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A System for Spectrum Decision in Cognitive Radio Networks

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***Abstract*—In Cognitive Radio (CR) networks, licensed radio channels are allowed to be used by Secondary Users (SUs) as long as SUs do not harmfully impair the transmission of Primary Users (PUs). Therefore, a crucial task for SUs is to decide which available channel should be selected, the so-called spectrum decision. To provide intelligent spectrum decision strategy to SUs, we suggest a system called Spectrum Decision Support System (SDSS). SDSS takes into account both heterogeneity aspects and interoperability requirements of CR networks. By this, SDSS is capable of jointly considering various channel characterizations and different decision making algorithms for doing spectrum decision. The paper is reporting the SDSS architecture as well as the related work-in-progress.**

I. Introduction

Cognitive Radio (CR) networks offer a promising capability for efficient use of spectrum resource. The underlying idea is to allow unlicensed users (i.e., Secondary Users or SUs) to temporarily use licensed radio channels, while SUs are not allowed to harmfully interfere with licensed users (i.e., Primary Users or PUs). Since PUs do not need to notify SUs of their activities, SUs need to decide which channel should be selected. The determination process is often referred to as *spectrum decision*. For a given SU, the goal of doing spectrum decision is to select an available channel, which could optimize the SU's transmission performance. Here, available channels are known as spectrum white spaces [1].

A large amount of studies on spectrum decision have been reported in recent literature. For instance, in [1], the authors characterize the channels by parameters like received signal strength, interference, path loss, wireless link error and link layer delay. Based on these parameters, the SUs can select the most available channels. Since such solution relies on the instant information, it is not flexible for SUs to adapt to the radio environment varying over time. Therefore, statistics of environmental changes is desirable for SUs. For example, the authors of [2] suggest an ON-OFF Markov chains based approach to theoretically study the interaction between SUs and PUs. In [3], the authors suggest a biologically-inspired algorithm to achieve efficient spectrum sharing among SUs. As a result, SUs can automatically access the most available channels in accordance with the largest handoff-decision value.

The above mentioned research works lay the ground to implement spectrum decision. However, to our best knowledge, less attention has been paid on heterogeneity aspects and interoperability requirements existent in CR networks. In our work, the heterogeneity is expressed in terms of vertical and horizontal properties of wireless communication system. The vertical property indicates the effective cross-layer design over several layers such as physical layer, Media Access Control (MAC) layer, network layer and so on. The horizontal property refers to wireless technologies like, e.g., Bluetooth, IEEE 802.11 and Code Division Multiple Access (CDMA), which can be extended or modified for CR based communications [4], [5]. The heterogeneity further leads to various channel characterizations, which are in terms of instant and statistical parameters. Moreover, different characterization parameters are related to different decision making algorithms. Subsequently, the spectrum decision maker requires an interoperability framework across various parameters and different algorithms.

In this paper, we introduce a system called Spectrum Decision Support System (SDSS) [6]. To address heterogeneity, we develop in SDSS the upper/lower Application Programming Interfaces (APIs). They help SDSS users to embed SDSS in other tasks like, e.g., architecture setting up, testbed evaluation, algorithm developments. To support interoperability, SDSS adopts a parameter Fuzzy Channel Availability (FCA) defined from fuzzy logic point of view. The goal of using FCA is to transform different types of characterization parameter in an uniform type with respect to FCA. Based on this, an overlay decision maker can be set up, and it can jointly consider different decision making algorithms.

The rest of paper is organized as follows. Section II describes the architecture of SDSS. Section III discusses the setting up of an overlay decision maker in SDSS. The related works in progress are presented in Section IV. Finally, we conclude the paper in Section V.

II. Spectrum Decision Support System

A. Spectrum Decision Function in SDSS

Compared with previous research work on spectrum decision, SDSS has a novel representation of spectrum decision function. This representation is focused on the identification of the elements involved in doing spectrum decision. By *element*, we mean an individual entity in CR networks, which can be like, e.g., a PU, a SU, a channel, a CR network model, a decision making algorithm.

Further, we classify various elements in three sets, namely, active unit, information base, and algorithm factory. They are described as follows.

1) Active Unit: it includes the PU, SU, radio channel, transmission scheme and CR coordinator. PUs, SUs and radio channels are essential elements in CR networks. PUs and SUs can do transmission by using an ad-hoc or an infrastructure based manner. The corresponding transmission scheme can use either time-slotted basis or continuous basis. The channel availability for SUs can be spatial invariant or be spatially varying [7]. CR coordinator is responsible for allocating available channels to SUs, and it can be deployed in either centralization or decentralization way [8].

