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A Game Theoretic DSA-Driven MAC Framework for Cognitive Radio Networks

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***Abstract*-The game theoretic dynamic spectrum allocation (DSA) technique is an efficient approach to coordinate the cognitive radios to share the spectrum. However, existing game based DSA algorithms lack a platform to support the game process. On the other hand, existing medium access control (MAC) protocols for cognitive radio (CR) networks do not fully utilize the adaptability and intelligence of the cognitive radio (CR) to achieve efficient spectrum utilization, let alone fairness and QoS support. Therefore it is necessary to develop a DSA-driven MAC protocol with the game theoretic DSA embedded into the MAC layer. In this paper, based on the analysis of challenges for the game theoretic DSA in realistic applications, we conclude that a unified game theoretic DSA-driven MAC framework should constitute of four integral components: 1)DSA algorithm, which derives the steady strategy of each radio to guide the channel access for data communication; 2) negotiation mechanism, which coordinates game players to exchange game information and update their strategies in the right game timing; 3) clustering algorithm, which limits the negotiation of game players in one cluster to solve the scalability issue; 4) cluster based collision avoidance mechanism, which is to avoid collisions among negotiations in different clusters. Subsequently, we design each component to construct an effective DSA-driven MAC framework with low cost. Our proposed game theoretic DSA-driven MAC framework can fulfill the merits of game theoretic DSA algorithms including high spectrum utilization, collision-free channel access for data communication, QoS and fairness support. Through simulations, the merits of the DSA-driven MAC framework are demonstrated.**

I. INTRODUCTION

Compared with the static spectrum allocation in traditional radio networks, CR networks offer a much more intelligent way to fully and fairly utilize the spectrum, by adjusting the CR's transmission parameters to accommodate to the fluctuations of the communication environment. To achieve the global optimization throughout the entire network, dynamic spectrum allocation (DSA) techniques, a group of techniques to allocate spectrum with ability of adaptability, reasoning and self-learning, are widely investigated recently [1]. Among various DSA algorithms, game theoretic DSA is especially fit for the CR networks due to its inherent advantages:

1) The CR's strategies (e.g. power, channel etc.) can be very complex. By modeling the intricate CR networks into a game, these complicated elements can be studied in a uniform way;

2) The local goal of each CR can be quite different from each other and game theory enables various optimality criteria fit for each player's local goal;

3) Adaptation is a quite important feature of the CR; nevertheless each CR's adaptation changes the outside environment of all the other radios, so the actions of CRs may appear as a recursive interactive decision process, which can be naturally represented by a repeated game.

Attractive performance as game theoretic DSA can achieve [2-5], it faces several challenges to be implemented in CR networks. First is the scalability problem. In a large CR network, the overhead and delay of the game process will be unbearable if all the users play a single game; on the other hand, it is not reasonable to let nodes that are set apart far way (thus has little direct mutual impacts) play the same game. Therefore, the cognitive radios should be grouped into multiple clusters according to the strengths of their mutual impacts and let the members in the same cluster play the same game. The Second is the problem of game timing synchronization. In the repeated game, the players should update their strategies according to certain timing schemes, e.g. synchronous timing, round-robin timing and so forth [6]. Therefore the users should coordinate themselves to play the game in the right order based on the game timing. The last consideration is the game collision problem. The information exchange in one game may interfere with other games in different clusters. Therefore, collision avoidance should be considered in the game process.

