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Cooperative Cognitive Systems

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1. Introduction

Cognitive Radio is a new paradigm in wireless communications to enhance utilization of limited spectrum resources. It is defined as a radio able to utilize available side information, in a decentralized fashion, in order to efficiently use the radio spectrum left unused by licensed systems. The basic idea is that a secondary user (SU)(a cognitive unlicensed user) is able to properly sense the spectrum conditions and, to increase efficiency in spectrum utilization, it seeks to underlay, overlay or interweave its signals with those of the primary (licensed) users (PUs), without impacting their transmission. In this sense, the cognitive radio paradigm defines a set of rules for the coexistence of two or more radio systems in a given spectrum allocation. These systems are given different usage rights and a set of rules to abide. While coordination between different systems is not a requirement, it may improve the performance of both primary and secondary users, as it is argued in this text. In particular, the book chapter is organized in two parts. In the first part (section 2), we provide several mechanisms which require cooperation and improve different functions of the cognitive radio mechanism. Secondary spectrum usage, requires more sophisticated spectrum management and coexistence techniques than licensed or unlicensed spectrum operation. Different degrees of cooperation are possible: from simply following the spectrum regulation and keeping transmission power below the specified mask, to accurate sensing and tracking of the primary licensee, or contribution of the SUs to the detection of the primary signal. A higher degree of cooperation entails a higher degree of complexity, both in terms of hardware design and in terms of network coordination. This results in a tradeoff between performance gain and complexity increase, which may result in the adoption of a particular cooperative solution. Then, we focus on mechanisms requiring cooperation at the physical layer level, in terms of signal design and we address the most significant relaying techniques. In the second part of the chapter 3, we focus on the decisions the cooperative cognitive radios have to make. These decisions strongly depend on those made by the other radios, since the licensed users performances are limited by the aggregated interference generated by all the cognitive radios simultaneously transmitting in their band. This is why the performance is analyzed using game-theoretic tools, already proven good at modeling interactions in decision processes. As a result, the focus of the second part of the chapter is to take advantage of the cooperative schemes introduced in the first part in order to model and control the interference generated at the licensed users by the cooperative and cognitive system. We propose a particular kind of games, characterized by favorable convergence characteristics, i.e. potential games, and we describe how to design and identify these games, in both cases of complete and incomplete information. Finally, we summarize the chapter conclusions in chapter 4.

2. Cooperation Mechanisms for Cognitive Radio

2.1 Cognitive Radio Techniques: Interweave, Underlay, Overlay

Different strategies for cognitive radio environments have been defined, depending on how secondary usage of the spectrum is carried out. A first strategy, which is in line with the original idea of secondary spectrum usage, consists in utilizing the *spectrum holes* left by primary systems to establish communications between SUs. This approach has been referred to as *interweave*Srinivasa (2007). A second approach consists in ensuring that secondary transmissions are always below the maximum allowable interference temperature at the primary receivers[1]. This approach is referred to as *underlay*. Finally, a third approach consists in the SUs cooperating with the primary transmission while transmitting their own signal. This scheme is known as *overlay*. These schemes are schematically represented in Figure 1.

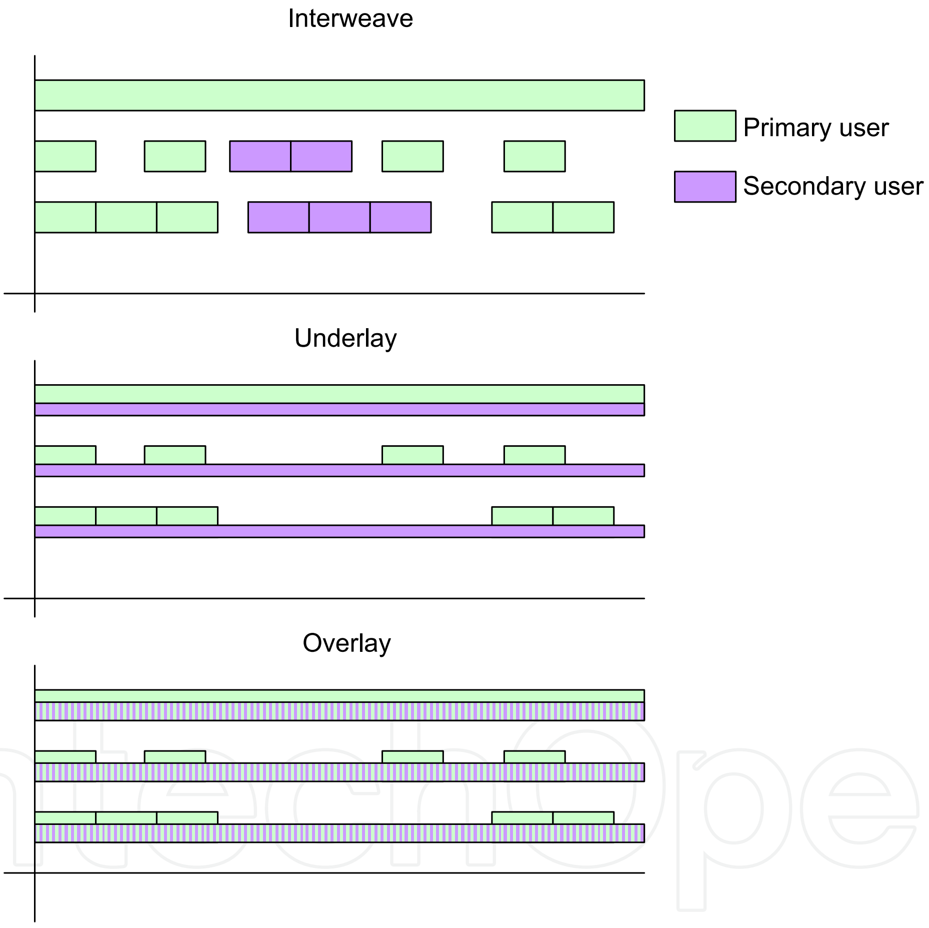

Fig. 1. Different types of cognitive radio schemes: interweaved transmission of primary and secondary signals, underlay of secondary signal, and cooperative overlay of secondary signal.

