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Survey Paper on Topology Control in Cognitive Radio Networks

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***Abstract*— In cognitive radio networks (CRN's), secondary users must vacate the spectrum when it is reclaimed by the primary users. The author in paper [1] gives us brief view of the topology control problem in CRNs with the objective of minimizing the number of required channels while satisfying conflict-free and bi –channel-connectivity constraints. In paper [2] the author has introduced a new definition of g-bi-connectivity for designing fault tolerant topologies for CRNs. In paper [3], the author has considered a SIC-based topology control framework for exploiting the potential benefits of underlay paradigm in CRN's. In order to achieve the objective, the author has proposed both centralized topology control algorithm and distributed topology control algorithm. The main aim of these algorithms is to minimize the number of required channels while satisfying conflict-free and bi-channel connectivity constraints. The three technologies are compared in the form of a table.**

***Index Terms*— Successive Interference cancellation, bi-channel-connectivity, cognitive radio networks, topology control, fault-tolerance, bi-channel-connectivity.**

I. INTRODUCTION

Topology control is important to maintain the connectivity of cognitive radio networks. Cognitive Radio Network is a form of wireless communication in which a transceiver can intelligently detect which communication channels are in use and which are not, and instantly move into vacant channel while avoiding occupied channels. In paper [1] the author has considered connectivity and bi-channel conflict free topology as a main parameter to maintain the connectivity of different CRNs without successive interference cancellation. There are two types of users: 1) Primary Users (licensed users of the spectrum) 2) Secondary Users (unlicensed users of the spectrum). The secondary users have to vacate the spectrum on the demand of the primary users. In this situation the secondary users have to move the neighboring free spectrum because the secondary users may interfere with the transmission of the primary users. As a result of this shifting there is loss of data and delay in transmitting the data between the affected secondary users. To solve this problem, the author has proposed two algorithms, i.e. Centralized Topology Control Algorithm and Distributed Topology Control Algorithm. The author combines power control and channel assignment to construct a bi-channel and conflict- free topology using the minimum number of channels. Bi- Connectivity is ensured only if the CRN's remains connected when any channel currently being used by an SU is occupied by the PU's.

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In this paper the author conveys that the derived topology can maintain connectivity in the event of any single channel interruption by PU's.

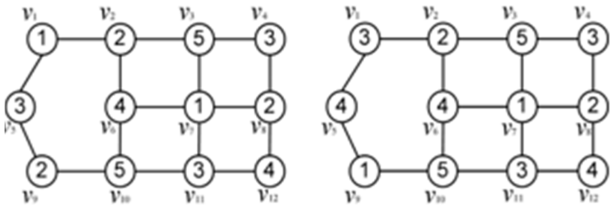
In this paper [2], the author conveys that Bi-connectivity is a basic requirement for configure fault tolerant topologies in wireless networks. Fault tolerance is the property that enables a system to continue operating properly in the event of the failure of (one or more faults within) some of its components inside a network. In this paper the author has introduced generalized bi-connectivity (g-bi-connectivity). The definition of g-bi-connectivity is that the CRN still remains connected when any one of the two events occurs: (i) any node fails; (ii) any channel becomes unavailable.

The main aim of the author in this paper is to minimize the maximum transmission power of the users and the number of the channels required by building a g-bi-connected network.

In paper [3], the author has used topology control with successive interference cancelation (SIC) in cognitive radio network. The author explains to us clearly that both the PU's and SU's can use same spectrum without any interference, SU's are equipped with SIC avoid the interference from SU's. The author has proposed both Centralized SIC-based topology control algorithm and Distributed SIC-based topology control algorithm to avoid the unpredictable activities of PU's and the potential interference between SU's. The author integrates power control with channel assignment to construct a bi-channel-connected and conflict-free CRN with the fewest required channels.

II. METHODOLOGY

In paper [1], the author mainly focuses on bi-connectivity of the network to avoid the partition of the network which results in packet loss or data delay for SU's. Bi-connectivity is a basic requirement for designing fault tolerant topologies in wireless networks. Fault Tolerant is a property that enables a network to continue operate or remain connected in the event of the failure of node or link. Bi-connectivity is mainly concerned with node/link failure and thus not suitable to CRNs because the available channels of SU's change over time due to unpredictable activities of PUs. Therefore, the author has introduced a new definition of generalized-bi-connectivity (g-bi-connectivity). A CRN is said to be g-bi- connected if the remaining network is still connected when any one of the two events occurs i.e., when any node fails or when any channel becomes unavailable.



