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Discrete time analysis of cognitive radio networks with imperfect sensing and saturated source of secondary users

A.S. Alfa [a,b], V. Pla [c,*], J. Martinez-Bauset [c], V. Casares-Giner [c]

[a] University of Manitoba, Winnipeg, MB, Canada
[b] University of Pretoria, Pretoria, South Africa
[c] Universitat Politècnica de València, Valencia, Spain

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ABSTRACT

Sensing is one of the most challenging issues in cognitive radio networks. Selection of sensing parameters raises several tradeoffs between spectral efficiency, energy efficiency and interference caused to primary users (PUs). In this paper we provide representative mathematical models that can be used to analyze sensing strategies under a wide range of conditions. The activity of PUs in a licensed channel is modeled as a sequence of busy and idle periods, which is represented as an alternating Markov phase renewal process. The representation of the secondary users (SUs) behavior is also largely general: the duration of transmissions, sensing periods and the intervals between consecutive sensing periods are modeled by *phase type* distributions, which constitute a very versatile class of distributions. Expressions for several key performance measures in cognitive radio networks are obtained from the analysis of the model. Most notably, we derive the distribution of the length of an *effective white space*; the distributions of the waiting times until the SU transmits a given amount of data, through several transmission epochs uninterruptedly; and the *goodput* when an interrupted SU transmission has to be restarted from the beginning due to the presence of a PU.

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1. Introduction

Cognitive radio (CR) has been proposed as one approach to deal with the limited unlicensed spectrum availability [1]. Most of the licensed spectrum bands are not fully utilized most of the time. Capturing the unused time slots, which are known as spectrum holes, on these licensed spectrum bands and using them efficiently is what CR is about.

Depending on how the licensed spectrum is accessed, the operation of CR can be classified into two categories: *overlay* and *underlay*. In overlay CR, a licensed channel can be accessed by secondary users (SUs) only if it is not being used by a primary user (PU). Consequently, SUs can only transmit during the idle periods of the primary network. In contrast, in underlay CR, given that PU signals may be successfully decoded if the interference generated by the other sources is tolerable, SUs can access the spectrum even when there is a PU transmitting, as long as the generated interference at the PU receiver is lower than a pre-defined threshold. More recently, hybrid approaches combining overlay and underlay paradigms have been proposed [2]. In this paper we focus on overlay CR.

The key to success for CR consists of effective and efficient sensing of the channels by the SUs, the unlicensed users, to detect *white spaces* when they occur. A decision making process then follows the sensing, based on the outcome of the sensing exercise.

If we observe the activity of PUs in a licensed channel—that is, a certain spectrum band in a certain spatial area—, it is either busy or idle. For that channel and in that location, the idle periods are the spectrum holes referred to as *white space*. The busy and idle periods form an alternating sequence of events which may be correlated. An SU sensing this channel at some time points either finds the channel busy or idle. When SUs sense the channel during a *white space* then the SU is able to effectively utilize the remaining *white space*, which we call the *effective white space*. The ideal sensing strategy is one that results in the SU capturing most of the *white space* and ceasing its transmission shortly after a busy periods starts, i.e. the one that can minimize the difference between the lengths of the *white space* and the *effective white space*, while keeping resource utilization (e.g., energy) and interference to a minimum. Here, by sensing strategies we imply using different statistical distributions and mean values for the durations of the sensing periods and of the intervals between sensing periods.

As pointed out by Yücek and Arslan [3], sensing is one of the most important and challenging issues in CR networks. Selection of sensing parameters raises several tradeoffs involving achievable throughput,

* Corresponding author. Tel.: +34 963879733.
E-mail addresses: Attahiru.Alfa@ad.umanitoba.ca (A.S. Alfa), vpla@upv.es (V. Pla), jmartinez@upv.es (J. Martinez-Bauset), vcasares@upv.es (V. Casares-Giner).

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energy consumption and interference caused to PUs [4–11]. In general, more frequent and longer sensing periods reduce the achievable throughput, but increase the reliability of sensing and lower the interference that is caused to PUs. This is the so-called *sensing-throughput tradeoff* (STT) that has been addressed in many studies; see, for example, [4,5,9] and references therein. In the majority of these studies, achievable throughput is used as the main performance metric. To obtain the achievable throughput it is assumed that SUs always have data to transmit and that there is no overhead due to the coordination and/or collisions between SUs; in this paper we follow the same approach. In that sense, the achievable throughput is a useful measure to assess how well a sensing strategy does in the STT, but it must be made clear that throughput figures so obtained are not really achievable. In real settings, coordination among SUs in the same network and coexistence mechanisms among different secondary networks will unavoidably reduce the maximum throughput that SUs can obtain [12].

Sensing more often and doing it for longer periods increases energy consumption, which can be a critical aspect in some applications (e.g., sensor networks). This has brought energy consumption into the equation and some studies treated energy efficiency as a fundamental part of spectrum sensing [7,8,10,11]. As a matter of fact, energy efficiency has become a major issue in communication networks, not only for battery operated devices but for all type of devices and infrastructures [13].

