THE STATE OF THE ART OF DYNAMIC SPECTRUM ACCESS

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ABSTRACT

Cognitive Radio is one of the most promising paradigms for wireless communication, as it enables a flexible use of the radio spectrum. For this, several new techniques were developed that provide a good overview about the current spectrum usage and facilitate dynamic adaptation to it. Moreover, it was investigated how to integrate those techniques into the current static spectrum assignment. This article surveys the state of the art of those methodologies that pave the way for Cognitive Radio usage in the military domain.

1. INTRODUCTION

In the recent years wireless communication has suffered from frequency spectrum scarcity, as newly developed techniques always demanded an additional exclusive spectrum access. Nevertheless, the utilization of the assigned spectrum still only ranges between 15% and 85% [1]. In order to use those remaining spectrum holes, effort is put on achieving *Dynamic Spectrum Access* (DSA). This requires new techniques to adapt to the changing environment.

Moreover, those new techniques enable a DSA-capable device to autonomously select the best available channel. Due to this cognitive capability this device is called *Cognitive Radio* (CR). A Cognitive Radio has three main functions: *spectrum sensing*, *spectrum management* and *spectrum mobility*. According to [1], there is a fourth function named *spectrum sharing*, but this is basically a sub-function of spectrum management[1]. To improve those capabilities, several Cognitive Radios are grouped to a *Cognitive Radio Network* (CRN) in order to share spectrum information and therewith to provide a better overview for each node. This invokes cooperation not only between transmitter and receiver, but between all nodes of the network. This concept is referred to as *Coordinated Dynamic Spectrum Access* (CDSA). CDSA is however not only limited to the network-internal cooperation. According to the NATO Research Task Group on Cognitive Radio, coordination is also desirable between different networks. Note that CDSA does not necessarily imply sharing of spectrum information between the nodes or networks, it might just stand for a coordination of actions for not interfering with each other.

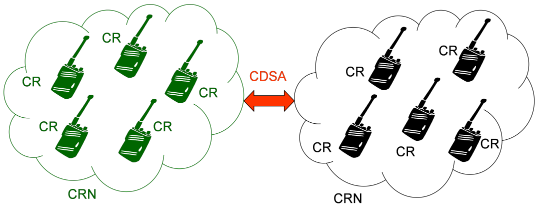

Figure 1: CDSA of two CRN

CR, CRN and CDSA all rely on the ability to sense, manage and change the spectrum. Only then integration into the current static spectrum assignment is pos-

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[1] In [1] spectrum management is described as "Capturing the best available spectrum to meet user communication requirements", while spectrum sharing means to provide "the fair spectrum scheduling method among coexisting xG users". In the authors' opinion both functions tend to manage the spectrum, the first one considering just one user, the second one considering all coexisting users.

sible. Section 2 describes models how this integration can be achieved. Section 3 and 4 will deal with the spectrum sensing and the Cognitive Manager. The last section will summarize the main issues.

2. DYNAMIC SPECTRUM ACCESS MODELS

According to [2] and [3], DSA can be separated into three models. The *Dynamic Exclusive Use Model*, the *Hierarchical Access Model* and the *Open Sharing Model*.

2.1. Dynamic Exclusive Use Model

Dynamic Exclusive Use deals with regulation of the spectrum by licensing models. A license allows a user to occupy a certain *frequency band* at a given *time* in a defined *geographic area*. Usually those licenses are issued by regional and national regulation authorities like the Federal Communications Commission (FCC) in the USA. In many cases the licensees do not utilize their spectrum at all times. Consequently, it is proposed to sub-lease these free frequency bands. This could be done by allowing the licensee to sell and trade spectrum. Thus a sub-licensee can be given the right to exclusively use this resource without being mandated by a regulation authority. This approach is called *Spectrum Property Rights*, as the license - or the right - is based on the three spectrum properties: frequency band, time and geographic area.

