Final Report For Project Cognitive Radio

YE FENG (5070309520), MA CHU (5070309503),
LU XIAOFEI (5071109046), WANG ZHENGCONG (5070309517)

I. OVERVIEW

A. Introduction

Todays wireless networks are regulated by a fixed spectrum assignment policy, i.e. the spectrum is regulated by governmental agencies and is assigned to license holders or services on a long term basis for large geographical regions. In addition, a large portion of the assigned spectrum is used sporadically as illustrated in Fig. 1, where the signal strength distribution over a large portion of the wireless spectrum is shown. The spectrum usage is concentrated on certain portions of the spectrum while a significant amount of the spectrum remains unutilized. According to Federal Communications Commission (FCC) [?], temporal and geographical variations in the utilization of the assigned spectrum range from 15there is a dramatic increase in the access to the limited spectrum for mobile services in the recent years. This increase is straining the effectiveness of the traditional spectrum policies.

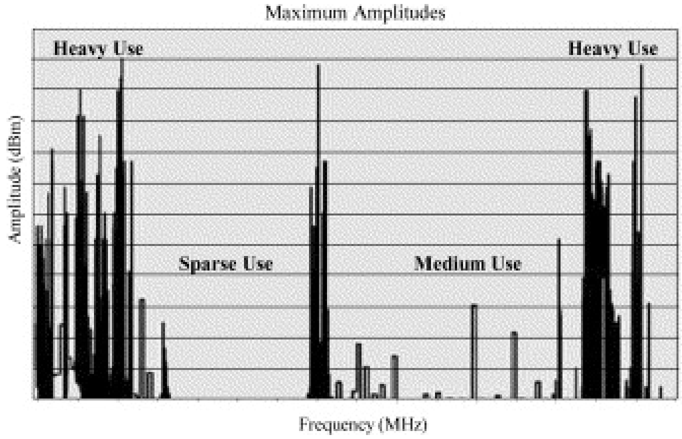

Fig. 1. Spectrum utilization

The limited available spectrum and the inefficiency in the spectrum usage necessitate a new communication paradigm to exploit the existing wireless spectrum opportunistically [?]. Cognitive radio is proposed to solve these current spectrum inefficiency problems.

Cognitive radio technology is the key technology that enables an xG network to use spectrum in a dynamic manner. The term, cognitive radio, can formally be defined as follows [?]: *A Cognitive Radio is a radio that can change its transmitter parameters based on interaction with the environment in which it operates.*

B. Main characteristics of CR

From this definition, two main characteristics of the cognitive radio can be defined [?] and [?] R.W. Thomas, L.A. DaSilva, A.B. MacKenzie, Cognitive networks, in: Proc. IEEE DySPAN 2005, November 2005, pp. 352C360.[?]:

- *Cognitive capability:* Cognitive capability refers to the ability of the radio technology to capture or sense the information from its radio environment. This capability cannot simply be realized by monitoring the power in some frequency band of interest but more sophisticated techniques are required in order to capture the temporal and spatial variations in the radio environment and avoid interference to other users. Through this capability, the portions of the spectrum that are unused at a specific time or location can be identified. Consequently, the best spectrum and appropriate operating parameters can be selected.
- *Reconfigurability:* The cognitive capability provides spectrum awareness whereas reconfigurability enables the radio to be dynamically programmed according to the radio environment. More specifically, the cognitive radio can be programmed to transmit and receive on a variety of frequencies and to use different transmission access technologies supported by its hardware design [?][?].

The cognitive radio concept was first introduced in [?][?] J. Mitola III, Cognitive radio for flexible mobile multimedia communication, in: Proc. IEEE International Workshop on Mobile Multimedia Communications (MoMuC) 1999, November 1999, pp. 3C10.[?] and [?], where the main focus was on the radio knowledge representation language (RKRL) and how the cognitive radio can enhance the flexibility of personal wireless services. The cognitive radio is regarded as a small part of the physical world to use and provide information from environment.

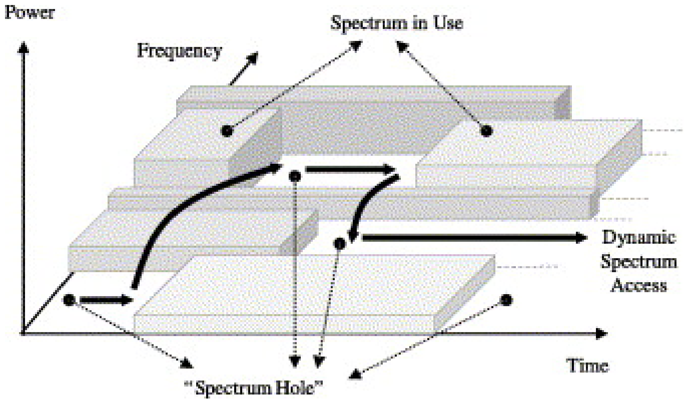

Fig. 2. Spectrum hole concept

C. *Main process*

In some papers the opportunistic exploration of the white space by users other than the primary licensed ones on a non-interfering or leasing basis is studied. Such usage is being enabled by regulatory policy initiatives and radio technology advances.[?]Concerned with the study of the secondary users who observe the channel availability dynamically and explore it opportunistically , secondary users refer to spectrum users who are not owner of the spectrum and operate based on agreements/etiquettes imposed by the primary users/owners of the spectrum. The impact of the opportunistic spectrum availability on the secondary users who explore the spectrum when allowed by the primary users of the spectrum are studied.

