Topology Reconfiguration in Cognitive Radio Networks using Ant Colony Optimization

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Abstract—**Considering the inevitable trends for heterogeneous network convergence and self-adaptation ability, Cognitive Radio Network (CRN) concept has been proposed with some essential characteristics to achieve global end-to-end goals. CRNs are composed of cognitive devices which have the capable of changing network configurations based on the dynamic environment. This capability opens up the possibility of designing flexible and dynamic topology control strategies with the purpose of opportunistically reusing idle licensed spectrum and effectively achieving data transmission. This work focuses on the problem of designing effective topology reconfiguration algorithm to offer optimal routing solutions. We analyze the topology control for CRNs finding the topology problem can be formularized as a multi-objective optimization problem. In this context, as an intelligent technology for complex multi-objective optimization, the ant colony optimization (ACO) techniques are applied in topology reconfiguration for optimal decision making in this paper. Finally, the reconfiguration algorithm is simulated, and the simulation results with detailed are analyzed.**

Keywords- cognitive radio network; topology reconfiguration; route; ant colony optimization

I. INTRODUCTION

In recent year, the huge success of wireless communication applications has caused the increased demand in spectrum resource management. The concept of cognitive radio (CR) was firstly proposed for tackling the challenging issues stemming from the radio resource limitations through its capability of awareness, learning and adapting [1]. CR technologies mainly focus on the spectrum usage in the wireless network, such as spectrum sensing, dynamic spectrum access and dynamic spectrum sharing. The devices which have the cognitive capabilities are combined to create the cognitive radio networks (CRNs) as the solutions for addressing the limited spectrum availability and the inefficiency in the spectrum usage [2]. CRNs manage both the spectrum resource and the network status through the CR capabilities and their own capabilities such as autonomic computing and self-management [3]. However, the recent progress in radio communication not only offers more flexible network services but also makes CRNs have a trend towards increasingly complex, heterogeneous, and dynamic [4]. Given that future data transmission will have to face multiple radio access standards and complex spectrum allocation situations, topology reconfiguration has emerged as a key technological enabler for supporting transmission among heterogeneous networks, adapting the time-varying environment and managing the joint radio resource across different spectrum bands. In this context, the effective topology reconfiguration solutions must be integrated into CRN so that new challenges can be addressed and solved, while taking the unique properties of the cognitive environment into account.

Topology reconfiguration as a large-scale reconfiguration is studied to guarantee the information transmission in the dynamic cognitive environment. The focus of the present paper is on a particular solution to the problem of topology reconfiguration which considers the link quality, the bandwidth allocation for the transmission as well as the route reparation to treat the unpredictable route failures. However, the research is targeted to specific multi-objective optimization problem. In this work, we show how ant colony optimization (ACO) algorithm can be used to the optimization problem of topology reconfiguration in CRN. The characteristics of ACO algorithms, such as parallel computation, self-organization and positive feedback, can help reconfiguration to achieve the multi-objective optimization, and moreover, get the global optimization solution.

The remainder of the paper is organized as follows. Section II describes related work on topology reconfiguration in CRN. In section III, a system overview including scenarios description and problem formulation is given. The ant system and enhanced ACO algorithm for topology reconfiguration are introduced in section IV. Simulation results of the algorithm are investigated in Section V. Finally, the paper is concluded in Section VI.

II. RELATED WORK

In this section, we describe and discuss related work on reconfiguration and topology reconfiguration. Even though the topology reconfiguration is essential for many the cognitive reconfiguration algorithms, limited work have been done in the development of algorithm that dynamically manage the topologies.

The reconfiguration is introduced in CRN as an essential characteristic for it can realize interoperability between heterogeneous networks, make full use of radio resources and adapt to the dynamic environment. The reconfiguration concept is also the basis for several research activities and projects [5] such as E^2R (End-to-End Reconfigurability) project and E^3 (End-to-End Efficiency) project which aim to design, develop, prototype and showcase solutions to guarantee interoperability and flexibility between existing system and future wireless systems. Originally, the researches of reconfiguration focus on making the terminals and the network devices in CRN reconfigurable to select the best configuration intelligently to adapt the environment conditions [3], which can be categorized as the small-scale reconfiguration. Most of the researches have focused on this kind of small-scale reconfiguration [6-8], but the scope of reconfiguration needs further scale-up in order to convergence the heterogeneous networks, support the multi-standard mobile system and manage the radio resource.

