Dynamic Channel Assignment using Ant Colony Optimization for Cognitive Radio Networks

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***Abstract*—Considering the inevitable trends for heterogeneous network convergence, Cognitive Radio Network (CRN) concept has been proposed with some essential characteristics to achieve adaptation and global end-to-end goals. This motivates a more flexible and effective dynamic channel assignment scheme which can utilize the licensed spectrum effectively through reusing idle licensed spectrum opportunistically. This paper focuses on the dynamic channel assignment which offers optimal resource allocation mechanism to satisfy the requirement of users and networks in transmission. Owing to the optimization problem of channel assignment is constituted as a nonlinear programming, we propose the use of Ant Colony Optimization(ACO) algorithm as a way to manage and assign channel resource dynamically in CRNs. The ACO, as an intelligent technique, has the capacity to solve the complex multi-objective optimization problem and simplify the computational process. Finally, the dynamic channel assignment algorithm is simulated, and the numerical results with detailed are analyzed.**

Keywords-cognitive radio network; dynamic channel assignment; ant colony optimization

I. INTRODUCTION

The concept of cognitive radio network (CRN) was proposed as the solutions for addressing the limited spectrum availability and the inefficiency in the spectrum usage through its capability of awareness, learning and adapting [1]. However, the rapid development of the wireless communication not only offers more flexible network services but also makes CRNs have a trend towards increasingly complex, heterogeneous, and dynamic [2]. This motivates a more flexible and effective dynamic channel assignment scheme which can utilize the licensed spectrum effectively using opportunistic spectrum access technologies, and meanwhile, adapt the heterogeneous environment. On the one hand, by adopting the dynamic channel assignment, the overall channel resource utilization can be improved conforming to the user and service requirements. On the other hand, dynamic channel assignment achieves the switch from one frequency band to another which supports diverging Radio Access Technologies (RATs) among heterogeneous networks continuously and seamlessly. However, the interference to primary users(PUs) which is caused by the transmission among cognitive nodes should be taken into account in the dynamic channel assignment design criteria. All that justifies three important objectives for CRN: maximize the spectrum utilization, maximize the network performance and adapt the complex environment and requirement [2]. While several studies have focused on identifying available spectrum and channel based on spectrum sensing techniques, the dynamic channel assignment which takes the user requirement and the heterogeneous environment into account is still a challenging problem in CRN. Hence, in this paper we focus on the study of designing an optimal dynamic assignment scheme which can maximize system performance, spectrum utilization and quality of data transmission.

There exists a lot of researches effort on the channel assignment problem in CRNs. Based on overlay or underlay system, control channel or data channel, cooperative or non-cooperative manner, lots of methods have been proposed for spectrum allocation and channel assignment [3-4], including queuing theory [5], hidden Markov model [6], swarm intelligence [7], Lagrange multiplier technique [8] and graph coloring [9]. Assuming that each subscriber of the cognitive network can be either active or idle and only active subscribers require downlink transmission, a spectrum allocation model is proposed in [10], and interference graph is introduced to solve this mixed-integer linear programming. As the assignment model can be inherently seen as an optimization problem [7-12], we introduce the ant colony optimization (ACO) algorithm for channel assignment problem of CRN in this paper.

Owing to the optimization problem of channel assignment commonly is constituted as a mixed integer nonlinear programming which is known as the NP-hard problem, the general approach in recent studies is simplifying the optimization objective [11]. ACO algorithms, which are stochastic search methods that mimic the social behavior of species, has feasibility and advantage in solving this kind of complex optimization problems. Moreover, the characteristics of ACO algorithms, such as parallel computation, self-organization and positive feedback, can help the multi-objective optimization get a global optimization solution, and meanwhile, obtain less computing time and computational complexity [12]. In this paper, we first investigate how ACO can be used to dynamically manage channel assignment in CRNs. Our design goal is to maximize the throughput of system achieved by all cognitive users(CRUs) with respect to the dynamic channel assignment. The process of formulating the dynamic channel assignment problem as an optimization problem and solving based on the ACO is described in the next sections.