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[1] Interference temperature is a measure of the noise and interference power level at the receiver.

2.1.1 Interweave Cognitive Radio

Interweave cognitive radio follows an interference avoidance strategy. SUs are only allowed to use the spectrum when primary users are inactive. Such method is opportunistic in the sense that SUs take advantage of spectrum that otherwise goes unused, and implements the original idea that cognitive radio should exploit the so-called spectrum holes left by the primary licensee. The main difficulty in the interweave scheme is that of sensing and predicting the activity of the primary user in several radio channels, i.e. detecting the spectrum holes. This task becomes more difficult if PUs are highly dynamic, i.e. their spectral activity changes fast, and it requires secondary transmission equipment to be very agile in switching on and off, and in switching frequency channels. It also becomes more difficult when the range of secondary transmissions increases, as the primary activity sensed by the secondary transmitter and secondary receiver may vary due to different signal strengths of the primary signal. These factors decrease the correlation between the spectrum sensed at the transmitter and at the receiver, and therefore reduce the effectiveness of secondary spectrum utilization.

2.1.2 Underlay Cognitive Radio

The underlay approach is a more conservative choice. Rather than tracking the primary user activity and adapting to it, it consists in transmitting at very low power to ensure that the interference temperature of the primary user does not exceed a predefined limit. This method has very different requirements on the secondary transceiver equipment than the interweave scheme. Rather than time and frequency agile radios, the secondary transceiver must be able to operate at very low SNR (Signal to Noise Ratio). This typically restricts underlay cognitive radio to low data rate applications or very short range applications.

Underlay cognitive radio has been adopted by regulatory bodies worldwide, and is allowed when SUs transmit using the Ultra-wideband (UWB) signal format. The UWB signal format is limited by a very strict spectral mask, allowing very low power transmission in a large bandwidth which overlaps with other licensed services (the actual bandwidth varies in different countries and is defined by their corresponding regulatory bodies). Due to its large bandwidth, the spectrum used by UWB spans several primary services. The spectral mask, along with additional restrictions on its operation (passive beacons, for example, are not allowed, and outdoor usage is restricted to handheld devices) ensures that secondary (UWB) transmission does not interfere with primary bandwidth usage, as the received UWB power at any primary receiver is typically well below the noise floor. However, such restrictive regulation limits the applicability of UWB to very short range applications (below 10m), such as personal area networks or cable replacement applications. Longer range operation, up to 300m, is possible but at very low data rates.

2.1.3 Overlay Cognitive Radio

In the overlay approach, SUs devote part of its transmit power to enhance the primary signal and facilitate its detection at the primary receiver. In exchange, they may be allowed to increase the interference temperature level further than the underlay approach. The fact that they contribute to improve the detection of the PU may also contribute to a higher acceptance of this technique by primary licensees. Thus, the overlay approach can be seen as an evolutionary step from the underlay technique, where a tighter degree of integration between primary and secondary is necessary, and higher performance is achieved. However, the overlay approach has not been yet implemented. The basic principle is that SUs that are close to the primary transmitter have access to a high quality primary signal which they are able to successfully decode. Then, they use knowledge of the primary message to produce a signal that complements the primary signal and improves the detection probability of the primary receiver. At the same time, the secondary transmitter communicates with the secondary receiver with a low-power signal. It may be assumed that either the secondary transmitter or secondary receiver have knowledge of the primary signal, or both. Depending on the assumption made, several techniques, such as dirty paper coding, or successive interference cancelation, may be applied.

The main advantage of this approach is the higher interference temperature that can be tolerated, and better detection of the primary signal. On the other hand, this technique requires a higher degree of complexity in the secondary transceivers, and assumes that these are able to produce a compatible signal format when aiding the primary transceiver. Furthermore, this scheme may require knowledge of the channel state in order to guarantee that the primary signal is successfully detected. Finally, a power control mechanism must be put in place which determines the power that secondary transmitters devote to the primary and secondary signals, respectively.

2.2 Cooperation in Interweave Cognitive Radio Systems

In the initially proposed interweave cognitive radio scheme, where the SUs track the activity and spectrum usage of the primary licensee and adapt to it, several mechanisms have been proposed to improve their spectrum utilization.

In the event of lack of coordination, SUs must use sophisticated algorithms to track and predict the activity of PUs. Such mechanisms, may be effective for static, predictable primary licensees, such as television broadcasters. However, several factors decrease the efficiency of an uncoordinated approach, as argued earlier.

If one allows for a certain degree of cooperation between secondary users, these can exchange the outcome of their spectrum sensing and collectively provide a better notion of the primary spectrum occupancy Ghasemi & Sousa (8-11 Nov. 2005, Baltimore, USA). For example, a shadowed user may learn from the presence of a primary through the exchange of spectrum occupancy information with other SUs.

