Competitive Spectrum Sharing for Cognitive Radio on Scale-Free Wireless Networks

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Abstract—In this paper, we describe the Spectrum Sharing methods for Cognitive Radio Networks in communications for ad hoc networks in general having Scale-Free and Random topology. Power-law distribution of node degree in scale-free networks is important for considering the traffic distribution and resource management. Competitive Indexing Algorithm (CIF) is proposed and shown to have better performance compared to Random Indexing (RI) in Spectrum Sharing. We demonstrate that CIF outperforms RI algorithm in Scale-Free networks while in Random networks RI performs as well as CIF.

Keywords- Cognitive Radio, Spectrum Sharing, Scale-Free Networks, Random Networks.

I. INTRODUCTION

In current communication networks, the average spectrum utilization is between 15% to 85%. Cognitive Radio (CR) is a solution to increase the spectrum utilization and ultimately the network capacity leading to generating new revenue streams with higher quality of service. With increasing demand for higher capacity in wireless networks due to the rapid growth of new applications such as multimedia, the network resources such as spectrum should be used more efficiently to fulfill the need for both quantity and quality of service. This implies an optimum resource management [1][2]. Spectrum is one of the most challenging network resources which needs to be carefully consumed. Cognitive Radio Networks (CRN) are supposed to efficiently use idle portions of the spectrum (resource grid). There are many techniques to sense the idle spectrum channels and manage them to increase the networks efficiency. The works done in spectrum sharing has faced some challenges and can be categorized as *centralized spectrum sharing vs. distributed spectrum sharing, and cooperative spectrum sharing vs. non-cooperative spectrum sharing*. Spectrum sharing can also be considered from *inter or intra network* perspective as either one or two operators share the resources. On the other hand, the network topology and the user distribution are determining factors that directly affect the network state of being either overloaded or underloaded. CRs can be employed in many applications. CR using dynamic spectrum access can alleviate the spectrum congestion through efficient allocation of bandwidth and flexible spectrum access. It provides additional bandwidth and versatility for rapidly growing data applications. Moreover, a CR network can also be implemented to enhance public safety and homeland security. A natural disaster or terrorist attack can destroy existing communication infrastructure, so an emergency network becomes indispensable to aid the search and rescue. CR can also improve the quality of service when frequency changes are needed due to conflict or interference, the CR frequency management software will change the operating frequency automatically even without human intervention. Additionally, the radio software can change the service bandwidth remotely to accommodate new applications. As communication networks tend to become more social-like networks, Ad hoc networks and in particular *power-law* distributed networks i.e. scale-free networks are proposed in this paper to be considered for developing spectrum sharing technique then a new method for sharing the spectrum is proposed and proved to have the optimum performance in increasing the network capacity. At the end the results are presented and compared.

II. NETWORK TOPOLOGY

The network topology is one of the main factors in considering the traffic flow and resource management in the telecommunication networks. There are different topologies like random, ad hoc and scale-free discussed in network theories each presenting certain characteristics.

A. Random topology

There are classes of networks where the nodes are attached to the network in a random way meaning that the number of connections of nodes has a normal distribution. The degree (number of links to the node) distribution of nodes in such networks is a Gaussian type distribution.

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B. Scale-Free topology

In 1999, A. L. Barabasi, and R. Albert (BA) proposed a scale-free network model based on a mechanism of growth with preferential attachment characterized with power-law distribution of the nodes degree [4]. Scale-free networks are robust to random attacks (node removal) and very well describe the nature of real world networks where there are always few nodes with much higher degree called hubs. Each new node enters the network initially with ability to have ***m*** links to existing nodes. The probability to connect to an existing node is dependent on the degree of that node meaning that the new node gets connected most probably to nodes with higher degree. The degree distribution for this model is a power-law distribution. The probability of a node to have a degree $\boldsymbol{d_i}$ is given by

$$P\{d_i\} = d_i^{-\gamma} \tag{1}$$

Where $2 < \gamma < +\infty$. The distribution tail shows the nodes with highest degree called hubs. Here we use scale-free properties to better sense network traffic and manage the resources. Since hubs have the highest degrees amongst the nodes and because of their many connections, they have big impact on overall behavior of the network [4]. Consider a cluster of having $\mathbf{N_0}$ nodes and some newcomers tends to attach to this network. The newcomer starts to scan its neighborhood in a radius of $\mathbf{r_x}$ which is determined by minimum satisfactory bitrate. There will be some existing nodes within $\mathbf{r_x}$ from which only one node is selected to be connected to based on scale-free algorithm and that is the node with highest degree and of course the one with the best link quality as in Figure 1.