Consequently, the game theoretic DSA calls for a cluster based negotiation platform to manage the nodes to follow the game policy. We observe that the negotiation platform is preferred to be constructed on the MAC layer as the MAC protocol directly deals with the spectrum usage. On the other hand, most existing MAC protocols [7-13] can be classified into: 1) non-collaborative MAC protocols [7,8], in which each user makes decisions based on monitoring the data channels and predicting others' behaviors through certain reasoning process; and 2) collaborative MAC protocols [9–13], which follow the common wisdom that, upon the receipt of the request packet which includes the available data channel list from the sender, the receiver replies with the selected data

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channel based on certain spectrum selection policy. They are all based on simple non-cognitive rules which cannot fulfill the global optimization in the network scale, thus fail in achieving efficient spectrum utilization, let alone QoS and fairness support. In essence, CR networks starve for intelligent mechanisms in MAC protocol to efficiently instruct channel access among contending CRs under complex spectrum utilization requirements. Therefore, it is natural to embed DSA into the MAC protocol to form a unified DSA-driven MAC framework. In this paper, a DSA-driven MAC framework is proposed to support the adaptive behaviors of CRs directed by game-based model, which can make the best of merits of game theoretic DSA algorithms under low cost.

II. STRUCTURE OF DSA-DRIVEN MAC FRAMEWORK

Based on the analysis presented in section I, we proposed a game theoretic DSA-driven MAC framework (as shown in figure 1) composed of four indispensable components: 1) game theoretic DSA; 2) negotiation mechanism; 3) clustering algorithm; and 4) collision avoidance mechanism. The cluster structure is the basis to support game negotiation mechanism since negotiation should be constraint to each individual cluster to achieve mutually beneficial channel access agreement among directly competing local CR nodes in a scalable manner. The design of the collision avoidance mechanism should guarantee reliability for negotiation and be adaptive to cluster structure to avoid mainly inter-cluster collision. The negotiation mechanism is in charge of exchanging the game information required by the DSA algorithm. The concrete content of game information is dependent on the game policy adopted by the DSA algorithm.

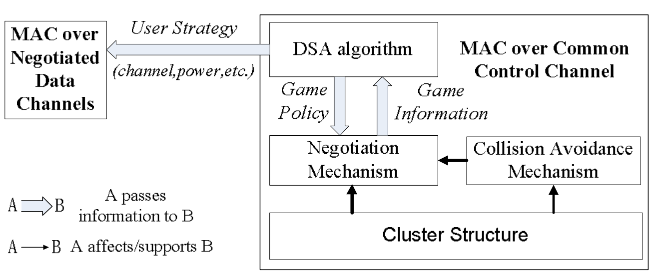

Figure 1: Structure of DSA-Driven MAC Framework

To provide a robust framework compatible to various kinds of DSA algorithms, the collision avoidance mechanism and the cluster structure should be independent to DSA algorithms. However, since a CR player is composed of a pair of data transmitter and receiver, once the cluster structure is independent to DSA algorithms, it may happen that the transmitter and the receiver are in different clusters. For this inter-cluster communication, the receiver participates in the game on behalf of the since the transmitter may not be able to directly communicate with all other players in the receiver cluster. If the transmitter is involving with the game process in the receiver's cluster, it cannot participate in the game process in its own cluster since one player cannot participate in two games simultaneously. After the negotiation, the receiver would feedback the final strategy to the sender.

The strategies of channel access for data communication are instructed by the game theoretic DSA algorithm. To prevent the game process from interrupting the ongoing data communication, a common control channel is chosen for negotiation among game players.

III. DSA-DRIVEN MAC: GAME THEORETIC DSA

Most game theoretic DSA algorithms work on transferring a global optimization problem into a distributed local optimization problem. As such the global optimization solution can be transferred to the Nash Equilibrium of a distributed game. Instructed by the DSA algorithm, each game player keeps updating its strategy to maximize its local utility function until all the players are not willing to change their strategy, i.e., the game process converges to Nash Equilibrium (NE). When game process converges, all the users can perform collision free channel access for data communication as they all transmit over the agreed spectrum with appropriate transmission power.

