Report 2 on Resource Allocation in Cognitive Radio Networks Group 8

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***Abstract*—This report is the most updated track of our research in cognitive radio network. Our research in the last month mainly focuses on two categories: the spectrum auction and the MAC protocol. In the spectrum auction part, we mainly discussed the best-paper-nominated 'ebay in the sky' by Heather Zheng et al. We paid special attention to what can be improved in the auction. In MAC protocol, we read some papers about preamble design and made some summaries about present techniques in the CR MAC design. Last but not the least, we learnt something about Game Theory, which is an important tool in the analysis of CR network. Some relevant ideas will be introduced in this report.**

I. Introduction

Spectrum auction is a hot topic nowadays in the research of cognitive radio network. In order to stimulate the licensed users to lease their spectrum for the use of the secondary users, they can be financially rewarded. However, allocation and pricing can be problems here.

The radio environment is fast-changing, therefore to efficiently allocate the spectrum is of critical value. Also we have to make sure that there are as many secondary users as possible whose demands are satisfied.

Auctions are among the best-known market-based allocation mechanisms due to their perceived fairness and allocation efficiency C everyone has an equal opportunity and the goods are sold to bidders who value them the most. Indeed, FCC (Federal Communications Commission) and its counterparts across the world have auctioned unused spectrum for billions of dollars in the past decade. However, a FCC-style spectrum auction targets long-term national/regional leases, requiring huge up-front investments. It often takes months or years to conclude, involves only a few large corporate players, and entails significant manual negotiations.

Spectrum Auction is basically a economic and mathematic problem just like a normal auction design. However, there are some characteristics that are unique in the wireless communication area. For example, unlike normal merchandizes, spectrum can be owned by several different bidders as long as they do not interfere with each other. This will cause the constraints to be different in the optimization problems. Also, the auction algorithm should be designed to be computationally efficient so that the spectrum resources can be better used. Therefore, there are many algorithms proposed to solve the problem. VERITAS is one of them, and we will discuss it later in section II.

In most of the researches on CR, the channel detection part has been assumed to be accurate and each radio can know the usage pattern of a channel, i.e. they know whether the channel is being used by the licensed user. Also, in the papers about MCMR, people mainly focus on how to assign different channels to users. However, coordination between the transmitter and receiver is essential to ensure that data can be transmitted via different channels. These problems are dealt with in the area of MAC design.

The concept of Cognitive Radio Networks has introduced a new way of sharing the open spectrum flexibly and efficiently. In a CRN (Cognitive Radio Network), the Secondary Users (SU) communicate only in those frequencies in which the primary users (PU) are inactive. So, the SUs should scan for the unused bands (channels) from time to time. This process is called spectrum sensing. After this stage, every SU has a list of free channels. The list of free channels may differ from one SU to another. Two SUs can communicate if there is at-least one common channel in their free channel lists. Since the unused spectrum is shared among a group of independent users, there should be a way to control and coordinate access to the spectrum. More details can be seen in section III.

In section IV, we will introduce some basic ideas in Game Theory, (abbreviated as GT). This proves to be a powerful tool in CR network analysis.

In section V and VI, we propose some possible problems we are going to deal with in the future, and we conclude this paper.

II. Spectrum Auction

As the auction models appear on scene, there is a fear about the manipulation of the market. The auctioneer can maximize its revenue by assigning the spectrum to bidders who value it the most. One auction model called VERITAS which supports the dynamic eBay-like spectrum market, makes an important contribution of maintaining truthfulness while maximizing spectrum utilization.

The true auction guarantees that if a bidder bids at the true value, its utility will be no less than if it lies. The VERITAS performs similarly like the greedy allocation algorithm if not consider the truthfulness.

Bidder utility is defined as:

$$u_i = v_i \cdot d_i^{\alpha} - p_i \quad (1)$$

Where v_i is the true value bidder i willing to pay for each channel, and this is only known by the bidder itself. $d_i$represents the number requested by the bidder i. p_i is the price charged by the auctioneer, and is called the clearing price for each winner i.

