A Topology Control Mechanism for Cognitive Smallcell Networks under Heterogeneous Traffic

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Abstract—The deployment of Heterogeneous Networks (HetNets), specifically the smallcell networks ranging from picocells, microcells and femtocells, have been increased dramatically with the proliferation of next generation wireless devices and broad traffic demands. Embedding the promising Cognitive Radio (CR) technology into the smallcells have brought complementary increases in spectrum utilization as well as the topological flexibility. This paper deals with the topological control of such CR based smallcell networks by considering the spectrum utilization, packet losses, delay and jitter parameters. The proposed framework analytically models the spectral topology assignment taking into account the analysis of the CR user requests and decides to assign the proper spectrum to the CR smallcell users by dividing the topology in an optimal manner. This optimality is achieved by taking into account different Quality of Service (QoS) parameters like throughput, delay, jitter and packet losses. The proposed frameworks’ mathematical model also provides optimal QoS parameter values for more efficient and fair topology assignment, considering the heterogeneous background CR traffic in the surrounding. The proposed method is evaluated for different types of CR traffics and thorough simulation results show that the proposed topology control mechanism provides an optimum number of smallcell CR networks to maintain fair and efficient QoS requirements in the unlicensed bands.

Index Terms—Cognitive Radio Networks, Spectrum Utilization, Smallcells, Topology Management, QoS

I. INTRODUCTION

Today’s wireless network technologies need to deal with various demanding of users such as video downloading, online applications, voice transmission, text transmission, etc. One of the best deployment solution to meet these various demands is Heterogeneous Network (HetNet). An HetNet can be described as a network that orchestrates different types of devices with different protocols and also described as a network composed of different topological formats including the base station, radio access networks, transmission solutions and power levels.

Cognitive Radio (CR) based smallcells, which are Software-Defined Radio (SDR)-based low-powered radio access nodes that have a range of 10 meters to 200 meters, can be considered as a study case for HetNets. The main idea behind using CR smallcells is to clustering fewer users that utilize different channels and prevent the occurrence of bottleneck in the communication environment thanks to the dynamic spectrum access techniques. This paradigm is the opportunistic utilization of the licensed channels by the smallcell users (CR users), without causing any interference to the licensed owners (Primary Users, PU) [1].

While solving the spectrum scarcity problem caused by the unbalanced fixed assignment, this promising paradigm faces two major challenges. First one is that the CR smallcell network mechanisms should perform an accurate spectrum sensing and monitoring to detect the available channels. Second one is to maintain a reliable topology control which is directly related to the available spectrum and the utilization of the licensed channels. Such a utilization based topology control also helps the available channel detection and protects the PUs by mitigating the interferences caused by the opportunistic CR smallcell usage. More specifically, by using the CR techniques, the smallcells are encouraged to take advantage of the different spectrum opportunities which are not used by the Primary Users. We can also think that in a bigger coverage area of a mobile operator, there is less capacity per user as more users need to share the same capacity in the same area. In such areas, CR smallcells can be used to reduce the coverage area that leads sharing the capacity between fewer users. This results in higher capacity per user, faster data transmission speed and improved quality of service. The increase of smallcells in a wireless topology makes the service quality better.

The topology control mechanism in CR smallcell networks should also focus on increasing performance and good quality of service in a network topology. Service quality is related number of users that are served in the same area which specify communication parameters such as power consumption, data throughput, packet losses, etc. These parameters determine the QoS for a specific application and service providers want optimum quality. Therefore, the QoS depends on the topology management of operators and number of users in the same area.