The remainder of the paper is organized as follows. In section II, a system overview including system model description and operational requirement is given. The problem formulation of dynamic channel assignment and enhanced ACO algorithm are introduced in section III. Simulation results of the algorithm are investigated in Section IV. Finally, the paper is concluded in Section V.

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II. PROBLEM DEFINITION

A. System Model

We consider a system containing multiple heterogeneous CRNs with a certain number of CRUs, PUs and channel resource, where the quantities of them vary dynamically based on the number of contending users and available vacant channels. Assuming M channels are orthogonal in the frequency domain which are completed by the I CRUs. We also assume that channel occupied pattern of the PU is static and aware to avoid the PU from interference.

Our objective is to maximize system performance, spectrum utilization, and meanwhile, satisfy the users application requirements. In this context, the system is analyzed subject to the following constraints:

- Wireless users can connect one of several available network access opportunities for the purpose of both network performance and user application requirement in a multiple heterogeneous CRNs co-existed environment.
- A cognitive receiver or transmitter cannot receive or transmit with more than one transmitter/receiver.
- The interference of the transmission of the PU from CRUs should satisfy the interference constraint.
- The interference among CRUs when they access the same channel should be under certain threshold.
- All the CRUs have a common transmission range and a common interference range. CRUs adjust its interference range on the given channel to avoid interfering with PUs.

To facilitate further elaboration, a list of notations is given as follows:

- $D=\{d_{ik},1<i,k<I\}$ is the distance matrix: d_{im} denotes the distance between user i and user k.
- $P=\{p_{im},1\le i\le I,1\le m\le M\}$ is the transmit power matrix which records the transmit power of the user i when it accesses the channel m.
- $R=\{r_{im},1<i<I,1<m<M\}$ is the interference range matrix: r_{im} denotes the interference range when user i use the channel m. The range can be adjusted through varying the transmit power p_{im}.
- $L=\{l_{im}\mid l_{im}\in\{0,1\},1\le m\le M,1\le i\le I\}$ is the channel availability matrix: if $r_{im}<d_{in}-r_{nm}$ then $l_{im}=1$ which denotes the channel m is available to CRU i.
- $C=\{c_{ijm}\mid c_{ijm}\in\{0,1\},1\le m\le M,1\le i,j\le I\}$ is the interference constraint matrix: if $d_{ik}<r_{im}+r_{km}$ then $c_{ijm}=1$ which denotes that the user i interfere user j when they access the channel m simultaneously.
- $A=\{a_{im}\mid a_{im}=\{0,1\},1\le i\le I,1\le m\le M\}$ is the assignment matrix: $a_{im}=1$ denotes that the channel m is assigned to the user i, $a_{im}=0$ denotes otherwise.
- $B=\{b_{im},1\le i\le I,1\le m\le M\}$ denotes the channel reward matrix: b_{im} denotes the channel reward from the user i using the channel m. The reward represents the gain from spectrum band by user i using the channel m, such as bandwidth or throughput. In this paper, it is defined as the channel capacity for a CRU using a channel:

$$b_{im}=\log(1+r_{im}^2) \tag{1}$$

- $F=\{f_{im}\mid f_{im}=\{0,1\},1\le i\le I,1\le m\le M\}$ is the cost matrix: f_{im} denotes the cost from the user i accessing the channel m.

B. Operational Requirements

Our objective is to maximize system performance and spectrum utilization, which can be supported under several different conditions:

- **C1.** The total amount of the interference caused by all cognitive transmissions to each PU must be controlled under a predefined threshold, which can guarantee the transmission performance and channel gain of PUs.
- **C2.** For each CRU of transmission, the received signal to interference plus noise ratio (SINR) must be above a predefined threshold, which guarantee the transmission performance and channel gain of CRUs.

Since the system performance takes both the PUs and secondary users into account, the objective can be analyzed in two aspects.