However, One critical issue in such communication scenarios is the timely evacuation of secondary users upon the return of primary users.Therefore, the secondary users that detect the return of primaries need to propagate such evacuation information to other secondaries quickly and reliably. We call this information dissemination process the evacuation process and the evacuation information the warning message.

D. *Ultimate objective of CR*

The ultimate objective of the cognitive radio is to obtain the best available spectrum through cognitive capability and reconfigurability as described before. Since most of the spectrum is already assigned, the most important challenge is to share the licensed spectrum without interfering with the transmission of other licensed users as illustrated in Fig. 2. The cognitive radio enables the usage of temporally unused spectrum, which is referred to as spectrum hole or white space [?]. If this band is further used by a licensed user, the cognitive radio moves to another spectrum hole or stays in the same band, altering its transmission power level or modulation scheme to avoid interference as shown in Fig. 2.

II. SPECTRUM ACCESS

A. *Introduction*

objective of the spectrum access is to maximize the achievable capacity (throughput) of the SU. In other words, an SU can decide its sensing scheme, access scheme, packet length and distribution, and back-off duration and distribution to maximize its capacity.

B. *Objective of the spectrum access*

The main functions of Cognitive Radios are:[?]

a. Spectrum Sensing: detecting the unused spectrum and sharing it without harmful interference with other users, it is an important requirement of the Cognitive Radio network to sense spectrum holes, detecting primary users is the most efficient way to detect spectrum holes. Spectrum sensing techniques can be classified into three categories:

- Transmitter detection: cognitive radios must have the capability to determine if a signal from a primary transmitter is locally present in a certain spectrum.
- Cooperative detection: refers to spectrum sensing methods where information from multiple Cognitive radio users are incorporated for primary user detection.
- Interference based detection.

b. Spectrum Management: Capturing the best available spectrum to meet user communication requirements. Cognitive radios should decide on the best spectrum band to meet the Quality of service requirements over all available spectrum bands, therefore spectrum management functions are required for Cognitive radios, these management functions can be classified as:

- spectrum analysis
- spectrum decision

c. Spectrum Mobility: is defined as the process when a cognitive radio user exchanges its frequency of operation. Cognitive radio networks target to use the spectrum in a dynamic manner by allowing the radio terminals to operate in the best available frequency band, maintaining seamless communication requirements during the transition to better spectrum
d. Spectrum Sharing: providing the fair spectrum scheduling method, one of the major challenges in open spectrum usage is the spectrum sharing. It can be regarded to be similar to generic media access control MAC problems in existing systems

C. *Main process*

Cognitive radio access control has been a popular topic of research. Including distributed spectrum sensing and access strategies under an energy constraint on secondary users [?]. The design of sensing policies for tracking spectrum opportunities is explored [?][?]. A partially observable Markov decision framework to devise an optimal sensing and channel selection policy in a multi-channel opportunistic communication [?]. In multi-channel Cognitive Radio Networks, the optimal bandwidth selection is discussed by authors of ”Optimal Bandwidth Selection in Multi-Channel Cognitive Radio Networks: How Much is Too Much? ” [?]Before 2009, the design of a common control channel to exchange spectrum access and sensing information and facilitate collaborative sensing and spectrum reservation/sharing. Co-existence of cognitive users in unlicensed band has also been studied. Much work has been focused on packet collision probability as the protection requirement for PUs. Study of the effect of multiple PU protection requirements on SU policy making and performance under the assumption of both exponential and general idle time distributions of PUs is in the process. Many challenge is to efficiently utilize the spectrum opportunities due to PU activity while protecting the performance of PUs.

D. Status quo

Thus far, ”listen-before-talk (LBT)” is the state-of-the-art opportunistic spectrum access approach to cognitive radio.[?]

- Advantage : LBT simply relies on spectrum sensing, thereby enabling a secondary user (SU) to access the spectrum of a primary user (PU) spectrum unoccupied band. LBT is natural and practical, not requiring any modification to the existing PU infrastructure.
- Disadvantage : LBT only senses primary transmission activities and it is unaware of the actual receiver conditions. More specifically, it neither solves the hidden receiver problem nor utilizes any capacity that robust interference-resistant PU networks may provide.

E. Problem solving

Fig. 3 illustrates a wireless scenario under investigation that involves the co-existence of a primary and a secondary link. The PU access is time-slotted for packet transmissions. The high priority PU may transmit the available packets at the beginning of each slot. We assume that the SU uses that same slot length and that the SU actions are in synchronization with the PU time slot. The PU traffic is randomly busy or idle, irrespective of the SU action.

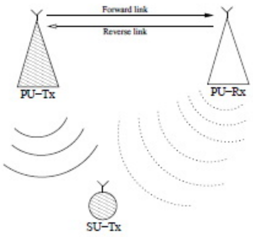

Fig. 3. SU learning environment

In ”Cognitive Spectrum Access Control Based on Intrinsic Primary ARQ Information”, the access control policy they seek consists of a sequence of functions $\pi = \{\mu_0, \mu_1, ..., \mu_t ...\}$where each function $\mu_t(.)$maps the information state p_t into an action $s_t \in I, S, T$. At time t, upon taking action a_t, the $SU-Tx$ uses the current and past observations to determine a maximum-a-posteriori(MAP) estimation of the next PU-traffic transition moment. Given a policy π they define the value function of the SU-Tx from time $t_s = 0$ as:

$$V_\pi(q, t_s, \tau_0(t_s)) = E_\pi[\sum_{t=t_s}^{+\infty} \alpha^t r(p_t, a_t) | p_{t_s} = q] \qquad (1)$$