A second approach for the Dynamic Exclusive Use Model is *Dynamic Spectrum Allocation*. For this the temporal and spatial traffic statistics are exploited, which is valuable for sub-leasing long-term applications, such as UMTS or DVB-T. Sub-leasing based on traffic statistics leads to a much more flexible spectrum allocation than in the previous approach. But again, dynamic is limited to the capabilities of the licensee, so it is unlikely that with either of these approaches the spectrum holes can be optimally filled [2].

2.2. Hierarchical Access Model

Hierarchical Access is concerned with unlicensed secondary users, utilizing spectrum without interfering with licensed primary users. Concerning this matter two approaches are known, *Spectrum Underlay* and *Spectrum Overlay*. Both have in common that secondary users need to have an overview about the current spectrum in order to detect and identify primary users.

Spectrum Underlay exploits the spectrum by using it despite a primary user transmission, but by causing interference only below prescribed limits. This can be achieved by using spread spectrum techniques, resulting in a signal with large bandwidth but low spectral power density, which can coexist with primary users.

For not interfering with other signals, Spectrum Overlay is investigated. This approach intends to use spectrum holes in an opportunistic way (*Opportunistic Spectrum Access*), meaning that the spectrum is periodically monitored by the secondary user for absence of primary users in order to use the gaps to transmit oneself.

In some papers, like e.g. [4], Opportunistic Spectrum Access is referred to as *Interweave*. Spectrum Overlay is there defined as doing some pre-coding at the transmitter in order to diminish the interference at the receiver. Therefor extensive knowledge about other signals in the spectrum is necessary. This technique is also known as *Dirty Paper Coding* [8].

2.3. Open Sharing Model

While the Dynamic Exclusive Use Model and the Hierarchical Access Model assume primary users having a license to use a certain part of the spectrum, the Open Sharing Model assumes a free spectrum with only peer users. Again two different approaches how to organize interference-free communication are discussed. On one hand, a *centralized sharing strategy*, based on a central coordinator, is investigated, on the other hand a *distributed sharing strategy* is examined, where users have to avoid collision by negotiation. In order to achieve an optimal spectrum utilization, it is considered to organize Open Sharing based on a *Cognitive Manager*, e.g. by utilizing Game Theory.

2.4. Use of DSA in military environments

As DSA promises dynamic adaptability and robust communication, it is interesting for military applications. In a typical scenario there will be both several primary and several secondary users with which a DSA-capable device has to cope. Consequently, a military Cognitive Radio must implement the Hierarchical Access and the Open Sharing Model, the first one with respect to primary users or legacy systems, the latter one to compete with other secondary users for spectrum holes.

One of the keywords for the military technical evolution in recent years was Network Enabled Capabilities (NEC), in USA also referred to as Network Centric Warfare (NCW). As pointed out in [7], “NCW is built around the concept of sharing information and assets” to achieve “battlespace awareness and knowledge”. This corresponds to the idea of connecting several CR to a CRN. So it can be expected that for military environments CRNs will be in the focus of interest, and as there will be several of them, one of the most important challenges to overcome will be CDSA.

Nevertheless the application of CDSA in NEC yields to some advantages. It does not only support information exchange without intensive frequency planning, it is even more valuable for Electronic Warfare (EW). For Electronic Support (ES) it e.g. provides a good overview about other forces in the environment and knows the current spectrum status. In the same way CDSA can support Electronic Attack (EA) and Electronic Protection (EP), e.g. by coordinated attacks or dynamic circumvention of hostile attacks. Moreover the application of Dirty Paper Coding and Spectrum Underlay techniques is very promising for security aspects like Low Probability of Detection (LPD), Low Probability of Intercept (LPI) and Anti-Jamming (AJ).

A disadvantage of using CDSA is that its dynamic and adaptive nature yields new vulnerabilities. In [16] the four main differences between a legacy and a Cognitive Radio are pointed out: A Cognitive Radio is reconfigurable, utilizes spectrum sensing, bases its operation on spectrum policies and needs correct geolocation. Attacking any of these properties, e.g. by making the spectrum appear fully utilized or by jamming the GPS signal, might lead to a Denial of Service (DoS) or a misfunction of the Radio.