1) Protection Requirement for PUs

For taking the minimization of the interference of PUs as the objective, the optimization problem of channel assignment can be defined as follows:

$$U=\arg\min\sum_m\sum_i a_{im} \tag{2}$$

$$s.t.\quad a_{im}(p_{im}-\eta)<\overline{\varsigma},\forall i,j\in\{1,\dots,I\},m\in\{1,\dots,M\}, \tag{3}$$

$$l_{im}a_{im}\ge 1,\forall i\in\{1,\dots,I\},m\in\{1,\dots,M\} \tag{4}$$

Where η stands the loss from CRU to PU, $\overline{\varsigma}$ is the predefined threshold for interference to each PU which is caused by all cognitive transmissions. This corresponds to the condition **C1**.

2) SINR Requirement of CRUs

For taking the maximization of the SINR of CRUs as the objective, the optimization problem of channel assignment can be defined as follows:

$$U=\arg\max\sum_m\sum_i a_{im} \tag{5}$$

$$s.t.\quad \frac{a_{im}p_{im}}{N_0+h(p_{nm})+a_{jm}\cdot\sum_{\substack{j=1\\ j\ne i}}^{I}c_{ijm}p_{jm}}>\overline{\gamma}, \tag{6}$$

$$\forall i\in\{1,\dots,I\},m\in\{1,\dots,M\},n\in\{1,\dots,N\},$$

$$l_{im}a_{im}\ge 1,\forall i\in\{1,\dots,I\},m\in\{1,\dots,M\} \tag{7}$$

Where N_0 stands for the noise, $\sum c_{ijm}p_{jm}$ stands for the co-channel interference caused by other CRUs, $h(p_{nm})$ presents the interference caused by PUs and $\overline{\gamma}$ is the predefined threshold for SINR of CRUs. This corresponds to the condition **C2**.

III. DYNAMIC CHANNEL ASSIGNMENT USING ACO

A. Dynamic Channel Assignment Problem Formulation

As introduced before, designing effective dynamic channel assignment solutions requires cooperation between the SINR requirement and the PU protection requirement such that the dynamic channel assignment module can be aware of the surrounding environmental changes to take more appropriate decision. In this context, the dynamic channel assignment problem principally consider several aspects including the transmission quality of CRUs, the interference between CRU and PU, the channel conflict among CRUs in the same channel, and meanwhile, the cost and reward of CRUs for using a channel.

Before formulating the optimization problem for the dynamic channel assignment, the following principles are presented to guarantee the channel assignment scheme is feasible and effective.

- **P1.** For all $i, m \in \{1 \le i \le I, 1 \le m \le M\}$, if $a_{im} = 0$ then $p_{im} = 0$.
- **P2.** For all $i, m \in \{1 \le i \le I, 1 \le m \le M\}$, if $a_{im} = 1$ there must exist $l_{im} = 1$.
- **P3.** For all $i, m \in \{1 \le i \le I, 1 \le m \le M\}$, if $c_{ijm} = 1$ there must exist $a_{im} + a_{jm} \le 1$.
- **P4.** For all $i, m \in \{1 \le i \le I, 1 \le m \le M\}$, if $a_{im} = 1$ then p_{jm} and p_{nm} satisfy the inequality in (1).
- **P5.** For all $i, m \in \{1 \le i \le I, 1 \le m \le M\}$, if $a_{im} = 1$ then $a_{im'} \ne 1$.
- **P6.** For all $i, m \in \{1 \le i \le I, 1 \le m \le M\}$, if $a_{im} = 1$ then $l_{im} p_{im}$ satisfy the inequality in (2).

In the above definition, principle **P1** achieves the energy conservation by decreasing unnecessary power loss. Principle **P2** guarantees the assigned spectrum is available. Principle **P3** avoids the co-channel interference between CRUs. Principle **P4** corresponds to the SINR requirement of CRUs and interference constraints between CRU and PU. Principle **P5** means the CRU cannot use more than one channel simultaneously. Finally, principle **P6** corresponds to the protection requirement for PUs.