The optimized access policy is an admissible policy π^* that maximizes the expected value function():

$$\pi^* = argmax\{V_pi(q, t_s, \tau_o(t_S))\} \qquad (2)$$

F. A.Information state update equations

At time t, the SU-Tx takes action$a_t = v$ and uses ${O_t}^v$ and O_{-t} to determine the next PU traffic transitions via a MAP estimator. Since the MAP estimator is error-prone, the SU-Tx will base its channel admission control on the information state p_t to fine-tune the PU channel state. Let $\tau_j(t)$be the latest estimated PU traffic transition at t, the information vector is defined $\forall > 0$:

$$p_t = P[s_t = 1 | {O_{t-1}}^{a_{t-1}}, \tau_j(t-1)] \qquad (3)$$

G. B. Optimal value function and policy calculation

We define $V(p, t, \tau_j(t))$ as the maximum expected discounted value function that the SU-Tx can get at time slot t, with the information state p assuming that the latest PU traffic transition was to state j. From the Bellman equation:

$$V(p, t, \tau_j(t)) = max_{a \in \{I,T,S\}} \{V_a(P, T, \tau_j(t))\} \qquad (4)$$

where $V_I(p, t, \tau_j(t))$, $V_S(p, t, \tau_j(t))$, $V_T(p, t, \tau_j(t))$ are the value function associated with actions Idling, Sensing, and Transmitting, respectively. The time indices of the current and next state is omitted for simplicity.

H. Conclusions and Future works

- Conclusions: In ”Cognitive Spectrum Access Control Based on Intrinsic Primary ARQ Information”, they investigated means of improving the basic LBT access strategy for cognitive radio systems. Exploiting data-linkcontrol messages that can be overheard by the SU-Tx, our new approach can enhance the traditional spectral sensing and more accurately determine the operating conditions of the primary reception for protection. Based on the simple ACK/NAK signals from the PU-Rx and the prior knowledge of the PU idle-busy probability distribution, we applied partially observable Markov-decision processes to devise an optimal channel access control strategy in order to maximize the secondary user utility.
- Future works: The future works include investigating means for SU capacity enhancement by detecting the robust mode of the PU-Rx under SU interference as well as developing more versatile ways of SU access such as multi-level power access.[?]

III. DISTRIBUTED POWER CONTROL

A. Introduction

Cognitive radio networks enable secondary users (SUS) to utilize spare bandwidth of primary users (PUS) by limiting their interference.[?] As we know,the traditional listen-before-talk(LBT) based schemes still suffers several drawbacks: (a) they need to handle the SNR-wall issue ; (b) they do not solve the hidden receiver problem; (c) they fail to effectively exploit the excess system capacity of interference-resistant PU networks.

In order to overcome the limitations of LBT, we advocate a cognitive access methodology that exploits the feedback channel in two-way primary communi- cation links for better spectrum utility and protection against interference. The algorithm is fulfill by letting secondary users dynamically control access and power based on primary ACK/NACK messages.[?]

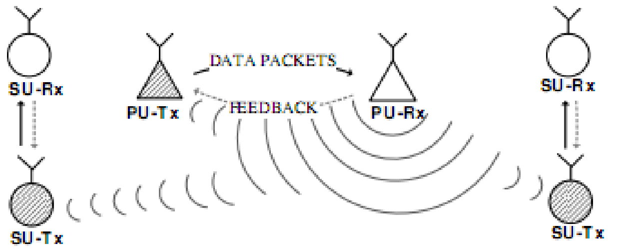

Fig. 4. System model

B. System model and basic assumptions

Figure 6[?] provides the system model where SUs can overhear the feedback from the PU-Rx to the PU transmitter (PU- Tx). This feedback information enables an SU to observe the performance of PU-Rx (affected by one or more SUs), and adjust its own access parameters accordingly.

For convenience, we assume that both PU and SU transmissions are slotted with the same slot duration and that the SU access is synchronized with the PU.

Define Z_t as the observation outcome at the SU-Tx on ACK/NACK at the end of time slot t:

$$Z_t = \begin{cases} 1 & \text{if a NCAK is received at time t} \\ 0 & \text{if an ACK is received at time t} \end{cases} \tag{5}$$

Define P_t as the transmit power of the SU-Tx at slot t,where $t = 1, \cdots, T$ and $P_t < \overline{P}$. The immediate reward for the SU pair with action Pt = P at time slot t is the supported data rate on the forward link given as

$$\gamma(P) = \log(1 + GP) \tag{6}$$

Define ζ_t as the PU NACK rate and $\zeta_t = f_e(P_t)$,which is an monotonically increasing function.

Define the terminal cost by $f_c(x_t)$,which penalize the SU based on the total number of NACKs caused during the entire access period.

C. Adaptive su power control

Most related is the work using power control to mitigate the interference on PUs for SUs.