A further step is to allow coordination between primary and secondary systems. An effective approach is that the PU signals with beacons the spectrum occupancy in its channels. SUs may then monitor the beacon channel and learn about spectrum holes. In addition, such beacons can be designed to be easily detected with strong modulation and channel coding formats. Several options are possible in a beacon system: to use grant beacons to signal spectrum availability; to use denial beacons to warn about the activity of the primary system, so that SUs do not transmit; or to use a dual beacon approach, which is better in the case of multiple primary transmitters Mangold (2006). In this case, users must wait until they hear a grant beacon and, at the same time, no denial beacon is detected. The advantage of this approach is that a SU that is "hidden" from the primary transmitter (and does not receive the denial beacon) may not receive a grant beacon either, thus refrain from transmitting and interfering the primary communication.

In the following section we study a second type of cooperation where SUs actively contribute to enhance the quality of the primary signal at the primary receiver.

2.3 Cooperative Transmission for Overlay Cognitive Radio

In the previous section, several techniques were described in order to facilitate the coexistence of primary and secondary signals in a cognitive radio spectrum. Of the techniques described, the overlay of secondary signals requires SUs to relay the primary signal in order to compensate for the increased interference temperature. Such requirement is implemented using so-called physical layer cooperative transmission. The most important aspect of this technique is that SUs shall be able to relay the primary signal in such a way that its detectability at the primary receiver is increased. In this section we shall review the concept of physical layer cooperative transmission, and outline the most effective techniques.

The wireless channel is a shared medium, where a transmission intended to a particular user is overheard by many others. While this often creates unwanted interference, it also provides the transmitted signal to neighouring nodes *for free*. The concept of physical layer cooperation takes advantage of this property by reinforcing the direct transmission through additional transmissions from other nodes in the network which have overheard the original signal. In a multiuser network, such transmissions can take place along with each user's own transmission.

The foundations of such scheme lay in the information-theoretic relay channel model, as well as in the models described in Sendonaris et al. (2003), among others. In qualitative terms, the following benefits can be derived from physical layer cooperation:

- Spatial diversity: cooperating nodes provide antenna diversity in a similar fashion to multiple antenna terminals. Spatial diversity can be exploited to make the received signal more robust to channel impairments and decrease the outage probability
- Increased range: relaying has been typically used to extend the range of transmissions. In a cognitive radio environment, relaying can be used to extend the range of the primary signal.
- Increased availability: service availability is typically limited by shadowing of obstacles in the coverage area, such as buildings or mountains. Physical layer cooperation can be used to go around obstacles and therefore reduce the number and size of shadowed areas.

The system model for overlay cooperation is shown in Figure 2; the primary transmitter signal is detected by the SUs. These transmit two signals, one intended for the primary receiver and a second one intended to the secondary receiver.

2.3.1 Relaying Techniques

Relaying techniques have been thoroughly studied. Classically, relaying has been performed at the network layer, where packets are forwarded from one hop to the next according to the information in the routing tables. At the physical layer, relaying should be seen as a transmission technique focused on improving the end-to-end reliability of a wireless transmission involving multiple hops. Therefore, rather than being the transition from one hop to the next, relaying assumes that the receiver will decode the packet using both the information received directly from the source and the relayed signal. We shall focus on the simpler case of the parallel relay channel, where one or more relays communicate with source and destination, but not among them. The more complex case of serial relaying deserves a more elaborate treatment.

A first broad classification of relaying techniques is regenerative versus non-regenerative relaying. Regenerative techniques assume that the relay is able to decode the source signal, and re-process it in order to increase the effectiveness of relaying. Non-regenerative techniques assume that the relay is not able to retrieve any information about the received signal, and therefore the relaying operation is not able to distinguish between desired signal, noise,

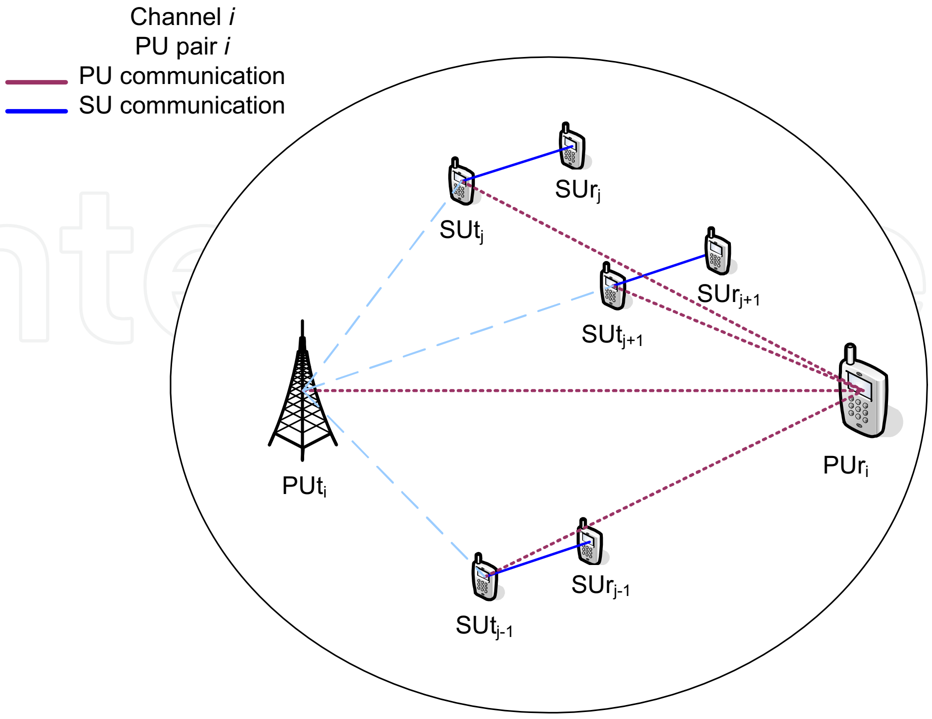

Fig. 2. Implementation of overlay cognitive radio through SU cooperation. SUs relay the primary signal and contribute to improve its reception at the primary receiver. In exchange, they are allowed to increase the interference temperature by communicating in that same band.

or interference. While non-regenerative relaying shall, in general, underperform regenerative techniques, it has the advantage of allowing more users to participate in the cooperative transmission, since they do not need to be able to decode the transmitted signal.

