COGNITIVE DYNAMIC SYSTEMS

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ABSTRACT

The first half of the paper addresses the rationale for why we need to study Cognitive Dynamic Systems, with particular reference to two wireless applications: Cogitative radio for communication, and cognitive radar for remote sensing.

The second half of the paper discusses the issues involved in dynamic spectrum management and transmit-power control, which are of particular importance to cognitive radio. The iterative water-filling algorithm, in a noncooperative radio environment is discussed, and its virtues and limitations are highlighted.

Keywords: Cognitive Dynamic Systems defined. Cognitive radio. Cognitive radar. Spectrum holes. Interference temperature, Dynamic spectrum management and transmit-power control. Iterative water-filling algorithm.

I. INTRODUCTION

Dynamic systems serve as major foci in the study of signal processing, communications, and control. Much of that study has been built on traditional ideas drawn from digital signal processing, statistical communication theory, information theory, and stochastic control. By exploiting some of those ideas, significant advances have been made in the last ten years or so on diverse fronts: digital subscriber lines (DSLS), multiple-input, multiple- output (MIMO) wireless communications, and turbo processing. Indeed, it is truly remarkable that so much has been accomplished by relying on traditional ideas. In the context of the three examples cited herein, namely, DSL, MIMO, and turbo processing, the breakthroughs are attributed to “creative thinking outside the box”.

In some recent papers and articles [1-5], I have been articulating the need for broadening our horizons beyond the traditional ones. Specifically, I have advocated the benefits that could be gained by including statistical learning theory and neuroscience as important and relevant sources of new ideas to expand our “kit of tools”. The motivation behind this new way of thinking has been the *human brain*, which is best described as a massively parallel and highly powerful information-processing machine. The brain is capable of performing numerous tasks in signal processing, communications, and control, which outperform what we, as system designers, are able to accomplish by concentrating on traditional ideas.

It is this motivation that has led me to focus my own research effort almost exclusively on Cognitive Dynamic Systems with applications to new generations of cognitive radio, cognitive radar, and hearing aids.

As a working definition. I say[1]

> **Cognitive dynamic systems build up rules of behavior over time through learning from continuous experiential interactions with the environment, and thereby deal with environmental uncertainties.**

II. WIRELESS APPLICATION OF COGNITIVE DYNAMIC SYSTEMS

In traditional radio systems, for example, only ten percent of the electromagnetic radio spectrum assigned to a primary (legacy) user is typically employed at any given time [8,9], which is a waste of a highly valued natural resource. A cognitive radio system, on the other hand, would be able to identify sub-bands of the radio spectrum that are currently unemployed and assign them to unserviced secondary users [10]. The idea of cognitive radio and its architectural software considerations were first discussed by Mitola in his doctoral dissertation [11].

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[1] This definition is taken from the Proc. IEEE “point-of-view” article [1]. In a related context, two other points are noteworthy:
(i) A book on Cognitive Dynamic Systems is under preparation [6].
(ii) The idea of cognition has also been exploited in Cognitive immunity [7] for the protection of software against cyberattack.

For the example on radar, consider the performance of a surveillance system. The moment the radar is switched on, it becomes electromagnetically linked to its surrounding environment, thereby registering any changes perceived within the scope of its coverage. However, the environmental data accumulated by the standard surveillance radar last no longer than a few scans of the transmitting antenna. Valuable historical data, built up over time, are thus lost. This loss can be particularly serious when the environment is nonstationary, as is often the case. Cognitive radar [5], with its built-in capability to preserve environmental information for comparative evaluations, provides a novel method, not just for discerning environmental changes, but also for anticipating them by recognizing identifiable patterns.

A perfect example of cognitive radar is found in the echolocation system of the bat [12]. In a classic demonstration of experiential learning, the bat stores environmental information concerning its habitat, which it has accumulated through a lifetime of experience. With this information, the bat is equipped to locate its prey with an accuracy and resolution that would be the envy of radar and sonar engineers.

Although the intended applications of cognitive radio and cognitive radar are indeed different, they do share two common features:

1. *Scene analysis*, which enables the radio/radar receiver to "sniff" its surrounding environment on a continuous basis and thereby learn from it.
2. *Feedback channel*, which connects the receiver to the transmitter and thereby makes it possible for the transmitter to adapt itself to the environment in light of the information passed on to it by the receiver.

From this description, it is apparent that both cognitive radio and cognitive radar are examples of closed-loop feedback control wireless systems. An important point to take from this brief description is two-fold:

- Feedback is the facilitator of intelligence; moreover, feedback is rooted in cybernetics, which owes its origin to the pioneering work of Norbert Wiener [13].
- Care has to be exercised in designing the system to maintain stability, and thereby sustain the full benefits of cognitive processing.

III. DYNAMIC SPECTRUM MANAGEMENT AND TRANSMIT POWER CONTROL

In cognitive radio terminology, *spectrum holes* refer to certain sub-bands of the electromagnetic spectrum, which are assigned to a primary (legacy) user; the sub-bands are partially or fully underutilized at a particular time and geographic location by that user [2]. It may therefore be said that spectrum holes represent a *new degree of freedom* not available to traditional radio for wireless communications. Depending on the varying needs of the primary user over the course of time, the spectrum holes come and go, with the result this new degree of freedom is not only time varying but also a source of uncertainty.

The identification of spectrum holes is performed in a passive manner at the receiving end of a cognitive radio link by listening to incoming electromagnetic waves in the local nightbourhood of the receiver. The results of the identification are sent to the transmitter by the receiver over a feedback link (operating at a low bit rate compared to the forward link from the transmitter to the receiver.)