With the perfect ACK/NACK observation, the SU-Tx maintains a record on the total number of NACK received by the beginning of slot t+1, Xt. We have:

$$X_t = \sum_{k=0}^{t} Z_k \tag{7}$$

with the transition probabilities

$$\begin{aligned} P_r[X_{t+1} = k | X_t = k] = 1 - \zeta_{t+1}, \\ P_r[X_{t+1} = k+1 | X_t = k] = \zeta_{t+1} \end{aligned} \tag{8}$$

The SU power control policy specifies a sequence of functions $\pi = [\mu(1), \cdots, \mu(T)]$, where $\mu(t)$ defines a mapping from state space $\{Xt\}$ to the action space$[0, P]$. Suppose that the number of NACK packets observed at the SU-Tx until time slot t is $X_{t-1} = x$. Let $V_t(\pi, x)$ be the total net-reward of the SU when there are T-t+1 slots left until terminating slot T under a given power control policy π. We then have

$$V_t(\pi, x) = E_\pi[\sum_{k=t}^{T} \gamma(P_\kappa) - f_c(X_T) | X_{t-1} = x] \tag{9}$$

The objective is to find a power control policy π that has the maximum expected total net-reward during the entire access period, i.e.,

$$\overline{\pi} = argmax V_0(\pi, 0) \tag{10}$$

D. Optimal Control Policy

According to the Bellman optimality equation[?][?], we have the following iterative relation on Vt(x):

$$\begin{aligned} V_t(x) = max\{\log_2(1 + GP_t) \\ + f_e(P_t) V_{t+1}(x+1) \\ + (1 - f_e(P_t)) V_{t+1}(x)\}; \end{aligned} \tag{11}$$

and $v_{T+1}(x) = -f_c(x)$. Backward induction can be used to obtain the optimal power control policy $\overline{\pi}$.

If fe(Pt) is a convex increasing function of Pt, with fe(0) = 0, we can show analytically that the optimal power control policy can be iteratively derived by differentiating with respect to Pt before setting the derivative equal to zero. Specifically, we have for $t \leq T$ and $\forall k \in [0, T]$, the optimal transmit power is the solution to the following equation:

$$f_e^{'}(P_t) = \frac{1}{(1 + P_t G)[V_{t+1}(k+1) - V_{t+1}(k)]} \tag{12}$$

Note that we have used the fact that the maximum number of NACK packets during time interval (0, T] is T.

E. Imperfect NACK Detection

In practical systems, the reception of the ACK/NACK packets at the SU-Tx may not be perfect, especially when the SU-Tx is far away from the PU-Rx. Here, we propose a suboptimal approach is a modification of the optimal policy obtained for perfect ACK/NACK reception case. Due to the potential errors of the ACK/NACK detection, the SU-Tx does not know the exact number of PU packets lost. An iterative method is proposed for the SU-Tx to estimate the NACK rate perceived by the PU-Rx. Denote the estimated NACK rate at time slot t as $\hat{\zeta}_t$, we have:

$$\hat{\zeta_{t+1}} = \hat{\zeta}_t + \zeta_{t+1}\left(\frac{X^A_{t+1}}{X^A_{t+1} + X^N_{t+1}} - f_e(0)\right) \tag{13}$$

where $\zeta_{t+1}$is the step size at time t + 1, X^A_{t+1} and X^N_{t+1} denote the number of successfully decoded ACK and NACK packets until time slot t+1, respectively. If the SU-Tx cannot decode the ACK/NACK packet successfully, it will update the value of Xt+1 as:

$$X_{t+1} = X_t + \hat{\zeta}_t \tag{14}$$

F. Conclusion

•The NACK rate increases slightly with the number of SUs.
•Unlike the fairness results in access control simulations, the individual SU throughput differs significantly with power control.
•When the distance from the PU-Rx to the SU-Tx in-creases, SUs can obtain better throughput performance, while the NACK rate is kept low.

G. Further research

In this work, we limited the discussion to exploiting the ACK/NACK message of the two-way primary communication systems. In further works, we would like to analyze and develop in-depth understanding on the SU performance under different security constraints. We are particularly interested in assessing the tradeoff between the security concerns and the reward of adopting unencrypted link control feedback by the PUs. We shall also investigate different PU system feedbacks and evaluate the convergence property of the proposed heuristic algorithms in a dynamic system.

IV. SENSING AND TRANSMISSION STRATEGY

A. Introduction

The listen-Before-Talk (LBT) strategy has been prevalent in cognitive radio networks where secondary users opportunistically access under-utilized primary band. To minimize the amount of disruption from secondary users to primary signals, secondary users generally are required to detect the presence of the primary user reliably, and access the spectrum intelligently.

In this section, we study the following two questions based on Xin Liu's results[?][?]:

- What is the optimal sensing-transmitting strategy? Is it optimal to perform LBT on packet level, especially when the sensing time is large?
- What is the impact of imperfect collision detection, which may not faithfully indicate the presence/absence of the PU during a secondary packet transmission?
- Is the optimal method easy to put into application? How can it be modified into an easier one but do not lose much of the performance?

Xin Liu shows that one optimal sensing and transmission policy has a simple threshold- based structure, where the posterior probability of the PU being idle is compared to the threshold. This result coincides with the heuristic that the SU should continue transmitting packets until the estimated idle probability falls below the threshold.

After a study of her results , we apply them to the design of an real cognitive radio network–Intelligent Home System, which has several pu and SU pairs. The SU pairs want to access the pu spectrum randomly based on the sensing outcomes.

B. System Model and Problem Formulation

1) System Model: We consider a system consisting of a primary link, and a secondary link that opportunistically accesses the PU channel.

Since the PU's traffic pattern is independent of the SU activities, its state transition does not depend on the SU actions. However, the PU state transition depends on the time instance. Define t as the time elapsed since the PU's most recent state transition from BUSY to IDLE. Given that the PU is idle at time t, the probability that the PU will remain idle during the SU action (transmission or sensing) is

$$g^S_t = \frac{1 - F_X(t + K_S)}{1 - F_X(t)}, g^T_t = \frac{1 - F_X(t + K_T)}{1 - F_X(t)} \tag{15}$$

where $F_X()$ is the cumulative distribution function of the PU idle time, and superscripts S and T represent that the SU senses the channel and transmits a packet, respectively.

