Int. J. Electron. Commun. (AEÜ) 85 (2018) 12–22

Contents lists available at ScienceDirect

Int. J. Electron. Commun. (AEÜ)

journal homepage: www.elsevier.com/locate/aeue

Regular paper

Throughput optimization using availability analysis based spectrum sensing for a cognitive radio

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ARTICLE INFO

Keywords:
Cognitive radio
Semi-Markov Process
Bayes' risk
Average availability
Achievable throughput

ABSTRACT

Recently, cognitive radio has been projected to facilitate the utilization of vacant licensed frequency bands through dynamic spectrum access. Availability analysis of frequency bands may be considered necessary to avoid wastage of time to sense already occupied bands. In this article, we propose availability analysis by modeling the trend of state transition of a frequency band from occupied to vacant or vice versa as a two-state Semi-Markov Process. The state transition rates are treated as random variables and their estimates are found by Bayesian approach. We start the analysis with different prior distributions and find out respective posterior distributions of the state transition rates. Subsequently, Bayes' risk has been calculated using several loss functions and estimates are found out by minimizing it. Average availability is then calculated over a time horizon that consists of a number of time frames. Each frame is divided into sensing and transmission slots. Initially, a frame length has been calculated under constant false alarm and detection rates to maximize the achievable throughput. Next, the sensing time in a frame has been calculated under constant detection rate and average availability for maximizing the achievable throughput. Numerical results are provided to substantiate the findings.

1. Introduction

Recently, it is experienced that spectrum demand is high due to diverse wireless applications whereas traditional fixed spectrum allocation policy is unable to meet the requirement due to heterogeneous crowding in the available frequency bands [1]. Spectrum regulatory bodies like Federal Communication Commission (FCC) have their detailed studies about the usage patterns of different frequency bands. The studies reveal that spectrum is underutilized in different geographical regions [2]. Cognitive radio (CR) has been envisioned as a plausible solution to mitigate spectrum scarcity problem by exploiting underutilized licensed frequency bands through dynamic spectrum access (DSA) [3–7]. Spectrum sensing is the most essential task to find vacant frequency bands or spectrum holes and so far different methodologies have been proposed in different literature [8–10]. However, the sensing technique requires some time and there is enough possibility that spectrum sensing does not give fruitful result even after several attempts. This in turn may reduce the total throughput of the CR user due to wastage of time. There is always a trade-off between sensing time and throughput for a CR user [11–13] and consumption of time due to futile efforts in spectrum sensing can affect the performance. In this context, an intuitive approach for a CR user may be to analyze the spectrum usage pattern of a licensed or primary user (PU). Some prior knowledge regarding PU behavior can be utilized for spectrum sensing. This prior knowledge may be gathered from the studies of the spectrum regulatory bodies. Careful study of the available data may impart significant intelligence to a CR device. In this article, this study is termed as "availability analysis".

1.1. Related works

In recent times, some studies have been made to characterize the idle time (or wasted time) behavior of a CR device. In [14], the authors studied DSA in a CR network where the CR user has no idea about the PU behavior. Its communication has been modeled as a renewal process. They quantified the interference caused by the CR users in the renewal theory and found the optimized arrival rate and transmission time of the CR users in order to control the interference experienced by the PU. In [15], the authors considered an interweave CR network performance consisting of several CR users utilizing single channel. They derived the closed form expressions for the average interference and transmission time in a renewal cycle. In [16], the authors identified

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https://doi.org/10.1016/j.aeue.2017.12.024
Received 30 September 2017; Accepted 20 December 2017

some prediction techniques where an observation sequence is necessary to train the prediction models. The observation sequence can be obtained from the previous studies of a CR user regarding a frequency band. In [17], the authors suggested for neural network based multilayer perceptron (MLP) and Hidden Markov Model (HMM) for channel status prediction. They investigated both of the prediction techniques in details. In [18], the authors proposed channel quality prediction by modeling the spectrum sensing through non-stationary HMM. They inferred the parameters by means of Bayesian inference along with Gibbs sampling and utilized the parameters to predict the channel quality. In [19], the authors modeled the PU behavior using HMM and developed a channel switching simulator to study the SU performance. From the obtained results from GSM traffic, they validated that if the modeling is appropriate, the SU throughput increases while the PU disruption rate decreases. In [20], the authors considered spectrum prediction while maintaining energy efficiency and analyzed the SU model with and without spectrum prediction. In [21], the authors proposed a novel frame structure in case of cooperative spectrum sensing where the reporting time is also used for spectrum sensing. They defined a utility function that considers spectrum efficiency and energy efficiency simultaneously. In [22], the authors proposed spectrum monitoring in a CR network by exploiting spectrum prediction and mobility simultaneously for the detection of emergence of PU. They combined both results using different fusion rules and found closed form expressions of various parameters. In [23], the authors proposed a novel algorithm that can maximize the throughput of a CR in a network. They analyzed the spectrum access in a partially observable Markov decision process (POMDP). Yadav and Misra [24] considered the problem of temporal variation of channel availability in a CR network and proposed two novel algorithms on a specific network topology to ensure connectivity in the network. Determination of radio spectrum usage pattern by autocorrelation based scanning has been demonstrated in [25]. The authors exploited Universal Software Radio Peripherals (USRP) and GNU radio sequentially for practical realization of the proposed technique. In [26], the authors elaborated Kernel Based Learning (KBL) in details. They also enlightened on several potential applications of KBL in CR networks. In [27], the authors proposed for robust cooperative spectrum sensing in the crowd of low-end personal spectrum sensors. The proposition is effective to circumvent the problem of unreliable sensing results coming from the sensors. Detailed studies of sparse recovery algorithms for compressive sensing are presented in [28] that encompass the Bayesian category. In [29], the authors proposed a Bayesian recovery technique for signals in case of compressive sensing. Here the authors suggested a compressive sampling technique based on Toeplitz matrix following a Bayesian model for signal recovery.