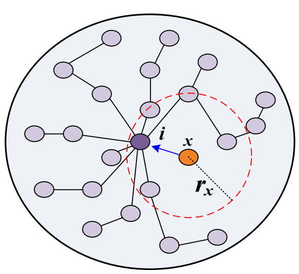

Figure 1. Scale-Free network formation

III. Proposed Spectrum Sharing Technique

In communication networks, there are always unused resources due to mismanagement or the traffic usage pattern. However, it is possible to share the inactive resources between different portions of the network and in some cases share them with other service providers. Therefore, implementing spectrum sharing would highly improve the spectrum utilization efficiency and reduce the request blocking rate (Grade of Service). We assume that the network topology is mainly scale free which has ad hoc properties plus that nodes are preferentially distributed mostly around hubs; different portions of the network are then categorized as clusters which have access to certain part of the resources[2][3]. In this paper we deal with a case where clusters are overloaded and needs extra resources for providing acceptable quality of service. Figure 2-a shows the infrastructure of scale free inter-network interaction. Each cluster is defined with a cluster hub and a range of operation. Clusters A, B, and C each of N_A, N_B, and N_C active users are initially planned to operate in separate allocated resource blocks (A_U, AD), (B_U, BD), and (C_U, CD), respectively as in Figure 2-b. Index **U** represents the uplink and **D** is for downlink communications. If a new user attaches to cluster A and all of the resources in resource block A are busy, the hub node in cluster A i.e. H_A, tries to see if there is available idle resources in neighboring clusters. The resource elements in this portion are in the form of RE_U and RE_D. For instance, $RE_U(i,j)$ represents the resource element for uplink at i^{th} subcarrier and j^{th} time slot. Now consider a new user willing to attach to cluster A by sending a request to the cluster hub, H_A. We presume at the time of request all of the resources of cluster A are occupied. The new user is not blocked at this stage like conventional communication networks. Instead, H_A starts to sense and search for potential available resources in neighboring clusters like B, and C. if the resource is available in either neighboring clusters for more than a *limited period of time*, it will be granted to cluster A and finally allocated to the new user. There is a process to consider associated criteria for releasing and granting the resources from other clusters to requesting clusters. In real world applications the hubs in clusters are distinguished mainly with their degree which is the number of active links either terminated to or originated from these hub nodes. Hubs are basically supposed to have access to as many resources as the number of active links connected to them. This leads to initially interrogating the more populated clusters as opposed to handshaking with less important (lower degree) nodes. The degree of the nodes is then considered in evaluating the merit for a specific hub. The *Merit function* determines the merit value for each requesting node given a certain set of available resources in granting cluster. One of the main factors in merit function is that the idle resources in neighboring clusters are not idle for unlimited time. As opposed, based on the number of active users in granting clusters, there is an average number of requests coming from user side which leads to always updating a request queue. This queue will be monitored at the time of releasing the idle resource to make sure that there is no potential demand from local cluster for the idle resource.

A. Cognitive Parameters

The hubs are presumed to be Cognitive Enabled in order to be able to sense unoccupied channels. A channel is said to be unoccupied if the instantaneous radio frequency (RF)

