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On k-channel connectivity in cognitive radio networks through channel assignment

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ABSTRACT

Cognitive radio network (CRN), forces the secondary users (SUs) to vacate the channel and switch to other unused channel when a primary user (PU) starts using its channel. Thus, the channels available for an SU vary over time depending on PU's activities. This temporal variation in channel availability can cause network partitioning, if there is no other available channel is present in the network which poses challenge among researchers "how to ensure robust connectivity in CRN?" A topology generated by a channel assignment is called k-channel connected if the nodes in the remaining topology can be connected when any set of $(k-1)$ channels from channel set have been reclaimed by PUs and become unavailable to SUs. To the best of our knowledge, this is the first work on k-channel connectivity in CRN. We proved that this problem is NP-hard using c-colorability problem. To address this problem, we first present a polynomial time centralized algorithm, called Centralized k-channel Connected Spanning Subgraph ($CCSS_k$), which use $O(k^2 \log n)$ approximation algorithm to find minimum cost subset k-connected subgraph problem as a subroutine. Based on $CCSS_k$, we propose a distributed algorithm, called Distributed k-channel Connected Spanning Subgraph ($DCSS_k$) with message complexity $O(2n + n(1+\Delta) + n\log^2 n)$, where n denotes the number of nodes and Δ is the maximum node degree in topology under maximum transmission power. Through simulations it has be observed that the proposed algorithms are able to preserve minimum energy paths and reduce the number of required channels efficiently to address the k-channel connected topology control problem. Simulation results also show that the $CCSS_k$ and $DCSS_k$ reduce the number of links by 55% and 45% respectively.

1. Introduction

According to FCC report, substantial portions of licensed spectrum are not completely utilized by licensed users also called primary users (PUs). This low utilized spectrum can be used to mitigate the spectrum scarcity problem in next generation wireless network and can fulfill the ever-increasing demand of spectrum using opportunistic spectrum access (OSA) paradigm. This requires an advance communication technology called cognitive radio network (CRN) to implement OSA. The concept of cognitive radio [1] implements techniques that provides capability to access the available licensed channels opportunistically. In CRN, secondary users (SUs) access channels along with primary users (PUs). But, SUs are allowed to utilize the channels after validating when PUs are idle and not accessing their licensed channels using spectrum sensing [2,3]. Thus, CRN enables SUs to access the underutilized spectrum which are licensed to PUs by ensuring no interference to the PUs' transmissions. A pair of communicating SUs must vacate the channel and have to switch their transmissions over other available channel, just after a PU reclaims the channel in use with SUs.

Multiple transmissions of secondary network may be affected due to arrival of PUs on their licensed channels. This results multiple SUs to terminate their transmissions or move over other available channels (if possible). Sometimes, it leads to network partitioning if there is no alternative channel available when a PU arrives. So, if two SUs in CRN are communicating using available channel, and respective PU arrives on its own channel, it may cause CRN to be partitioned and network may be disconnected(if other alternative channels are not available). This temporal variations in channel availability poses a research challenge for assuring connectivity of SUs at the time of multiple PUs' arrivals. To ensure the connectivity of CRN, it is required to assign available channels to the SUs in such a way that it preserves connectivity when a set of channels are re-claimed by PUs. To address the connectivity issue in CRN, we define the notion of k-channel connectivity. A network is called k-channel connected if remaining network preserve connectivity when any set of $(k-1)$ channels is reclaimed by PUs. So, the k-channel connectivity is a extremely important in CRNs to generate PUs' dynamics tolerant

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topology. In our proposed algorithms, k is a network parameter that is a positive integer. The value of k defines the robustness against channels reclamation by PUs. For a given CRN, if the value of k is larger this means the network topology is more potent and robust against PUs' channels reclamation and remains connected on larger number of channels reclamation due to PUs arrival on their licensed channels.

Most of the reported works in the field of CRN mainly address the issues related to spectrum sensing [4–6] and spectrum hand-off [7] to avoid the interference with PUs. The issues related to connectivity in traditional wireless networks has been address potentially in [8–11]. The works reported in [8] address 1-connectivity whereas [9] [10] [11] investigate the issues related to k-connectivity. But none of the reported works is suitable for CRN due its divergence form traditional wireless network. First, many SUs transmissions may be affected, if they are transmitting on the channels that are reclaimed by PUs since the interference range of a PU is usually larger than that of an SU [12]. Second, it demands significant time for spectrum sensing, neighbor discovery and shifting ongoing transmissions to desired channels. This leads to unacceptable packet loss or considerable delay in packet delivery [13]. Third, the channel availability in CRN varies over time due to PUs' activities and it is very difficult to predict accurately in advance that when a PU will appear on its channel [14], hence it is hard to address connectivity problem. Thus, a challenging question arises that how to ensure connectivity in CRN when channels are reclaimed by PUs? To address connectivity in CRN, we introduce a novel term called k-channel connectivity. Specifically, the k-channel connectivity in CRN is to assign channels to SUs such that the remaining network is stay connected whenever any set of $(k-1)$ channels has been reclaimed by PUs. We will use the terms "SU" and "node" synonymously.