Insofar as the utilization of spectrum holes is concerned, the transmitter has two related functions to perform:

1. To manage the spectrum holes among multiple users in a dynamic and statistically equitable manner.
2. To control the level of transmitted power, so as not to exceed the preassigned interference temperature limit specified for the input of each receiver.

The *interference temperature* is a metric that is intended to quantify and manage the sources of interference at a receiver's input. The interference temperature limit specifies a "worst-case" characterization of the radio environment. Cognitive radio therefore distinguishes itself from conventional radio in yet another way: it is receiver- rather than transmitter-centric.

For the transmitter to perform its two-fold function properly, two major functions have to be considered:

- The transmission of information on the spectrum holes across the feedback link takes time.
- The duration for which the spectrum holes are likely to remain available for utilization by secondary users is uncertain.

Accordingly, the design of the receiver would have to include a *predictive model* that accounts for these two factors [2].

In designing the functional unit responsible for dynamic spectrum management and transmit-power control, two strategies that deserve consideration are

- *Iterative water-filling*, rooted in information theory [14], and
- *No regret learning*, rooted in game theory [15].

Both of these two strategies have their advantages and disadvantages, which are discussed in [2]. In what follows, important features, virtues, and limitations of the iterative water-filling algorithm are highlighted.

IV. ITERATIVE WATER-FILLING

The iterative water-filling algorithm was originally developed for dynamic spectrum management in digital subscriber lines [14]. It is equally applicable to cognitive radio, with one particular modification that would have to be incorporated into the design of the algorithm, namely, the variable nature of spectrum holes.

Consider a cognitive radio environment involving *n* transmitters and *n* receivers. The environmental model is based on two assumptions:

(i) Communication across a channel is asynchronous, in which case the communication process is viewed as a *noncooperative game*. For example, in a *mesh network* consisting of a mixture of ad-hoc networks and existing infrastructured networks, the communication process from a base station to users is controlled in a synchronous manner, but the multi-hop communication process across the ad-hoc network could be asynchronous and therefore noncooperative.

(ii) *A signal-to-noise ratio (SNR) gap* is included in calculating the transmission rate so as to account for the gap between the performance of a practical coding-modulation scheme and the theoretical value of channel capacity. (In effect, the SNR gap is large enough to assure reliable communication under operating conditions all the time.)

In mathematical terms, the essence of transmit-power control for such a noncooperative multi-user radio environment is stated as follows:

> *Given a limited number of spectrum holes, select the transmit-power levels of n unserviced users so as to jointly maximize their data-transmission rates, subject to the constraint that the interference-temperature limit is not violated.*

It may be tempting to suggest that the solution of this problem lies in simply increasing the transmit-power level of each unserviced transmitter. However, increasing the transmit-power level of any one transmitter has the undesirable effect of also increasing the level of interference to which the receivers of all the other transmitters are subjected. The conclusion to be drawn from this reality is that it is not possible to represent the overall system performance with a single index of performance. Rather, we have to adopt a *tradeoff* among the data rates of all unserviced users in a computationally tractable fashion.

Ideally, the objective is to find a *global solution* to the constrained maximization of the joint set of data-transmission rates under study. Unfortunately, finding this global solution requires an exhaustive search through the space of all possible power allocations, in which case the computational complexity needed for attaining the global solution assumes a prohibitively high level.

To overcome this computational difficulty, an optimization criterion called *competitive optimality* is used to solve the transmit-power control problem, which may now be restated as follows:

> *Considering a multiuser cognitive radio environment viewed as a noncooperative game, maximize the performance of each unserviced transceiver, regardless of what all the other transceivers do, but subject to the constraint that the interference-temperature limit not be violated.*

This formulation of the distributed transmit-power control problem leads to a sub-optimum solution that is of a *local* nature.

The iterative water-filling algorithm is well-suited for cognitive radio. In particular, the practical virtues of the algorithm are:

1. The algorithm operates in an *autonomous* manner, thereby avoiding the need for a centralized station.
2. It avoids the need for the deployment of explicit communication links among the multiple users, thereby simplifying the design of the cognitive radio network.
3. The algorithm uses *convex optimization*, which makes it possible for it to converge relatively rapidly to a *Nash equilibrium;* however, once this point is reached, no user is permitted to change its power level in a unilateral manner.
4. Computational complexity of the algorithm is relatively low, being on the order of the product of two numbers: the number of users and the number of spectrum holes (i.e., underutilized sub-bands of the radio spectrum).

As it is with every algorithm, the iterative water-filling algorithm has certain limitations of its own:

- The algorithm is suboptimal.
- With the algorithm designed to operate in a noncooperative and therefore “selfish” manner, the performance of the algorithm is likely to be seriously compromised in a certain situation. Specifically, there is no provision in the structure of the algorithm that would guard it against a “clever” user who will try to exploit dynamic changes or limited resources (i.e., spectrum holes) for its own selfish benefits.

One way of taking care of such a provision is to expand the structure of the algorithm to include a simple form of cognitive immunity against exploitation; this is work in progress.

V. CONCLUSION

I see the emergence of a new discipline, called Cognitive Dynamic Systems, which builds on ideas in statistical signal processing, stochastic control, and information theory, and weaves those well-developed ideas into new ones drawn from neuroscience, statistical learning theory, and game theory. The discipline will provide principled tools for the design and development of a new generation of wireless dynamic systems which include cognitive radio and cognitive radar with efficiency, effectiveness, and robustness as the hallmarks of performance.

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