Using the channel assignment matrix as variables and the principles as the constraint conditions, we can formulate the problem of dynamic channel assignment as the following mixed-integer linear programming (MILP):

$$Maximize_{a_{im}} \sum_{m=1}^{M} \sum_{i=1}^{N} a_{im}(b_{im} - f_{im}) \tag{8}$$

$s.t.$

$$\sum_{m=1}^{M} a_{im} \le 1, \forall i \in \{1, 2, \ldots, I\}, \tag{9}$$

$$l_{im} a_{im} \ge 1, \forall i \in \{1, 2, \ldots, I\}, m \in \{1, 2, \ldots, M\}, \tag{10}$$

$$a_{im} + a_{jm} \le 1, \forall c_{ijm} = 1, i, j \in \{1, 2, \ldots, I\}, m \in \{1, 2, \ldots, M\}, \tag{11}$$

$$\frac{a_{im} p_{im}}{N_0 + h(p_{nm}) + a_{jm} \cdot \sum_{\substack{j=1 \\ j \ne i}}^{I} c_{ijm} p_{jm}} > \overline{\gamma}, \tag{12}$$

$$\forall i \in \{1, 2, \ldots, I\}, m \in \{1, 2, \ldots, M\}, n \in \{1, \ldots, N\},$$

$$a_{im}(p_{im} - \eta) < \overline{\varsigma}, \forall i, j \in \{1, \ldots, I\}, m \in \{1, \ldots, M\} \tag{13}$$

The (12) and (13) can be integrated as follows:

$$(N_0 + h(p_{nm}) + a_{jm} \cdot \sum_{\substack{j=1 \\ j \ne i}}^{I} c_{ijm} p_{jm})\overline{\gamma} < a_{im} p_{im} < \overline{\varsigma} + a_{im}\eta \tag{14}$$

It is clear that the principles **P1-P6** guarantees the constraints (9)-(13) above. An observation of the objective and constraints of the optimization problem shows that the problem takes account many complex factors into the decision-making process which makes the problem is hard to solve. Moreover, the dynamic of CRN requires a more intelligent mode to make decision. In this context, ACO techniques, as an intelligent technology for solving complex issues, are applied to address these challenges.

B. Enhanced Ant Colony Algorithm

In ACO, the artificial ants build solution through moving from one vertex to another in the constraint graph. The characteristics of ACO, such as parallel computation, self-organization and positive feedback, can help the dynamic channel assignment problem to achieve multi-objective optimization, self-adaptation and learning capability so that we can get a global optimization solution [13]:

1) Parallel computation: In ACO system, the task executing process of each ant is independent of others, which means the accomplishment of assignment relies on multi-individuals operating simultaneously in task space. That is, the ACO algorithm, as a distributed multi-agent system, is competent for multi-objective optimization and also can keep the solution reliable and global optimal.

2) Self-organization: In ACO system, the artificial ant tends to the optimal solution spontaneously through searching pheromone. The self-organization characteristic make the system evolved from unordered to ordered automatically, which guarantees the optimization result can adapt the environment.

3) Positive feedback: In ACO system, a cumulus of pheromone is a positive feedback process which guarantees the computation process toward the optimization solution. The positive feedback characteristic, which presents the optimization result influenced by both the current state and the historical state, can realize the learning capability of control.

We use an enhanced Ant Colony Algorithm (EACO algorithm) to get effective optimization solution in solving multi-objective optimization problem in this paper. It is obvious that the flexibility of nodes in CRNs demands the learning mechanism to achieve reliable results. We improve the mechanism of searching the next node and updating pheromone in ACO model which can decrease the optimization time and advance astringency. In EACO system, the artificial ants build solution through moving among vertexes follow the principle as:

$$p_{ij}^{a}=\begin{cases}\dfrac{\tau(i,j)}{\sum_{s\in C}\tau(i,s)} & ,if \quad q\geq q_0\\ p(\arg\max(\tau(i,j))) & ,otherwise\end{cases} \tag{15}$$