Another important aspect is the implementation of the cooperative scheme. We first shall distinguish between full-duplex relays, able to transmit and receive simultaneously in the same frequency band, and half-duplex relays. The former is difficult to implement in practice and more of an academic interest, therefore the latter shall be assumed hereafter. If half-duplex relaying is implemented, relays first listen to the source transmission and then occupy the channel to communicate with the destination. They may do so simultaneously (in a space-time coded signal or using beamforming), taking turns in a time division multiplexing scheme, or upon request, in an ARQ-like style. These implementations are shown in Figure 3.

In the following we address relaying techniques in more detail.

Decode and Forward: With this approach, the relay decodes the source signal and retrieves the transmitted data bits. These are then reencoded and transmitted to the destination. One of the main advantages of this technique is its flexibility. Relays may use different strategies when reencoding the signal, from regenerating the source signal to transmitting incremental redundancy. Moreover, they may choose different encoding schemes depending on the relay-to-destination channel. On the other hand, decode and forward requires the relay to

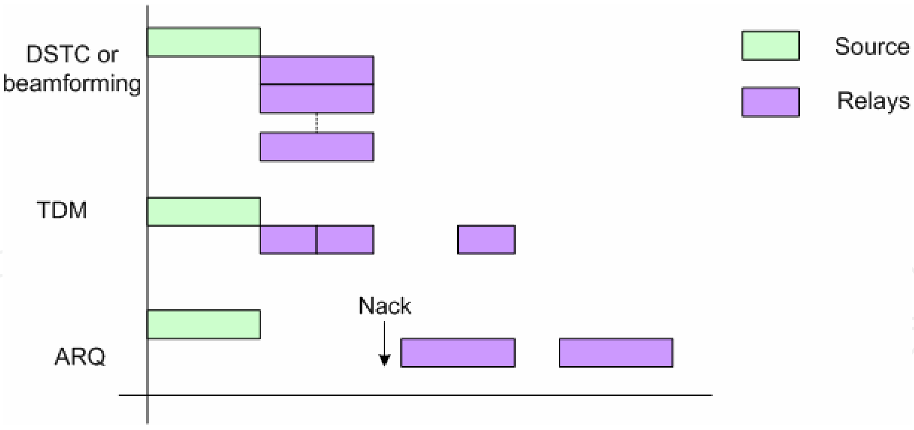

Fig. 3. Implementation schemes of parallel relaying: distributed space-time coding (DSTC) or beamforming, where relays transmit simultaneously; time-division multiplexing (TDM), where relays are organized in consecutive time slots; Automatic Repeat Request (ARQ), where relays transmit upon receiving a negative acknowledgment from the destination.

decode the source signal in order to cooperate with the transmission. In many instances, this is not possible and severely limits the number of potential cooperating users. As a result, the diversity gain of this technique is typically smaller than that of non-regenerative techniques.

Linear Relaying: In non-regenerative relaying, the relay takes the signal at its input and reproduces it at its output, after some processing. The main difference with decode and forward is that the relay is not able to recognize the desired signal from noise and interference. In linear relaying, the relay processing is limited to a linear operation. Amplify and forward constitutes the simplest form of linear relaying schemes, where the output is an amplificated version of the input. In more general case of linear relaying, the output is a linear function of past inputs. The linear relaying relay channel can be characterized as a multipath channel. However, unlike traditional multipath channels, the relays amplify noise and interference. With this technique, the beamforming or TDM schemes can be used (this type of relay would not understand a NACK from the transmitter, therefore the ARQ-like approach is not feasible). For the beamforming scheme, the relay should be able to retrieve phase information for the incoming signal, and then transmit coherently to the destination.

Compress and Forward: Compress and forward constitutes a non-linear approach to non-regenerative relaying. In this technique, relays quantize the signal received from the source, compress it, and transmit it to the destination with the appropriate channel coding. Either lossy or loss-less compression can be used. In this technique, relays transmit different data, therefore the TDM or ARQ schemes should be used. While this technique shares the advantage of linear relaying that all relays can cooperate, it is limited by the capacity of the relay-destination channel to transmit all the quantized data. This limitation becomes more severe as the number of relays increases.
Figure 4 del Coso & Ibars (2009) shows the performance of different relaying schemes as a function of the relative distance between source and relay.