2) Information Base: it consists of two different parts, namely, the information content and the way of collecting information. The information content is about the characterization of CR networks, which are in terms of instant or statistical parameters like, e.g., signal-to-noise ratio, channel bandwidth, average arrival and departure rates of PUs, average idle time on channels. Further, the collecting of information can be done through solutions like, e.g., spectrum sensing by SUs and information exchange among SUs.

3) Algorithm Factory: it contains various algorithms used to do spectrum decision. Notice that different algorithms may have different characteristic features. For instance, a key characteristic feature related to fuzzy logic is given by the *fuzzy membership degree*. Moreover, different decision making algorithms may have respective decision criteria, and each decision criterion prescribes a way to judge which channel is most available for SUs.

According to the above described classification, we observe that the spectrum decision function has two important tasks. The first task is to choose one or more decision making algorithms provided by the algorithm factory, and thus to process the channel characterizations with respect to corresponding decision criteria. The second task is to use the selected algorithms to do decision making to find the most available channels. These two tasks in SDSS are specifically called *information processing* and *overlay decision making*. The relationships among the two tasks and three elements sets are shown in Fig. 1.

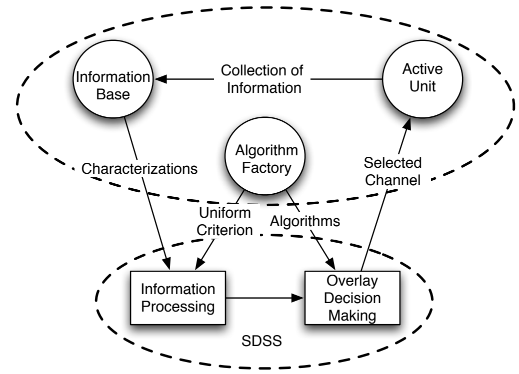

Fig. 1. Information processing and overlay decision making.

B. Scientific Functionalities of SDSS

Based on the above identified spectrum decision function, we suggest five scientific functionalities for SDSS, which are described as follows.

1) Overlay Decision Maker: so far, most of decision making algorithms are independently used for different research goals. This motivates us to develop an overlay decision maker, with the goal to manage and to coordinate different decision making algorithms to work together.

2) Learning and Prediction: to identify channel availability, SUs need to observe different parameters of channels. The observation activity can be like, e.g., spectrum sensing. Since the continuous observation at SUs side is inefficient in terms of energy consumption and hardware demanding, the observation usually is done on a periodic time basis, for instance, time-slot based spectrum sensing. To approach the full knowledge of channel availability, we suggest the SUs to learn from historical observation results. Further, by using the learned knowledge, the decision maker is capable of estimating in advance the channel availability in the near future. The corresponding estimation process is known as prediction.

3) Secondary Users Cooperation: to avoid SUs overcrowding in available channels, we suggest SUs to work in a cooperative manner. That is, the SUs need to exchange the information of channel utilization via the Common Control Channel (CCC) or other signaling protocols [8], [9]. Based on this, the SUs can behave in self-organizing manner to efficiently share the available channels.

4) Queueing Modeling: the particular spectrum decision strategy may affect the overall performance of the whole CR network system. Investigation of related performance characteristics is usually based upon theoretical analysis or simulation experiment. In SDSS, we employ queueing modeling to carry out theoretical analysis.

5) Cognitive Radio Simulator: to validate the theoretical study on CR network performance, we develop a CR simulator to conduct simulation based experiments. The simulator consists of two parts. The first part is to configure the simulation parameters and scenarios. For instance, the simulation parameters related to ON-OFF model can be like the arrival rates of PUs and SUs. The second part is to simulate the dynamic behaviors of both PUs and SUs, and to deal with the interactions among PUs and SUs. The interactions can be like, e.g., a PU accesses/releases a channel, a SU vacates a channel due to PU channel occupancy.

C. SDSS Structure

We abstractly illustrate the structure and application of SDSS in Fig. 2. In the figure, the components in the area of grey color compose the SDSS. The connections among these components are described as follows:

1) The arrows of type (1): they indicate that SDSS is applied to upper objectives like testbeds/architectures development, simulation experiments.