The SU takes two actions: sensing and transmission. It uses a spectrum sensor (e.g., based on energy or feature) to determine whether the PU is idle or busy at a given time. The non-ideal sensing is characterized by a false-alarm probability

P_f and a detection probability P_d . False alarm (detection) represents the event of declaring BUSY when the PU state is IDLE (BUSY). Note that despite the best effort of the SU sensor, sensing of current PU state cannot assure that the PU will be idle in the future because PU traffic is not synchronized or slotted. Thus, if the PU reclaims the channel when the SU is transmitting, a collision happens. Given δ as the SU time unit, we assume

- A fixed sensing time $K_S \times \delta$;
- A fixed SU packet length $K_T \times \delta$;
- Each successful SU packet earns a reward R$\times K_T \times \delta$.
- Collision penalty C per time unitδ.
- δ= 1 for notation simplicity.

We assume that sensing time is long enough such that the sensing is accurate. However, sensing outcome on current PU state cannot predict whether the PU will remain idle during the next time slot.

Upon receiving the packet from the secondary transmitter (SU-Tx), the secondary receiver (SU-Rx) may feedback an acknowledgment message.

For many reasons, we view the acknowledgment as inaccurate (in the sense of collision detection), which is different from most of existing works. We define the following two probabilities:

$$\gamma_1 = P_r[NACK|CollisionwithPU] \tag{16}$$

$$\gamma_0 = P_r[NACK|NoCollisionwithPU]. \tag{17}$$

Since the interference from the busy primary transmitter can only worsen the packet error rate of SU-Rx, we have $\gamma_1 > \gamma_0$. When the ACK/NACK of the SU faithfully reflects the collision result with the PU, we have $\gamma_0 = 0$ and $\gamma_1 = 1$.

2) Problem Formulation: Denote the action space of the SU as A = {a : 1(Transmit), 0(Sense)}. After each action, the SU observes the outcome of its action, O_t . For the sensing action, $O_t^S \in$ {I(Sensing IDLE), B(Sensing BUSY)}; for transmission, $O_t^T \in$ {A(ACK), N(NACK)}.

For each successful transmission, the SU receives a unit reward. Furthermore, because the PU has a higher priority on the spectrum resource, the SU will be charged a cost C for each packet collision with the PU. Obviously, without the collision penalty, the SU will always transmit if no other constraints is imposed. Thus, the collision penalty is important to control the aggressiveness of the SU's access activities.

Let p_t denote the conditional probability that the PU is IDLE at time t given $(p_0, a_0, , a_t?1, o_0, , o_{t-1})$, where a_t is the action of the SU at time t, and o_t is the observation after the action at time t. In other words, p_t is the information state at time t. At the end of action, the SU will update its estimation on the PU idle probability p_{t+K_S} or p_{t+K_T} based on the observation it received. Specifically, by Bayes' rule, we have the following information dynamics:

When $a_t = 0$, we only consider perfect sensing:

$$p_{t+K_S}(O^S) = \begin{cases} 1 & O^S = I \\ 0 & O^S = B \end{cases} \tag{18}$$

When $a_t = 1$:

$$p_{t+K_T}(O^T) = \begin{cases} \frac{p_t g_T^S(1-\gamma_0)}{p_t g_T^S(1-\gamma_0)+(1-p_t g_T^S)(1-\gamma_1)} & \text{ACK} \\ \frac{p_t g_T^S \gamma_0}{p_t g_T^S \gamma_0+(1-p_t g_T^S)\gamma_1} & \text{NACK} \end{cases} \tag{19}$$

Since we assume that the SU knows the beginning of the PU idle time, we have $p_0 = 1$.

The immediate expected reward/utility the SU obtains at time t, $r_t(p_t, a_t)$, with information state p t and action a_t , is

$$r_t(p_t, 1) = [p_t g_T^S(1-\gamma_0) + (1-p_t g_T^S)(1-\gamma_1-C)]K_T \tag{20}$$

$$r_t(p_t, 0) = 0. \tag{21}$$

3) Optimal Sensing and Transmission Strategy: Define V (t, p) as the maximum expected utility the SU can obtain at time t with information state p.

$$V(t, p) = \max_{0,1}\{L(t, p), M(t, p)\} \tag{22}$$

where L(t, p) and M(t, p) are the expected utility the SU can obtain by sensing the channel (Listening) and transMitting a packet, respectively.

When calculate the V(t,p), we use a different approach from the author.Liu Xin define the expression below as an optimal one:

$$L(t, p) = \sum_{i \in I,B} P_r(O_{t+K_S}^S = i)V(t + K_S, p_t + K_S(i)) \tag{23}$$

$$M(t, p) = (p_t g_T^S(1-\gamma_0) + (1-p_t g_T^S)(1-\gamma_1-C))K_T + \sum_{j \in A,N} P_r(O_{t+K_T}^T = j)V(t + K_T, p_t + K_T(j)) \tag{24}$$

Liu Xin calculate all the reward from time t to the end of this cycle. It is optimal, but also hard to put into application. So we modified it as follows:

$$L(t, p) = 0 \tag{25}$$

$$M(t, p) = (p_t g_T^S(1-\gamma_0) + (1-p_t g_T^S)(1-\gamma_1-C))K_T \tag{26}$$

When deciding whether to sense or to transmit in next stage, Liu Xin get a threshold for p_t from the V(t,p), while I just compare L(t,p) and M(t,p). As

$$L(t, p) = 0 \tag{27}$$

So we just calculate the M(t,p), it the answer is above 0, then sense, otherwise, send.