There exist many studies in the recent literature about the topology control mechanisms in smallcell networks as well as the CR smallcell networks. [2], [3] defines and proposes a smallcell-based CR network topologies and their management for enabling multtiered opportunistic access in next-generation broadband wireless systems. The underlying topology control combines the conventional femtocell idea with an infrastructure-based overlay cognitive network paradigm. [4] summarizes the main concepts of femtocells that are covered...
in literature and the major topological challenges faced in its large scale deployment. The main challenge of interference and topology management is also discussed in details. Some solutions proposed over the years to manage interference have been summarized in [2], [3], [4], [5] proposes spectrum-sharing schemes between macrocell and femtocell, as well as among femtocells, to improve spatial reuse gain. [6] We formulate the energy-efficient resource allocation problem in heterogeneous CR networks with femtocells as a Stackelberg game. In [7] necessary and sufficient optimality conditions are derived for different topologies and a global optimization algorithm based on the outer approximation method is proposed [1], [8] draw the novel architecture for the cognitive radio monitoring nodes where the cooperative sensing is suggested as the optimum solution for higher PU detection probabilities for adhoc topologies. In [9], [10], [11], a cooperative sensing approach is presented with the aid of monitoring network using the spatial and topological reuse mechanism without the PU QoS classification. Similarly, [12], [13], [14], [15] propose some protocols and schemes to solve the cooperation sensing problem, i.e. basically proposing some energy-efficient optimization schemes for the topology management.

Overall, the topology control based on different QoS parameters is still a crucial need in the CR smallcell network deployment. These aforementioned studies loosely consider the QoS requirements as well as the heterogeneous background traffic. Consequently, having these motivations in mind, we propose a topology control mechanism by making the following contributions:

- The CR smallcell users’ requirements and heterogeneous background traffic are monitored and analyzed continuously by the CR base station. This static and continuous monitoring provides more robust and accurate topology management.
- The topology analysis is done by considering different QoS parameters like spectrum utilization, packet losses, delay and jitter.
- A mathematical model is built for the spectrum utilization in order to analytically parameterize different assignment possibilities.
- The topology assignment is done according to the mathematical model, different QoS parameters and the background traffic.

The paper is organized as follows: In Section II, we introduce the system architecture and the proposed framework. In Section III, the performance of the proposed scheme is evaluated in terms of the spectrum utilization. We also give the mathematical model of the proposed topology assignment in this section. We conclude the paper by summarizing the achievements and giving future directions in Section IV.

II. THE NETWORK ARCHITECTURE AND THE PROPOSED FRAMEWORK

A. Network Architecture

The topology designed for the performance investigation includes base stations and wireless users communicating via these base stations. A figure about this situation is given in Fig. 1. Modeling of a topology control mechanism is aimed to optimize number of base stations for an area in order to provide better performance. In this work, we assume that there are 20 users communicating as 10 pairs and one of the pairs is chosen as reference pair to remain stable for all phases of the investigation. Other 9 pairs of users constitute background data traffic for the reference pair while they are communicating among each other. The background traffic is also arranged as heterogeneous. Some of them use CBR over UDP and some of them use FTP over TCP. In an area covered by a base station, there must be different traffic types in practice because different applications need different traffic types. Therefore, a heterogeneous traffic is supplied to obtain performance results more accurately.

In the first phase of the investigation, one base station is used to cover 20 users. Firstly, only one traffic stream is supplied between the reference pair and more traffic are added to the topology over time. Hence, the background traffic is increased as simulation time passes and a bottleneck occurs in the transmission medium that leads very poor communication performance between reference pair. Number of base stations is increased one by one for each phase of the investigation in order to observe the change in performance of reference pair. The background traffic also remains as heterogeneous in each cluster of users.

B. Proposed Framework

The proposed framework which is located in the CR Base Station, is composed of two main parts, Monitoring and Assignment as seen in Fig. 2. These modules are detailed as follows.
1) Monitoring: This module gathers the Quality of Service (QoS) requests of each CR user in terms of spectrum utilization, packet loss threshold at which the CR user can tolerate to maintain its connection, delay and jitter values which should not be exceed. Moreover, this module continuously monitors the background heterogeneous traffic in the network, to have an idea about the current channel and environmental situation around the topology. Once the CR requests and background traffic are collected, these are sent to the Assignment module as inputs.