(a) (b)

(a) not tolerant to failure of channel 2, (b) tolerant to failure of any channel

Figure 1. Two topologies of CRNs [2]

In Fig. 1 suppose that all links are bi-directed and the number associated on a node (SU) is the channel assigned to the node for communications. Clearly, the topology in Fig. 1(a) is bi-connected. However, disabling channel 2 causes failure of nodes v_2, v_8 and v_9, which results in disconnection of the network. Thus, the topology in Fig. 1(a) is not tolerant to the change of channel availability.

In contrast, the topology in Fig. 1(b) can provide fault tolerance to failure of any node and any channel, i.e., the remaining network is still connected if any node fails or any channel becomes unavailable. The objective of the author is given below: Firstly is to minimize the maximum transmission power of nodes and thus maximize the lifetime of networks. Since spectrum is one of the scares resource in CRNs. CRNs are mainly designed to for the purpose of improving spectrum efficiency. Second objective is to minimize the number of channels which is used to build the g-bi-connected topologies. The author has proposed a two-stage approach which consists of power assignment stage and channel assignment stage. We assign power on each node such that the network is bi-connected with maximum power of nodes minimized in the power assignment. The author has assigned channel on each node such that the network is conflict free and finally g-bi-connected in the channel assignment,

To minimize the maximum node degree while maximizing the average node degree, a degree control process in power assignment stage is integrated. The degree control operates iteratively. Each time, the node is selected with the maximum degree and locate its longest edge. The edge is removed if the remaining network is still bi-connected. The next node with the maximum degree is selected and similar operation continues until no more edge can be removed without violating bi-connectivity of the network. For each node, we assign with the channel which is available to the node, such that the following two conditions are satisfied: i) the network must be conflict-free, ii) for so-far-assigned nodes, disabling any channel will leave the remaining network connected. It is to ensure the final g-bi-connectivity of connected network. The author also proposed topology recovery algorithm, i.e., when a node is joining or leaving the network it still grantees g-bi-connectivity in topology change of node-join and node-leave by an efficient algorithm that re-computes and incrementally computes g-bi-connectivity.

The main aim of the author in paper [2] is to achieve bi-channel connectivity with topology control in cognitive radio networks. Topology control is a technique used in distributed computing to alter the underlying network to reduce the cost of the distributed algorithm. There is a collection of SU's and PU's in CRNs. When PU's request for their spectrum then SU's has to vacate the spectrum, thus it leads to partition in the network resulting in packet loss or packet delay for the SU's. To maintain the connectivity of the CRN, topology control is very essential. There are two challenges faced in controlling the topology. First, due to the large interference region of PUs, the emergence of an active PU is likely to affect multiple SUs transmitting on the same channel and located in the interference region of the PU or multiple SUs will be removed simultaneously upon the appearance of a PU in the CRN. Second, the channel availability in the CRN varies over time because of the activity of PUs. To solve the problem, the author has proposed centralized topology control algorithm and distributed topology control algorithm. There are two major draw backs in these two algorithm i.e., firstly during the channel assignment, connectivity test has to be performed on the entire network every time when assigning a channel c to an SU's, to check whether the CRN remains connected if channel c is reclaimed. Since the connectivity test is frequently performed to check the connectivity of the entire network, computational complexity is very high and it is not easy to implement this test in distributed systems. Secondly, the approach cannot effectively reduce the number of required channel.

The author of paper [3] propose two algorithms to control the topology with successive interference cancellation (SIC) in CRNs. Successive Interference Cancellation is a physical layer capability that allows a receiver to decode packets that arrive simultaneously in a sequential order, particularly the strongest signal is decoded first. The main aim of the author is to control the topology and to enable the transmission of both PU's and SU's and the same spectrum without any interference. Thus, by doing this spectrum efficiency is maintained and network partitioning can be avoided. There are two deployment paradigms for PU's to share the spectrum with SU's. i) Overlay paradigm allows SUs to access parts of the licensed spectrum unutilized by PUs. ii) Underlay paradigm, SUs are allowed to transmit with PUs on the same spectrum whenever they do not cause unacceptable interference to PUs. As know we that when the PU's reclaim the spectrum which the SU's are using, the SU's has to vacate the spectrum and have to find the other available spectrum for their transmission. Thus leading partition of the CRN, resulting in packet loss or delay between affected SUs occurs.