C. Simulation

As to illustrate that our modification on the optimal method does not lose much of the performance, we do some simulations and compare our results with the results in Liu Xin's paper.

1) Assumptions: The PU idle time is uniformly distributed in [0, 1000], and the SU packet length is $K_T = 5$. The per time unit reward is R = 1, and the mean of PU busy time is set as 500. Therefore, the available spectrum opportunity is 0.5. The performance shown in this section is normalized with respect to the sum of average PU idle and busy time. we set r_1 =0.1, 0.5, 1.0 ,K_S=30, $K_T = 5$ in our simulations.

We only consider one PU and one SU, perfect sensing and imperfect ACK/NACK.

2) Simulation Result for Single SU: In the result:

utility is the total reward and penalty in one PU IDLE-BUSY cycle.

SU throughput refers to SU successful transmission time normalized by the PU IDLE-BUSY cycle.

Collision Rate =Total Number of PU Packet Collisions/Total Number of PU Packets.

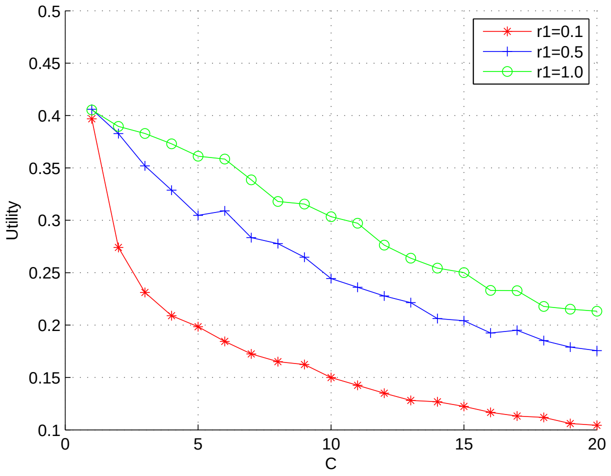

Fig. 5. Utility-C

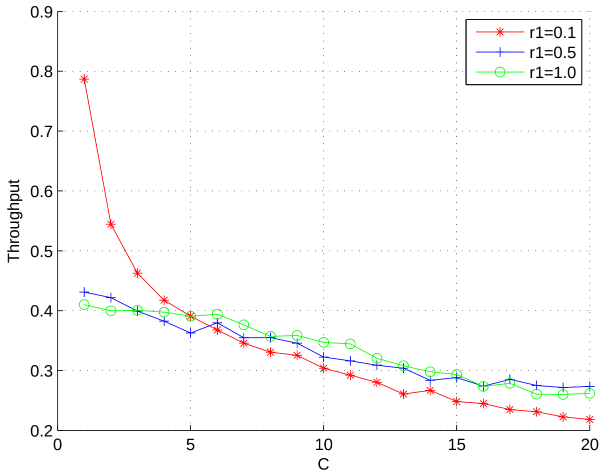

Fig. 6. Throughput-C

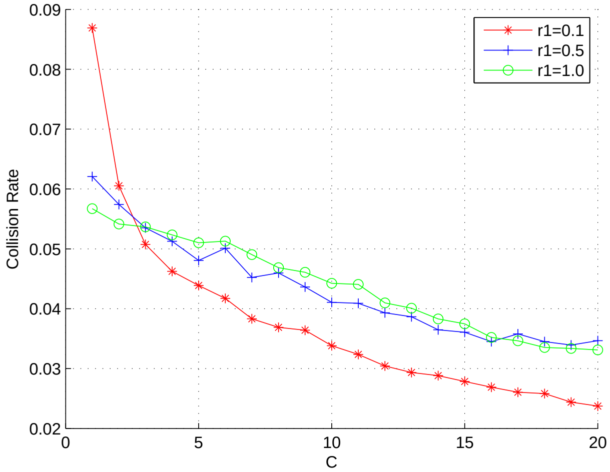

Fig. 7. Collision Rate-C

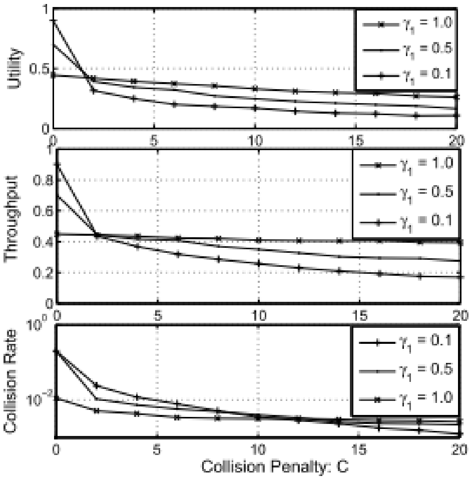

Fig. 8. Liu Xin's Result

3) Simulation Plan for Multiple SUs: We have two different methods based on the simulation methods for single SU.

The first one is as follows. When a SU_p-Tx's pt is higher than its threshold, it will keep sensing for an random delay time, after the delay time if pt still higher than threshold, it will send. When a SU-Tx's pt is higher than its threshold, it will sense for a fixed time(longer than maximum time of the SU_p delay time)and then it will keep sensing for an random delay time, after the delay time if pt still higher than threshold, it will send.

The second one is as follows. When a SU_p-Tx's pt is higher than its threshold, it will send at probability of p_1. When a SU-Tx's pt is higher than its threshold, it will send at probability of $p_2 (p_2 < p_1)$.

