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Cognitive Radio Technology: System Evolution

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***Abstract*—Cognitive Radio is a novel method of radio communication which enables more efficient use of the frequency spectrum. This efficiency is achieved by dynamically allocating frequency bands within the spectrum to different users. Within the field of Cognitive Radio, many different aspects of the system must be considered in order to achieve an optimal system. This includes methods for sensing whether the spectrum is available, sensing which channel is best for use, determining the time required to transmit data, and determining protocols which ensure all users achieve an adequate quality of service. This paper reviews a section of current topics in Cognitive Radio research on how cognition is used to make optimal channel selection. Paper compares various methods and identifies significance of various options and their efficiencies.**

***Index Terms*—Cognitive Radio, Dynamic Spectrum Sensing, Opportunistic Spectrum Access**

I. Introduction

Cognitive Radio is a new method of implementing radio communications which allows for more efficient use of the frequency spectrum. This is necessary since currently there is a large portion of the spectrum which is underutilize [1]–[3]. Cognitive radio is a broad category of research initiatives attempting to rectify this usage issue. These include Adaptive Reconfigurable Access and Generic Interfaces for Optimization in Radio Network (ARAGORN), Sensor Network for Dynamic and Cognitive Radio (SENDORA), and physical Layer for Dynamic Spectrum Access and Cognitive Radio (PHYDYAS).

In general, Cognitive Radio refers to software built on the radio platform which is context aware [4]. This system would be able to analyze current spectrum use and autonomously reconfigure the system to exploit these available spectrum resources [4]. Many methods of achieving this broad goal have been suggested. Here, some topics pertaining to dynamic spectrum access, spectrum sensing and femtocell networks are reviewed.

This paper examines a section of current topics in Cognitive Radio research which includes Thompson sampling and service time analysis of packet transmission for opportunistic spectrum access [5], [6] (Section III), frame correlation reduction for fast-Fourier transform (FFT) based energy detection [7] (Section IV), centralized collusion attack for spectrum sensing [8] (Section V), and cooperation strategies employed in cognitive femtocell networks [9] (Section VII).

II. Dynamic Spectrum Access

In general, dynamic spectrum access can be thought of as opposing static spectrum access; the current frequency spectrum usage being static. Just as there are many different ways to transmit data statically over the spectrum, there are a several of models classified as dynamic spectrum access.

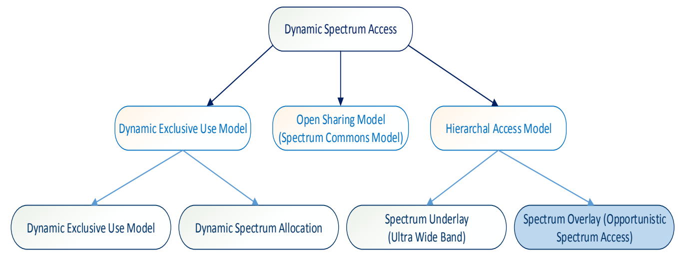

Fig. 1. Different strategies used in Dynamic Spectrum Access.

The IEEE has attempted to unify terms pertaining to dynamic spectrum access in order to clarify existing research [4]. The categorization of the different strategies is as shown in Figure 1. The three main models are the dynamic exclusive model, the open sharing model and the hierarchal access model. The dynamic exclusive use model includes the current regulatory model in which specific bands may be purchased for use by private entities [4]. The open sharing model adopts a policy of sharing the spectrum among peers where no one entity may own a frequency band within a given region [4]. The hierarchal model adopts policies in between the two extremes. While spectra may be owned by so-called primary users, secondary users who have no claim to the spectra may also use them given that they do not interfere with the primary users.

III. Opportunistic Spectrum Access

The overall goal of opportunistic spectrum access (OSA) is to provide spectral access to secondary users without affecting the reliability or performance of the primary users service. In order to achieve this, the process must include the ability to detect when the system is free and can be used (spectrum sensor and sensing strategy), as well as provide a regulatory system which will maintain the service of the primary users (access strategy).