In addition to avoiding interference to PUs, interference among SUs' transmissions should be also be avoided. In particular, when the nearby SUs access the same channel, it introduces interference among communicating SUs that degrades the system performances. Therefore, a novel channel assignment algorithm is necessary to avoid conflict among SUs' transmissions, called conflict free channel assignment. Our goal is to achieve k-channel connected and conflict-free topology using minimum number of channels. For conflict free topology, the conflicting nodes must be assigned with different channels. To fulfill the k-channel connectivity constraint, the underlying graph must be at least k-vertex connected (k-connected). The low power level to nodes may not achieve desired k-connectivity and high power level may increase the number of channels to achieve desired properties in generated topology as well as may cause interference to PUs' transmissions. So, it is required to assign optimal power level to each node [15]. Since both constraints affect the number of channels so the channel assignment and power assignment to each node are the key factors and they should be considered carefully in designing algorithms [16].

Since our main objective is to minimize the number of channels with satisfying both the constraints, the channel re-usability is highly desirable that can be achieved by minimizing power level of nodes. To minimize power level, the topology has to preserve minimum-energy path between every pair of nodes. So, the problem to construct a k-channel connected and conflict free topology using minimum number of channels by preserving minimum power paths is called k-channel connected topology control problem. Among the above goals, the k-channel connectivity in CRN is very challenging and is different that simple constructing k-connected sub graph of given CRN. In order to fulfill conflict-free property, every color class form an independent set in constructed topolog after channel assignment phase. When a PU reclaims a channel, a subset of corresponding color class SUs are removed from networks and may disconnect the remaining network. So, only k-connected network is not sufficient to achieve the solution of k-channel connected topology control problem [17].

1.1. Contributions

To address the k-channel connected topology control problem, we propose a centralized algorithm called Centralized k-channel Connected Spanning Subgraph ($CCSS_k$), which combines both power assignment and channel assignment. First, we build a topology robust against interruption of PUs arrival. We also control the transmission power of every node to create a topology that preserves minimum energy path between every pair of nodes in order to minimize the energy consumption in CRN. Next, we use the concept of graph coloring algorithm in channel assignment to achieve conflict free topology. We consider the PU occupancy probabilities of channels during channels assignment to SUs in channel assignment phase to improve networks stability. Based on $CCSS_k$, we propose a distributed algorithm, called Distributed k-channel Connected Spanning Subgraph ($DCSS_k$) to address the k-channel connected topology control problem.

The rest of the paper is organized as follows. First, we summarize the related work in Section 2. Next, we present the system model and problem definition in Section 3. Then, we describe our proposed algorithms $CCSS_k$ and $DCSS_k$ in Sections 4 and 5 respectively. Finally, we present various simulation results and conclude the paper in Sections 6 and 7 respectively.

2. Related work

Connectivity is very important property of wireless network. Without connectivity network is out of service and a nodes can not communicate with other nodes. The complexity of connectivity issues have been well studied for traditional wireless networks [8,18–20]. Because of different nature of CRN from traditional wireless network, the results are not applicable for CRNs. There are few works that discuss about the connectivity in CRNs [21,22]. Ren et al. address the connectivity in CRN in [21,23] by using continuum percolation theory. They characterize the connectivity analytically and divide the cognitive radio network into connected and disconnected regions based on the density of SUs and the density of PUs. They studied the impacts of different factors such as SU's transmission power, SU's average degree etc. on connectivity. In [24], Ao et al. have studied the relationship among connectivity, interference, latency and other system parameters of the heterogeneous cognitive radio network in underlay approach. In [25], Li et al. have studied the network connectivity and analyzed the effects of different parameters using the concept of graph coloring. They used different labeling rules to explore the connectivity and its impact on it. In [26], Lu et al. have introduced the concept of Cognitive Radio Graph Model (CRGM) with continuum percolation and studied the effect of the number of channels and different activities of PUs over the network connectivity. The connectivity of cooperative SUs in cognitive radio network is studied in [22] from a percolation-based perspective. In literature, several works have been reported to deal with connectivity issues through controlling topology [27–29]. The topology control addressing the connectivity is assigning the channels to the links and transmission power to nodes in order to eliminate the chance of network partitioning at time of PUs arrival. Zhao et al. designed a channel assignment algorithm to achieve network connectivity through channel assignment in [27]. This work focuses on preserving connectivity with minimizing the channel interference when any single channel becomes unavailable due to reclaimed by PU. To improve the network performance channel interference must be minimized. However, the topologies generated by algorithms proposed in [27], are not fully-efficient because