2) The arrows of type (2): they indicate the process of doing spectrum decision. First, the characterizations of CR networks are obtained by doing spectrum sensing and spectrum analysis. Then, these characterizations are collected by the

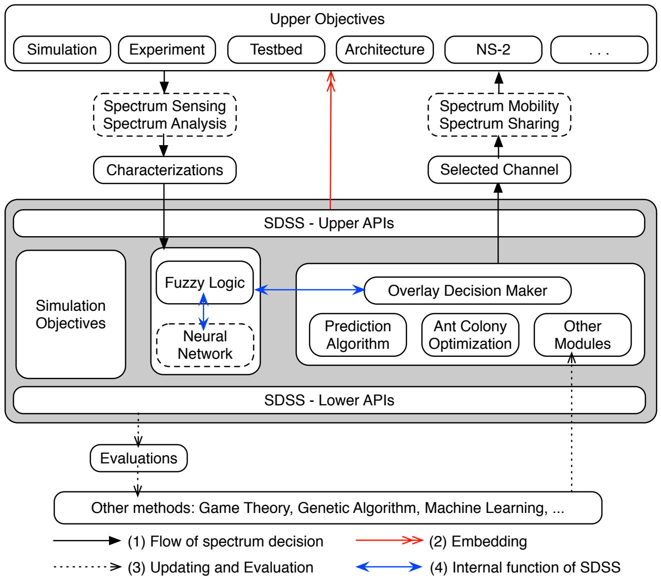

Fig. 2. Abstract structure of SDSS.

SDSS. After doing information process and overlay decision making, the SDSS provides the selected channels to the upper objectives.

3) The arrows of type (3): they imply that new decision making algorithms are added into the SDSS. The evaluation of these new algorithms can be done by upper objectives with using SDSS.

4) The arrows of type (4): they show the internal functions of SDSS. Fuzzy logic module is responsible for processing all input characterizations with respect to the uniform decision criterion. After doing this, the fuzzy logic module sends the processed information to the overlay decision maker. The overlay decision maker uses this information to do hybrid decision making based on different decision making algorithms. Moreover, the communication between the fuzzy logic module and overlay decision maker is bidirectional. This implies that the decision making inside SDSS is a self-learning process.

Clearly, as observed in Fig. 2, the key component of SDSS is the overlay decision maker. A detailed description is presented in the following section.

III. Overlay Decision Making

Since the channels in CR networks can be characterized by different parameters, the spectrum decision becomes a multiple-constraint based decision making problem of finding the most available channels. To solve this problem, a three-dimension model is used to represent channel characterizations, and an overlay decision maker is constructed by using fuzzy logic.

A. Channel Characterization

We consider a CR network with M radio channels denoted by c_1, $c_2, ...,$ $c_m, ...,$ c_M. Every channel is assumed to be characterized by a number, N, of independent parameters e_1, e_2,...,e_N. Let $a^m_{e_n}(t)$ denote the observed value of parameter

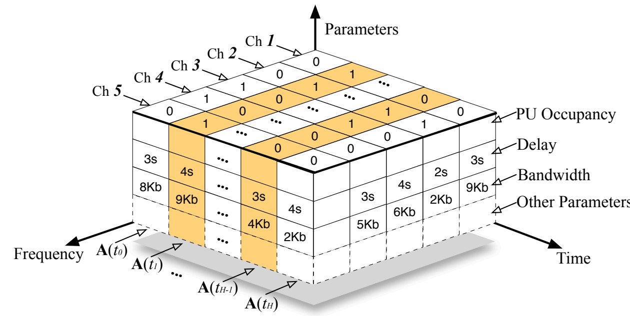

Fig. 3. Modeling of channel characterizations in interval $[t_0, t_H]$.

e_n on channel c_m at time t, where $n \in \{1, 2, ..., N\}$ and $m \in \{1, 2, ..., M\}$. The characterizations of M channels under N parameters can be represented by a matrix:

$$\mathbf{A}(t) = \begin{bmatrix} a^1_{e_1}(t) & a^1_{e_2}(t) & ... & a^1_{e_N}(t) \\ \vdots & \vdots & \ddots & \vdots \\ a^m_{e_1}(t) & a^m_{e_2}(t) & ... & a^m_{e_N}(t) \\ \vdots & \vdots & \ddots & \vdots \\ a^M_{e_1}(t) & a^M_{e_2}(t) & ... & a^M_{e_N}(t) \end{bmatrix} \quad (1)$$

The matrix $\mathbf{A}(t)$ is called the channel characterization of the CR network at time t. Furthermore, we assume that the observation of the N parameters is done on a periodic time basis with uniform duration δ. We also assume that the observation starts at time point t_0 and ends at time point t_H, where $(t_H - t_0) = H\delta$. Thus, we can obtain a set of channel characterization matrixes at discrete time points $\{t_0, t_1, ..., t_H\}$, which is expressed as:

$$\{\mathbf{A}(t_0), \mathbf{A}(t_1), ..., \mathbf{A}(t_H)\} \quad (2)$$

Subsequently, the characterizations of M channels in the time interval $[t_0, t_H]$ can be represented by a three-dimension model. The three dimensions are associated with three domains, namely, time, frequency (i.e., channels) and parameter, as shown in Fig. 3.