Assuming each bidder can only obtain 0 or $d_i$channels as it wishes,and the channel can not be used simultaneously, then we have two definitions:

1. A truthful auction is one in which no bidder i can obtain higher utility u_i by setting $b_i \neq v_i$;
2. An efficient and a truthful spectrum auction is one which maximizes the efficiency of spectrum usage subject to the interference constraints.

A secondary pricing spectrum auction allocates one channel to each of the top l biddrs and charge them the (l+1)th bidder's bid. first sort the bids in descending order and set each bidder's available channel set as channel 1 to k; then allocate one channel m to the first bidder i in the sorted order using the lowest indexed channel in i's available channel set, remove i from the list, remove m from i's conflicting neighbors' available channel sets; repeat the second step untill all the bidders have been considered. Charging the winner as the highest bid of i's neighbors.

The main algorithm of VERITAS is as following:

Algorithm 3 Range-VERITAS-Alloc(B, D, G)

```
B'=sorted B
while B' ≠ ∅ do
    i=TOP(B');
    if Distinct(N(i)) ≤ k then
        Assign(i, min(d_i, k − Distinct(N(i))))
    end if
    B' = B' \ {b_i}
end while
```

Fig. 1. Alloc algorithm, from H. Zheng et al's work in [6]

Extend the VERITAS to a ranged-VERITAS model. In the traditional VERITAS, when the available number of channels to bidder i is less than d$_i$,it gets zero channels. But in the ranged model, the bidder i gets whatever channels possible if less than d$_i$. And the total clearing price for i is the sum of prices charged for all its assigned channels.The algorithm is as following:

It can be demonstrated that both of the traditional and the ranged VERITAS algorithm is truthfulness, that it can achieve the largest utility.The experiment result shows that the sum of charges to all the winners can be the largest. And ranged-VERITAS can improve the satisfaction of the users greatly.

Algorithm 4 Range-VERITAS-Pricing(B, D, G, i)

```
B'=sorted B
owned_ch = Σ_{j=1}^{k} a_ij
if owned_ch = 0 then
    p_i = 0
    return
end if
p_i = 0
avail_ch = {c_1, c_2, ..., c_k}
B'' = B' \ {b_i}
while (B'' ≠ ∅) AND (owned_ch > 0) do
    q=TOP(B'')
    if Distinct(N(q)) < k then
        Assign(q, min(k − Distinct(N(q)), d_q))
        if q ∈ N(i) then
            avail_ch = avail_ch\ channels allocated to q
            if |avail_ch| < owned_ch then
                p_i = p_i + b_q · (owned_ch − |avail_ch|)
                owned_ch = |avail_ch|
            end if
        end if
    end if
    B'' = B'' \ {b_q}
end while
```

Fig. 2. Pricing algorithm, from H. Zheng et al's work in [6]

However, by valuing the bidders, the time slot must be at least the $\log N$ where N is the number of the bidders, because the bidders can be sorted. our group proposed an advanced algorithm based on the VERITAS. We can pre-arrange the queue of the bidders by training the bids. Before the auction, the most probable winner will be know by the auctioneer, and the sorting work will not be that large.

III. MAC PROTOCOL

The concept of Cognitive Radio Networks has introduced a new way of sharing the open spectrum flexibly and efficiently. In a CRN (Cognitive Radio Network), the Secondary Users (SU) communicate only in those frequencies in which the primary users (PU) are inactive. So, the SUs should scan for the unused bands (channels) from time to time. This process is called spectrum sensing. After this stage, every SU has a list of free channels. The list of free channels may differ from one SU to another. Two SUs can communicate if there is at-least one common channel in their free channel lists. Since the unused spectrum is shared among a group of independent users, there should be a way to control and coordinate access to the spectrum.