Where $\tau(i,j)$ is the pheromone remained on the edge (i,j) by ant a, q is a random number and q_0 is a predefined threshold value. We integrate two kinds of searching mechanism into EACO to guarantee the global optimization of the solution. To avoid the residual pheromone submerging the heuristic information, pheromone will be locate-updated after one ant finishes a path searching with this principle:

$$\tau_{ij}(t+1)=(1-\rho)\cdot\tau_{ij}(t)+\rho\cdot\tau_0 \tag{16}$$

Where τ_0 is a initial pheromone value and ρ is the evaporation coefficient of pheromone. When all the ants in the system complete the circle, the pheromone will be global-updated with this principle:

$$\tau_{ij}\leftarrow(1-\alpha)\cdot\tau_{ij}+\alpha\cdot\frac{1}{G_{\max}} \tag{17}$$

Where α is a constant and $G_{\max}$ is the maximum of objective function.

C. Dynamic Channel Assignment Based on EACO Algorithm

In this paper, the dynamic channel assignment algorithm is accomplished via an enhanced Ant Colony Algorithm — EACO algorithm to get effective optimization solution in solving multi-objective optimization problem in the continuous domain. The implementation of EACO channel assignment algorithm is described as follows:

Step 1. Initialization: Initialize the parameters, including the number of iterations, the number of CRUs and PUs, the population of the ant colony, the evaporation rate, the initial value of the pheromone, noise density and the power spectral density. The EACO model is initialized as Fig.1, which illustrates the relationship between CRU and the channel allocation. The ant starts from the first layer to find the appropriate node in EACO model.

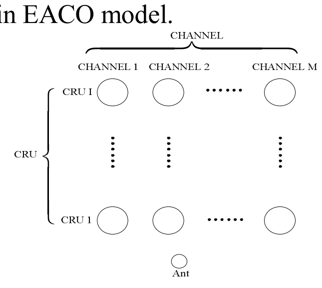

Figure 1. EACO model

Step 2. Searching process: The ants travel among the nodes according to the probability defined in equation (15) and the constraints in (9)-(13), then result a group of potential assignment arrangements as the solution set.

Step 3. Local optimization procedure: Update the pheromone with the equation (16) after every ant achieves an integrated process of searching.

Step 4. Global optimization procedure: Compare the obtained channel assignment arrangements from all the ants based on the objective function described in equation (8), and select the optimum channel assignment arrangement, which can maximize the objective function, as the best solution in this iteration. Update the pheromone with the equation (17), after the global optimization result is acquired.

Step 5. Control consequence: When the stopping condition or the number of iterations is satisfied, the channel control operation manages and regulates channel assignment according to the globally optimal solution. Else, return to Step 2.

IV. Performance Evaluation

A. Parameter Setting and Experimental Setup

We consider a rectangular area of size 450×450 in which a CRN model is deployed. We automatically generate a topology structure which includes N nodes in each evaluation. The locations of the CRUs and PUs are randomly assigned in this service area. We set the maximum transmit power of a CRU as $p_{\max}=50mW$, the noise power density as $N_0=-100dBm$, the number of channels available is varied from 8 to 20, the maximum tolerable interference for each PU is -110dBm.

In this paper, the parameters of ACO algorithm are defined as: the population size of ants is form 10 to 30; the probability q_0 is set to 0.01; the initial pheromone value $\tau_0=0.01$; the evaporation coefficient of pheromone $\rho=0.8$; the constant $\alpha=0.8$; the maximum number of iterations is 100.

B. Performance Evaluation and Comparsion

In order to evaluate the performance of the proposed EACO algorithm on the optimization problem (8), we compare it with two schemes defined in optimization problem (2) and (5): only consider the protection requirement for PUs and only consider the SINR requirement of CRUs.

First of all, the objective function values attained in each iteration based on different population size of ants are plotted in Fig.2. We can see that the objective function values obtained by EACO channel assignment algorithm after 100 iterations are different with the number of ant colony varying. It illuminates that the performances of algorithms are basically reached the same level when population size of ants is 30 and 40 in three different environments, and meanwhile, the performance is poor when population size of ants is 20. As stated previously, we choose the 30 as the appropriate population size of ants for it has lower computational complexity and acceptable performance.