A user who is limited to a single transceiver on a set of real-time channels may use one of several intelligent algorithms to acquire the knowledge of which channel should be selected for transmission. This is based on the user attempting to gain maximum throughput where Alnatheer and Man [5] discuss two main approaches to this problem: the myopic approach and the online learning algorithm. Takai et al. [7] suggest yet another approach using window functions to reduce correlation between frames in order to better detect energy produced on a channel when it is in use.

The algorithms in OSA are required to provide an optimal channel selection strategy which maximizes the throughput of the system at any given time. Since this problem is quite complex, it must be solved in a reasonable amount of time while still producing accurate results. The following two approaches are those commonly used to solve the OSA problem. A summary of the approaches is given in Table I.

TABLE I
COMPARISON OF OPPORTUNISTIC SPECTRUM ACCESS ALGORITHMS

Algorithm	Comments
Myopic	Require knowledge of channel statistics.
	Simple, yet not consistently accurate.
	Unable to track channel evolution.
	Typically used to compare access strategies or spectrum sensors.
Online Learning	Require no prior knowledge of the channel.
	Can be used with Thompson Sampling to find the best channel for unlicensed users.
	Can be used to predict whether switching channels or remaining on the same channel is optimal.

A. Myopic Algorithms

The myopic approach to the OSA problem requires some knowledge of the channel statistics, or the correlation of the channel [5]. Different algorithms would be applied based on the correlation of the channel. However, even with this knowledge, optimal results could only be achieved for identical, positively correlated channels. While these algorithms are simple in comparison to others that may be used, they require the algorithm to formulate assumptions on the correlations between the channels.

Another issue with this approach is the lack of ability to track the evolution of a channel. Since one of the basic requirements of cognitive radio is the ability to adapt to current spectrum usage, it is necessary that the algorithm be malleable based on the current primary users on the system.

Typically, this approach is used to compare different access strategies or spectrum sensors. Since it is simple to implement, it allows the researcher to test different aspects of the system while keeping the sensing algorithm constant [10].

B. Online Learning Algorithms

This approach will search for the best possible channel to connect to in the spectrum. In its search, this algorithm requires no prior knowledge of the channel or the correlation between channels. Rather, it works by learning a sufficient amount of this information using heuristics searches [5].

Alnatheer and Man [5] attempt to show that an optimal approach to access strategy would be to use an online learning algorithm in which the Thompson Sampling algorithm is extended into the case of Markovian rewards. The system model will select the best channel for unlicensed users to communicate with other unlicensed users on channels used by licensed users.

The Thompson sampling algorithm, which can be used to explore different channels on the spectrum, is designed for Bernoulli rewards. However, Alnatheer and Man [5] have designed a system model for Markovian rewards. Performance is evaluated by using pseudo-regret, which the difference between the total rewards is obtained using a single best channel to the total rewards obtained by the agent.

$$L = \sum_{j=0}^{N} [\mu^* - \mu^\lambda] n_j, \tag{1}$$

where L is pseudo-regret, n_j is the number of times a channel is selected, and $\mu^* - \mu^\lambda$ is the difference between average best channel and agent average throughput using heuristic policy λ. In order to adapt the algorithm, the sample size must be increased, and two Beta distributions must be used for each transitional parameter rather than a single one for the rewards themselves.

This Thompson sampling algorithm applied to Markovian rewards was compared to the myopic algorithms, both for positive and negative correlation, regenerative cycle upper confidence bound algorithm, and balance index policy for feedback multi-arm bandit. Alnatheer and Man [5] found the Markovian rewards algorithm had better results than the myopic algorithms and the regenerative cycle upper confidence bound algorithm when the channels are not *bursty*. That is, this algorithm should be used when the average reward from the best channel is greater than the average reward of switching between channels.

IV. SIGNAL DETECTION SCHEMES

One principle of dynamic spectrum access is that the secondary user must not interfere with signals sent by primary users. To achieve this, the cognitive radio system must be able to autonomously detect signals on the medium and act according to these detections. The signals must be known for the entire radio spectrum in order to effectively analysis each parameter of the spectrum which can be modulated: time, space and frequency [11]. No realizable system is able to attain all the information for the entire spectrum, although these wide-band spectrum sensing devices have been described in theory [11]. Narrow-band devices are able to effectively attain the information needed for the entire spectrum by analyzing a narrow segment of the spectrum at a time.