Only very recently, the research community has started realizing the potentials of the topology reconfiguration which can enable a wide range of high-quality data transmission in CRN. In [9], the authors provide an overview of the research in the field of topology for CRNs, proposing Cognitive Topology Control (PCTC) to predict the available duration of links. Based on the link prediction, PCTC constructs a reliable topology which is aimed at improving network performance. However, these researches involve in a complex computational process which need a more intelligent computational method to simplify.

Finally, some recent publications propose the usage of artificial intelligence techniques for topology reconfiguration in CRN. In a few works [10-12], the ant colony algorithm has been proposed for routing finding in a CRN context. These proposals, however, are targeted to search the appropriate route with the basic function of artificial ant directly, neglecting the global optimization of the topology. To design more robust and scalable topology reconfiguration algorithm for CRN and take into account the efficiency of optimization, we introduce ACO computational process to the topology reconfiguration problem solving.

III. SYSTEM OVERVIEW

We consider a system containing multiple heterogeneous CRNs with a certain number of cognitive users, primary users (PU) and channel resource, where the quantities of them vary dynamically based on the number of contending users and available vacant channels. Our objective is managing and reconfiguring the topology to maximize the quality of all the transmissions over all channels, meanwhile, satisfy the users application requirements and guarantee the system performance. In this context, the system is analyzed subject to the following constraints:

Constraint 1. 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, which lead to instability of the topology.

Constraint 2. The set of idle channels which are not utilized by primary users can be allocated to cognitive users to use.

Constraint 3. A cognitive receiver/transmitter cannot receive/transmit with more than one transmitter/receiver.

Constraint 4. The cognitive users cannot interference the transmission of the primary user.

In this context, the problem of topology reconfiguration in CRNs targets the creation and the maintenance paths based on both the varying environment from the different RATs and the spectrum to be used on each link of the path.

A. Topology Reconfiguration Sceniros

To set the stage for our analysis, we first describe three scenarios for topology reconfiguration: first, the case of reconfiguration in dissimilar network environment when the user accesses the different RAT for achieving preferable system performance; second, the case of reconfiguration in unpredictable node damage situation when some specific nodes are unusable; third, the case of reconfiguration in the channel occupation situation when a primary user suddenly appears.

1) Environmental alteration: topology reconfiguration achieves self-adaptation

Figure 1 depicts a situation where a user accesses the appropriate RAT, which causes the modification of topology along with the radio environment alteration. In such a situation, the topology reconfiguration effects on all nodes to find the suitable transmission link which can reflect the adaptation of the environment and the protection of the data transmission.

2) Unusable network nodes: topology reconfiguration achieves self-healing

Figure 2 shows the situation where a CRN has to find another topology arrangement when some nodes are unusable in inchoative data link. In these situations, the nodes which locate in front of the unusable nodes need to find another suitable route according to the failure message of the data transmission.

3) Primary user appearance: topology reconfiguration achieves self-management

Figure 3 illustrates the situation where the sudden appearance of the primary user blocks the data transmission among the cognitive users. In these situations, the available channel resource for cognitive users needs to be reallocated which can ensure the transmission to proceed.

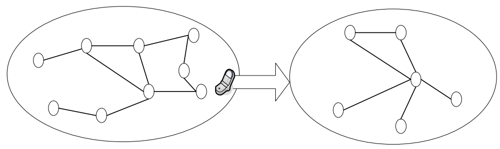

Figure 1. Topology reconfiguration achieves self-adaptation when users access another heterogeneous network

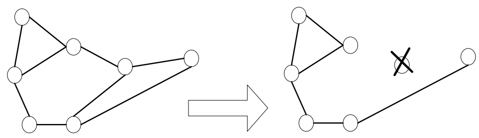

Figure 2. Topology reconfiguration achieves self-healing when some nodes are unusable

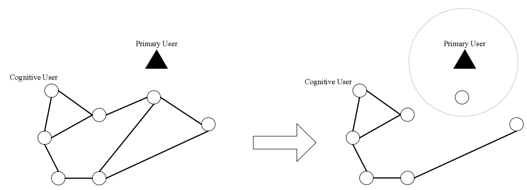

Figure 3. Topology reconfiguration achieves self-managemen when the primary user appears and occupies the channel resource

B. Problem Formulation

As introduced before, designing effective topology reconfiguration solutions requires cooperation between the link maintenance and the spectrum management functionalities such that the link maintenance module can be aware of the surrounding environmental changes to take more appropriate reconfiguration decision.