There are three characteristics of the CRN should be taken into account when constructing such robust topologies. Firstly, when PU occupies a channel, multiple SUs have to keep silence to protect the transmission of PU. Secondly, PUs can willfully access channels at any time, which makes the available channels for SUs time varying. Moreover, it is hard for SUs to make accurate predictions of the PUs' activities. Thirdly, the SUs operating on the same channel may interfere with each other. Channel assignment is widely applied to maximize the CRN performance by reducing the interference to PUs, as well as the interference among SUs. Compared to the overlay paradigm, the underlay paradigm, where the SUs are allowed to access the spectrum if they do not disturb PUs, can further improve the spectral efficiency in the CRN. Furthermore, this paradigm enables us the opportunity to establish more robust topologies. With this paradigm, not only the interference from SUs to PUs, but also the interference from PUs to SUs should be taken into account. The above mentioned two types of interference can be avoided if the interference caused by PU's and SU's are below the threshold level. The benefits promoted by the underlay paradigm, SU's should possess the capability to cancel the interference from PU's.

The author has proposed two algorithm centralized topology control algorithm and distributed topology control algorithm. To solve the topology control problem, the author has proposed centralized topology control algorithm.

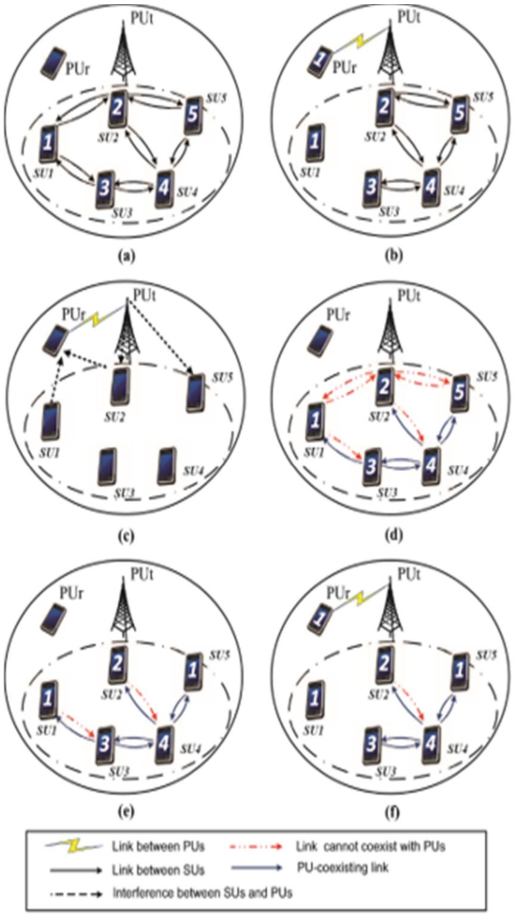


Figure. 2. Illustration of different topologies of the network, the number associated with each SU indicates the channel requested by the SU [3].

Fig. 2 to show how the algorithm can satisfy the bi-channel-connected and conflict-free constrains with less number of channels, as compared to the algorithm of overlay paradigm. Fig. 2 gives a five SUs CRN where the black solid lines present the links between SUs, and the number associated with each SU indicates the channel requested by the SU. Each SU in Fig. 2 interferes with its 1-hop and 2-hop neighbors, so they have to be assigned with different channels to avoid the interference. It is obvious that the CRN in Fig. 2(a) is bi-channel-connected and conflict-free with the overlay paradigm. The reason is that when PUs reclaim any channel, the remaining CRN can still be connected by removing all the SUs assigned with that channel.