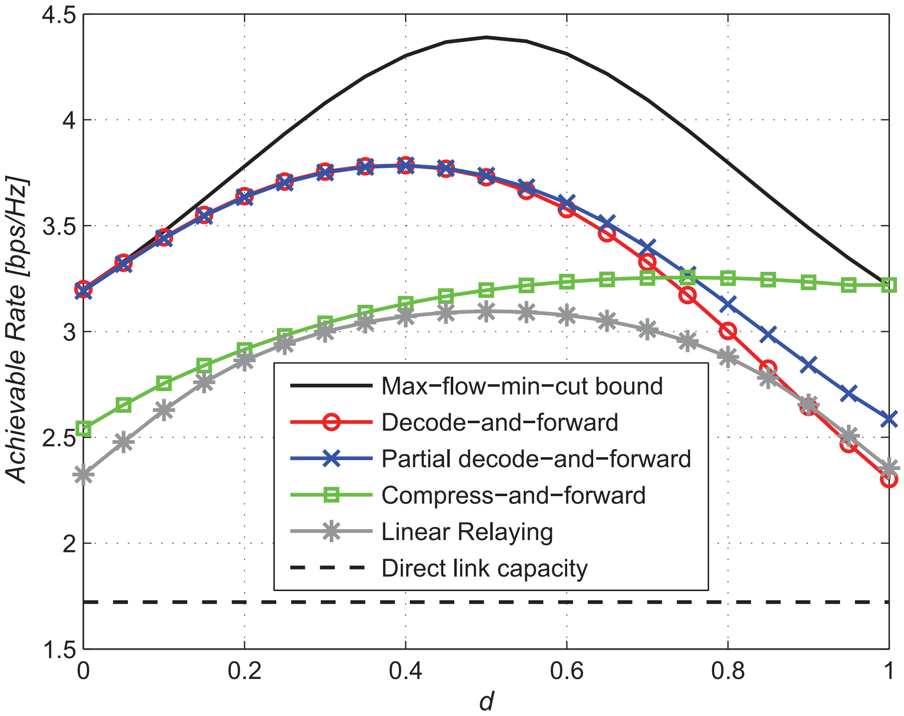

Fig. 4. Performance comparison of parallel relaying schemes, in a two-relay scenario where the source-relay distance varies from 0 to 1 and source-destination distance is fixed at 1: regenerative techniques are nearly optimal when the relays are close to the source, and non-regenerative techniques have an advantage when they are close to the destination. All techniques outperform the direct link capacity. A beamforming / DSTC scheme is assumed in all cases.

3. Game-theoretic Interference Management

The performance of cognitive radio networks are ultimately limited by interference, so that smart algorithms for power and channel control become key element in the network design. An additional difficulty arises because cognitive radios, independently make decisions about transmission power level and frequency channel, to maximize their own benefit. Such actions affect not only their performance, but also that of the entire network.

The cognitive radio network can be naturally modeled using a game theoretic framework, in which the players of the game are the radio terminals, their actions are their choices of transmission parameters (e.g. transmission powers, frequency channels, access probability, relay nodes), and their utilities are their defined performance measure that each radio tries to maximize. The players choose their actions independently, but their choice impacts on all the users in the network. The players are also assumed to be rational, i.e. they act in their best interest, to maximize their own utility. The underlay paradigm for cognitive radio, already introduced in the previous subsections, can be modeled by means of game theoretic approaches Nie & Comaniciu (8-11 Nov. 2005, Baltimore, USA). The main drawback of this approach is that the maximization of the game utility function represents an incentive to reduce the interference at the PU's receiver, but not a guarantee that the aggregated interference generated by the SUs is maintained below a certain threshold, especially in scenarios where the spatial reuse is most challenging, e.g. where PU's receivers are passive or where SU's transmitters are very close to PU's receivers. In this context, cooperation of SUs and PUs (overlay approach) can significantly reduce the interference at the PU's receivers. As a result, in this section, after briefly introducing the basic concepts of game theory (3.1), we consider this discipline to model cooperation among SUs and PUs (3.2). Specifically, we present a game to model channel and power allocation for cooperative cognitive radios. We will consider both the hypothesis where complete and incomplete information about the other players' channel conditions and actions is available across the SUs. To solve the problem of incomplete information a Bayesian game has to be considered.

3.1 Game Theory

Game theory is a discipline to model interactive decision making processes. A significant amount of work in wireless communications is related with the use of game theory. A game consists of a finite set of N players. Each player $i \in N$ selects a strategy $s_i \in S_i$ with the objective of maximizing a utility u_i. The strategy profile s is the vector containing the strategies of all players: $\mathsf{s} = (s_i)_{i \in N} = (s_1, s_2, ..., s_n)$. It is customary to denote s_{-i} the collective strategies of all players except player i. The space of strategy profiles is defined as the Cartesian product of the individual strategy spaces: $\mathsf{S} = \times_{i \in N} S_i$. Finally, the utility function characterizes each player's sensitivity to everyone's actions. It is therefore a scalar valued function of the strategy profile: $u_i(s_i, s_{-i}) : \mathsf{S} \longrightarrow \Re$.

The most well known equilibrium concept in game theory is the Nash equilibrium. The Nash equilibrium is a joint strategy where no player can increase its utility by unilaterally deviating. That is:

Definition 1: A strategy profile $\mathsf{s} \in \mathsf{S}$ is a Nash equilibrium if $u_i(s_i, s_{-i}) \geq u_i(s_i^{'}, s_{-i}), \forall s_i^{'} \in \mathsf{S}_i, \forall i \in N$.

An alternative interpretation of the definition of Nash equilibrium is that it is a mutual best response from each player to other players' strategies.

Definition 2: The best response $br(s_{-i})$ of player i to the profile of strategies s_{-i} is a strategy s_i such that: $br_i(s_{-i}) = argmax_{s_i \in S_i} u_i(s_i, s_{-i}))$.

The first step towards solving a game is to investigate the *existence* of a Nash equilibrium. Once we have verified that a Nash equilibrium exists, we have to determine whether it is a *unique* equilibrium point. If the players have identified various Nash equilibria, it still might be difficult for them to coordinate on which one to choose. In case that there exists only one Nash equilibrium, we would be guaranteed that the player would play it. In order to have this favorable convergence characteristics, some mathematical properties have to be imposed on the utility functions. In particular, certain classes of games have shown to always converge to a pure Nash Equilibrium when a best response adaptive strategy is applied. An example of them is the class of Exact Potential Games. This kind of games is characterized by complete information about the utility functions across the multiple players. However, to model a broader class of real life situations, incomplete information should be considered by means of the so called bayesian potential games.