3. SPECTRUM SENSING

In the Open Sharing Model as well as in the Hierarchical Access Model it is indispensable to perform a reliable spectrum sensing to detect the presence of primary or other cognitive users. The data from the spectrum sensing function is needed to adapt the transmission parameters of the cognitive radios in order to avoid interference with others. Interference is a phenomenon that occurs at the receiver, while the transmitters can be hidden from each other, meaning that they are out of each others transmission range. This hidden node problem makes the spectrum sensing a challenging problem and can put severe requirements on the sensing sensitivity of the cognitive radio. In general, the sensing sensitivity, i.e. the ability of sensing the presence of a signal, must outperform the sensitivity of the (primary) receivers. The sensitivity of a receiver is defined as the minimum level of a received signal to be correctly decoded. As the sensitivity of a modern receiver is only a few dB above the noise floor, the cognitive radios must be able to sense the presence of other transmitters near or even in the noise. The latter is called sub-noise sensing.

The signal detection problem can be mathematically described as a binary-level hypothesis test over the received signal in a given frequency band:

$$\begin{aligned} H_0 : y(t) = &\quad n(t) \\ H_1 : y(t) = &\quad s(t) \quad + n(t), \end{aligned} \tag{1}$$

with H_0 the hypotheses of only noise $n(t)$ present and H_1 the hypotheses of the presence of a signal $s(t)$ and noise.

Several digital signal processing techniques can be used to improve sensing sensitivity of a cognitive radio. The most common ones are matched filtering, energy detection and cyclostationary feature detection, described in the next sections.

3.1. Matched filtering

The matched filter is the most optimal detector when the signal structure is known a priori, since it maximizes the received signal-to-noise ratio. Another advantage of the matched filter is that from the three above mentioned detectors, it has the smallest sensing time. Only $O(1/SNR)$ samples are needed to obtain a given probability of detection [5]. However, using a matched filter has some major disadvantages. It requires a coherent demodulation of the user signal, meaning that all parameters of the signal have to be known in advance and a dedicated filter is needed for each waveform. When the signal parameters are inaccurate, the performance of the detector degrades. Hence uncertainties on carrier frequency (Doppler shift) and channel information will impose practical limitations on the sensitivity of the detector. Below a given SNR threshold the detection will even become impossible.

3.2. Energy detection

The second detector is a non-coherent detector, for which no demodulation is needed. The energy detector is based on the estimation of the power spectral density function (PSD) over the frequency band of interest. If the PSD exceeds a given threshold, a signal is considered to be present. The problem here is to have a good PSD estimate. One way of doing this is by averaging frequency bins of a Fast Fourier transform (FFT), also called Welch periodogram averaging, as represented in Figure 2. The more samples N, that are taken for the FFT, the better the frequency resolution will be. The more time averages are taken, the less variance the PSD estimation will have, which will improve SNR. Energy detection can also be used under the presence of multi-path fading. It is shown in [9] that antenna diversity enhances the detection performances. Note that besides the Welch periodogram, other non-parametric and parametric PSD estimators exist [10], however they often also need some a priori knowledge about the signal structure.

The energy detector also has some disadvantages. First, it is not easy to set the detection threshold when the noise variance is unknown or changes over time. Secondly, the energy detector performs poor for spread spectrum signals or frequency hoppers, and third, the sensing time is proportional to $1/SNR^2$ to meet a given probability of detection.

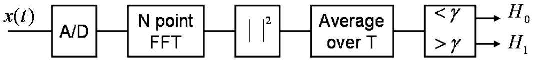

Figure 2: Implementation of an energy detector

3.3. Cyclostationary feature detection

A modulated signal is in nature a stochastic process that, is often for convenience considered to be stationary. Unfortunately, this assumption is not always valid. However, modulated signals normally have some build-in periodicity like sinusoidal carriers, periodical keying, etc. These signals are said to be cyclo-stationary, as they exhibit a periodicity over time in their statistics, such as mean and auto-correlation functions [11]. A cyclostationary feature detector will exploit cyclostationarity hidden in modulated signal for detection purposes. An important characteristic here is the Spectral Correlation Function (SCF), that is a generalization of the PSD. The Spectral Correlation Function is defined as