In the game theoretic DSA, the interactive behaviors of cognitive radios are modeled as a repeated game model $\Gamma = \langle N, \{S_i\}, \{u_i\}, T \rangle$. Here N is the set of the players; S_i denotes the strategy of player i; u_i is the local utility function of player i; T is the decision timing for the game, determining the time when radios can update their strategies, and the round-robin decision process is used in most game theoretic DSAs [2-6]. The player set is obtained from the negotiation mechanism while the game timing, as a part of the game policy, should be provided to negotiation mechanism to instruct the negotiation order. Other game information required in negotiation is determined by the concrete form of the utility function. The utility function is often composed of two parts: one is the payoff of the strategy the player makes; the other is the price the player should pay for its strategy to other players. QoS and fairness requirements can also be reflected by the utility function. Due to the page limit, interested readers are suggested to refer to [2-6] for the details of the game theoretic DSA mechanisms.

IV. DSA-DRIVEN MAC: CLUSTERING ALGORITHM

The cluster structure is the basis of the negotiation mechanism and the collision avoidance mechanism. Since most of existing clustering algorithms ([14, 15], etc.) are proposed for shortening the routing path or reducing the routing overhead, they are not suitable to support the negotiation in MAC layer. For the game theoretic DSA-driven MAC framework, a desirable clustering algorithm should satisfy the following properties: 1) Only CR users with non-negligible mutual impacts should be within the same cluster running the same game; 2) the clustering algorithm should be scalable to fit any size/topology of networks; 3) the cluster should be stable to avoid frequent reconstruction; d) the cluster formation process should be as simple as possible to reduce the overhead for cluster construction.

As the strength of mutual impacts between two CR users is mainly determined by the Euclidean distance between them, geographical position based clustering algorithm is preferred. Besides, to avoid frequent cluster reconstruction, it is

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desirable that the cluster is independent from behaviors of the nodes. This can be easily realized if the cluster is only determined by its geographical position.

Therefore in our clustering algorithm, the identity of each cluster is exclusively determined by its location. In this case, each cluster's identity is not affected by the arrival or departure of CRs. Moreover, each CR can decide which cluster it belongs to independently, which simplify the cluster formation process. Furthermore, the cluster formation is also independent of the network infrastructure. Besides, the position based clustering algorithm is scalable since the maximum number of clusters only depends on the network area, not affected by the number of CR nodes.

The cluster size design is an integral part of geographical clustering algorithm. To support the negotiation mechanism efficiently, we set the cluster as a fully connected cluster. That is, the CR nodes within one cluster can all communicate with each other directly. As such, the players in the same cluster can negotiate without multi-hops, so they can avoid routing process to exchange control messages. This also concurs that the game should only be played among the nodes that have strong interference with each other.

Suppose the maximum communication distance is d , all the nodes within a fully connected cluster must be located in a circle with the diameter of d . However, the circles cannot cover the whole plane of the entire CR network without interspaces, so they should be approximately replaced by the isogons with external diameter of d . To fully cover the whole network plane, it can be proved that the regular hexagon is the optimal option to approach the circle. Hence nodes within one hexagon form a cluster in our design. Each cluster is assigned with a unique cluster id C_{id} (a two-integer pair $< k_i, l_i >$), which is exclusively determined by the hexagon center's coordinates (x_{ci}, y_{ci}) . It can be proved that if node i belongs to the cluster $< k_i, l_i >$, the distance from the node i to its own cluster center (x_{ci}, y_{ci}) is smallest among the distances from the node i to all cluster centers. Therefore, any node can choose the hexagon which has the closest center (x_{ci}, y_{ci}) to itself as its cluster. After nodes choose their clusters on their own, they broadcast their coordinates and the IDs of their chosen clusters using the maximum transmission power and thus obtain the information of other nodes within their clusters. For an existing cluster, the new arriving node should report to the cluster header when it wants to join in a game.

The cluster header is responsible for handling the arrival and departure of players,, initiating and ending the game, and processing the control packet within one cluster. Since the roles of all the players in a game are equal and the computation load of the game should be distributed among players, it is not desirable to assign one specific node as a permanent header within a cluster. Here we propose a virtual header mechanism, in which the header of a cluster is no longer a node but a cluster-unique packet called Virtual Header (VH). In VH mechanism, all the jobs that a normal header does are reflected in the VH and its carried token: the player list in token can reflect the arrival and departure of players; the initiation and ending of a game can be reflected by the beginning and termination of VH propagation; the control packet processing can be done only by the VH node, a node to which the VH is granted. Details about VH bestowing will be discussed in section VI.