Both methods above are try to reduce the chance of collisions, include the SU-SU, and SU-PU collisions.

D. Application

After spending a long time trying to understand and modify Liu Xin's theory and do simulation, we applied them to an special scenario–Intelligent Home System,which use different kinds of sensors to collect information and transmit this information to a CPU through wireless networks using RF models.

The wireless networks here are a single channel system with multi-primary users and multi-secondary users. They all want to send information to one center node. Our goal is to decrease collision rate and increase throughput.

In the Intelligent Home System, there exist two types of sensors, Physiology sensors and Environment sensors. So there must be multiple Pus and SUs. What's more, physiology information is relatively more important than the environment information, so we have to set different priorities for them.

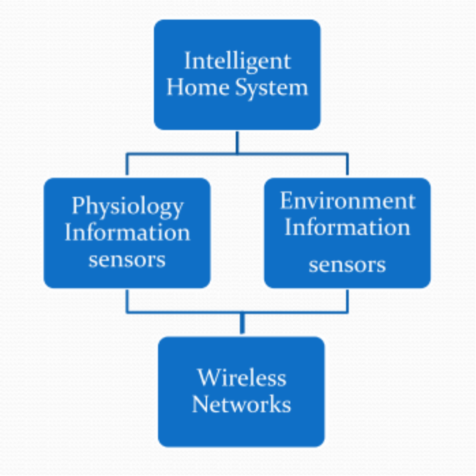

Fig. 9. Intelligent Home System

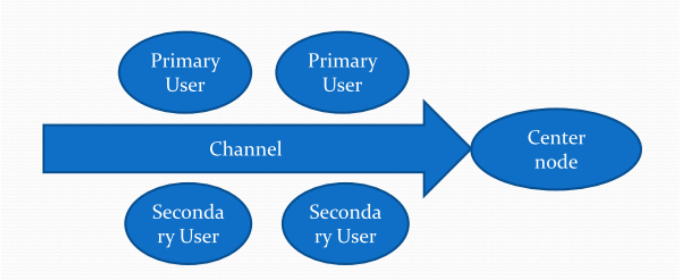

Fig. 10. Wireless Network Model

E. Conclusion

In this section, we learn Liu Xin's work on optimal sensing and transmitting strategies.

Given a reward mechanism for Successful SU transmission and collision penalty, an adaptive control policy to decide whether to sense/transmit in each decision stage is developed, considering the impact of inaccurate collision detection with PU traffic on spectrum access policy. The optimal spectrum access policy has a simple threshold-based structure. With this structure, the optimal policy can be found by simply searching for the optimal threshold, with which the computation complexity is greatly reduced.

We modify Liu Xin's method into an easy one, which still has relatively good performance but more easy to put into application. Then we do some simulations to test our modification.

After that, we apply them to a Intelligent Home Systemand put forward two simulation methods.

V. FUTURE WORK

We have establish the model only with single PU and single SU with only one bands, in our future work, we will do three extended research as following:

- Study the cases with multiple PU bands and multiple SUs, establish models.
- Use our result to finishing the simulation for the Intelligent Home System, which has multiple SUs.
- Another possible extension is to consider the general distribution for PU busy/idle time.

REFERENCES

[1] FCC, ET Docket No 03-222 Notice of proposed rule making and order, December 2003.

[2] I.F. Akyildiz, Y. Altunbasak, F. Fekri and R. Sivakumar, AdaptNet: adaptive protocol suite for next generation wireless internet, *IEEE Communications Magazine 42* (2004) (3), pp. 128C138.

[3] DARPA XG WG, The XG Architectural Framework V1.0, 2003.

[4] DARPA XG WG, The XG Vision RFC V1.0, 2003.

[5] S. Haykin, Cognitive radio: brain-empowered wireless communications, IEEE Journal on Selected Areas in Communications 23 (2005) (2), pp. 201C220. Full Text via CrossRef — View Record in Scopus — Cited By in Scopus (1556)

[6] R.W. Thomas, L.A. DaSilva, A.B. MacKenzie, Cognitive networks, in: Proc. IEEE DySPAN 2005, November 2005, pp. 352C360.

[7] J. Mitola III, Cognitive radio for flexible mobile multimedia communication, in: Proc. IEEE International Workshop on Mobile Multimedia Communications (MoMuC) 1999, November 1999, pp. 3C10.

[8] Senhua Huang, Xin Liu, and Zhi Ding, ”On Optimal Sensing and Transmission Strategies for Dynamic Spectrum Access”, IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN) 2008, Chicago, IL.

[9] X. Liu and S. Shankar, ”Sensing-based opportunistic channel access.” ACM Journal on Mobile Networks and Applications (MONET), Volume 11, Number 1, February 2006, p. 577-591.

[10] S. Huang, X. Liu, and Z. Ding, ”Opportunistic spectrum access in cognitive radio networks” IEEE INFOCOM 2008

[11] IEEE 802.22

[12] Y. Chen; Q. Zhao; A. Swami, ”Distributed Spectrum Sensing and Access in Cognitive Radio Networks With Energy Constraint,” IEEE Trans. Signal Processing, 57(2):783-797, Feb. 2009.

[13] Q. Zhao; L Tong; A Swami and Yunxia Chen, ”Decentralized cognitive MAC for opportunistic spectrum access in ad hoc networks: A POMDP framework,” IEEE Journal Selected Areas in Communications,25(3):589-600, April 2007.