B. Uniform Decision Criterion

The key idea of overlay decision maker is to set up an uniform decision criterion. To do this, we introduce a new parameter called FCA. FCA is a fuzzy logic based parameter to represent three different levels of channel availability for SUs. The three levels are respectively formalized as three fuzzy sets, namely, *"high-level"*, *"medium-level"* and *"low-level"* channel availabilities. The use of FCA is to map different types of parameter values to an uniform type, i.e., fuzzy membership degree.

Let α_{e_n}, β_{e_n} and γ_{e_n} denote three fuzzy sets *"high-level"*, *"medium-level"* and *"low-level"* under parameter e_n, respectively. Further, let σ_{e_n} denote the set of all possible values of parameter e_n. For the m^{th} channel at time t, we have $a^m_{e_n}(t) \in \sigma_{e_n}$. By considering fuzzy set theory, we introduce a function g_{e_n} acting as characteristic function of set σ_{e_n}. Specifically, g_{e_n} is generalized to a *membership function* in such a way that, for every $a_{e_n}^m(t) \in \sigma_{e_n}$, we assign $g_{e_n}(a_{e_n}^m(t))$ a value from the unit interval $[0.0, 1.0]$. Accordingly, the fuzzy membership degrees of $a_{e_n}^m(t)$ to three fuzzy sets of FCA are denoted $g_{e_n}^{\alpha}(a_{e_n}^m(t))$, $g_{e_n}^{\beta}(a_{e_n}^m(t))$ and $g_{e_n}^{\gamma}(a_{e_n}^m(t))$.

Moreover, let $\pi_\times$, π_+, and π_- denote the importance weights of three fuzzy sets *"high-level"*, *"medium-level"*, and *"low-level"*, respectively, on spectrum decision. Let $w_1, w_2, ..., w_n, ..., w_N$ denote the importance weights of N parameters on spectrum decision. Then, the FCA-based characterization of parameter e_n in channel c_m at time t is given by

$$\xi_{e_n}^m(t) = g_{e_n}^{\alpha}(a_{e_n}^m(t))\pi_\times + g_{e_n}^{\beta}(a_{e_n}^m(t))\pi_+ + g_{e_n}^{\gamma}(a_{e_n}^m(t))\pi_- \quad (3)$$

Based on this equation, the numerical channel availability (for SUs) of channel c_m at time t is computed as

$$\eta_m(t) = \xi_{e_1}^m(t)w_1 + \xi_{e_2}^m(t)w_2 + ... + \xi_{e_n}^m(t)w_n + ... + \xi_{e_N}^m(t)w_N \quad (4)$$

Consequently, the most available channel is associated with the largest value of $\eta_m(t)$, which is given by:

$$\eta^*(t) = argmax\{\eta_1(t), \eta_2(t), ..., \eta_M(t)\} \quad (5)$$

IV. Latest Results

We have implemented several functionalities of SDSS. The detailed descriptions are reported in [10]–[12]. In this section, we provide a survey on these works.

In [10], a channel usage prediction based algorithm for spectrum decision is developed. This algorithm is accomplished by using Lezi-update scheme and fuzzy logic. The channel usage prediction is based on the joint consideration of sensing error, SUs competition and SUs transmission collision. The prediction goal is to help SUs in knowing in advance the channel availability, and thus the SUs can choose the most available channels. The effectiveness and performance of the developed algorithm is evaluated by simulation experiments.

In [11], a fuzzy logic based decision making algorithm is developed for competition-based channel selection. The underlying decision criterion integrates both the statistics of PUs' channel occupancy and the competition level of SUs. By using this algorithm, the SU competitors can achieve an efficient sharing of the available channels. Simulation results are reported to demonstrate the performance and effectiveness of the suggested algorithm.

In [12], a Markov chain based queueing model is developed to represent the Opportunistic Spectrum Access (OSA) performance in CR cellular networks. To do this, both SUs intra-cell and inter-cell spectrum handoff are considered. By assuming that multiple cells show identical statistics in steady state, we determine the values of arrival rates of inter-cell handoff users. We also derive the corresponding performance metrics in terms of blocking and forced-termination probabilities of SUs, service-completion throughput of SUs and inter-handoff throughput of SUs. The numerical analysis is validated by simulation experiments.

V. Conclusion

An intelligent system, called Spectrum Decision Support System (SDSS), was suggested for spectrum decision in CR networks. SDSS was designed to jointly take into account various parameters and decision making algorithms to select the most available channels for SUs. To do this, the elements of CR network were classified in three sets: active unit, information base and method factory. Based on this classification, the functionalities and structure of SDSS were presented. Further, the setting up of an important SDSS function, i.e., overlay decision making, was discussed in detail. Our latest work results related to the development of SDSS were also presented. Future work is to investigate and improve the system performance of CR cellular networks.

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