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Analysis of a multi-user cognitive radio network considering primary users return

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ABSTRACT

Multi-user cognitive radio networks have been considered in the literature recently. However, there is no analytical framework which can provide a model in order to derive the system performance metrics. This paper presents an analytical continuous time framework for a multi-user cognitive radio in which secondary users (SUs) communicate on a single common control channel, the most common protocol discussed in the multi-user category. The proposed analysis method is based on the renewal theory. We prove that the spectrum access of SUs with respect to the primary user (PU) traffic behavior forms a renewal process. Furthermore, the corresponding renewal cycle is derived and metrics such as collision probability and interference time due to both sensing error and PU re-occupancy are formulated in the renewal cycle. Thanks to the proposed continuous time analyses, the transmission efficiency for the secondary network is formulated. Finally, some numerical analyses are provided on the derived equations to discuss the optimum transmission time for SUs in order to have the maximum efficiency under the prescribed collision constraint. As an example, for the sensor, probabilities of false alarm and miss-detection are taken to be equal to 0.1 and 0.01, respectively, with a primary network in which the idle and busy cycle rates are 0.1 and 0.3; also, the transmission time must be bounded to 500 ms in order for the collision probability to remain under 0.01. At the end, we show that simulation results are consistent with the numerical analyses.

1. Introduction

Allocating specific frequency bands to wireless systems is a conventional strategy used for spectrum access to prevent colliding or at least to alleviate the interference between systems. This strategy is known as *Fixed Spectrum Access (FSA).* However, rapid increase in wireless systems and in demands for dedicated spectrum bands has caused this methodology to be inefficient, leading to the shortage of the spectrum resources. Furthermore, measurements carried out by the Federal Communications Commission (*FCC*) have shown that 70% of the exclusively allocated spectrum bands in US and other countries have not been well-utilized [1,2]. Therefore, the cognitive radio system was proposed to provide a solution for the spectrum scarcity as a natural resource on the one hand, and spectrum underutilization on the other hand. This concept has offered *Dynamic Spectrum Access* (*DSA*) policy for spectrum usage. There are three basic models of DSA in the literature [3]. Among them, *Interweave* model is one popular method of accessing the spectrum dynamically, and is classified under hierarchical model. It is also known as *Opportunistic Spectrum Access* (*OSA*). In OSA, an alternative system called secondary

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can coexist with a licensed network and use its spectrum when the licensed network users, which are called primary users, (PUs) do not access their own spectrum. In other words, the secondary users (SUs) are not allowed to access the spectrum simultaneously with the incumbent users in order to prevent collision with secondary users' transmission. To reach this aim, the cognitive users should evolve in at least four classes of functionality, namely, *spectrum sensing, spectrum access decision, spectrum sharing* and *spectrum mobility*. Not only does Spectrum sensing play an important role in cognitive systems to detect spectrum holes and transmission opportunities, but also protects PU from the unwanted collisions. Spectrum decision is centered on whether or not to access the spectrum. Since spectrum sensing is imperfect, there is always a level of uncertainty on accessing the spectrum, hence for the secondary user, there is a constraint on accessing the spectrum which is called collision probability, or, sometimes, probability of interference. This constraint definitely affects the spectrum decision policy; for example, how long can the secondary user gain the spectrum for data transmission? The aforementioned constraint along with other bonds (such as throughput, energy or power) makes the spectrum access process more complicated. To prevent collision with the primary user, a strategy called *Listen Before Talk (LBT)* has been adopted. It simply means each time an SU has data to transmit, sensing the frequency band is necessary beforehand. An innate trade-off arising is that sensing the spectrum before each transmission wastes the time and energy and consequently, reduces the network throughput and efficiency. This is usually referred as sensing time overhead in the literature [4,5]. To reduce this overhead and increase network throughput, several techniques in spectrum sensing and optimization problems have been proposed. These problems have usually addressed the joint optimization of sensing and access and employed a wide area of mathematical modeling including traffic parameter estimation, spectrum prediction, subcarrier and power allocation and channel estimation. In the next section, a literature review of these techniques is presented.

2. Related works

As discussed earlier, spectrum sensing and decision are the two main functions of cognitive radios that are bound firmly to each other. Different scenarios and protocols have been investigated in the literature. Aiming to categorize enormous studies, we could best divide the adopted techniques into two classes of single channel access and multi-channel access. Since we study single channel access in this paper, a brief overview of single channel spectrum access is given below.

Some studies have addressed sensing time optimization to reach the best point in the receiver operating curve (ROC) in order to minimize the collision between primary and secondary users. In [6], different sensing times have been considered for different primary channel occupancy states and in [7], the total sensing time is divided into two phases in order to sense two primary channels.

Simple joint optimization of sensing and transmission time (with no additional network constraints) has been carried out in [8–10] to reach the maximum throughput. Some other papers have formulated the inherent trade-off of sensing and transmission times under different scenarios and constraints. In most works, the frame structure was divided in two parts, one for sensing and the other for transmission; the main author concern has been to find the best portion of the whole frame for each of the two. Because there is an essential trade-off between these two parts, i.e., the more time allocated to the sensing process, the more accurate the sensing process and hence, the less the collision occurring, the less time is left for data transmission. Probability of interference was introduced in [11] as a constraint for maximizing the throughput. In [12,13], PU traffic was modeled at the packet level hence, and the length of packets and the arrival time between packets were addressed as the main statistical parameters of the traffic model. Therefore, to maximize PU detection probability and throughput, the optimum sensing time and sensing period were derived. Additional constrains, such as the maximum number of cooperating users, were introduced in [14].

Green communication has come in to the cognitive radio concept recently, leading to another class of studies. In these works, the objective was to maximize energy efficiency (EE) [15]. For example, in [16], a cooperative sensing-throughput trade-off was proposed in the multiple input single output cognitive radio system. In this scheme, secondary user could use some antennas to transmit its data and some others to help transmit the PU data by performing relay and cooperative communication if the presence of the PU were detected. Accordingly, the energy efficiency was investigated under the combination of massive MIMO (when the ratio of antennas per BS to the number of user terminals per cell was very large) with Femto cells. The authors concluded that the combining massive MIMO at the micro cell level with Femto cells could lead to some CRN EE improvement. Trilateral trade-off between sensing, contention and transmission time in a Split Phase CRN was studied in [17]. Energy efficiency in OFDM based cognitive radio was analyzed in [18,19] under constraints such as power allocation and subcarrier assignment. In [19], to consider collision-free transmitted data bits, a new metric for energy efficiency, called Energy Per Goodbit (EPG), was introduced. Sensing throughput trade-off for an energy efficient CR network under fading in both sensing process and reporting channel was formulated in [20]. The trade-off between spectrum efficiency and energy efficiency and that for sensing bandwidth and energy were considered in [21] and [22], respectively.

To summarize and mention the shortcomings of the above studies, it should be noted that collision-free data bits or equivalently successful transmitted time could be the best metric in the network efficiency (along with energy, spectrum or throughput) in order to evaluate and design a typical network. However, in cognitive radio networks, analyzing successful transmission time entails formulating two kinds of interference. The first one is related to primary user return or PU re-occupancy, and the second one emanates from imperfect sensing. To investigate the former, SU spectrum access must be modeled based on PU traffic behavior and for the latter, spectrum sensing error probabilities of false-alarm and miss-detection must be considered. Note that in the Interweave model with the non- external sensing strategy, the most popular