$$S_x^\alpha(f) = \lim_{T \to \infty} E\{X_T(f+\alpha/2).X_T^*(f-\alpha/2)\} \quad (2)$$

with $X_T(v)$ the finite time Fourier transform. $S_x^\alpha(f)$ is a two dimensional transform, in general complex valued. α is called the cyclic frequency. In [11] and [12] the SCF is calculated for the most commonly used types of modulation. In general, depending on the modulation type, lines will appear in the SCD at values for $\alpha \neq 0$. The presence of those cyclospectral lines is an indication of the presence of a modulated signal. Figure 3 shows a practical implementation of a cyclospectral feature detector.

The most important drawback of cyclostationary feature detection is its complexity. The calculation of the SCD and the detection of the cyclospectral lines is computational intensive. Furthermore the sensitivity of the method is limited by model uncertainties.

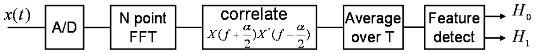

Figure 3: Implementation of a cyclospectral feature detector

4. COGNITIVE MANAGER

As already mentioned in section 2, in order to achieve an optimal spectrum utilization e.g. in the Open Sharing Model, there is a need for a Cognitive Manager. It has to be noted that normally the Cognitive Manager will not only influence the spectrum usage, but also other transmission parameters like transmit-power, modulation strategy, etc.

In a centralized Open Sharing Model, there is only one centralized Cognitive Manager that controls the whole cognitive radio domain. The Cognitive Manager can be straightforwardly implemented using an expert system, or the problem can be seen as an optimization problem for which a global optimum has to be found. The centralized approach assumes however that there is a reliable cognitive signaling channel connecting each radio to the centralized manager.

In the distributed Open Sharing Model or the Hierarchical Access approach, decision making is more complicated. Decisions have to be taken locally by all the transmitter-receiver pair, meaning that there must be a Cognitive Manager in every node. In this case, coordination between pairs or coalitions of pairs can facilitate the spectrum sensing and enhance the quality of the information, on which the pairs can rely to make their decisions.

4.1. Game Theory

In the decentralized approach, the Cognitive Manager can be based on Game Theory [6]. Game Theory is used to analyze strategic situations, in order to predict the outcome of decisions taken by self-interested, rational decision makers, so called players. Such a game can be expressed as $G = \langle M, A, \{u_i\}\rangle$, where M is the set of players, $A = A_1 \times A_2 \times ... \times A_M$ is the space defined by the set of actions A_i for each player i and u_i is the objective function that player i wishes to maximize. This objective function is a function of the action a_i taken by player i and the actions taken by all other players, denoted as a_{-i}. If the action tuple a taken by all players result in a steady-state, meaning that a deviation of any player i from his action a_i to an action b_i does not result in a larger payoff for this player, then a is called *Nash Equilibrium*.

Consequently, the aim of most games is to achieve a Nash Equilibrium. As in most cases not the complete information about the status of all other players is available, the problem is expressed as a non-cooperative game. In the absence of competition and in the assumption that every player has the correct information on the status of the other players, the game can be seen as an entirely cooperative game. In this case the problem simplifies to the optimization by every player of a single cost function and thereby eliminating the game-theoretic aspect of the problem.

For applying Game Theory to the process of decision making in a Cognitive Radio, the decision making process needs to be modeled in a game. First of all it must be known if there is a centralized or a distributed DSA model, like e.g. the centralized or the distributed Open Sharing Model. Secondly, it must be decided which performance metric, like e.g. the throughput or the delay, is to be optimized. Thirdly, all information about any Cognitive Radio in the environment of the decision maker needs to be collected, like e.g. the possible actions and the preferred strategy[2]. Finally, a mapping of the elements of a Cognitive Radio to a game must be carried out, as depicted in table 1. E.g. the number of players can be mapped to the number of transmitter - receiver groups, where a group consists of one transmitter and an arbitrary number of receivers.