2) Assignment: This module is responsible of the current topological analysis as well as the new decision for topology assignment. Once the CR requests are collected, this module analytically model the current spectrum utilization according to the topological behaviors which characterized using the background traffic density. It can be claimed that the relation between traffic density and throughput utilization is monotone. Therefore, the change in the spectrum utilization with respect to traffic density in the topology can be expressed as a nonlinear mathematical function:

\[ u(x) = a \cdot e^{(b \cdot x(t))} \]  

where \( x(t) \) is density of traffic stream at a given moment \( t \), \( a \) is non-negative (\( a > 0 \)) and \( b \) is a negative model coefficients (\( b < 0 \)). The values of \( a \) and \( b \) depend on number of assigned frequencies in the topology. The formulas below are used and substitution method is applied to obtain the values of \( a \) and \( b \).

\[ \sum_{i=1}^{n} y_i e^{bx_i} + a \sum_{i=1}^{n} e^{2bx_i} = 0 \]  

\[ \sum_{i=1}^{n} y_i x_i e^{bx_i} - a \sum_{i=1}^{n} x_i e^{2bx_i} = 0 \]

The coefficient of determination, \( R^2 \), is one of the common goodness of fit for regression models. We have used the \( R^2 \) calculation to interrogate the performance of the proposed mathematical model, i.e. the nonlinear model in Eq (1), using the formula below:

\[ R^2 = 1 - \frac{\sum_{i=1}^{n} (u_i(x) - f_i(x))^2}{\sum_{i=1}^{n} (u_i(x) - u(x))^2} \]

\[ = 1 - \frac{\sum_{i=1}^{n} (a \cdot e^{(b-x_i(t))} - f_i(x))^2}{\sum_{i=1}^{n} (a \cdot e^{(b-x_i(t))} - a \cdot e^{(b-x_i(t))})^2} \]  

where \( f(x) \) is the spectrum utilization values from the simulations. The value of \( R^2 \) changes in a range of 0 and 1 such that \( R^2=1 \) means a full fit and \( R^2=0 \) means no fit with actual data set. The \( R^2 \) value of the regression analysis obtained as 0.9986.

III. PERFORMANCE EVALUATION

The performance evaluations are done in the Network Simulator 2 (ns2). The trace files of the simulation are processed with the aid of C++ based data processing scripts. The heterogeneous traffic patterns and parameters, which are expressed as traffic densities in all the evaluations (y-axis in the figures) are given in Table I.

The throughput, packet losses, jitter and latency parameters are measured for performance review. Throughput utilization of the topology is also computed for each phase of the investigation. Brief descriptions and the formulas used about these parameters are given below:

- **Latency.** \( L \), is measurement of time between releasing a data packet from sender (Ts) and receiving the same packet in the receiver (Tr). Sending and receiving times of a packet is taken from trace file of simulation and latency is computed as \( L = Tr - Ts \) in (s).
- **Throughput** is calculated as the average rate of successful data packet delivery over a transmission medium and it is computed as \( 8n \times 1000000L \) in (Mbps) where \( L \) is latency and \( n \) is the number of bits carried successfully.
- **Losses.** \( Lo \), implies that the ratio between number of packet dropped and number of packet delivered over a transmission medium in a communication. Status of each packet is given in the trace file and losses parameter is computed as \( Lo = Nd/Np \) where \( Nd \) and \( Np \) are the number of dropped packets and the number of delivered packets respectively.

| TABLE I
<table>
<thead>
<tr>
<th>Configuration Parameters</th>
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<tr>
<td>TCP</td>
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<td>Packet Size</td>
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<td>Window Size</td>
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<tr>
<td>CBR</td>
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<tr>
<td>Packet Size</td>
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<tr>
<td>Rate(Interval)</td>
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<td>Random</td>
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• **Jitter** means the statistical deviation of data packets inter-arrival time. The following formula is used to compute jitter:

$$J(i) = J(i-1) + \frac{|(D(i-1, i) - J(i-1))|}{16} \quad (5)$$

where $D(i-1, i)$ is the difference of relative transition times between two consecutive packets $i$ and $i-1$ and computed as follows:

$$D(i, i-1) = (R(i) - R(i-1)) - (S(i) - S(i-1)) \quad (6)$$

where $R$ is the receiving time and $S$ is the sending time. This technique computes jitter between packets iteratively and the expression $(|D(i-1, i)| - J(i-1))/16$ is used to reduce the noise which is added to previous jitter value.

• **Utilization** is computed by proportioning throughput values under different conditions. The fully utilized ratio of throughput is considered as 1 and the relative utilization values are computed between 0 and 1.