A. Common Control Channel Problem

The common control channel problem is one of challenging issues of CR network. Cognitive radio networks are designed by assuming the availability of a dedicated control channel. Intuitively, it seems that to setup a dedicated control channel is a convenient solution to exchanging the information about spectrum usage. However, a common control channel solution actually has several drawbacks [3]:

- It waste channel resources, especially for Ad hoc networks
- A control channel would get saturated as the number of users increases
- Adversaries can cripple the dedicated control channel by intentionally flooding the control channel

B. Spectrum Sensing Problem

Although most researches on cognitive radio networks assume that each secondary user in the network is able to check out which channel is not being used by sensing the spectrum. However, in actual networks this sensing task has two main disadvantages:

- Spectrum Sensing equipment is expensive
- Spectrum Sensing is time consuming
- Spectrum Sensing is energy consuming

Each SU has to be equipped with instruments to sensing the spectrum and has to wait a long period for finding a suitable channel. Therefore, Spectrum Sensing is really a challenge for CR network.

C. Preamble Solution

To solve the common control channel problem, there is already some great ideas. Transmitting the spectrum information in pre-defined preambles of data packets is one of solutions. The information is embedded in the preamble of each data packet, allowing the transmitter to adapt spectrum usage on a per-packet basis. Located at the beginning of each data packet, the preamble is a set of predefined sequences used for time synchronization, frequency and channel usage information. [4]

In a traditional centralized network, BS (Base station) could inform every secondary user in the network which band is available at present and how much bandwidth there is. Once a SU receive and decode the preambles, it can make decisions based on these information and policies predefined.

In an Ad hoc network, the function of a common control channel can also be replaced by such preambles. Once the receiver successfully detects and decodes the preamble, it can use the spectrum information to adapt its receiving process.

Since most spectrum holes available to secondary user are non-contiguous, OFDM systems are most suitable for transmitting data through several subcarriers at one time.

1) Preamble structure: As a part of each data packet, the preamble is a set of predefined sequences that are used for time synchronization, frequency estimation and channel estimation. In the 802.11- 2007 OFDM system, the preamble consists of 10 identical Short Training Symbols (STS) and 2 identical Long Training Symbols (LTS) separated by a guard interval as shown in Fig.3. Short training symbols are used for packet detection, coarse frequency estimation and timing synchronization. Long training symbols are used for fine timing synchronization, fine frequency estimation and channel estimation.

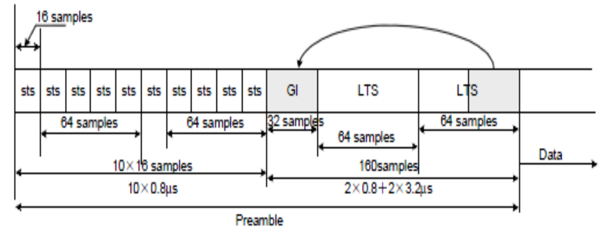

Fig. 3. The preamble structure of the 802.11-2007 OFDM system

2) Packet detection, coarse frequency estimation and timing synchronization: STSs are used for packet detection, coarse frequency estimation and timing synchronization. To illustrate the difference between contiguous and non-contiguous spectrum usage, we use a set of widely used mechanisms for these tasks[10]. The synchronization procedure of 802.11 receivers is shown in Fig.4

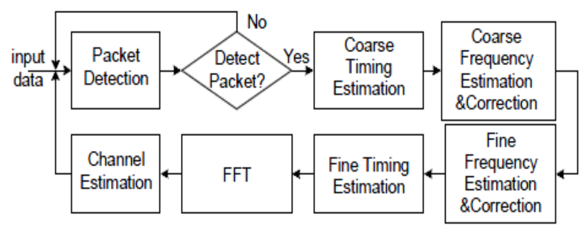

Fig. 4. The synchronization procedure of the 802.11-2007 OFDM receiver

3) Design of short training sequence: As discussed before, STSs are used for packet detection, coarse frequency offset estimation and time synchronization. Since the length of short sequence in time domain is short (16), we choose not to embed the spectrum patterns in STS. Hence, the challenge of our design is how to perform the packet detection and synchronization when the STSs are transmitted using a set of subcarriers unknown to the receiver. As shown in Section II, the performance of packet detection algorithm depends on the delay correlation and is independent of the correlation property of the STS sequence. So the main design requirement for STS is to minimize the Peak-to-Average Power Ratio (PARR).