Game Theory	Variable	Cognitive Radio
No. of players	M	No. of transmitter - receiver groups
Entirety of actions	A	Transmission parameter sets
Utility function, Payoff	u	Performance metrics

Table 1: Mapping of Cognitive Radio elements to a game, based on [14]

As described in [14], decision making based on Game Theory can be applied to all transport-oriented layers of the ISO/OSI Reference Model. Dependent on the problem, it might moreover be necessary or helpful to apply a certain type of game. In [15] it is e.g. explained how to model a network of Cognitive Radios as a potential game.

4.2. Iterative Water-Filling

As an alternative to Game Theory, the decision making problem can be approached using the iterative water-filling algorithm [6], rooted in information theory. In this approach a competitive sub-optimum is found. The available frequency band is divided into several sub-bands. A receiver i will calculate for each sub-band

$$\frac{\Gamma(N+I)}{|h_{ii}|^2} \tag{3}$$

which is a measure for the quality of that sub-band. N is the noise power in the considered sub-band, I the interference power introduced by all other users, h_{ii} characterises the direct channel between transmitter and receiver i, and Γ is the SNR gap. If the value in (3) for a sub-band exceeds a given water level L, the sub-band is considered too bad, and will not be used. If, on the other hand, the value in (3) is below the water level L, transmit power can be put in that band, as if power is poured into a reservoir up to the water level. The water level is chosen so that the total amount of power poured into the reservoir corresponds with the maximum transmit power of the transmitter. Iterative water-filling is the fact the water-filling algorithm is iteratively passed through by all players.

In many examples of the iterative water-filling algorithm found in literature (e.g. [6]), the strategy for the users is to maximize the cumulative bit rate over all users, constraint by the power budget of the individual users. However, this strategy implies a kind of centralized control to monitor the cumulative bit rate over all users. A more practical way of implementing the iterative water-filling algorithm is finding an equilibrium that optimizes the transmit power of each user autonomously, while trying to achieve an individual target bit rate, constraint by a maximum transmit power. This strategy is called distributed power control [13].

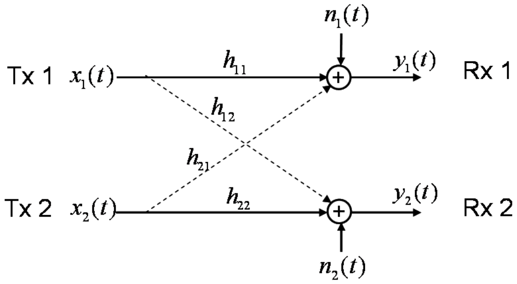

Figure 4: Interference channel model

Consider a simple scenario where two pairs of cogni-

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[2] The amount of information that can be achieved is related to the ability and willingness of the nodes to cooperate. E.g. in a purely centralized model all relevant pieces of information are collected at the centralized Cognitive Manager, so that this can be seen as a cooperative game.

tive radios try to communicate over a flat-fading channel, subdivided in four possible sub-bands. The interference channel model is represented in Figure 4 and characterized by a complex-valued baseband channel matrix

$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{21} \\ h_{12} & h_{22} \end{bmatrix} \tag{4}$$

that is considered the same for all four sub-bands. Both radio pairs have a target bit rate, a maximum transmit power, a perfect knowledge of their own channel and dispose off a feedback channel from receiver to transmitter. First receiver 1 and 2 will go iteratively through the water-filling algorithm. They will in turn sense the noise-and-interference in all four sub-bands, run the water-filling algorithm and report the outcome of the algorithm back to their respective transmitter, who will adapt its transmit power in each sub-band. After some iterations of this inner loop, the two receivers will individually evaluate the obtained data rate, compare it with the target date rate and accordingly adapt the total transmit power for the next iteration of the outer loop. The algorithm is illustrated in Figure 5. Iteratively, and completely independent from each other, the two radio pairs will converge to an equilibrium in only a few iterations. Figure 6 shows the result of a Matlab simulation, implementing the distributed power control iterative water-filling algorithm. For the simulation, the following numerical values are taken: each of the four sub-bands has a bandwidth of 25 kHz, the target bit rate is set to 128 kbps for both transmitters and the channel matrix equals

$$\mathbf{H} = \begin{bmatrix} 1 & 0.9 \\ 1.1 & 1.3 \end{bmatrix} * 1e^{-6}. \tag{5}$$

It can be seen that the two radio pairs independently converge to a kind of FDMA solution, where transmitter 1 is only using sub-band 2 and 3, and transmitter 2 only sub-band 1 and 4.