[14] Y. Chen; Q. Zhao; A. Swami, ”Joint Design and Separation Principle for Opportunistic Spectrum Access in the Presence of Sensing Errors,” IEEE Trans. Info. Theory, 54(5):2053-2071, May 2008.

[15] Q. Zhao; B. Krishnamachari; K. Liu, ”On myopic sensing for multichannel opportunistic access: structure, optimality, and performance,” IEEE Trans Wireless Comm., 7(12):5431-5440, Dec. 2008.

[16] Dan Xu, Eric Jung, and Xin Liu, ”Optimal Bandwidth Selection in Multi-Channel Cognitive Radio Networks: How Much is Too Much? ” , IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN) 2008, Chicago, IL.

[17] Fabio E. Lapiccirella, Zhi Ding, and Xin Liu, ”Cognitive Spectrum Access Control Based on Intrinsic Primary ARQ Information”,ICC 2010.

[18] Enrico Del Re, Gherardo Gorni, Luca Simone, Ronga Rosalba Suffritti, ”Resource Allocation in Cognitive Radio Networks: A Comparison Between Game Theory Based, and Heuristic Approaches,” Wireless Pers Commun, vol, 49, pp. s375-390, 22 March 2009

[19] K. Liu and Q. Zhao, ”Distributed Learning in Cognitive Radio Networks: Multi-Armed Bandit with Distributed Multiple Players” : Proc. of IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP), March, 2010.

[20] W. Ren, Q. Zhao, and A. Swami, ”Connectivity of Cognitive Radio Networks: Proximity vs. Opportunity” , Proc. of ACM MobiCom Workshop on Cognitive Radio Networks, September, 2009.

[21] W. Ren, X. Xiao, and Q. Zhao, ”Minimum-Energy Multicast Tree in Cognitive Radio Networks”, Proc. of IEEE Asilomar Conference on Signals, Systems, and Computers, November, 2009.

[22] K. Liu, Q. Zhao, and Y. Chen, ”Distributed Sensing and Access in Cognitive Radio Networks” Proc. of 10th International Symposium on Spread Spectrum Techniques and Applications (ISSSTA), August, 2008.

[23] Senhua,Xin Liu,and Zhi Ding,”Distributed Power Control for Cognitive User Access based on Primary Link Control Feedback”,University of California, Davis, CA 95616, USA.

[24] Fabio E.Lapiccirella,Senhua Huang,Xin Liu and Zhi Ding,”Feedback-based access and power control for distributed multiuser cognitive networks”,Electrical and Computer Engineering University of California,Davis, California 95616.

[25] Q. Zhao and B. Sadler, ”A survey of dynamic spectrum access: signal processing, networking, and regulatory policy,”IEEE Signal Processing Magazine, vol. 55, no. 5, pp. 2294C2309, 2007.

[26] R. Zhang and Y. C. Liang, ”Exploiting hidden power feedbacks in cognitive radio networks,”Poster Session, the 3rd IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN), 2008.

Fig. 11. Xiaofei Lu

Student ID: 5071109046
Group leader of group 18, he decided the research topic. Before report II, he read some papers and did the ”CR overview” part both in that report and in report III.

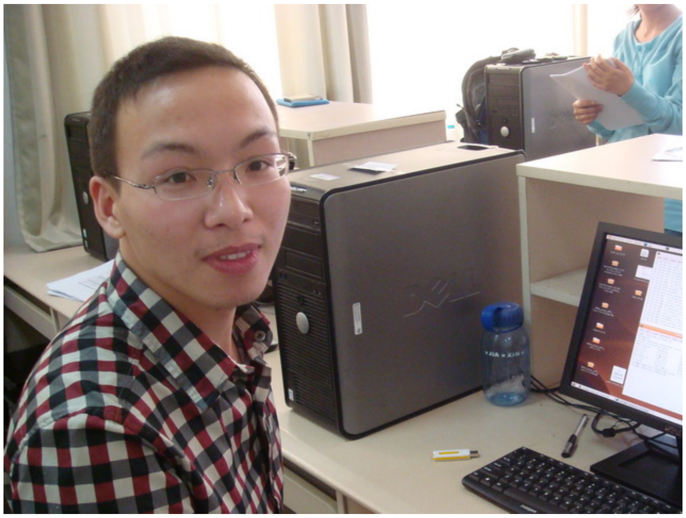

Fig. 12. Zhengcong Wang

Student ID: 507030517
He assisted in deciding the research direction. Before report II, he read some papers and did the ”power control” research, which is helpful in our model and will be important in our future work. He is in charge of that part both in report II and report III.

Fig. 13. Feng Ye

Student ID: 5070309520
Before report I, he decided what to do first, found the papers to understand what is CR, and what are the main directions about CR research in the past 3 three years. He finished report I with the help of MA CHU. Before report II, He read some papers and did the research of ”Spectrum access” to which was useful in the model we established, and he was in charge of the part ”Spectrum access” in report II. He also decided how to do the presentation, and helped MA CHU to finish report III.

Fig. 14. Chu Ma

Student ID: 5070309503
Helped YE FENG finished report I. She finally decided the research direction after report I was handed over. She also found the relating papers and divided them into 4 parts and gave out them to each member in our group, which was presented in report II, and she is in charge of ”Sensing and transmission strategy” part both in report II and report III. She also converged the researches we did and established the model with simulations. It was not in report II because the model was not good enough to compare with the Xiu Liu’s model at that time. Before the presentation, she finally finished the model and convincing simulations, the model and result are presented in the final report.