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On the impact of primary traffic correlation in TV White Space☆

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ABSTRACT

In TV White Space, a secondary user must access periodically to a geolocated database to acquire the spectrum availability information. Furthermore, it can access on-demand to the database to update such an information. The more frequent are the on-demand accesses, the higher are the communication opportunities available to the secondary user but the higher is the induced overhead. Hence, in this manuscript, the on-demand access is investigated to a-priori determine whenever it is advantageous to perform it by accounting for the correlation exhibited by primary traffic patterns. To this aim, first the on-demand access is modeled through the general notions of reward and cost. Then, it is proved that the on-demand access maximizing the total reward available to the secondary user is a Markov Decision Process. Stemming from these results, a computational-efficient algorithm is designed. Finally, the theoretical analysis is validated through numerical simulations.

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1. Introduction

Nowadays, regulators worldwide are beginning to allow unlicensed access to unused segments of TV spectrum, known as TV White Space (TVWS) [1]. Secondary users (SUs) can access to the TVWS only if harmful interference on the primary users (PUs) is avoided. To this aim, the general consensus among FCC, Ofcom and ECC is on obviating the spectrum sensing [2–4] as the mechanism for the SUs to recognize and exploit portions of the TVWS spectrum whenever they are vacated by the licensed users. Instead, they require the SUs to periodically access to a geolocated database service [5–7], known as White Space DataBase (WSDB). Specifically, any SU must acquire the spectrum availability by accessing to a WSDB with a fixed timeframe. Within such a timeframe, the SU can freely access to the WSDB on-demand to update the spectrum availability information, but the specifics of the on-demand access are not detailed by the standards. The choice of whether or not to update the spectrum availability information through the on-demand access affects the overall performance of any secondary network. In fact, whenever the SU accesses to the WSDB, it can acquire some new knowledge on the current PU activities over the different channels. Hence, the more frequent are the on-demand accesses, the better the SU can exploit such availabilities to increase its communication opportunities. On the other hand, the more frequent are the on-demand accesses, the higher is the induced overhead.

Despite its importance, the on-demand database access issue in TVWS is still largely unexplored, since current research focuses on security issues [8], spectrum leasing [9], local sensing [10], or video streaming [11]. In [12] some preliminary results are obtained by assuming the PU traffic modeled as a Bernoulli process. Such an assumption is simplistic in TV scenarios, since the TV signal patterns are correlated [13,14], as confirmed by Fig. 1 reporting the PU

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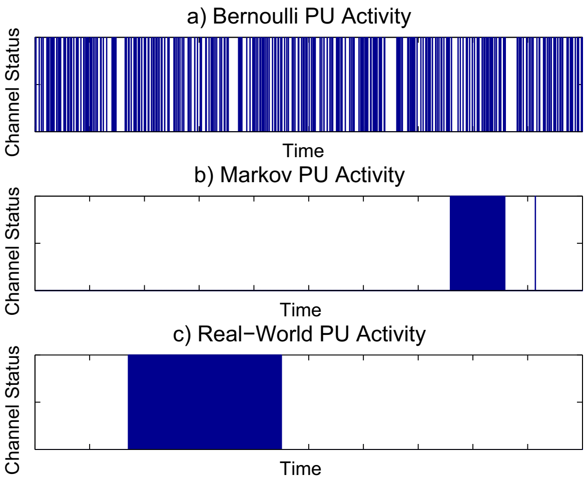

Fig. 1. PU activity pattern over 24 hours: (a) modeled as a Bernoulli process with parameter p modeling the PU on probability equal to 0.3; (b) modeled as a two-state Markov process with stationary distribution p modeling the PU on probability equal to 0.3; (c) measured in real world experiment [14]: channel 27, Zhongshan, Monday, Dataset 1.

activity experimentally measured [14] over a time interval equal to the timeframe between two mandatory database accesses as specified by FCC rulings [5], i.e., 24 h.