As shown in Fig. 2(b), the CRN is connected by the interruption of PUs on channel 1. Different from the above paradigm, we consider the simultaneous transmissions of SUs with PUs. In Fig. 2(c), SU1 and SU2 disturb the transmission of PUs, respectively. Hence, when PUs reclaim their channel, their outgoing links have to be removed. Meanwhile, SU2 and SU3 are interfered by PU_t, respectively. We assume that SU2 and SU3 can firstly cancel the interference from PU_t and then decode the signal from SU4 with SIC, respectively. Accordingly, the PU-coexisting links of the CRN are denoted by the blue solid lines, while the links that cannot coexist with PUs are represented by the red dashed lines in Fig. 2(d). Next, we tailor the topology in Fig. 2(a) to Fig. 2(e) by utilizing the PU-coexisting links as the key edges.

Although the link (SU1, SU3) or (SU2, SU4) has to be taken out when PUs switch to the channel of SU1 or SU2, it has no effect on the connectivity of the remaining CRN, e.g., in Fig. 2(f), the remaining CRN is still connected with channel 1 occupied by PUs. More importantly, there are only 4 channels used by the CRN in Fig. 2(e) while 5 channels used in Fig. 2(a). As illustrated in the examples, our design philosophy is to ensure the set of the removed links is not the edge-cut set of the CRN when PUs emerge at any channel. Therefore, we place the PU-coexisting links as the key edges and key paths of the topology. In this way, we can control the unpredictable activities of PUs. In the meantime, the edges or paths between SUs in the tailored topology can be reduced and thus the number of the conflicting SUs can be reduced as well. Hence, fewer channels are required to construct the conflict-free CRN.

In distributed topology control algorithm, the first stage is neighbor discovery. Each SU *u* needs to discover its distance-2 neighbors and collect the available information between them. The stage of neighbor discovery is divided into two time slots. In the first slot, SU *u* is aware of the edges between its 1-hop neighbors by broadcasting the HELLO messages. Particularly, each SU chooses an idle channel to broadcast a HELLO message with its maximum transmission power, and the HELLO message should include the SU's ID and location information. Then, likewise, each SU broadcasts its neighbors list with its maximum transmission power in the second time slot. The neighbor list consists of the IDs and the location information of its 1-hop neighbors. Upon the received neighbor lists, each SU *u* can obtain the edges between the 2-hop neighbors so that it can build a local subgraph.

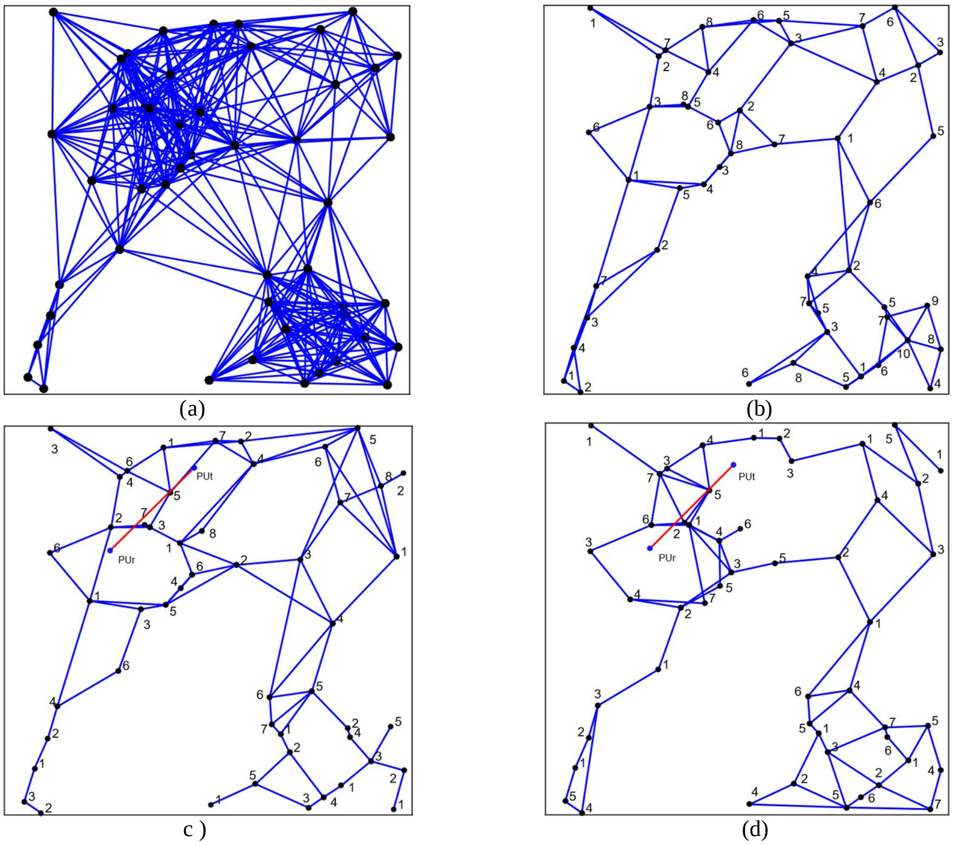
Secondly, topology construction with the local weight matrixes. Each SU tailors its local subgraph to spanning subgraph. SU firstly employs the Dijkstra's algorithm to construct a subgraph by finding the minimum power paths from it to its 2-hop neighbors and then add all the edges of the subgraph. Thirdly is power adjustment, each SU sets its 1-hop neighbors in S_u as its logical neighbors and then adjusts its transmission power to reach the furthest logical neighbor. Fourthly is channel assignment, based on the resulting subtopology S_u, distributed coloring algorithm will operate. It is easy for each SU *u* to know the conflict degree of other SUs in S_u via the information exchanges. The SU with the more conflict degree will be with the higher priority to request the channel. Particularly, SU *u* finds the channel ID (e.g., *k*) with the lowest occupancy probability. If there are no other SUs in S_u with channel *k* conflicting with it, SU *u* assigns itself with channel *k*. Then, it broadcasts the channel massage (*u*, *k*) to its neighbors in S_u. If SU *v* receives a color message (*u, k*) and *u* is the neighbor of *v*, it will mark SU *u* with channel *k*. As a result, the number of edges between SUs has been reduced due to the simultaneous transmissions of SUs with Pus thus leading to the reduction of the conflict neighbors of Sus. Thus the required channels are also decreased drastically which helps in efficient use of the spectrum.