V. DSA-DRIVEN MAC: COLLISION AVOIDANCE MECHANISM

The collision avoidance mechanism is an assistant to the negotiation mechanism in our DSA-Driven MAC framework, to avoid the collisions among negotiations in different clusters. Since the negotiation mechanism relies on cluster structure, a cluster-based busy tone collision avoidance mechanism is proposed here.

There are two types of narrow-band out-of-band busy tones [16] broadcasted by a node that is receiving or overhearing: BT_i (inside-cluster busy tone) is set up by the node that is receiving messages, which is used to prevent nodes out of a cluster from interfering the negotiation within the cluster; BT_o (outside-cluster busy tone) is set up by the node which is overhearing the messages from other clusters, which is used to avoid negotiation in a cluster when the nodes in the cluster are interfered by nodes from other clusters. The transmission range of busy tones is twice of the maximum transmission range. Any node should detect the busy tones before it transmits and if the busy tone is sensed, it should defer from sending any information to avoid collisions on nodes that send out busy tones.

VI. DSA-DRIVEN MAC: NEGOTIATION MECHANISM

The negotiation mechanism takes charge of managing all the control messages, and coordinating CR nodes to play the game at the right game timing. Before the game process, the game player set should be set up and the communication spectrum environment parameters (e.g., the noise) required by the game should be collected. Therefore, the negotiation process of the MAC framework should be divided into two stages: the *inquiry stage* and the *formal negotiation stage*. In the inquiry stage, all the cluster members will be inquired of their intention on data communication by a token packet in the

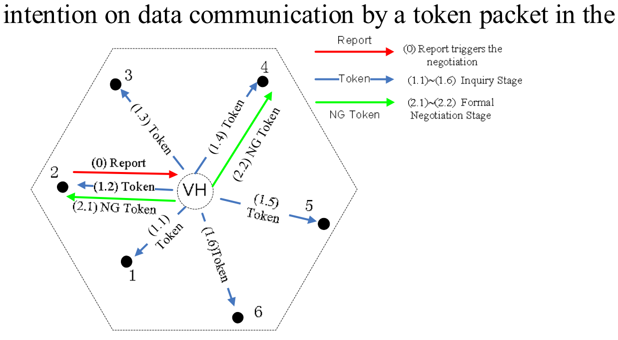

Figure 2: Typical Negotiation Process

order of their cluster member IDs. Nodes intending to transmit data will become quasi game players and put the corresponding player information into the token. Then only the players conduct the formal game in the following formal negotiation stage. During this stage the game information, is piggybacked on a negotiation token packet and passed among players. A typical negotiation process is illustrated figure 2, in which node 2 who wants to start communication first reports to the VH node (suppose it is node 1), then the VH carries a token to inquiry all the cluster member in the order of their member IDs and after that the VH carries an NG token to coordinate node 2 and 4 to process the formal game.

Whenever a node, which is not the VH node, wants to start a new transmission or end an ongoing transmission, it will broadcast a REPORT packet intended for the VH node in its cluster. If a VH node not in inquiry stage receives a REPORT, if there is no record of this report in the VH, the VH node will record this report in the VH. Otherwise, the VH node just discards this redundant report. Once a report is recorded in VH, the future VH node will initiate the inquiry stage when it is not in negotiation process. If a VH node in the inquiry stage receives a report, the VH node first compares its member ID and the member ID of the reporter. If the member ID of the VH node is smaller than the reporter's, the report is discarded because the reporter will be inquired in this inquiry stage; otherwise, if there is no report recorded in VH, the VH node records the report into the VH and the inquiry stage will be initiated after the current negotiation process.