Hence, in the following, we investigate the on-demand database access by modeling the correlation among the PU traffic patterns through a two-state Markov process. As shown in Fig. 1, such a model is able to effectively describe the typical TVWS traffic patterns by properly setting the transition probabilities according to experimental measurements [14]. Specifically, the objective of this work is to determine *whenever it is convenient for an SU to access to the WSDB on-demand* in presence of correlated PU activity. This problem is not trivial, since the PU traffic correlation greatly complicates any theoretical analysis. Through the manuscript, we first model the WSDB accesses through the general notions of reward and cost. Then, by modeling the correlation among the PU traffic activities through a Markov process, we prove that the choice of the on-demand access maximizing the total reward available to the SU can be formulated as a Markov Decision Process. Furthermore, closed-form expressions for the decision transition probabilities are derived. Stemming from these results, we design a computational-efficient algorithm allowing any SU to a-priori establish whenever an on-demand access should be performed. Finally, we validate the analysis through numerical simulations.

To the best of our knowledge, this is the first work investigating the on-demand database access for TVWSs in presence of correlation among the PU traffic patterns.

The rest of the paper is organized as follows. In Section 2, we describe the network model along with some preliminaries. In Section 3, we design the optimal strategy, whereas in Section 4 we validate the analytical framework through numerical simulations. Finally, in Section 5, we conclude the paper.

2. Network model and preliminaries

In this section, we first describe the system model, and then we collect several definitions that will be used through the paper.

We consider a secondary network operating within the TVWS spectrum according to current regulations [5–7] and standards [15]. The SU time is organized into[1] L slots of duration T, with KT denoting the duration of a *database access period*. The database access period represents the time interval between two mandatory database accesses, i.e., K denotes the maximum number of consecutive time slots of duration T during which an SU is authorized to use the available TVWS spectrum without querying the database. Within a database access period KT, the SU can access on-demand to the WSDB for updating the spectrum availability information, which consists of a list of available channels and, for each channel, the duration of each authorization.

The spectrum is organized in M distinct channels, denoted with the set $\Omega = \{1, 2, \ldots, M\}$. The PU activity within channel $i \in \Omega$ during an arbitrary time slot is modeled as a two-state Markov process, and hence the activities in subsequent time slots are correlated each other. In the arbitrary nth time slot, the ith channel is available with probability $p_i \triangleq P(S_i(n) = 1)$ where $S_i(n)$ denotes the status of the ith channel, whereas the ith channel is unavailable with probability $q_i \triangleq P(S_i(n) = 0) = 1 - p_i$. By denoting with $p_i(0|1) \triangleq P(S_i(n+1) = 0|S_i(n) = 1)$, $p_i(1|1) = 1 - p_i(0|1)$, $p_i(0|0) \triangleq P(S_i(n+1) = 0|S_i(n) = 0)$ and $p_i(1|0) = 1 - p_i(0|0)$ the transition probabilities,[2] and by accounting for the Markov chain property, the following relations hold: $q_i = p_i(0|1)/(p_i(0|1) + p_i(1|0))$, $p_i = p_i(1|0)/(p_i(0|1) + p_i(1|0))$. Furthermore, $\{N_i(n) = x_i(n)\}$ denotes the availability of the ith channel for $x_i(n)$ consecutive time slots starting from time slot n.

Definition 1 (Reward and cost)**.** The non-negative *channel reward*[3] r_i represents the quality of the ith channel. The non-negative *database access cost* c represents the overall overhead associated with a database access.

Remark. We note that the notions of reward and cost given above can model a variety of real-world scenarios, given that the two notions are commensurable in terms of dimension(s). As instance, if the reward models the achievable average number of bits successfully transmitted through the channel during an arbitrary time slot, the cost should model the average number of bits exchanged during a database access.

Remark. In the following, we consider r_i and c as dimensionless quantities. In such a way, the proposed model achieves the following key features: (a) it abstracts the derived results from the particulars; (b) it restricts our attention on the effects of the database access strategy; (c) it can be

[1] Physically, the time horizon LT represents the time interval during which the SU plans to opportunistically use the TVWS spectrum.

[2] The SU can estimate the transition probabilities through the past PU activity histories [16,17].

[3] In the following, without loss of generality, we assume the channel set Ω ordered according to the channel rewards, i.e., $r_i \geq r_{i-1}$ $\forall i = 2, \ldots, M$.

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