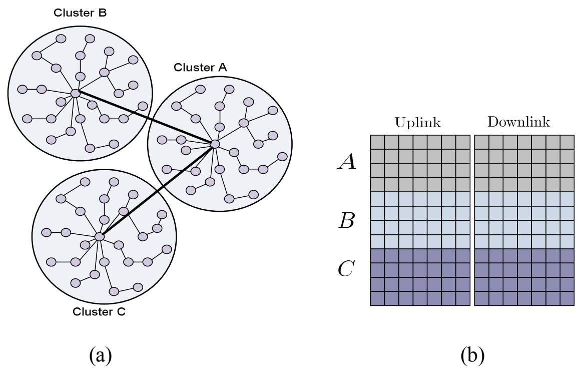

Figure 2. (a) Scale-Free Network (b) Resource Grid allocated to clusters

energy (plus noise) in this channel, is less than the certain interference limit. The probability that the channel is available for a period of time is greater than a threshold p_{th}, These measures can be evaluated by the CR node through monitoring the traffic pattern. The Interference is measured using Carrier to Interference ratio $(\frac{C}{I})$ for each subcarrier. The probability of a channel to be available for a certain period of time is predicted by looking up the traffic profiles both in real time and the traffic history.

Because the network has a scale-free topology, the requesting users/nodes are characterized with their degree. d_i is the degree of i^{th} node in a cluster. The degree information of the nodes is also communicated along with the request or obtained from network statistics. Nodes with higher degree have higher priority. This information is known in the local cluster and there is no need for global information broadcast [5][6].

Another criterion for granting the network resources to requesting users is the Costumer Classification (Q_i). Each of these new users has a specific service profile with different QoS like gold, silver and bronze. When a resource is reported to be available, it's now time to see which users of what level of quality (priority) have requested the resource. There are users with different subscription profiles which enables the decision making process directed based on the required QoS from user side. Another level of priority is also defined for emergency and security cases which dominate all incoming requests.

Signal to Noise Ratio (SNR) is important parameter that is considered for the users. Finally, the interrogated CR node from neighboring cluster reports the available channels with a set of information $(\frac{C}{I})$, p to the overloaded cluster. At the requesting cluster, d_i, Q_i are used to classify the users for granting borrowed resources.

B. Merit Function

For the reported available resources to be granted to requesting users/nodes in a fairly optimum way there needs to be a function that considers the *Cognitive Parameters* to calculate the merit for users/nodes.

C. Channel Indexing Function

Let **R** denote the set of available resources reported by the CR node. (Hub node in neighboring cluster(s)). The Channel Indexing Function (CIF) is meant for indexing the elements in **R** based on received Cognitive Parameters $\mathbf{R} = \{r_1, r_2, ..., r_L\}$ Where $r_i = \phi_i((\frac{C}{I})_i, p_i)$ for every available channel. Then CIF operates on R to generate χ

$$\Phi(\mathbf{R}) = \chi \tag{2}$$

$\chi = \{x_1, x_2, .., x_L\}$ is the output of Channel Indexing Function, $\mathbf{\Phi}$, which consists of sorted performance indices for all available channels. **U** is the list of cognitive parameters collected from requesting users/nodes from requesting clusters. $\mathbf{U} = \{u_1, u_2, ..., u_L\}$ where $u_i = \psi_i(SNR_i, Q_i, d_i)$. Then the Merit Function is applied to calculate the merit value for requesting users.

$$\Psi(\mathbf{U}) = \mathbf{M} \tag{3}$$

where **M** is the set of merit values for all requesting users i.e. $\mathbf{M} = \{m_1, m_2, ..., m_L\}$. ϕ_i and ψ_i are CIF and Merit functions operating on each resource and user respectively and can be defined as:

$$\phi_i = \omega_p p_i + \omega_I (\frac{C}{I})_i \tag{4}$$

$$\psi_i = \omega_D d_i + \omega_Q Q_i + \omega_S SNR_i \tag{6}$$

All ω parameters are set according to technical and commercial constraints. We define the SNR for target node i as the summation of uplink(UL) and downlink(DL) SNRs.

$$SNR_i = SNR_i^{UL} + SNR_i^{DL} = \frac{P_x/N_i}{r_x^2} + \frac{P_i/N_x}{r_x^2} \tag{7}$$

$\mathbf{P}_x$ and $\mathbf{P}_i$ represent the transmit power of the newcomer node x and target node i, respectively. $\mathbf{N}_x$ and $\mathbf{N}_i$ are the noise power at newcomer and target node receivers.