In this context, topology reconfiguration principally considers two aspects including the link quality and the channel allocation. Before formulating the problem, we define T as the topology matrix with binary entries $t_{ij} \in \{0,1\}$ as follows:

$$t_{ij} = \begin{cases} 1 & , \textit{if node } i \textit{ transmits data to node } i \\ 0 & , \textit{otherwise} \end{cases} \tag{1}$$

The quality of the link associated with link (i, j) depends on the link capacity and subjects to the expenses restriction and QoS restriction. The link capacity is given by:

$$C = \sum_{i=1}^{n} \sum_{\substack{j=1 \\ j \neq i}}^{n} t_{ij} b_{ij} \log(1 + \frac{p_{ij}}{\mu}) \tag{2}$$

Where b_{ij} is the bandwidth, μ is the ambient Gaussian noise density, n is the number of the nodes and p_{ij} is the transmit power of the transmitter which can be given by:

$$p_{ij} = P \cdot d_{ij}^{-k} \tag{3}$$

Where P is the power spectral density, k is the path loss index and d_{ij} is the distance between node i and node j. Meanwhile, to examine and weigh expenses restriction we can calculate the expenses equation as follows:

$$h_e = \sum_{i=1}^{n} \sum_{\substack{j=1 \\ j \neq i}}^{n} e_{ij} t_{ij} \tag{4}$$

Where e_{ij} is the expense between node i and node j. Then the QoS expression for measuring QoS restriction can be formulated as follows:

$$h_{qos} = \sum_{i=1}^{n} \sum_{\substack{j=1 \\ j \neq i}}^{n} f(t_{ij} b_{ij} - b_{QoS}) + f(l_{QoS} - \sum \sum l_{ij} t_{ij}) \tag{5}$$

Where b_{QoS} is the bandwidth of QoS requirements, l_{QoS} is the latency of the QoS requirements, l_{ij} is the latency of the transmission between node i and node j and $f(.)$ is defined as follows:

$$f(u) = \begin{cases} u & , \textit{if } u \geq 0 \\ 0 & , \textit{if } u < 0 \end{cases} \tag{6}$$

To maximize the link capacity, reduce the cost and guarantee the QoS requirement, the optimization problem of topology reconfiguration can be given as follows:

$$\begin{aligned} \max \quad & \sum_{i=1}^{n} \sum_{\substack{j=1 \\ j \neq i}}^{n} t_{ij} b_{ij} \log(1 + \frac{p_{ij}}{\mu}) - \sum_{i=1}^{n} \sum_{\substack{j=1 \\ j \neq i}}^{n} e_{ij} t_{ij} \\ & + \sum_{i=1}^{n} \sum_{\substack{j=1 \\ j \neq i}}^{n} f(t_{ij} b_{ij} - b_{QoS}) + f(l_{QoS} - \sum_{i=1}^{n} \sum_{\substack{j=1 \\ j \neq i}}^{n} l_{ij} t_{ij}) \end{aligned} \tag{7}$$

Meanwhile, the optimization problem also takes the appearance of primary user into account which can be described as a constraint condition as follows:

$$\begin{aligned} & \sum_{k} \sum_{j} \sum_{i} [g(t_{ij} \alpha_{ik} d_{ik}) - D] \geq 0 \\ & \textit{where} \quad g(u) = \begin{cases} \infty & , \textit{if} \quad u = 0 \\ 0 & , \textit{otherwise} \end{cases} \\ & \alpha_{ik} = \begin{cases} 1 & , \textit{if PU } k \textit{ is active in the vicinity of node } i \\ 0 & , \textit{otherwise} \end{cases} \end{aligned} \tag{8}$$

Where the binary entries $\alpha_{ik} \in \{0,1\}$ presents the location and activation of primary user, and D is the protection distance for primary user transmission. The optimization problem introduces the constraint condition with respect to primary user based on equation (7) as follows:

$$\begin{aligned} \max \quad & \sum_{i=1}^{n} \sum_{\substack{j=1 \\ j \neq i}}^{n} t_{ij} b_{ij} \log(1 + \frac{p_{ij}}{\mu}) - \sum_{i=1}^{n} \sum_{\substack{j=1 \\ j \neq i}}^{n} e_{ij} t_{ij} \\ & + \sum_{i=1}^{n} \sum_{\substack{j=1 \\ j \neq i}}^{n} f(t_{ij} b_{ij} - b_{QoS}) + f(l_{QoS} - \sum_{i=1}^{n} \sum_{\substack{j=1 \\ j \neq i}}^{n} l_{ij} t_{ij}) \\ s.t \quad & \sum_{k} \sum_{j} \sum_{i} [g(t_{ij} \alpha_{ik} d_{ik}) - D] \geq 0 \end{aligned} \tag{9}$$

Where b_{ij}, p_{ij}, e_{ij}, l_{ij}, α_{ik} are all constants and t_{ij} is the optimization variable. The objective is finding the optimal topology matrix T through solving the optimization problem.