1.2. Scope of the present work

The present work mainly demonstrates how to utilize already available data regarding a channel usage pattern in spectrum sensing. Thus the technique may be envisaged as a data-driven technique. Two states of a frequency band are considered – open or closed. The transition for a frequency band from closed to open states or vice versa has been modeled as a two-state Semi-Markov Process (SMP) where the sojourn times for state transitions are exponentially distributed. This is basically a two-state continuous time Markov chain (CTMC) [30–32] that involves sojourn times along with discrete time Markov chain (DTMC) corresponding to its transition probability matrix. The DTMC is also known as embedded Markov chain (EMC) associated with an SMP [32]. The transition rates between the states have been treated as random variables as in real time situations these rates will vary at different time points. Posterior distributions of the transition rates are found from respective prior distributions and the available data. Different standard loss functions are considered next to calculate the Bayes' risk. Subsequently, parameters are estimated by minimizing the Bayes' risk [33,34]. After the estimation, we find the average availability over the time horizon of interest. The calculated average availability is treated as the probability of vacancy of the channel during that time interval. It is then used to set some parameters of spectrum sensing. Here, we consider frame wise periodic sensing as proposed in [12]. The CR senses the channel for some time. If the channel is found idle, the CR transmits in the remaining time of the frame. The following assumptions are made:

1. All the estimated transition rates do not vary during the entire time limit of interest.
2. Total number of frames is fixed.

The achievable throughput in a frame can be found from [12] where the average availability plays a vital role. Under constant false alarm rate (CFAR) and constant detection rate (CDR) [35], we find an approximated closed form expression of a frame length to maximize the achievable throughput while sensing time is constant. In the very next section, a frame length is kept fixed under constant average availability (CAA). Under CAA and CDR situations, an approximated closed form expression of the sensing time is found to maximize the achievable throughput. The contributions of the paper can be summarized as follows:

- State transition rates are estimated by Bayesian method with the available data.
- The average availability has been calculated over the time interval of interest. This is the probability that the channel is idle during the time interval. The probability in turn becomes a function of the frame length. In the currently available literature, this probability is taken as a constant. This may not be always true.
- An approximated closed form expression of the optimum frame length has been computed for maximizing the achievable throughput under CFAR and CDR conditions.
- An approximated closed form expression of the sensing time has been found for maximizing the achievable throughput under CAA and CDR conditions.

A question may arise in this context that how much a detection performance is affected if availability analysis is not done. Spectrum prediction has also become popular of late where an observation sequence is required to train a prediction model. The observation sequence can be collected from some previous studies. However, this technique may not be effective after long time period. This is because within this period, the PU activity may change. For availability analysis no separate training is necessary. Basically, this technique gives clear guidance to choose frame length and sensing time simultaneously in periodic sensing. To the best of our knowledge, no such guidance is available till now. In [11], the authors have given a methodology to find frame length for maximizing throughput while sensing time is fixed. They formulated frame length with Lambert's W function. However, the solution space is very limited here. In [12], the authors tried to optimize sensing time but there is no guideline how to choose the frame length. In our analysis, sensing time in a frame is obtained under CFAR and CDR conditions and optimum frame length is formulated with the help of average availability expression. On the other hand, under CAA and CDR conditions, frame length gets fixed for constant average availability and optimum sensing time is obtained under constant detection probability. Thus availability analysis plays a vital role in both the cases of spectrum sensing.

The rest of the paper is organized as follows. Section 2 discusses the estimation of parameters by Bayesian approach. Section 3 elaborates the availability analysis. Computation of frame length under CFAR and CDR conditions is shown in Section 4. Computation of sensing time under CAA and CDR conditions is discussed in Section 5. Numerical results are given both in Sections 4 and 5 to validate the propositions.