### A. Comparison for Different Topological Control Scenarios

According to the performance review of simulation results, it can be advocated that the performance is getting better as the number of assigned frequencies is increased. Throughput utilization of reference pair is increased as the number of clusters (or different frequencies) in the background topology is incremented. The relation between spectrum utilization and density of traffic stream depending on number of base stations (or number of clusters which are defined by assigned frequencies) in the topology is shown in Fig. 3. As seen in the figure, the utilization increases with the number of assigned frequencies for different CR smallcell increases. Our framework defines the optimal frequency assignment in such cases. As an example, if the traffic density is 90% (the x-axis of Fig. 3), and the spectrum utilization threshold for each CR small cell is at least 0.75 (the y-axis of Fig. 3), the proposed framework selects to assign four frequencies (red line in Fig. 3), and not an higher value. This optimization leads more effective topology management in the CR smallcell deployment.

The number of dropped packets decreases as the number of different assigned frequencies in the background topology is increased. This leads a decrease in the losses parameter and provides a better performance. Fig. 4 implies the relation between losses parameter and traffic density depending on number of CR smallcells in the topology. Here again, our framework defines the optimal frequency assignment for such cases according to packet loss QoS parameter. As an optimization example, if the traffic density is 90% (the x-axis of Fig. 4), and the packet loss threshold for each CR small cell is at least 0.1 (the y-axis of Fig. 4), the proposed framework selects to assign four frequencies (green line in Fig. 4), and not an higher value. This optimization leads more effective topology management in the CR smallcell deployment.

The relation between the latency parameter and the traffic density according to number of assigned frequencies is also given as Fig. 5. For a CR smallcell base station that serves lots of users, the base station keeps incoming packets in a queue and sends them in an order. The amount of waiting time for each packet decreases since number of assigned frequencies in the topology is incremented in order to provide less user per a base station. Hence, latency parameter decreases as number of base stations in the background traffic is increased. Our framework defines the optimal frequency assignment for such cases according to latency QoS parameter. As an example, if the traffic density is 90% (the x-axis of Fig. 5), and the latency threshold for each CR small cell is at most 0.0005 sec. (the y-axis of Fig. 5), the proposed framework selects to assign five frequencies (green line in Fig. 5), and not an higher value. This optimization leads here again more effective topology...
management in the CR smallcell deployment.

The fluctuation in some parts of the graphs above is caused by the simulation environment ns2. Each base station in the topology controls the mobile nodes in its coverage area periodically by sending control packets. These packets also use the available channels capacity for a moment, leading more crowded. This affects the simulation statistics and leads to small decreases in number of actual data packets carried.

B. Mathematical Model vs Measurements

Fig. 6 below indicates the close fit between the mathematical model and actual values for five base stations in the topology. The curved blue line belongs to actual values coming from simulation statistics. The dashed line belongs to the mathematical model expressed as in Eq.(1) where \( x(t) \) is the traffic density, \( a=1.015 \) and \( b=-0.007 \). Here, values of \( a \) and \( b \) computed using regression analysis method. As seen in the figure, the mathematical model follows the general behavior of the simulation results, thus the framework’s analytical model expressed by Eq.(1) could give the optimum spectrum utilization value with a goodness of fit \( R^2 = 0.9986 \).

IV. CONCLUSIONS

Topology control mechanisms have a considerable role on performance of CR smallcell network deployment scenarios. In this paper, a novel topology control mechanism is proposed with clustering lots of users in a large coverage area and also splitting the large coverage areas into small ones. This is realized by analytically modeled the background traffic with respect to the number of possible frequencies which are likely to be assigned. The background traffic that consists of other CR smallcell users is increased to evaluate the performance of the proposed topology control mechanism. The mathematical model demonstrates the relationship between performance and number of assigned frequencies under heterogeneous background traffic. It can be claimed that the performance is improved as a large coverage area with one frequency is divided into small coverage areas with more frequencies. Another result obtained from this evaluation can be represented as environmental effect of developing such a topology control mechanism. It can be asserted that a CR base station has the ability of covering large areas and lots of users expends a lot of power and radiate lots of heat. On the other hand, the same large area can be covered using more than a base station that result in less power consumption and less heat radiation. Hence, the bad effect of base stations on the environment can be minimized.

REFERENCES