IV. THE ACO MODEL FOR TOPOLOGY RECONFIGURATION

In ACO, the artificial ants build solution through moving from one vertex to another in the constraint graph. ACO algorithms have already got some achievements in solving combinatorial optimization problems for their advantages. Moreover, the characteristics of ACO algorithms, such as parallel computation, self-organization and positive feedback, can help cognitive topology reconfiguration to achieve multi-objective optimization, self-adaptation and learning capability in order to get a global optimization [13].

A. Enhanced Ant Colony Algorithm

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:

$$p_{ij}^{a} = \begin{cases} \dfrac{\tau(i,j)}{\sum_{s \in C} \tau(i,s)} & , if \quad q \geq q_0 \\ p(\arg\max(\tau(i,j))) & , otherwise \end{cases} \tag{10}$$

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:

$$\tau_{ij}(t+1) = (1-\rho)\cdot\tau_{ij}(t) + \rho\cdot\tau_0 \tag{11}$$

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:

$$\tau_{ij} \leftarrow (1-\alpha)\cdot\tau_{ij} + \alpha\cdot\frac{1}{G_{\max}} \tag{12}$$

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

Moreover, the mutation mechanism can adjust several elements of the local best solution according to the definite principle which can enlarge the searching range so that the optimization solution will not fall into the locally optimal solution. We assume the path which an artificial ant has passed as a vertex set $v = \{v_1, v_2, \ldots, v_i\}$. The mutation operation is changing several vertexes of the vertex set with the principle:

$$v_i' = \begin{cases} v_i + r\max\{u_i - v_i, v_i - l_i\} & ,if \quad p > p_m \\ v_i & ,otherwise \end{cases} \tag{13}$$

Where $p_m \in [0,1]$ is the default mutation probability, $p \in [0,1]$ and $r \in [-1,1]$ are random numbers, u_i and l_i are the upper bound and lower bound of v_i respectively. After the mutation operation, the mutation vertex sets v' is got which will be compared with the original vertex sets v to determine one of them as the best local solution.

B. EACO Topology Reconfiguration

In this paper, the topology reconfiguration algorithm is accomplished via an enhanced ACO algorithm — EACO algorithm to get effective optimization solution and improves the performance of ACO. The implementation of EMACO topology reconfiguration algorithm is described as follows:

Topology Reconfiguration Algorithm based on EACO

Step 1: Initialization: Initialize the parameters, including the number of iterations, the number of cognitive users and primary users, the population of the ant colony, the evaporation rate, the initial value of the pheromone, ambient Gaussian noise density and the power spectral density. The ants are distributed on the nodes randomly.

Step 2: Searching process: The ants travel among the nodes according to the probability defined in equation (10) and result a group of potential topology arrangements as the solution set.

Step 3: Local optimization procedure: Compare the obtained topology arrangements based on the objective function described in equation (9), and select the optimum topology arrangement, which can maximize the objective function, as the local best solution in this iteration.

Step 4: Mutation process: Calculate the mutated solution following the mutation mechanism described in the equation (13). After comparing the mutated solution and quondam solution, update the local solution as the topology arrangement which achieve larger value of objective function in equation (9). Meanwhile, update the pheromone of the local optimization solution based on equation (11).

Step 5: Global optimization procedure: Compare the local optimization solution in each iteration and choose the best one as the globally optimal solution. Update the pheromone of the global optimization solution based on equation (12).

Step 6: Reconfiguration consequence: When the stopping condition is satisfied, the topology reconfiguration operation manages and regulates topology according to the globally optimal solution. Else, return to Step 2.

V. PERFORMANCE EVALUATION

In this section, the proposed scheme is evaluated via computer simulations. In the simulation, we consider the nodes in a 100x100 area with a random location. We assume the bandwidth, the cost of transmission and the latency allocated on each link are different which are defined in matrix respectively, and meanwhile, the path loss index and the power spectral density are identical for all links.

In the simulation, we evaluate the performance of the topology reconfiguration algorithm through comparing with the static topology (adopts the shortest path algorithm in routing finding) in routing searching based on 4 different pairs of source-destination nodes.

Fig.4 shows detailed convergence process of the EACO topology reconfiguration algorithm with the varying ant colony number. Through simulation, it is shown that the algorithm convergence rate will be influenced by the amount of ant colony: the algorithm converges to the optimal value lagging others when the ant number=11.