4) Design of long training sequence: Long training symbols are used for channel estimation, fine timing and spectrum usage pattern identification in noncontiguous spectrum transmission mode. The requirements for the long training sequence are:

- Good periodic auto-correlation to provide good timing synchronization.
- Good cross-correlation property to reliably identify spectrum usage patterns.
- Large family size to support large number of non- contiguous spectrum usage patterns.
- Low PAPR.

5) Short Summary: The performance of preamble solution depends heavily on the available spectrum ratio and the interference to signal power ratio. This information, if available to the transmitter, allows the transmitter to choose the spectrum usage patterns intelligently and improve spectrum usage efficiency. Compared to existing solutions, this solution differs significantly because it does not require any dedicated control channel.

D. Distributed Spectrum Sensing

As we discussed at the beginning of this section, spectrum sensing is necessary but costful for secondary users. For example, PDA, notebooks and smart phones are mostly constrained by volume and battery energy. Besides, in highly mobile scenarios spectrum states of usage are changing very quickly, so frequently sensing and allocating channels may greatly slow the rate of transmission. In the paper [1], they focus on the design of distributed medium access control (MAC) protocols for OSA under an energy constraint on secondary users. Secondary users each has a finite amount of initial energy, exploiting temporal spectrum opportunities in a slotted primary system. In each slot, a secondary user either turns off its transceiver to save energy or chooses a channel in the spectrum to sense and possibly access, resulting in different levels of reduction in its battery energy. A MAC protocol governing such a sequential decision-making process thus consists of two components:

- A sensing strategy that specifies whether to sense and where in the spectrum to sense
- An access strategy that determines whether to access based on the sensing outcomes

The design objective is to maximize the throughput of a secondary user during its battery lifetime. Optimal MAC protocols for both the continuous and the bursty traffic models are proposed.

E. Cooperative Sensing

Cooperation is proposed in the literature as a solution to problems that arise in spectrum sensing due to noise uncertainty, fading, and shadowing. In addition, cooperation can solve hidden primary user problem and it can decrease sensing time. [2]

1) Centralized Sensing: In centralized sensing, a central unit collects sensing information from cognitive devices, identifies the available spectrum, and broadcasts this information to other cognitive radios or directly controls the cognitive radio traffic.

2) Distributed Sensing: In the case of distributed sensing, cognitive nodes share information among each other but they make their own decisions as to which part of the spectrum they can use. Distributed sensing is more advantageous than centralized sensing in the sense that there is no need for a backbone infrastructure and it has reduced cost.

3) External Sensing: Another technique for obtaining spectrum information is external sensing. In external sensing, an external agent performs the sensing and broadcasts the channel occupancy information to cognitive radios. External sensing algorithms solve some problems associated with the internal sensing where sensing is performed by the cognitive transceivers internally.

4) Use History to Prediction: For minimizing interference to primary users while making the most out of the opportunities, cognitive radios should keep track of variations in spectrum availability and should make predictions. Stemming from the fact that a cognitive radio senses the spectrum steadily and has the ability of learning, the history of the spectrum usage information can be used for predicting the future profile of the spectrum.

IV. About Game Theory

Game theory has become an essential tool in the analysis of Cognitive Radio Network, often with conflicting objectives. As such, Game Theory deals with interactive optimization problems. While many economists in the past few centuries have worked on what can be considered game-theoretic models, John von Neumann and Oskar Morgenstern are formally credited as the fathers of modern game theory. Their classic book Theory of Games and Economic Behavior, von Neumann and Morgenstern (1944), summarizes the basic concepts existing at that time. Game Theory has since enjoyed an explosion of developments, including the concept of equilibrium by Nash (1950), games with imperfect information by Kuhn (1953), cooperative games by Aumann (1959) and Shubik (1962) and auctions by Vickrey (1961), to name just a few. Citing Shubik (2002), In the 50s ... game theory was looked upon as a curiosum not to be taken seriously by any behavioral scientist. By the late 1980s, game theory in the new industrial organization has taken over ... game theory has proved its success in many disciplines.