III. SIMULATION RESULT

The performance of our centralized and distributed topology control algorithms (C-TCSIC and D-TCSIC) is evaluated on random topologies via extensive simulations and compare them with the centralized and distributed algorithms. All SUs have to vacate the channel, when PUs occupy a channel,. We consider a network in a 1000 x 1000 m^2 area, where the locations of SUs and Pus are generated randomly. Note that the distance between Put and PUr ranges from 0 to max((PPU=_PU)1=_; 1000) m with $\alpha = 4$. Moreover, we set both PU's and SUs' receive sensitivity, i.e β_{PU} and β as =-80dBm. In addition, the occupancy probabilities of the PUs are randomly generated while satisfying $\sum_{i=1}^{K} Pi = 1$. The transmission power of PUt , PPU, ranges from 256mW to 51.2W. The maximum transmission power of each SU, Pmax, is 256 mW and the corresponding maximum transmission range Rmax is 400m. Results are averaged over 400 simulation runs.

At first, we give a 50 SUs network for illustration in Fig.3. Fig. 3(a) indicates the maximum power topology while Fig.3(b) shows the obtained topology by CBCC, where the number associated with each SU denotes its assigned channel. It can be seen in Fig. 3(b) that there are at least two independent paths between each pair of SUs, and 10 channels are required to guarantee the bi-channel-connected and conflict-free properties of the CRN. In Fig. 3(c) and Fig. 3(d), we give the derived topologies by C-TCSIC with PPU = 256mW and 51.2W, respectively.

Due to the simultaneous transmissions of SUs with PUs, the number of edges between SUs has been reduced, leading to the reduction of the conflicting neighbors of SUs. Hence, the number of required channels has be decreased to 8 and 7, respectively.



(a) (b)

c) (d)

Fig. 3: (a) Maximum power topology. (b) The topology derived by CBCC (the number denotes the assigned channel). (c) The topology derived by C-TCSIC with $P_{\mathrm{PU}} = 256\mathrm{mW}$. (d) The topology derived by C-TCSIC with $P_{\mathrm{PU}} = 51.2\mathrm{W}$ [3].

