in channel sensing. And there also rises another tradeoff. Assume that there are \( N \) channels and all channels are independent. And then the probability that at least one channel will be
idle at any given time interval \( t \) is:

\[
P(D > 1) = 1 - \prod_{i=1}^{N} P_i(B)
\]

From (8) it can clearly be observed that the more the number of channels the CR system operates on, the greater the probability that there will be at least one idle channel at any given time interval. On the other hand, as the number of channels to sense increases, the probability of sensing delay and average sensing delay will increase.

Fig. 7 and Fig. 8 depicts the comparison between two different spectrum sensing policies. The red line represents the dynamic spectrum sensing sequence, i.e. the sensing sequence is changing according to estimation of PU signal arrival and departure. Although, a SU device with the dynamic spectrum sensing performs better than a SU with fixed spectrum sensing policy, cooperative spectrums sensing with two SU devices outperforms it. However, note that there will be extra overhead due to collaboration between two SU devices.

5. Conclusion

In this paper, we propose a spectrum sensing framework with independent sensing sequences for cognitive radio overlay access networks. SU devices which may have different sensing protocols and sensing sequences can independently sense the channels and then exchange the hypothesis bitmap to build a local database. Although some overhead is added, this collaboration leads to better spectrum sensing results.

References