In the following subsections, we are going to talk about some important kinds of games. Some are specific and some are more general. By studying these kinds of games, we will have a powerful tool in the analysis in Cognitive Radio Network.

A. Non-cooperative static games

In non-cooperative static games the players choose strategies simultaneously and are thereafter committed to their chosen strategies, i.e., these are simultaneous move, one-shot games. Non-cooperative GT seeks a rational prediction of how the game will be played in practice. The solution concept for these games was formally introduced by John Nash (1950) although some instances of using similar concepts date back a couple of centuries.

A game in the normal form consists of (1) players indexed by $i = 1, ..., n,$ (2) strategies or more generally a set of strategies denoted by $x_i, i = 1, ..., n$ available to each player and (3) payoffs $\pi_i(x1, x2, ..., xn), i = 1, ..., n$ received by each player. Each strategy is defined on a set $X_i, x_i \in X_i$, so we call the Cartesian product $X_1 \times X_2 \times ... \times X_n$ the strategy space. Each player may have a unidimensional strategy or a multi-dimensional strategy. In most CR applications players have unidimensional strategies.

B. Dynamic games

A significant portion of the CR literature is devoted to dynamic models in which decisions are made over time. In most cases the solution concept for these games is similar to the backwards induction used when solving dynamic programming problems. There are, however, important differences as will be clear from the discussion of repeated games. As with dynamic programming problems, we continue to focus on the games of complete information, i.e., at each move in the game all players know the full history of play.

Due to the space limitation, we will leave out the details.

C. Cooperative games

Cooperative GT involves a major shift in paradigms as compared to non-cooperative GT: the former focuses on the outcome of the game in terms of the value created through cooperation of a subset of players but does not specify the actions that each player will take, while the latter is more concerned with the specific actions of the players. Hence, cooperative GT allows us to model outcomes of complex problems that otherwise might be too difficult to describe. For example, in ad-hoc cognitive network, the throughput and capacity of a session is determined by every single hop in the link. So all the nodes along the link will be in a subset of players and will cooperate to gain the maximum profit.

Recall that the non-cooperative game consists of a set of players with their strategies and payoff functions. In contrast, the cooperative game, which is also called the game in characteristic form, consists of the set of players N with subsets or coalitions $S \subseteq N$ and a characteristic function $v(S)$ that specifies a (maximum) value (which we assume is a real number) created by any subset of players in N, i.e., the total pie that members of a coalition can create and divide. The specific actions that players have to take to create this value are not specified: the characteristic function only defines the total value that can be created by utilizing all players resources. Hence, players are free to form any coalitions that are beneficial to them and no player is endowed with power of any sort. Furthermore, the value a coalition creates is independent of the coalitions and actions taken by the non-coalition members.

V. Our Plans for the Future

In the spectrum auction part, we observe that there are still a lot of work to be done in the future. For example, decentralized auction algorithms have their unique value since they don't require a lot of control channel and other resources. However, the coordination between each local bidders could be a challenge here.

Iterative auctions could also be a part of our work. In iterative auctions, buyers submit bids in multiple rounds, and adjust bids based on market feedbacks. Auctioneers use clearing algorithms to derive prices and allocations and provide feedbacks. The challenge lies in simulating feedback and adjusting the bids accordingly.

Finally, we found that there are also a lot of work about power auction instead of spectrum auction. In fact, power and spectrum could be combined to formulate a new kind of auction, which might be a branch of our future research.

VI. Conclusion

In this report, we summarized our recent work on spectrum auction, MAC protocol and Game Theory. We presented some important works done previously in these fields and we proposed some problems we might be dealing with in the future.

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