Scanning a wide frequency band in search of unused channels and switching channels (when a PU appears in the currently used one) are power-intensive CR operations [14]. Therefore, in those scenarios where energy consumption is critical, a common strategy for SUs upon detecting the presence of a PU is to remain silent in the current channel and wait for the channel to become idle again, instead of performing a spectrum handoff to switch to a different channel [8,15]. In this paper we focus on this type of strategies.

Most of the existing works that aim to optimize spectrum sensing parameters assume that PUs transmissions have a temporal structure that is known by the CR network. The CR network can then structure its transmission in frames that are temporarily aligned with those of PUs. This way, the CR network can sense the state of the channel at the beginning of the frame, and rest assured that whatever the outcome of the sensing was it will not change throughout the remaining of the frame. This assumption has been relaxed in recent papers in which it is considered that a PU can change its status at any time during an SU frame [6,16,17]. Here we follow the latter more general approach.

Another aspect which is often overlooked in the studies dealing with spectrum sensing is the effect that collisions with PUs may have on the effective throughput of SUs [5,6]. Collisions with PUs may occur due to either sensing errors or the sudden arrival of a PU while the SU is transmitting. As noted in [5], this effect and its impact on the effective throughput have been rarely addressed in the literature to date. In this paper the impact of PU interference on SU effective throughput is considered in the analysis of the *goodput* as explained below.

The vast majority of models that have been developed for studying CR networks, and in particular for studying spectrum sensing, assume that the durations of both the busy and idle times are governed by the exponential distribution (or its discrete time counterpart: geometric), see for example [18,19] and all the references given above for sensing related studies. However, this assumption is not backed with empirical evidence. Geirhofer et al. [20] were among the earlier researchers to show from measurements that the idle time duration was more of a lognormal distribution. This was further confirmed by Wellens et al. [21] who showed that the idle time duration has lognormal distribution for long durations and geometric distribution for the short ones. Most of the previous works also ignored the possible correlation between the busy and idle times, even though logically one would expect some correlation to exist between the two intervals, and between consecutive busy and idle periods as observed in [21].

The study of sensing strategies in CR networks is not a new topic, nor is the development of mathematical models for their analysis and optimization. However, the models presented in this paper contain several contributions arising from the generality of the assumptions and the performance measures derived. Our aim is to provide representative mathematical models that can be used to analyze sensing strategies under a wide range of conditions. We do this by representing the busy and idle periods of PUs in a licensed channel as alternating Markov phase renewal processes [22] and develop a model to determine relevant performance measures under different sensing strategies. This Markov phase renewal process allows the busy and idle times durations to assume a wide variety of distributions and also captures much broader correlation aspects of the two intervals. Our model of PUs activity is similar to the one by Bae et al. in [23], although their model did not consider the correlations between busy and idle periods.

Our model of the SU behavior is also largely general. The duration of transmissions, sensing periods, and intervals between consecutive sensing periods are modeled by general *phase type* distributions [22]. In the modeling literature, it is acknowledged that the phase type distribution provides an excellent balance between tractability and applicability (it is general enough to fit empirical data and there exist algorithms for this purpose) [24]. Moreover, in the current paper we assume that sensing is imperfect and consider two types of misdetections and false alarms, depending on whether the SU is transmitting or not. This, allows us to cover a wide range of situations.

As mentioned above, in our modeling approach a number of random variables that refer to durations are described by discrete time phase type distributions. A known advantage of this type of distributions is that a constant value (i.e., a deterministic distribution) can be easily represented as a discrete time phase type distribution. It is worth noting this point since most of the proposed sensing schemes consider constant values for the sensing period and for the interval between sensing periods [4]. The often made assumption is that sensing should be done periodically and the issue is determining the interval between the sensing times [5,25]. However, there are no documented studies supporting the idea of using constant interval between sensing times as the optimal strategy. Therefore, while our model can be easily set so that sensing related durations are constant, allowing these durations to be general does not involve much extra modeling effort, and makes the model more general.

An important part of the sensing strategy is the physical layer functions aimed at determining whether a certain spectrum band is being used or not. These functions rely on signal processing techniques and are usually known as *spectrum sensing algorithms*. In the literature, a number of spectrum sensing algorithms have been proposed (see [3,26,27] for an overview). Although it is an important part of the sensing strategy, the spectrum sensing algorithm itself is outside the scope of this paper and its detailed operation is not described by our model. In that regard, our model is not tied to any specific spectrum sensing algorithm. It can be setup to model sensing strategies based on different specific spectrum sensing algorithms by setting appropriately the misdetection and false alarm probabilities; the duration assigned to a time slot and the energy consumed per slot by sensing activities will also vary depending on the spectrum sensing algorithm. In the case of cooperative spectrum sensing algorithms, there exists an additional delay until the decision is made due to the required reporting and fusion of the distributed measurements [28]. Our model does not include this delay overhead. As a consequence, it could only be used with cooperative sensing schemes whose delay overhead can be considered negligible.

From the analysis of our model we obtain the expressions for several key performance measures in CR networks. Most notably, we derive the distribution of the length of an *effective white space*, and

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