Finally, it is useful to identify a method to assess the efficiency of the reached equilibrium point. This method is based on the comparison of the strategy profiles using the concept of Pareto-optimality. To introduce this concept, we first define Pareto-superiority.

Definition 3: The strategy profile s is Pareto-superior to the strategy profile $\mathsf{s}^{'}$ if for any player i: $u_i(s_i, s_{-i}) \geq u_i(s_i^{'}, s_{-i}^{'})$, with strict inequality for at least one player. In other words, the

strategy profile s is *Pareto-superior* to the strategy profile $\mathsf{s}^{'}$, if the utility of a player i can be increased by changing from s to $\mathsf{s}^{'}$, without decreasing the utility of other players. Based on the concept of Pareto-superiority, we can identify the most efficient strategy profile.
Definition 4: The strategy profile s^p is Pareto-optimal if there exists no other strategy profile $\mathsf{s}^{'}$ that is Pareto-superior to s^p.
In a Pareto-optimal strategy profile, one cannot increase the utility of player i without decreasing the utility of at least one other player. Therefore, using the concept of Pareto-optimality, we can eliminate poor Nash equilibria by selecting those with a Pareto-superior strategy profile.

3.1.1 Potential games

Potential games were defined and discussed together with their properties in D. & B. (1996). A game $\Gamma = \{N, \{S_i\}_{i \in N}, \{u_i\}_{i \in N}\}$ is an exact potential game if there exists a function Pot : $\mathsf{S} \longrightarrow \Re$ such that, for all $i \in N$, $s_i, s_i^{'} \in S_i$,

$$Pot(s_i, s_{-i}) - Pot(s_i^{'}, s_{-i}) = u(s_i, s_{-i}) - u(s_i^{'}, s_{-i}) \tag{1}$$

The function Pot is called *Exact Potential Function* of the game Γ. The potential function reflects the change in utility for any unilaterally deviating player. As a result, if Pot is an exact potential function of the game Γ, and $\mathsf{s}^* \in \{argmax_{s \in S} Pot(s)\}$ is a maximizer of the potential function, then s^* is a Nash equilibrium of the game. In particular, the best reply dynamic converges to a Nash Equilibrium in a finite number of steps, regardless of the order of play and the initial condition of the game, as long as only one player acts at each time step, and the acting player maximizes its utility function, given the most recent actions of the other players. Notice that, for a finite exact potential game, i.e. characterized by a finite strategy space and a finite player set, the game has at least one pure-strategy Nash equilibrium. In addition to this, another significant property is that if the players follow a better response dynamic (whenever a player has an opportunity to revise its strategy, it will chose one characterized by a higher utility than the current one), all the repeated games where each stage is the same finite exact potential game and all players are myopic, converge to the Nash equilibria of the stage game. Considering the interesting properties of potential games, it would be useful to know how to recognize or design one of them. There exist some properties that might be helpful in recognizing these games.
Definition 5: A *coordination game* is a game in which, for any choice of pure strategies, all the players receive the same utility. That is, $u_i(s) = u_j(s), \forall i, j \in N, \forall s \in \mathsf{S}$. As a result, there exists some function $V : \mathsf{S} \longrightarrow \Re$ such that $u_i(\mathsf{s}) = V(\mathsf{s}) \forall i \in N, \forall \mathsf{s} \in \mathsf{S}$. All the maximizers of V are Nash equilibria, and at least one of them must be Pareto efficient.
Definition 6: A *dummy game* is a game in which each player's utility is a function of only the actions of other players, so that unilateral deviations do not produce any change in the utility of the deviating player: $u_i(\mathsf{s}) = D_i(s_{-i}), \forall i \in N$.
Considering these two definitions, the result is that any exact potential game can be written as the sum of a coordination and a dummy game. That is, there exist functions $V : \mathtt{S} \longrightarrow \Re$ and $D_i : \mathtt{S}_{-i} \longrightarrow \Re$, such that $u_i(\mathsf{s}) = V(\mathsf{s}) + D_i(s_{-i}), \forall i \in N, \forall \mathsf{s} \in \mathsf{S}$.
As a result of that, one way of identifying an exact potential game is to try to separate the game into a coordination and a dummy game.
Finally, it is worth noting that for continuous and twice differentiable utility functions, a game is potential if and only if:

$$\frac{\partial P}{\partial s_i} = \frac{\partial u_i}{\partial s_i}, \forall i \in N \tag{2}$$

and

$$\frac{\partial^2 P}{\partial s_i \partial s_j} = \frac{\partial^2 u_i}{\partial s_i \partial s_j} = \frac{\partial^2 u_j}{\partial s_i \partial s_j}, \forall i, j \in N \tag{3}$$

3.1.2 Bayesian Potential games

When some players do not know the utility of the others, the game is said to have incomplete information. The case of perfect knowledge of utilities is a simplifying assumption that may be a good approximation in some cases. A game of incomplete information is defined as: $\Gamma = \{N, \{S_i\}_{i \in N}, \{\eta_i\}_{i \in N^+}, \{f_{H_i}(\eta_i)\}_{i \in N}, \{u_i\}_{i \in N}\}$, where, besides the players, the strategy space and the player's utility, we also have to define the player's type and its distribution probability. The player's type embodies any information that is not common knowledge to all players and is relevant to the players' decision making. This may include the player's utility function, his belief about other player's utility functions, etc. Each player is assumed to observe perfectly its type, but is unable to observe the types of its neighbors. As for the game with complete information, we need to find an equilibrium point from which no player has anything to gain by unilaterally deviating. In a Bayesian game, this point is a Bayesian Nash equilbrium, that is, a Bayesian Nash equilibrium is a Nash equilibrium of a Bayesian game. In particular, a strategy profile $\mathsf{s}^* = (s_1^*, ..., s_N^*)$ is a Bayesian Nash equilibrium if $s_i^*(\eta_i)$ solves (4), assuming that types of different players are independent.