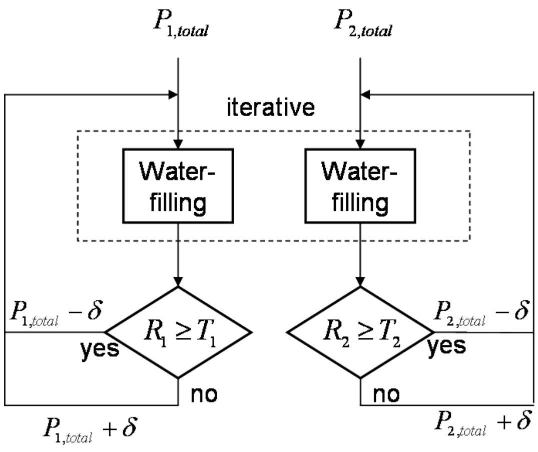

Figure 5: Iterative water-filling algorithm with distributed power control

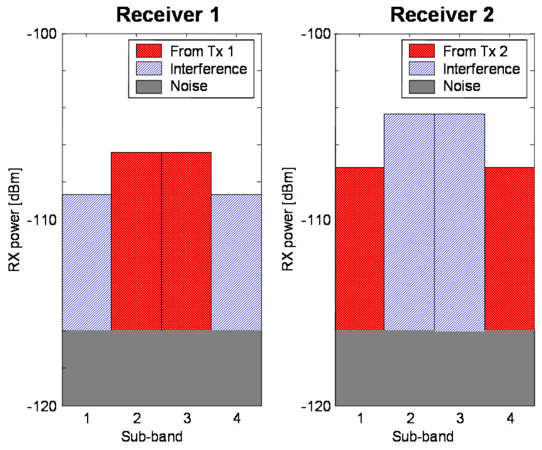

Figure 6: Result of a Matlab simulation implementing the distributed power control iterative water-filling algorithm, with two pairs of CRs and four sub-bands

5. CONCLUSION

In this paper, an overview is given about models and techniques to enable dynamic spectrum access.

For DSA, three models can be distinguished. The first model is the Dynamic Exclusive Model, in which frequency bands are sub-leased to other applications. In the Hierarchical Access Model, the second model, primary users have priority on the spectrum use. Secondary users are only allowed to access it, if they do not interfere with the primary users. In the third model, the Open Sharing Model, all users are equal and a strategy to avoid interference has to be put in place. This strategy can be centralized or distributed. In military applications, like NEC, the latter two models are the most interesting; the Hierarchical Access Model to cope with civil and military legacy systems, and the Open Sharing Model to avoid interference with other Cognitive Radio Networks. Utilizing CDSA technology for Electronic Warfare adds improvements and enables new features, but on the other hand it yields new vulnerabilities.

To enable DSA, a cognitive radio device has to implement some new functions. The first one is spectrum sensing. A reliable and fast spectrum sensing is indispensable for an efficient DSA, as decisions on the spectrum access will be made upon the outcome of this bloc. Due to the hidden node problem, the Cognitive

Radios have to be able to detect the presence of a signal in the noise. The most common detectors described in literature are the matched filter, the energy detector and cyclostationary feature detector. Each of these detectors has its advantages and drawbacks. Their performance is measured by their sensing sensitivity and the sensing time. It is clear that coordinated sensing will enhance the detection performances in a CRN.

A second important new function is the Cognitive Manager. In a completely centralized strategy the implementation of a Cognitive Manager can be straightforward, however, in a distributed strategy the implementation of it can be challenging. In this paper, two approaches are discussed: the first one based on Game Theory and the second one based on the iterative water-filling method. As a proof of concept, a simple scenario with two pairs of Cognitive Radios based on the distributed power control iterative water-filling algorithm, is simulated. It can be seen that the two radio pairs independently converge to a kind of FDMA solution.

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