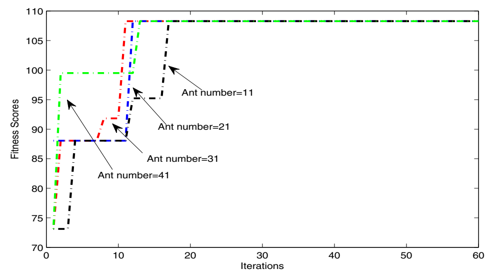

Figure 4. Convergence process in iterations with different number of ants

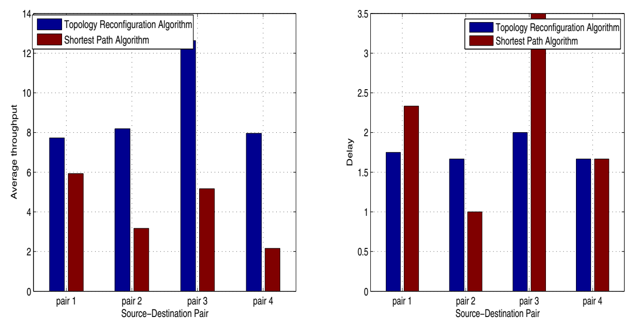

Figure 5. Topology reconfiguration vs. regular topology in routing searching

Fig.5, Fig.6 and Fig.7 demonstrate the topology reconfiguration algorithm compared to static topology arrangement with respect to the average throughput and time delay under three situations in the defined environment respectively: the ordinary situation, the unusable network nodes situation and the primary user appearance situation. In Fig.5, it can be seen that in the static topology the route quality of the defined source and destination are under the control of the environment and adopt no measures. Meanwhile, the topology reconfiguration operation can adjust the path according to the effect on network performance bringing from the dynamic environment. It is worth mentioning that the reconfiguration algorithm has the balance between throughput and time delay in achieving advanced system performance which is represented in Fig.5 (the delay of source-destination pair 2 is extended while the average throughput is maintained at a high level).

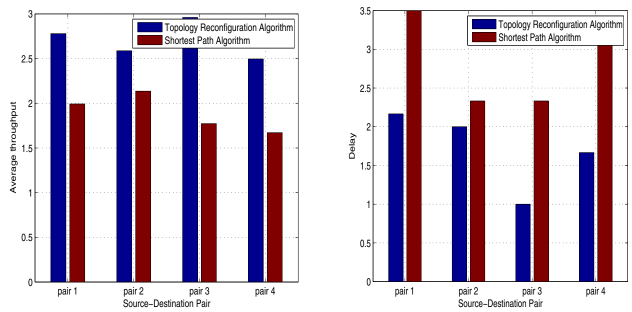

Figure 6. Topology reconfiguration vs. regular topology in unusable network nodes sceniro

As depicted in these figures, topology reconfiguration algorithm increases the effectiveness of the data transmission a lot relative to static topology arrangement through controlling and choosing the route flexibly and adaptively. In Fig.7, the shortest path algorithm is failed in routing finding under the static topology arrangement when the primary users appear to influence the channel assignment (the average throughput of source-destination pair 3 indicates the data transmission is interrupted when primary users occupy the channel).

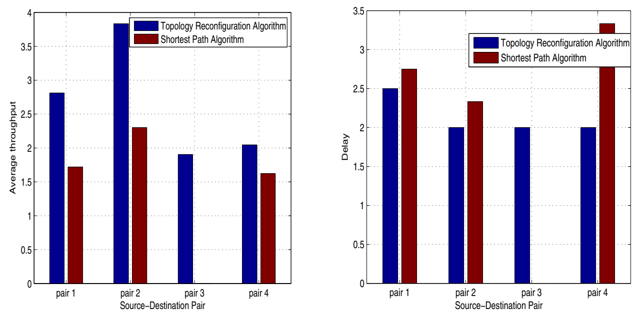

Figure 7. Topology reconfiguration vs. regular topology in primary user appearance sceniro

VI. CONCLUSION

Cognitive topology reconfiguration technology will have significant impact on data transmission and network performance in CRNs. We formulated an optimization problem with the objective of maximizing the link quality and transmission performance, which also takes the interference constrain, cost constrain and QoS restriction in 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 topology reconfiguration algorithm to provision cognition capability to the topology management based on EACO mechanism in CRNs, which can avoid the interference to primary users, maintain the route and adapt to the time-varying environment. The algorithm takes into account both the activation of the primary users and the quality of the transmission. We have evaluated the transmission performance over the result of topology reconfiguration by simulations. It was shown that, with the proposed topology management, the resulting network topology is simpler and high-performance.

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