$$s_i^*(\eta_i) \in \arg\max_{s_{i \in S}} \sum_{\eta_{-i}} f_H(\eta_{-i}) u_i(s_i, s_{-i}; \eta_i, \eta_{-i}) \tag{4}$$

As it is proven in Fuderberg & Tirole (1991), the existence of a Bayesian Nash equilibrium is an immediate consequence of the Nash existence theorem. As a result, considering that the potential games have shown to always converge to a Nash Equilibrium when a best response adaptive strategy is applied, it can be derived that for the Bayesian Potential game Γ there exists a Bayesian Nash equilibrium, which maximizes the expected utility function Facchini et al. (1997).

3.2 Game Theoretic Modeling of Cooperative Cognitive Radios

In this section we model joint channel and transmission power selection in a cognitive radio scenario as the output of a game where the players are the N SUs, the strategies are the choice of the transmission power and of the frequency channel, and the utility is a function of: (1) the interference each SU causes to the surrounding PUs and SUs simultaneously operating in the same frequency channel, (2) the interference each SU receives from the surrounding SUs simultaneously operating in the same frequency channel, (3) the satisfaction of each SU. The SUs are aware of the interference they receive, but to evaluate the interference they cause to the surrounding PUs and SUs, they need information about the wireless channel gains of their neighbors.

To retrieve this information, we consider two cases. In the first case, we foresee the existence of a CCC where all the users in the scenario share their transmission information, so that the decisions of the SUs are made with complete information. Much attention has recently been paid to this kind of channels, some examples are the Cognitive Pilot Channel (CPC) Perez-Romero et al. (17-20 April, Dublin, Ireland) proposed by the E2R2/E3 consortium, or the radio enabler proposed by the P1900.4 Working Group. In the second case, taking into account that the hypothesis of the existence of a CCC has often been rejected in the cognitive radio literature, we provide a more realistic and feasible proposal by avoiding the need of the CCC and assuming that the decisions of the SUs are made with incomplete information.

3.2.1 System Model

The cognitive radio network we consider consists of M transmitting-receiving PUs pairs, and N transmitting-receiving SUs pairs. We will indicate the transmission power levels of the PUs' transmitters as $p_i^P, i = 1, ..., M$, and the transmission power levels of the SUs' transmitters as $p_j^S, j = 1, ..., N$. PUs and SUs, both transmitters and receivers, are randomly and uniformly distributed in a circular coverage region of a primary network with radius R_{max}. The SUs are in charge of sensing the channel conditions and of choosing a transmission scheme which does not disrupt the communication of the PUs. A SU distributively selects the frequency channel and the transmission power level to maximize its throughput while at the same time not causing harmful interference to the PUs. On the other hand, according to a cooperative paradigm, besides selecting the transmission power and the frequency channel, the SUs devote part of their transmission power to relaying the primary transmission. As a result, the SU's transmission power level is split in two parts, 1) a power level $p_j^{S'}, j = 1, ..., N$ for its own transmission, and 2) a cooperation power level $p_j^{S''}, j = 1, ..., N$ for relaying the PU's message on the selected band, where $p_j^S = p_j^{S'} + p_j^{S''}$. The cooperative scheme used by the SUs is shown in Fig. 5, where half-duplex operation is assumed. The PU transmission is divided into frames, and each frame further into slots. Relays are assumed to operate in half-duplex mode. Therefore, each relay listens to the primary transmission during one slot and transmits during the next. The relay will choose, as part of its strategy, whether to listen during even or odd slots. Decode & Forward relay mode is assumed.

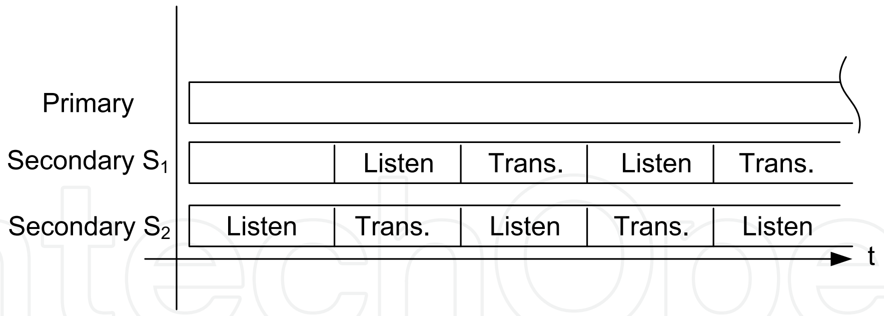

Fig. 5. Half-duplex relaying scheme for SUs. Each user chooses one slot to listen to the primary and retransmits in the following slot. Secondary users choose in which slot to transmit as a part of their strategy.