The entire inquiry stage is guided by a token generated by the current VH node at the beginning of the inquiry stage. In the inquiry stage, the token along with the VH packet will be passed around the cluster to collect the information of the quasi game players. The inquiry stage ends when the token returns to the token generator. The advantage of the token based inquiry is: since the token awarding is only allowed between two adjacent members by adjusting the transmission power for awarding the token, the interference caused by negotiation in the cluster to other clusters can be minimized. Another advantage is that the collisions within the cluster in inquiry stage can be eliminated since only one packet (the token) can be transmitted at any time.

At the end of the inquiry stage, the VH node broadcasts the token to the entire cluster, and subsequently each game player can construct the entire player set and strategy space locally. The VH is then passed to the first player in the player set who will then become the new VH node and the cluster steps into formal negotiation. Similar to the inquiry stage, the formal negotiation process is guided by a negotiation token (NG token). The NG token, which carries the dynamic game information required by the game players, is passed with VH around the game players in the order determined by the game timing. Each player updates the local strategy by the information contained the NG token and replaces the corresponding game information field in NG token according to the new strategy. It then passes the NG token as well as the VH to the next player. The process continues until the game converges to the NE.

VII. PERFORMANCE EVALUATION

We implemented a discrete event driven simulator to evaluate our proposed DSA-driven MAC framework. In this simulator, SC-QoSe-DSA [5] is chosen as the DSA algorithm module for the MAC framework. The player strategy in SC-QoSe-DSA includes channel selection and transmission power adjustment. To provide an objective performance evaluation of this framework, it is compared with another multi-channel MAC protocol also with the power adjustment ability, referred as Dynamic Channel Access with Power Control (DCA-PC) [12], via simulation.

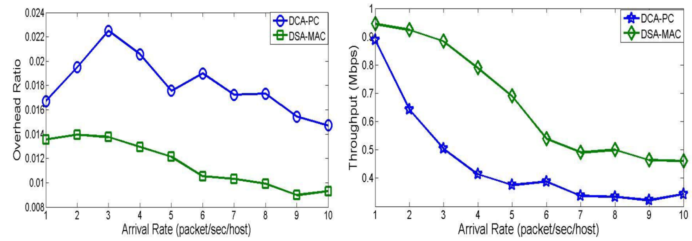

Figure 3: Overhead ratio and Throughput with QoS constraint

In our simulation settings, CR nodes are randomly distributed in 400*600 (m^2) areas with the density of 250nodes/km^2. The data packets arrive at each transmitter according to Poisson distribution. The free space model is chosen as the signal propagation model. There are three data channels and one common control channel, while each node can only access one of the data channels for data communication. The capacity of the control channel is 1Mbps. The QoS requirement on every transmitter-receiver pair is the

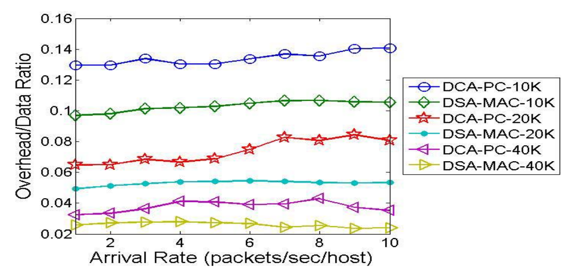

Figure 4: Overhead ratio for different data size with QoS constraints

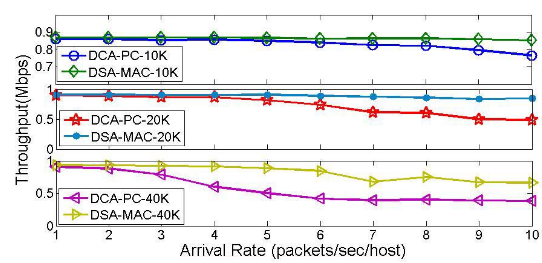

Figure5: Throughput for different data size with QoS constraints

same: the transmission rate should be above 0.2Mpbs and below 1.0Mbps. For DCA-PC, as the nodes cannot regulate transmission rate, we set every transmitter transmit at the maximum rate 1Mbps. The evaluation metrics are *average throughput* and *overhead ratio* (tsize of control message/size of data message). With the data packet size of 80Kbits, the communication overhead ratio and the average throughput for our DSA-driven MAC and that for DCA-PC are shown in figures 3. For other packet size, the simulation results are shown in figures 4 and 5.