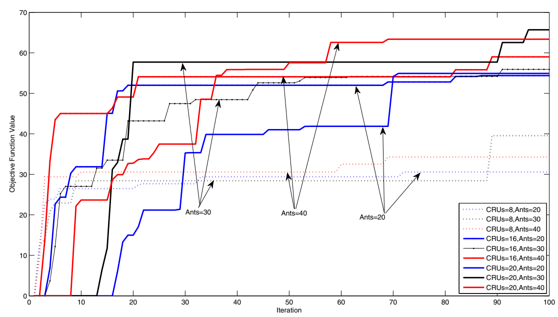

Figure 2. The convergence of EACO algorithm with different population size of ants

The Fig.3, Fig.4 and Fig.5 demonstrate the contrast between our channel assignment algorithm and other algorithm in protecting PUs, guaranteeing CRUs SINR and achieving system throughput. The proposed EACO channel assignment algorithm performs better than the algorithm which only consider CRUs(CRU algorithm) but worse than the algorithm which only consider PUs(PU algorithm) in protecting PUs aspect, and meanwhile, better than PU algorithm but worse than CRU algorithm in protecting CRUs aspect. Even though, the proposed EACO channel assignment algorithm performs the best in the system throughput aspect in Fig.5 which indicates it can take into account the protection of both PUs and CRUs and achieve optimal performance.

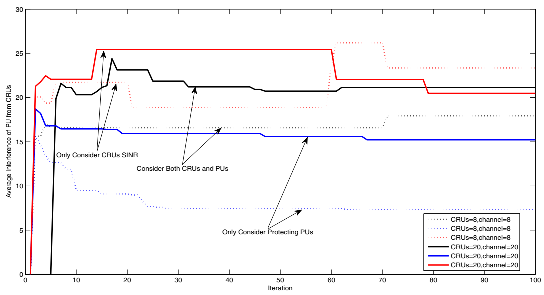

Figure 3. The curve of PUs interference in three schemes

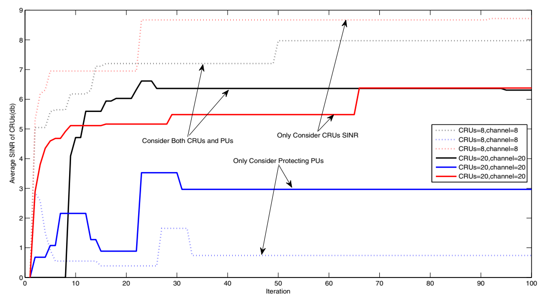

Figure 4. The curve of CRUs SINR in three schemes

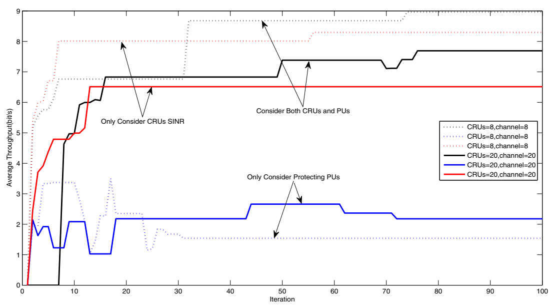

Figure 5. The curve of throughput in three schemes

V. CONCLUSION

In this paper, we considered a dynamic channel assignment problem to maximize the resource utilization in cognitive radio networks. We formulated an optimization problem with the objective of maximizing the reward of CRUs for using a channel, which also takes the interference constrain, conflict constrain and SINR constrain into account. Since the problem formulation is complex to solve, we introduce the ACO mechanism to the problem solution which has the advantages in solving multi-objective problem. Subsequently, we have proposed a dynamic channel assignment algorithm to provision cognition capability to the resource management based on EACO algorithm in CRNs, which can avoid the interference to primary users, guarantee reliable communications and adapt to the time-varying environment. The algorithm takes into account both the protection of the primary users and SINR requirement of the cognitive users. We have evaluated the network performance over the result of dynamic channel assignment by simulations. It was shown that, with the proposed management, the resulting channel allocation is high-performance.

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