The schemes for spectrum sensing are either non-cooperative or cooperative. Cooperative techniques are those where the receiver is able to individually measure the spectrum and decide whether the medium is free based on its findings [11]. This is done to minimize possible interference with hidden nodes. Non-cooperative schemes are those which only one sensing terminal is available, or no cooperation between terminals is achievable [11].

Several varieties of spectrum sensing are available for each configuration of receiver. A classic non-cooperative technique is the use of energy detectors. Energy detectors, as well as those using overlapped FFT, are summarized in Table II.

TABLE II
COMPARISON OF SPECTRUM SENSING METHODS

Method	**Comments**
Energy Detector	Assume signal level is higher than noise floor.
	Channel is assumed to be free if there is no energy detected above the noise floor.
	Discrete sampling can cause errors in energy detection.
Overlapped FFT Energy Detector	Variance of noise is reduced, improving the probability of energy detection.
	Window functions may be used to reduce correlation between frames and improve the effects of overlapped FFT.
	Upsampled Hamming windows have been shown to improve the probability of detection.

A. *Energy Detectors*

Energy detectors assume the signal level is higher than the noise. Rather than attempting to extract the signal itself, it compares the energy received from the medium to a threshold value which is calculated in advance [12]. The threshold is the variance of the noise energy on the medium [11]. When energy is below this threshold, the channel is free; otherwise the channel is in use and cannot be accessed.

The energy detector does have inherent problems based on sampling of the medium. Since the sampling is done discretely, the calculation of the energy is done with the approximation

$$\hat{\varepsilon} \triangleq \frac{1}{N} \sum_{k=1}^{N} |y(k)|^2 \tag{2}$$

where $\hat{\varepsilon}$ is the average power over N samples and y is the k-th discrete sample. The larger the value of N, or the higher the number of samples taken, the better the approximation of the energy on the medium [11]. Another issue is that in typical energy detectors, the value of the noise variance used at the threshold of comparison is taken to be constant. This may not be the case in reality and so can cause errors in the scheme.

The overlapped FFT scheme reduced the variance of the noise, thus improving the probability of energy detection [13]. The more the overlap, the more reduced the noise variance. However, overlap also increases the correlation between frames, and therefore also reduces the improvement in the noise variance threshold. Takai et al. [7] have suggested using specific window functions in a FFT based energy detection scheme rather than some other sampling mechanism. The window functions reduce correlation between frames, improving the effects of overlap in the FFT energy detection scheme.

Specifically, Takai et al. [7] have suggested using up-sampled Hamming windows to reduce correlation. Using either quad up-sampled or double up-sampled Hamming windows, the probability of detection is improved 9% and 6% respectively.

V. COGNITIVE RELAY NETWORKS

A major issue with cognitive radio is the efficiency of spectrum sharing with primary users. A technique is being developed that can improve the efficiency of spectrum sharing. Cooperative relaying is a technique which is being developed to improve the efficiency of spectrum sharing [14].

Cooperative relays forward information by opportunistically sensing spectrum holes. Cognitive Radio senses the primary users by utilizing an energy detector in the sensing channel (s-Channel) [15]. Spectrum holes are bands that can be utilized by unlicensed, or secondary, users. This topic extends further into something called the spatial domain. The spatial domain is a simplified way of viewing the complexity of images (signals) much like in the frequency domain. The difference between the two lies in how images are processed in each respective domain.

The manifestation of a relay in cognitive radio is quite intricate. The algorithms and methods being used can allow for a Cognitive Radio user to independently act as a relay station in certain instances [16]. For example, if a direct connection from a Cognitive Radio transmitter to a Cognitive Radio receiver is broken, an algorithm provides indirect communication through other Cognitive Radio users in the network that are in different spatial domains [16].

Even though efficiency is a major issue in Cognitive Radio, it is not the only aspect of the system that requires development. There is also a need for the development of a specified set of protocols, much like those used for the internet. Two strategies may be implemented in the system [17]:

Instantaneous Channel-State Information (ICSI) Based Relay Selection Strategy: Optimal relay assignments are achieved when the SAP (secondary access point) compares all of the potential relay-destination channels and selects a secondary user with the best channel to forward the information.