When there is no QoS requirement, as DCA-PC does not support heterogeneous transmission rates, we set the min-max transmission rate as the data transmission rate for DCA-PC. The min-max transmission rate is calculated under the situation that the distance between the transmitter and receiver is the maximum transmission range (to guarantee all senders can reach the rate), and the transmitter uses maximum transmission power (to maximize the achievable rate). For DSA-driven MAC, the data transmission rate relies on the final strategy of transmitters. Figure 6 shows the performance of the two protocols when there is no QoS requirement.

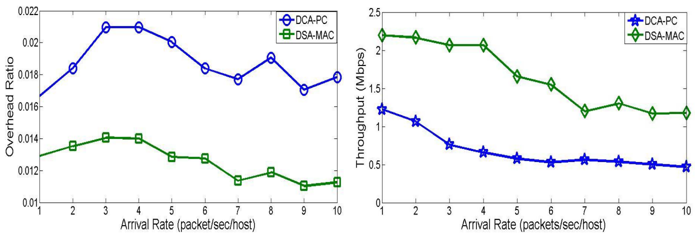

Figure 6: Throughput and Overhead ratio without QoS constraint

From figures 3-6, it can be shown that our DSA-driven MAC framework can achieve higher throughput due to the efficient utilization of data channels instructed by the game theoretic DSA; moreover, our DSA-driven MAC framework introduces less overhead for two reasons: 1) In DCA-PC, there are many collisions for control message when the transmitter density is high, which result in large number of retransmissions of control messages; while the cluster-based busy tone strategy in our DSA-driven MAC framework may achieve collision free control message exchange, 2) The packet size in the DSA-driven MAC is minimized, e.g. each node is only assigned a locally unique cluster member ID with rather smaller size than the MAC address. It can also be shown that the throughput gap between DSA-Driven MAC and DCA-PC is even larger when there is no QoS requirement. The reason is that the strategies of game players are more flexible without QoS constraint thus the players use the channel more efficiently instructed by game theoretic DSA. Results shown in figures 4 and 5 also demonstrate that DSA-Driven MAC also performs very well for different packet sizes.

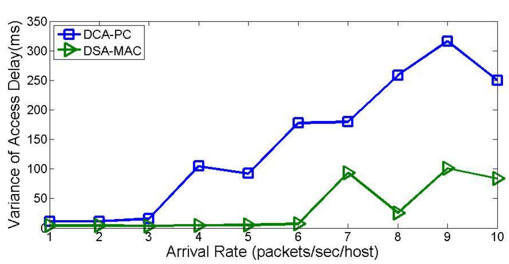

Figure 7: Fairness

Fairness of MAC access among different users in CR networks is another evaluation metric. We calculate the average delay of each transmitter to access the data channel, and use the variance of the delays as the benchmark to evaluate fairness. When there is QoS constraint and the data packet size is 40Kbits, the simulation results are shown in figure 7. As the game model guarantees the fairness among the game players, Our DSA-driven MAC outperforms DCA-PC with less variance from the fairness aspect.

VIII. CONCLUSION

In the recursive adaptation process among the intelligent CRs, each radio attempts to reach its own goal while causing interference among each other. It is therefore suitable to be modeled as a game. However, current game theoretic DSA techniques suffer from the issues of scalability, game timing synchronization and game collisions when they are implemented in CR networks. To conquer these challenges, we propose a game-theoretic DSA-driven MAC framework to fully utilize the merits of game theoretic DSA techniques, including high spectrum utilization, collision free channel access for resulting data communication, as well as QoS and fairness support. Performance evaluation results show that the proposed framework is very promising. We believe the DSA-driven MAC framework would be a new paradigm for efficient MAC design in CR networks.

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