D. Competitive Indexing Algorithm

M and χ are matched against each other to grant the best performing channel to the users/nodes with highest merit values because the users with higher value are those who require better quality of service and are in urgent need of resources to either use them or distribute them amongst their neighbors. Then the second best resource is granted to the second user with highest merit. This process goes on until either there is no request from overloaded cluster or comes a new request from the local cluster which leads to filling up the request queue in the local cluster.

Cluster **A** sends its request to the neighboring clusters. Matrix $\boldsymbol{\chi}$ is a set of performance indices for all available resources (channels) in neighboring clusters where x_i is the performance index for i^{th} available resource element which is a function of cognitive parameters for i^{th} subcarrier like interference and availability probability and other potential cognitive parameters that can be defined/measured as well.

Φ and Ψ are determined based on network statistics, measurements, topology and operators commercial strategies. Based on the proposed competitive algorithm for granting available resources, χ and **M** are sorted in descendingly and the winning channel which is the top indexed one in χ is granted to the user with highest merit value at the top of **M.** this process goes on until all the demands from cluster A(or all requesting clusters) are supplied. This algorithm gives optimum performance in terms of the increased capacity in the network compared to random allocation of resources (without indexing) in response to incoming request.

To evaluate the performance for different algorithms, We define a *resource sharing performance index*,$\Upsilon = M\chi^T$, which is maximized based on *rearrangement inequality* for proposed *competitive indexing algorithm*. Since χ and **M** are sorted, we can write:

$$x_1 \geq x_2 \geq, .., \geq x_L \qquad (8)$$

$$m_1 \geq m_2 \geq, .., \geq m_L$$

Let $\sigma_k(\chi)$ and $\sigma_l(M)$ be any arbitrary permutation of χ and M. The *rearrangement inequality* states that for sorted matrices χ and M :

$$\sum_{i=1}^{L} x_i m_i \geq \sum_{i=1}^{L} \sigma_k(x_i)\sigma_l(m_i) \qquad (9)$$

$$\Upsilon_{opt} = \sum_{i=1}^{L} x_i m_i \geq \sum_{i=1}^{L} \sigma_k(x_i)\sigma_l(m_i) = \Upsilon_{rand} \qquad (10)$$

Υ_{opt} is the performance index of the proposed competitive algorithm. Υ_{opt} can be defined as different known parameters like total increased capacity if χ and M are defined appropriately.

IV. SIMULATION

The network structure used in the simulation is a scale-free topology with N= 100 nodes and three hubs each of 19 , 17, and 15 links. The average degree of nodes in this network is 3.7 meaning that each user is in average connected to about 4 nodes. There are 3 clusters centered around aforementioned hubs called cluster A, B, and C respectively. Each cluster uses a typical OFDM (3GPP compliant) resource block of 12 subcarriers in 7 time slots for *Uplink* and another 7 time slots for *Downlinks* resulting total 84 resource elements. At each time instance, there are K_i incoming nodes to cluster A and K_o nodes leave this cluster drawn from *Poisson* distribution**.** Without spectrum sharing based on the distribution of the requests coming from the users side, cluster **A** may get overloaded. The capacity and load measures are simulated for cluster **A** without having