Fig. 4 illustrates the average number of channels required to construct the bi-channel-connected and conflict-free networks with different algorithms. OCFP barely increases since it only guarantees the conflict-free constraint. It can also be observed that other algorithms slightly increase, since their transmission ranges decrease as the number of SUs increases. Note that the performance of our algorithms is better than CBCC and DBCC [2], especially in the case that the transmission power of PUs is considerably larger than that of SUs.

The reasons are as follows: In the topology construction phase, SIC is adopted to reject the interference from PUs, thereby guaranteeing more simultaneous transmissions of SUs and PUs. As such, more PU-coexisting links are available for the SUs to achieve the bi-channel-connectivity.

In the channel assignment phase, by placing the PU coexisting links as the key edges and paths of the topology, the number of the conflicting neighbors of each SU can be reduced, following the alleviation of potential interference in the CRN. As a result, our algorithms require less channels to achieve the conflict-free goal

IV. CONCLUSION

In paper [1], the drawback was that every time the channel is assigned to SU's, a connectivity test has to be performed on the entire network to check whether the CRN remains connected if channel *c* is reclaimed. To overcome this problem, the author in paper [2], has proposed g-bi-connectivity for fault tolerant cognitive radio network. The main challenge was to construct a g-bi-connected network. The author in paper [3], considered a SIC-based topology control framework for exploiting the potential benefits of underlay paradigm in CRNs. In order to achieve the objective of minimizing the number of required channels while satisfying conflict-free and bi-channel connectivity constraints, we proposed a centralized and a distributed topology control algorithm. Simulation results also showed the average number of required channels can be reduced and the robustness of the network can be improved.

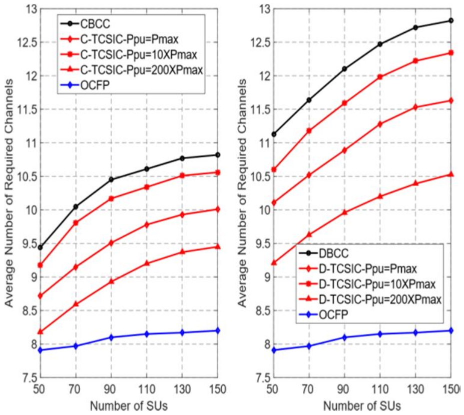
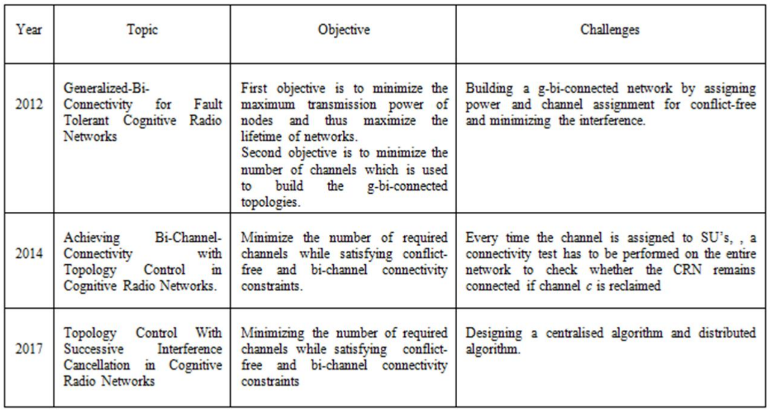


Fig. 4: Comparison of average number of required channels [3].

TABLE I. COMPARISON TABLE



Year	Topic	Objective	Challenges
2012	Generalized-Bi-Connectivity for Fault Tolerant Cognitive Radio Networks	First objective is to minimize the maximum transmission power of nodes and thus maximize the lifetime of networks. Second objective is to minimize the number of channels which is used to build the g-bi-connected topologies.	Building a g-bi-connected network by assigning power and channel assignment for conflict-free and minimizing the interference.
2014	Achieving Bi-Channel-Connectivity with Topology Control in Cognitive Radio Networks.	Minimize the number of required channels while satisfying conflict-free and bi-channel connectivity constraints.	Every time the channel is assigned to SU's, , a connectivity test has to be performed on the entire network to check whether the CRN remains connected if channel *c* is reclaimed
2017	Topology Control With Successive Interference Cancellation in Cognitive Radio Networks	Minimizing the number of required channels while satisfying conflict-free and bi-channel connectivity constraints	Designing a centralised algorithm and distributed algorithm.

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