3.2.2 Game Model with complete information

Rather than relying on a network operator to decide on the power and channel allocation of the SUs, suppose that each user i is free to choose its own power allocation with the goal to

minimize the interference at the PUs and at the other SUs, and to maximize its own throughout. The resulting interaction among SUs and PUs leads to a non-cooperative game, which is defined as follows:
i) N is the finite set of players, i.e. the SUs.
ii)The strategies for player $i \in N$ are:

- a power level p_i^S in the set of power levels $P^S = (p_1^S, \cdots, p_m^S)$;
- the power level $p_i^{S'}$ that the player devotes to its own transmissions, in the set of power levels $P^{S'} = (p_1^{S'}, \cdots, p_q^{S'})$, where q is the order of set $P^{S'}$;
- the cooperative power level $p_i^{S''}$ that the player devotes to relaying a PU transmission and which is computed as $p_i^{S''} = p_i^S - p_i^{S'}$. The set of these power levels, $P^{S''}$, is the same as $P^{S'}$;
- a channel c_i in the set of channels $C = (c_1, \cdots, c_l)$.
- a slot subset sl_i from the two possible subsets $\mathcal{S}_1$ (even) and $\mathcal{S}_2$ (odd)

These strategies can be combined into a composite strategy $s_i = (p_i^S, p_i^{S'}, p_i^{S''}, c_i, sl_i) \in S_i$. We define S $= \times S_i, i \in N$ as the strategy space.
iii) The utility of each player i is defined as follows:

$$\begin{aligned} u(s_i, s_{-i}) \; = \; & -\sum_{j=1}^{M} p_i^{S'} h_{ij}^{SP} f(c_i, c_j) \\ & -\sum_{j=1, j\neq i}^{N} p_j^{S'} h_{ji}^{SS} f(c_j, c_i) f'(sl_j, sl_i) - \sum_{j=1, j\neq i}^{N} p_i^{S'} h_{ij}^{SS} f(c_i, c_j) f'(sl_i, sl_j) \\ & + b \log(1 + p_i^{S'} h_{ii}^{SS}) + \sum_{j=1}^{M} p_i^{S''} h_{ij}^{SP} f(c_i, c_j) f''(\gamma_i^{PS} > \rho) \end{aligned} \tag{5}$$

where:

$$f\left(c_i, c_j\right) \doteq \begin{cases} 1 & \text{if } \; c_i = c_j \\ 0 & \text{if } \; c_i \neq c_j \end{cases} \tag{6}$$

and

$$f'\left(sl_i, sl_j\right) \doteq \begin{cases} 1 & \text{if } \; sl_i = sl_j \\ 0 & \text{if } \; sl_i \neq sl_j \end{cases} \tag{7}$$

In addition, in the Decode & Forward approach, the SU must be able to correctly decode the primary signal to relay it. In order to do that, the Signal to Noise and Interference Ratio (SINR) of the primary signal at SU i, which is given by

$$\gamma_i^{PS} = \frac{p_j^P h_{ji}^{PS}}{\sigma^2 + \sum_{k\neq i}^{N} p_k^S h_{ki}^{SS} f(c_k, c_i) f'(sl_k, sl_i)}, \quad i = 1, \cdots, N \tag{8}$$

must be above the sensitivity threshold, ρ. We define the function

$$f''\left(\gamma_i^{PS} > \rho\right) \doteq \begin{cases} 1 & \text{if } \; \gamma_i^{PS} > \rho \\ 0 & \text{otherwise} \end{cases} \tag{9}$$

It can be demonstrated that for a game with the utility function in 5, it can be found a potential function with the above described properties, so that the game is characterized by a pure Nash equilibrium.

3.2.3 Game Model with incomplete information

In a more realistic and feasible scenario, we should not rely on the existence of a CCC where SUs share their transmission information. As a result, we consider a situation where incomplete knowledge is available at the decision making agents. As a result, to model joint channel and transmission power selection for cognitive radios with incomplete information, we rely on the theory of Bayesian Potential game. The resulting game is defined as the one with complete information, but also the player's type have to be defined. For every $i \in N^{+}$, H_i is the finite set of possible types of player i, $\eta_i = (h_{1i}^{SS}, \cdots, h_{i-1i}^{SS}, h_{i+1i}^{SS}, \cdots, h_{Ni}^{SS}) \in H_i$, which includes the wireless channel gains of player i. Finally, also $f_{H_i}(\eta_i)$ have to be defined, being a probability distribution on $\mathrm{H} = \times H_i, i = 1, \cdots, N$, with the a priori probability density function (PDF) on H defining the wireless channel gain PDF.

4. Conclusions

In this chapter, we have described how cooperation can benefit the different phases of the so called cognitive radio cycle. In particular we have focused on physical layer cooperation, showing that benefits can be obtained for both the primary and the secondary system in terms of spatial diversity, increased range and increased availability. In addition, we have modeled the critical interference management problem in a cooperative and cognitive system through a game theoretical approach, as well as providing design guidelines for games with good convergence characteristics, in both cases of complete and incomplete information.

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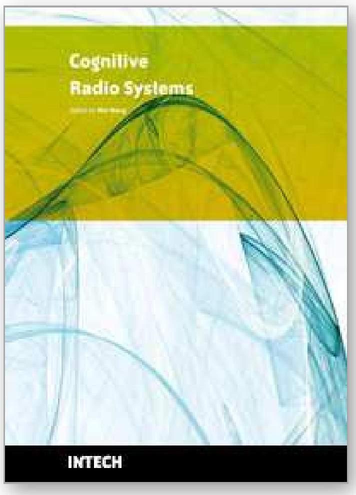

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Cognitive radio is a hot research area for future wireless communications in the recent years. In order to increase the spectrum utilization, cognitive radio makes it possible for unlicensed users to access the spectrum unoccupied by licensed users. Cognitive radio let the equipments more intelligent to communicate with each other in a spectrum-aware manner and provide a new approach for the co-existence of multiple wireless systems. The goal of this book is to provide highlights of the current research topics in the field of cognitive radio systems. The book consists of 17 chapters, addressing various problems in cognitive radio systems.

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