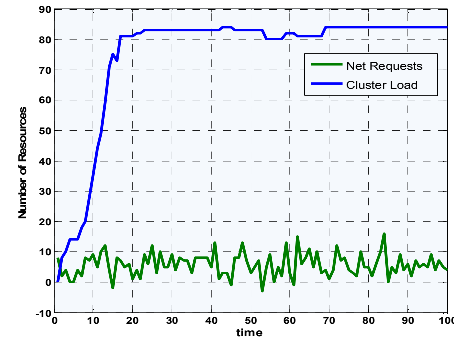

Figure 3. Load and Net Requests in clusters A

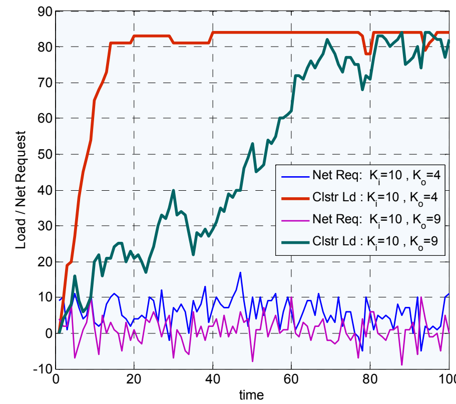

Figure 4. Capacity improvement in clusters A

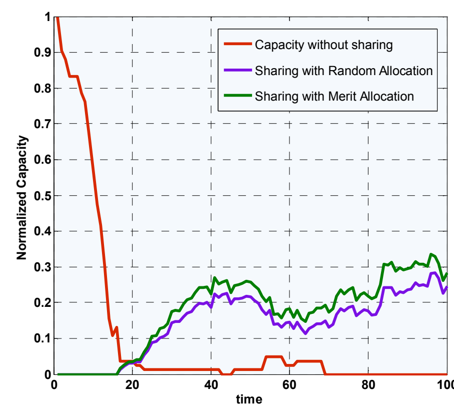

Figure 5. Capacity improvement in clusters A

the chance to borrow resources from neighboring clusters; Figure 5 demonstrates the performance of *Random Indexing* and *Competitive Indexing*. Our method in Spectrum Sharing outperforms the *Random Indexing*.

As we can see in Figure 3, the network gets saturated after a certain time and all resource elements will be occupied and the capacity tends to zero. Figure 4 shows the cluster load and net request for two different incoming and outgoing traffic. To avoid user blocking, CR nodes start to search to find idle resources in neighboring clusters. If the found resources are allocated randomly to requesting nodes, the capacity will increase to some extent like purple line in Figure 5, but the optimum algorithm i.e. *competitive indexing* will outperform any random allocation scheme as green curve in Figure 5. Depending on the distribution of incoming request from users, the capacity increase will be different. Figure 5 shows a case where K_i=10 and K_o=4.

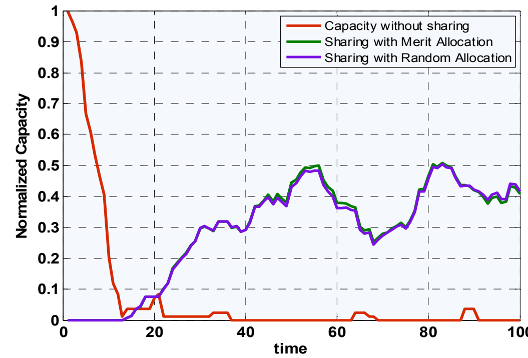

Figure 6. Capacity improvement in clusters A for random network

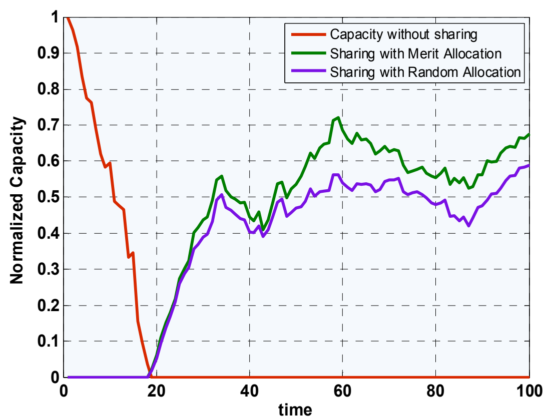

Figure 7. Capacity improvement in clusters A for Scale-Free network

Because the degree is directly proportional to the indexing performance, and in Scale-Free networks, the difference between users degree is prominent as a key factor, the outperformance of CIF compared to RI algorithm is much higher than when we apply CIF in Random Network shown in Figure 6 and Figure 7.

V. CONCLUSION

In this paper we presented the spectrum sharing technique for cognitive radio in scale-free networks. Power-law distribution of the scale-free networks is important for considering the traffic distribution and resource sensing in clusters. We proposed a new algorithm for sharing the spectrum and proved it to have better performance than random allocation of the idle resources. The simulation results also support the improvement of *Competitive Indexing Algorithm.* We also analyzed CIF algorithm outperforms in Scale-Free networks. This technique can be generalized for more complicated resource management and optimization through redefining the Channel Indexing and Merit Function and revisiting the cognitive parameters.

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