Partial Channel-State Information (PCSI) Based Relay Selection Strategy: Completes relay assignment based on the average channel information.

Overall there are three important parameters to take into consideration when assessing a Cognitive Radio system requirements. The first parameter is cost. If the budget is not adequate to develop a more expensive system, other options must take priority in the system design process. The second parameter is complexity. A system that is less complex and more practical may also have a lower cost and an easier method of implementation. However, the last parameter, performance, may sway designers away from cost saving practices for fear of being less competitive.

From the results of a study done on protocol design and performance, Chen et al. [18] note that there "is no doubt that the ICSI based strategy always outperforms the PCSI based one. ... Given the advantages of the PCSI based strategy, especially the low complexity, it could be a good and practical choice".

VI. Multiple Secondary Users

Cognitive radio must achieve a certain rate of transmission in order for it to be viable on the market in the future. Therefore, the effects of different rates are being studied in great detail for scenarios with one primary user and multiple secondary users.

To avoid interference from the primary user at the secondary users receiver, a *dirty paper coding* method is utilized to cancel out the interference [9]. This interference increases with the presence of more secondary users. Algorithms are being studied to optimize the performance of MIMO (multiple in multiple out) cognitive radio systems.

A. Dirty Paper Coding

Current algorithms are implementing a *dirty paper coding* (DPC) method which is a technique to transmit data over a channel with interference [9]. The data is pre-coded to allow for multi-layered transmission. It also works in a non-causal manner which requires that there be some sort of process that relays information to the transmitters. Thus, the ICSI based relay selection strategy may work well together with the DPC method of eliminating interference from the primary user without sacrificing power.

It will be interesting to see if other algorithms will be developed that would fit better into the PCSI based relay selection strategy. This could drive the system cost down and increase its practicality.

VII. Cooperation Strategy

A Femto Base Station (Femto-BS) is essentially a cooperative relay that works with a macro-mobile station to increase its throughput while gaining access to the macro-mobile station spectrum. For the two stations to work together, a strategy is being studied which provides optimal data rates, time allocation, and power allocation for the two stations. The critical cooperation region is the goal of the research behind these network structures [19].

New strategies of cooperation in cognitive radio will be conceived so that this technology can evolve and become viably efficient for the consumer market. It is likely that a cooperation strategy that offers the most throughput for the least power will become the most used strategy in cognitive radio, and could present somewhat of a de facto standard in the future.

VIII. Discussion

Several signal detection schemes exist which are able to sense whether the channel is in use. Commonly, energy detectors are used which are able to differentiate between noise and data being transmitted. This is best achieved using window functions such as the up sampled Hamming window in conjunction with an overlapped fast-Fourier transform. When the channel is available, the channel may be used by a secondary user without interfering with the primary user. In order to know which free channel will provide the best throughput for a secondary user, an online learning algorithm such as the Thompson sampling algorithm should be used. This method of detecting and accessing channels is an example of Cooperative Relaying. There are other algorithms which may be used to achieve similar, but less efficient results.

Since there are potentially many primary and secondary users on the system, a protocol must be set up to ensure the users are able to interact without conflict. The currently accepted scheme is the ISCI based relay selection strategy. This strategy assigns channels to the secondary user which will achieve the most efficient throughput after comparing all possible channels.

The ISCI strategy works with a coding method to eliminate any interference on the channel due to conflicts between the two users. The coding strategy, known as the dirty paper coding method, is a non-causal scheme which pre-codes data to allow for multi-layered transmission which reduces interference caused by multiple users.

IX. Conclusions

The use of cognitive radio techniques will enable far more efficient use of the frequency spectrum. The implementation of the system, however, requires more study before it will reach its optimal efficiency and efficacy. Here, we reviewed several techniques presented for detecting when the spectrum is in use, accessing the spectrum when not in use, selecting the most efficient channel for use by the secondary user, and transmitting over channels with high interference. In each of these categories, an optimal method was proposed. Future work in cognitive radio could lead to the discovery of how these techniques interact with each other to determine if they are able to form an effective system as a whole.

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